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Game-Theoretical Approaches to Water Conflicts in International River Basins --A Case Study of the Nile Basin

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A dissertation submitted to the faculty of the University of North Carolina at Chapel Hill in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Curriculum of Public Policy Analysis.

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ABSTRACT

Game-Theoretical Approaches to Water Conflicts in International River Basins --A Case Study of the Nile Basin

Xun Wu

(Under the direction of Professor Dale Whittington)

Water has become a scarce resource globally due to the phenomenal population growth in the last century. As the demand for water increases and exclusively national sources of water are exhausted, the only major sources of water that remain to be developed in the twenty-first century are likely to be international in nature. As a result, conflicts among nation states over the use of water in international river basins have been intensified.

This dissertation presents an analytical framework to evaluate key policy and strategic questions facing riparian countries and international organizations in dealing with water conflicts in international rivers. In particular, through a case study of the Nile basin, we have developed an analytical framework by integrating hydrological modeling, operations research and game theory.

While water conflicts have often been perceived as "zero-sum" games in which one riparian country would have to lose in order for another riparian country to gain, our analyses indicate that water conflicts in the Nile basin are clearly not "zero-sum" games. We have shown in our analysis how game-theoretical concepts such as the core and the Shapley value can help decision makers and negotiators of riparian countries to better understand their strategic choices in negotiation. In particular, game theoretical results may help riparian countries to narrow down their differences, and thus to form a basis for negotiation. They also help riparian countries to understand the sources of their negotiation power. The framework established in this dissertation may also be of interest to international organizations that are often called upon to play a critical role in international water disputes. We have shown that the actions and policies of international organizations may shift the power structure among riparian countries in disputes, and such effects should be taken into consideration.

To my parents, Deyuan and Yunyun Wu

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Chapter 1 Introduction

Water has become a scarce resource globally due to the phenomenal population growth in the last century. In 1995, a total of 44 countries with a combined population of 733 million had per capita annual renewable water resources that can be classified as "water stressed[1]." By the year 2050, two of the world's most populous countries—China and India—will join the list of water stressed countries. The impacts of water scarcity have been felt throughout the world, especially in developing countries, where the population grows very rapidly but the means of sustaining such growth is severely constrained.

In the international arena, one of the direct impacts of water scarcity is that the conflicts among nation states over the use of water in international river basins have been intensified. In the Middle East, for example, virtually all of the major international river basins are contested. As the demand for water increases and exclusively national sources of water are exhausted, the only major sources of water that remain to be developed in the twenty-first century are likely to be international in nature (Biswas, 1993). In a race to expand water supply to meet the demand of growing populations, riparian countries may have put themselves on a collision course with one another by competing for the same resources. To avert such a collision, riparian countries need to learn quickly how to cooperate and negotiate with each other on the use of waters in international rivers—a task that is taking center stage in an era of global water shortage.

The full complexity of this task has been reflected by the struggles in many major international river basins. One of the most challenging issues is that the water allocation in international rivers has not been defined clearly by any international law or regulation, and as a result, property rights are not well defined for waters in international rivers. In addition, the rigidity of the notion of sovereignty makes it harder for riparian countries to cooperate and negotiate with each other.

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[1] A country is considered water-stressed if it has annual renewable water resources per person below 1,700 cubic meters (Postel, 1996).

Dellapenna noted that nations are seldom willing to compromise their sovereignty over a basic resource such as water (Dellapenna, 1995).

On the other hand, the stakes are too high to fail. Water conflicts in international rivers can severely damage international relations, undermine regional stability and impede economic prosperity for all countries involved. Some commentators and politicians predict that the wars of the twenty-first century will be over water (Scheumann and Schiffler, 1998). This research is motivated by the urgent needs to develop innovative frameworks and mechanisms for resolving water conflicts in international river basins.

This chapter begins with an assessment of the cause, nature, and consequence of water conflicts in international rivers. The complexity of conflict resolution efforts cannot be fully appreciated unless one understands the specific economic, political and legal contexts giving rise to conflicts. To this end, we provide a typology of water conflicts, and discuss different strategies for riparian countries and international organizations to resolve them. The second part of the chapter reviews the literature on game-theoretical approaches to water conflicts—the literature upon which the bulk of this research is built, and discusses why such approaches might be relevant to addressing water conflicts in international rivers. In the last section we present the objectives and the organization of the dissertation.

1.1 Water Conflicts in International River Basins

A. International River Basins and Water Conflicts

International rivers are rivers shared by two or more riparian countries. There are 214 international river basins (Biswas, 1993) around the world, covering almost one half of the total land surface and affecting about 40% of the population. In fact, except for those of Australia, central China and Sahara, most of world's rivers are international (Soffer, 1999). Table 1-1 shows the distribution of international river basins by continent.

Table 1-1 Distribution of international river basins

	# of International rivers
Africa	57
Americas	69
Europe	48
Asia	40

Due to rapid population growth and economic expansion in many countries, the global consumption of fresh water has increased about ten-fold in the last century. As alternative water supply sources become exhausted, water in international rivers has been increasingly looked upon by many riparian countries as a key strategic resource to meet the demands for food production and human consumption. Conflicts have arisen when water available in international rivers cannot meet the requirements of all riparian countries. In many international river basins, downstream states are often the principal users of the water (Dellapenna, 1995), but such use may soon be contested as upstream states begin to harness the same resources.

Another subject of disputes among riparian countries is the operating policies of river regulation facilities in international rivers. Because of the differences in objectives among different riparians in using the river regulation facilities, the operation of these facilities may benefit one party at the expense of the other. For example, the operations of reservoirs in Turkey and Syria have frequently been sources of tensions among the three riparian states sharing the Euphrates-Tigris River. In 1974, Turkey and Syria stopped the river flow to fill their reservoirs, and Iraq called up its army and concentrated on the border on the Syria to press it to release water. In 1990, Turkey again stopped the river flow for 30 days to fill its reservoirs. In all of these events, both hydropower generation and crop production downstream suffered as a result.

Water quality in international rivers is also an important source of conflicts among riparian countries (Just and Netanyahu, 1998). The conflicts over water quality are often caused by the failure of upstream riparian countries to take into consideration the adverse impacts of their actions on water quality for downstream riparians. For example, vegetation changes in Ethiopia highlands resulting from severe deforestation have not only increased abnormal floods and droughts in Ethiopia but also had adverse impacts on agricultural and human settlements in the lower Nile riparian countries (Woube, 1994).

Water conflicts in international river basins have already taken a heavy toll on economic development and political stability. In Jordan basin, for example, the disputes among four riparian countries, i.e. Lebanon, Syria, Jordan, Israel and Palestine, over water usage, were once perceived as among the key factors constraining the Middle East peace process. In the Nile basin, the lack of water resources development along the Blue Nile resulting from the conflicts among some major riparian countries is at least partially responsible for the devastating famine and starvation of millions of people in Ethiopia and Sudan during the 1980s. In the Mekong River basin, struggles among the riparian countries (Burma, China, Cambodia, Laos, Thailand and Vietnam) over the control and access to its resources historically have helped to fuel enmity among these countries and continued to hamper the realization of the river's largely unleashed potential. As the world population is expected to increase by 60% in the next 50 years, water conflicts in international river basins are likely to intensify and may lead to severe economic and political crises.

B. Conflict Resolution of Water Disputes

Considerable effort has been put into peaceful resolution of water conflicts in international rivers in the last several decades, and such effort has resulted in several promising developments in recently years. For example, in 1996 India and Bangladesh reached a landmark water-sharing agreement for resolving a two-decade long dispute between the two nations over the use of water in the Ganges River. In 1997, for the first time in history, the International Court of Justice has been called upon to settle the dispute between Hungary and Slovakia concerning the Gabcikovo-Nagymaros project in the Danube.

However, several emerging trends might undermine future efforts in conflict resolution. First of all, conflicts often escalate if riparian countries unilaterally proceed with their water projects with little or no consultation with other riparian countries. In the Euphrates-Tigris basin, Turkey has unilaterally launched an ambitious development scheme that, once completed, would reduce flow of the Euphrates from 30 billion to 16 billion m^3 on an annual basis to downstream riparian countries (Chalabi and Majzoub, 1995). In the Nile basin, Egypt is proceeding with its New Valley project while Ethiopia is exploring the potential of constructing micro dams along the Blue Nile (Waterbury and Whittington, 1999), despite the fact that neither is desirable from the point view of economic efficiency. Second, conflicts in many basins may be transformed from bilateral to multilateral ones as more riparian countries join existing users as potential contestants for the water. This is especially true now that the number of member states in the UN has gone up noticeably. The emerging multilateralism will have profound impacts on the negotiation and cooperation process. Although cooperation based on integrated river basin planning and management is the preferable solution for water conflicts, in practice such cooperation rarely takes place (Shapland, 1995). Without such cooperation, the options for conflict resolution are severely constrained.

The resolution of water conflicts in international rivers has been confronted with several difficulties. First of all, property rights of water in international rivers are not well defined by any international law or regulation. The *Helsinki rules*, the dominant principles for guiding water allocation and utilization in international rivers, call for "reasonable and equitable" water allocation based on such factors as geography, hydrology, needs, availability of alternatives, population size and prior use, but they stop short of articulating what constitutes "reasonable and equitable." As a result, it is up to individual riparian countries to interpret the meaning of the *Helsinki Rules*. In the Nile basin, for example, while Egypt's interpretation would undoubtedly give great weight to population size and prior use, Ethiopia would put more emphasis on each nation's contribution to the water flow and future irrigation potential.

Lack of clearly defined water rights has several important economic implications as well as political ones. Resource allocation mechanisms, such as the markets, often cannot be considered and utilized, because they are conditioned on well-defined property rights. In addition, as in the cases of other open access resources, lack of clearly defined property rights can lead to the wasteful uses of water in many countries, which further exacerbates the water shortages and intensifies the water conflicts.

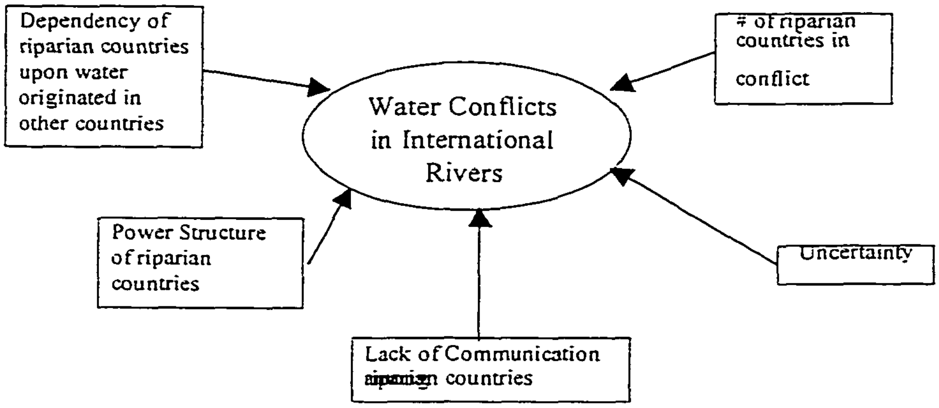
Uncertainty about the future may create commitment problems for riparian countries. It is not uncommon for riparian countries that the future supply and demand for water are both uncertain, and consequently, it is difficult for them to commit to any allocation schemes that might prove to be inadequate or unfair in the future. For example, although Ethiopia currently uses no water from the Nile, it has not yet committed any water for downstream uses. In the Euphrates-Tigris basin, although Turkey has set aside a certain amount of water for the two downstream riparian countries, it has made abundantly clear that "water in Euphrates-Tigris belongs to Turkey as oil belongs to Arab states."

A less recognized factor impeding conflict resolution is that internal conflicts over the management of water resources within national borders can also make the problems of international water conflicts more intractable. For example, the internal struggle between the south and north of Sudan has been a severe constraint on any effort to develop water conservation projects in the Sudd area.

C. A Typology of Water Conflicts in International Rivers

Conflicts in international rivers are not created equal, and comprehending such differences can help us to focus on international river basins where the intensity of conflicts is the greatest or where the involvement of third parties is the most warranted. Figure 1-1 shows some determining factors of water conflicts in international rivers.

Figure 1-1 Determining factors of water conflicts in international rivers



The first factor underlying water conflicts in international rivers is the number of riparian countries involved in conflicts. This is different from the total number of riparian countries in a particular international river in the sense that not all riparian countries are interested in using the water in the river. Particular attention should be directed to international rivers shared by more than two riparians, because the difficulties in resolving multilateral conflicts are much more pronounced than those with bilateral ones. When there are more than two riparian countries involved in conflicts, potential coalitions can be formed between (or among) groups of riparian countries, and, as we will see in the following chapters, this will change the dynamics of the negotiation process. The difficulties of dealing with multilateralism in international water conflicts have been demonstrated clearly by the fact that, while water conflicts are most acute in river basins shared by more than two riparian countries, there is virtually no water management agreement by more than two riparian countries in major international rivers.

Another factor influencing the formation and intensity of water conflicts is the disparity between contribution and use of water flow to the international rivers. Water conflicts are most acute where one or more riparian states have high dependence on water generated outside their borders. Table 1-2 shows the dependence of some selected riparian countries on water generated outside their borders. The high dependence would probably imply both issue rigidity—the room for negotiation is very narrow for these riparian countries, and flexibility—potential trade-offs can be made between losses in allocation and gains in long-term security.

Table 1-2: Dependence on water generated outside borders

Country	Share of total flow originating outside of border
Turkmenistan	98%
Egypt	97%
Hungary	95%
Mauritania	95%
Botswana	94%
Bulgaria	91%
Uzbekistan	91%
Netherlands	89%
Gambia	86%
Cambodia	82%
Syria	79%
Sudan	77%
Niger	68%
Iraq	66%
Bangladesh	42%
Thailand	39%
Jordan	36%
Senegal	34%
Israel	21%

Source: Sandra Postel, "Dividing the Waters: Food Security, Ecosystem Health, and the New Politics of Scarcity," *Worldwatch Paper* 132, 1996

The power structure among riparian countries can also have significant effects on the negotiation and cooperation in international rivers. The power of riparian states can be derived from their geographic, economic, political and military positions. Upstream riparian states possess the advantages to control the flow of rivers within their borders, and due to the unidirectional nature of such effects, downstream states often have little leverage to counter the moves made by upstream riparian countries. In some basins, political and military strengths of downstream states may serve to compensate for their geographic disadvantages: military strength can increase the credibility of making threats against adverse upstream development actions whilst political strength may be called upon to link water issues with other international issues. When the balance of all these advantages leans towards a single riparian country, hegemony of the river by that riparian country can be expected and the focus of attention may be shifted to conflicts among the rest of the riparian countries. Turkey in Euphrates-Tigris River can be regarded as a good example of such hegemony. In most basins, upstream countries are often more powerful in political, economic and military terms while geographic advantages rest with downstream states.

In his discussion of conflict resolution, Deutsch (1992) points out that the characteristic processes and effects elicited by a given type of social relationship (for example, cooperative and competitive) tend to reinforce that particularly type of social relationship. This is important in water conflicts in international rivers since conflicts might be the consequence of perceived differences rather than the actual ones, or even the results of miscommunication among the riparian countries. Therefore, the opportunity for contacts, channels of communication, and quality of dialogue among riparian countries may determine the outcome of conflict resolution.

The level of uncertainty is another factor that can differentiate water conflicts in international rivers. Cooperation may be more difficult to achieve when information on future demand and supply is highly uncertain for riparian countries. Long-term agreements on water allocation are difficult to reach because riparian countries' fear being locked into certain regimes that might be inadequate in the future. The level of uncertainty can be especially high for upstream riparian states where harnessing the resources in international rivers might be a relatively new venture. Furthermore, political instability of some riparian countries can also be a source of uncertainty. For example, in the Nile basin, the political unrest of Sudan and Ethiopia has created a commitment problem for Egypt: while it appears anxious to settle water allocation for the long haul, any agreement reached might be short-lived if the political regimes in upstream countries are not stable.

In order to summarize our analysis of water conflicts, the following comments can be given:

- The most acute water conflicts are those among three or more riparian countries, and emphasis should be placed on dealing with the aspects of multilateralism in conflict resolution
- Conflicts abound for international rivers where one or more riparian countries depend heavily upon water that originates outside their border(s)
- Balance of power is critical in conflict resolution; the hegemony of power may undermine efforts at conflict resolution
- The ability to resolve conflicts is enhanced by good communication among riparian countries
- Uncertainty about future demand and supply as well as political instability makes it difficult for riparian countries to reach water allocation agreements

D. Research Needs in Conflict Resolution

Perhaps one of the reasons for the limited progress in conflict resolution in international rivers is that the challenges posed by the water conflicts have not been fully embraced by the water research community.

The various theories and models for conflict resolution in international rivers can be broadly categorized into two approaches: process approach and outcome approach. The first approach draws heavily from insights of politicians and negotiation experts who emphasize capacity and institutions that would lead to either cooperation or conflict. While this approach helps us to understand why conflicts occur or why cooperation is imperative, it typically provides few insights into the questions of resource allocation among riparian countries.

The second approach is derived mostly from the work of engineers or economists, who often promise the "optimal" or "best" solutions that are grounded on the economic notion of Pareto optimality. While such an approach to river basin management might be more successful in dealing with issues of water allocation or usage among different regions or different sectors within a country (Tennessee Valley Authority, for example), it might not be directly applicable to international rivers because the benefits and costs are not confined by the national borders. The efficiency gains from cooperation in international rivers will only become relevant for individual riparian countries when the appropriate institutions exist to guarantee their incentives to cooperate. In addition, given the uncertainty on current and future demand and supply, a severe limitation of this approach is that the acceptance of the generated "optimal" results relies on whether or not different actors in the dispute can agree upon the parameter values and assumptions used in the analysis.

In addition, while water conflicts are the most acute in international rivers shared by more than two riparian countries (the Nile, the Tigris-Euphrates, the Jordan, and the Mekong, to name a few), specific difficulties arising from the multilateral nature of the conflicts have been largely neglected in the current literature. Due to the potential of partial coalitions formed by two or more riparian countries, and strategic interactions between different groups, the dynamics of water conflicts in a multilateral context differ dramatically from those in a bilateral context.

The divergence between theory and reality in dealing with international water conflicts has created a golden opportunity for quality policy analysis to make an important contribution. To materialize the opportunities of cooperation that are widely available in many major international rivers, solutions based on basin-wide planning and management would have to be assessed in the context defined by political reality and institutional feasibility. Therefore, policy analysis of conflict resolution may benefit from combining the research of both the process approach and the outcome approach.

Policy analysis can contribute to the real decision-making process only if it can address the most urgent questions facing political leaders or negotiators in riparian countries. Such questions may include the following:

- What are the economic consequences of foregoing cooperation?
- How to assess the trade-off between reaching agreement now and reaching agreement in the future?
- How to evaluate allocation proposals put forward by other riparian countries?
- What information is required to evaluate different alternatives?

International organizations looking for more active roles in conflict resolution also encounter several critical questions:

- When would the third party's involvement in conflict resolution be most effective?
- What positions should international organizations take in providing financing for development projects in disputed international rivers?
- How would such positions alter the outcome of negotiations among riparian countries?

In this research, we apply the concepts and theories of game theory to systematically address these and other important questions in international water conflicts. An emphasis on game theory as an important research tool is warranted because game theory can provide insights into important issues in multilateral negotiation, such as why nations form cooperative schemes and how such schemes could be sustained in the presence of potential partial coalitions by a sub-group of riparian countries. The following section examines the relevance of game theory to the conflict resolution in international rivers.

1.2 *Game Theory and Water Conflicts: A Survey*

As a science of strategic interaction, game theory is suitable for analyzing water conflicts in international rivers. In fact, in the past two decades, the literature on application of game-theory models to water resource management has grown considerably. It has extended to areas such as cost allocation (Gately, 1971; Young, Okida and Hashimoto, 1982; Tijs and Driessen, 1986), benefit allocation (Dufournaud and Harrington, 1990 and 1991; Dinar, Ratner and Yaron, 1992; Dinar and Wolf, 1994), water quality (Strobele, 1992; Frisvoid and Schimmelpfenig, 1998; Lichtenberg and Olsen, 1998) and water development projects (Frisvold and Caswell, 1997). However, the application of game-theoretical approaches to water conflicts in international rivers has been rare, and more important, game-theoretical approaches so far have contributed little to real decision-making in conflict resolution for international rivers.

A. Conceptual Framework for Analysis

The prototype of game-theoretical models is familiar to people with training in economics. The "prisoner's dilemma," for example, describes a situation where it is in both parties' best interest not to cooperate, given that the game will not be repeated infinitely. Games of this sort are referred to as "non-cooperative" games, and their analysis has been the main focus of mainstream game theory research. In water resources management, however, cooperative game theory has taken the center stage. This should not come as a surprise as very few games involving river basins are zero-sum types, and games can normally be "replayed" many times as long as participants desire. Here we introduce several concepts germane to our analysis.

A cooperative 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 utility function for each player measuring benefits as a function of the chosen coalition. To illustrate, let's suppose that three riparian countries denoted A, B, and C share an international river basin. They each can act independently or form coalitions with other countries, and hypothetical payoffs for all possible coalitions are displayed in Table 1-3.

Coalitions 1, 2 and 3 describe the payoffs for the three riparian countries when they act independently; Coalitions 4, 5 and 6 are partial coalitions between two of the three countries; and lastly, Coalition 7 represents basin-wide full cooperation. Except for the coalition between A and C, the payoffs from coalitions are greater than the sum of payoffs that countries in the coalitions can receive when they act independently. The gains from cooperation are common in the river basin management, as different users of water often have comparative advantage over the different aspects of water usage. For example, A may have good sites for hydropower generation and thus can offer cheap power; B may have large amounts of irrigable land and therefore its agricultural production is the most cost-efficient; lastly, C may be able to offer financial resources necessary for A and B to develop hydropower and irrigation schemes.

Table 1-3: Payoff for coalition formation

Coalition	Countries in the Coalition	Payoff for the Coalition
1	A	2
2	B	3
3	C	5
4	A and B	8
5	A and C	7
6	B and C	10
7	A, B and C	14

The first concept that is important for constructing game-theoretical models for water resource issues is the core. *The core is the set of feasible payoff allocations for which there is no other coalition that can obtain higher payoffs for all its members.* Let's examine some of the potential allocations for our hypothetical example. The total excess of payoffs for full cooperation case is 4 (14-2-3-5=4) compared to the scenario where all countries act independently. Suppose first that each country receives the same share of the total excess (1.3 per country), that is, an allocation of 3.3, 4.3 and 6.3 for A, B and C, respectively. This allocation is not in the core since A and B can both do better by deviating from full cooperation to the coalition between A and B. If A and B split the excess gains of this coalition, that is, an allocation of 3.5 and 4.5 respectively, then they both do better than the allocation for the full cooperation case. On the other hand, to allocate all the excess payoffs to A and B, for example, (4, 5, 5), can in fact be in the core, since there is no profitable coalition that would offer better payoffs for any two of these three countries.

As a matter of fact, a lot of allocations are in the core. Suppose X_a, X_b, and X_c are gains allocated to A, B and C, respectively, then the allocation (X_a, X_b, X_c) is in core as long as it satisfies the following conditions: 1) $X_a >= 2$, $X_b >= 3$, $X_c >= 5$; 2) $X_a + X_b >= 8$, $X_a + X_c >= 7$ and $X_b + X_c >= 10$, and 3) $X_a + X_b + X_c = 14$. Using the above rules, allocations such as (3.6, 4.4, 6), (3.8, 5, 5.2) and (3, 5.5, 5.5) are all in the core.

The "Core" is an essential economic concept, and its significance is that it depicts the incentives necessary to induce cooperation among all members of the grand coalition. It offers a starting point for different users in water resource negotiations, but it has two apparent shortcomings.

The first is that the core contains multiple allocations but it offers no rules to compare them. The second issue is that, although there is no profitable deviation for any of the water users in a core, a particular user may be motivated to deviate by the prospect that doing so might induce a different core allocation which is more favorable for it.

Several point solutions are devised to address these issues. The *nucleolus* is one of such point solution concept. *The nucleolus is the set of imputations under which the coalition least exceeds its independent payoff.* For an allocation (X_a, X_b, X_c), V(R)-$\Sigma(X_i)$ for *i* can be viewed as the objection raised by a coalition R against this allocation, and *nucleolus* chooses the payoff that minimizes the maximum objection, that is,

$$\underset{Xi}{Min}\{\underset{R}{Max}[V(R)-\sum_{i\in R} Xi]\}$$

Using a simple linear programming model to solve the above optimization problem[1], the nucleolus of this allocation game is (3.5, 5, 5.5). It is of special interest to point out that the nucleolus solution is consistent with Rawls' notion of "the veil of ignorance," that is, it is the allocation that would result if no player knows his or her future identity (Loehman, 1995). Therefore, in essence nucleolus maximizes the worst situation of all players.

Another important point solution is the *Shapley Value*. The Shapley value is the solution that complies with three axioms: symmetry, carrier and additivity. The symmetry axiom requires that players have equal probability weights; the carrier axiom means that gains of a coalition will be allocated fully among all players. The Shapley value can be computed with the following formula:

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

, where N is any finite carrier of v.

This formula indicates that the Shapley value for play *i* in game v is the weighted sum of terms of the form [v(S)-v(S-i)], which are player i's marginal contribution to coalition S. Therefore, the Shapley value can be interpreted as the solution corresponding to the marginal contribution of players in coalition.

For our hypothetical example, the Shapley value of the game can be calculated as follows:

$\phi(A)=(1/3)*(14-10)+(1/6)*(8-3)+(1/6)*(7-5)+(1/3)*(2-0)=19/6$

$\phi(B)=(1/3)*(14-7)+(1/6)*(10-5)+(1/6)*(8-2)+(1/3)*(3-0)=31/6$

$\phi(C)=(1/3)*(14-8)+(1/6)*(7-2)+(1/6)*(10-3)+(1/3)*(5-0)=34/6$

Several refinements of the Shapley value are also available for the concept to be more adaptable to various situations. *Generalized Shapley value* arises from the situation where players do not have equal probability to join the coalition[2], and some players might not join the grand coalition until some other players have joined. The *Shapley Nucleolus* is the solution that incorporates both the core and the Shapley value, as Shapley value might not be in the core. It aims to generate a Shapley value that is in the core.

Some recent work has also focused on Nash bargaining solutions (Loehman, 1995; Dinar, Ratner and Yaron, 1992; Just and Netanyahu, 1998). The Nash bargaining solution is not based on the characteristic function; instead it compares the utility distance for each player from a disagreement position and equalizes the utility gains for each player compared with a disagreement position. The Nash bargaining solution is closely related to the Shapley value. Harsanyi (1959) shows that for n-person games with transferable utility, the Nash bargaining solution is the same as the Shapley value.

It is important to point out that the above concepts (with the exception of nucleolus which depends on the assumption of transferable utility) can be developed under two broad frameworks: games with transferable utility (TU) and games without transferable utility (NTU). In general, TU is an unwelcome assumption in many economic situations, but developing solution concepts under NTU would introduce some additional difficulties. The implications of dropping the TU assumption in modeling water conflicts have not been fully understood, and it will be one of the issues addressed in this research.

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[1] It is not easy to give a general formula for calculate the nucleolus, and as a result, mathematics software with optimization algorithm is often used for calculation.

[2] The symmetry axiom for Shapley value requires that players who are treated identically by the characteristic function be treated identically by the value. In some situation, lack of symmetry may be present. For example, for a particular coalition to sustain, a greater effort is needed on the part of player A than on the part of player B; or player A may represent a large constituency while player B has small constituency. A generalized Shapley value is able to represent these differences.

In the remaining part of this section, we will discuss the application of game theory models in three important areas: cost or benefit allocation games, water quality games and games with incomplete and imperfect information. At the end of the section, we will provide a summary of the lesson from this literature.

B. Cost or Benefit Allocation Games

Cost allocation problems were among the first to receive attention in the literature on game theory and water conflicts. Gately (1971) considers a game of allocating gains from regional cooperation in electric power investment planning in Southern India. Each of the three areas studied can expand its electric power system either by being self-sufficient or by cooperating with other area(s). With the solutions from a mixed-integer programming model of investment planning, costs of expanding and operating the electric power system under different assumptions of cooperation are obtained, and the core of the game is identified. One of his contributions is the use of the concept "*propensity to disrupt*," by which he refers to the ratio of how much the other two players would lose if *i* refused to cooperate to how much *i* would lose if it refused to cooperate. A high value of "propensity to disrupt" means that the other two players would have much more to lose than player *i* without the cooperation, and player *i* can credibly carry out a threat of breaking up cooperation in the hope of achieving greater gains from the allocation. Two interesting findings of his study are: 1) some ethically appealing allocation principles, such as equal shares or equal ratio of total final costs to costs under self-sufficiency, cannot yield solutions that are in the core, as they do not take into account the bargaining power of each player; 2) in the cases with the Shapley value and the equal propensity to disrupt, mutually acceptable allocations can be obtained. Another important feature of his study is that investment and operation decisions are jointly considered.

Dufournaud (1982) argues that the addition of temporal considerations would have significant impacts on the solutions of the games. This is so because the spatial and temporal schedule for constructing the water development projects might leave some riparians vulnerable should cooperation not last until the end of the planning period. Dufournaud and Harrington (1990 and 1991) present a game-theoretical model that incorporates both the spatial and temporal dimensions of the decisions encountered by riparians. Their model involves three riparian countries and two time periods. Coalition can be formed in any of these periods and a riparian may break down the coalition after the first period. Using a linear programming model, they estimate the temporal and spatial distribution of benefits and costs among riparian countries to equalize *the propensities to disrupt* in each period. An interesting feature of their research is the discussion of the role played by the outsiders and the estimation of outside funding required for sustaining the cooperative scheme. The presence of the outsiders and outside funding might lead to some cooperative schemes that otherwise would be unattainable.

In "Evaluating Cooperative Game Theory in Water Resources," Dinar, Ratner and Yaron (1994) provide a critical assessment of the usefulness of using cooperative game theory in water resource management. Two difficulties encountered in these applications are discussed: 1) the assumption of utility as linear in money leads to questionable results; and 2) the soundness of utility transfer may not be obtained since the predetermined price per unit of water is often questionable and disputable among the riparians. They warn that although the game theory model can provide better understanding of the problems and could be useful in bargaining and arbitration, one should not expect to derive some clear-cut solutions from such modeling. Through two cases involving both water quantity and water quality conflicts, they conclude: 1) the use of utility functions leads to problems in gains allocation; 2) the core concept may be useless because it may either be too difficult to calculate or is empty in many cases; 3) gains allocation and the derived core are heavily dependent on probabilities of coalitions formation in the Shapley value or the Generalized Shapley Value.

Just and Netanyahu (1998) echo some of the same concerns raised by Dinar, Ratner and Yaron (1994). In addition, they discuss two assumptions often made in cooperative game theory models: that the selection of actions is made independently by members and non-members; and that the coalition's utility level is not affected by actions taken by nonmembers (Greenberg, 1994). These assumptions are unlikely to hold for international river basins, because when partial coalitions are considered, actions taken and utility gained by individual countries belonging to particular coalitions are clearly dependent on actions taken by nonmembers of the coalitions. Their model shows that the choice of partial rather than grand coalitions may be optimal when the transaction costs for forming the grand coalitions are formidable, or when water conservation encounters decreasing return to scale.

C. Water Quality Games

Conflicts over water quality have been seen in many international river basins (Postel, 1991). Consequently, the literature on water quality games has expanded rapidly; the applications surveyed here offer a flavor of this literature.

The first application we include here involves the principal-agent model. Although it's hard to imagine assigning the roles of "principal" and "agent" to riparian countries all with sovereign rights, the principal-agent model could potentially be very useful in the analysis of water conflicts in international rivers (Just and Netanyahu, 1998). Strobele (1991) analyzes an upstream-downstream water pollution problem with a principal-agent model. The information structure of the model is that the agent (the upstream party) knows perfectly what kind of action he has taken, but the principal (the downstream party) can only have observations of the outcome of water quality, which depends both on the states of the nature and actions taken by the agent. The principal wants to induce a certain behavior of the agent by offering a payment that depends on observed water quality.

Free riding is a persistent problem for any international agreement involving environmental resources including water in international river basins: each country has an incentive to allow others to abate pollution while withholding its own abatement effort. Due to the lack of effective mechanisms to prevent free-riding problems, recent theoretical research on self-enforcing international environmental agreements has been rather pessimistic (Frisvold and Schimmelpfenig, 1998). For example, Barrett (1994) concludes that a self-enforcing international environmental agreement involving many countries cannot be sustained in cases where potential gains from full cooperation are large. Contrary to such a view, Frisvold and Schimmelpfennig (1997) present a simple static model where countries negotiate an international environmental agreement to abate pollution of a shared water resource, and show that such agreement can be successful in dealing with trans-boundary water pollution problems. The international agreements will be especially effective for two cases: the one with few number of agents (5 or less) and the other involving many agents but the pollution is concentrated among a small number of agents. It is clear that the first case is particularly relevant for international water agreements as the number of negotiating countries is often fewer than five.

A cooperative bargaining framework is also appropriate where the number of riparians is few. Frisvold and Caswell (1997) employ a Nash bargaining framework to explore the potential benefits of bilateral negotiations over the transfer of water. The Nash solution maximizes the product of the net gains over the disagreement outcomes, and in their case, it requires that the marginal treatment costs be equalized across agencies. They find that increasing water available upstream generates an external benefit to the downstream party, offering an opportunity for the upstream and downstream users to jointly financing the projects to increase water quantity at the upstream sites. As in other bargaining solution, the implementation of the efficient contracts reached would require that terms of contract be readily monitored and enforceable.

D. Games with Incomplete or Imperfect Information

The literature on game-theoretical approaches to water conflicts is mostly developed in a deterministic environment. However, the water resource issues are full of uncertainty. For example, weather conditions may change farmers' demand for water and thus alter its economic value; political supports required by a certain coalition between two riparian countries might not be forthcoming following a revolution or other dramatic events. In addition, nation states may seek advantage in negotiation by withholding information from their negotiation partners.

Drawing from the literature on international macroeconomics policy coordination, Netanyahu (1998) studies the impact of uncertainty on the gains from cooperation over the management of water in international rivers. He investigates two types of uncertainty: additive and multiplicative. The additive uncertainties, such as exogenous agricultural demand or water reserve shocks, refer to shocks that affect government targets but do not change the effectiveness of its policy instruments, while multiplicative uncertainties refer to possible changes in government targets (for example, due to technological innovation), which affect the policy instruments. His findings are that the existence of multiplicative uncertainty is the key condition for gains from coordination while under either certainty or additive shocks, there is no incentive to coordinate trans-boundary policies.

In international river basin modeling, it is common that water availability and their benefits are uncertain. Moreover, these benefits will to a degree be privately held information. In "The Efficient Sharing of an Uncertain Natural Resource: A Contract Theory Approach," Barrett

(1998) considers a game where both the aggregate water availability and the benefits to individual parties are uncertain. He examines the implications of various contract structures to determine how well various pricing and control strategies fare in the Lesotho Highlands project. He concludes that nonlinear pricing could greatly enhance efficiency and that control should be given to the party with more variable marginal benefits or to the party with greater marginal benefits.

Water resource development projects are also important sources of tensions in international rivers. Downstream countries often feel insecure about any construction of upstream water resource development projects as these projects might affect the quantity and quality of water arriving at the downstream countries. As the hostility among riparians intensifies, it is possible that conflicts may lead to a water war or the destruction of the projects. Tsur and Zemel (1997) consider the political uncertainty in the form of sudden, discrete events that upon occurrence may irreversibly damage or terminate the development project. The impacts of such political uncertainty on project value and project duration are analyzed. They show that there will be a loss of project value, and that under such loss, the project owners will consider incentive schemes to expedite their operations while an optimal strategy might call for more prudent investment policy.

E. Summary and Comments

Several observations are in order to conclude our survey of the literature on game theory and water conflicts. First of all, more sophistication in modeling is required if solutions from game-theoretical approaches are to be taken more seriously. With few exceptions, most studies so far have relied upon either numerical examples or extremely simplified engineering models to support their analytical findings. While the potential of such models is undeniable, practitioners may quickly discard the outcomes of these models on grounds that they are inaccurate. In fact, barriers and opportunities may be neglected because the analyst chooses to ignore some geographic, hydrological or institutional details.

In addition, while applications of the game-theoretical approach typically assume that the actors know the structure of the game and everything else about it, they certainly leave out a great deal of what is critical in many conflicts. There are several circumstances where a player may not know fully the structure of the game he is engaged in. He might not be completely aware of all actors in the conflicts; he might not know what the preferences of his opponents are; or he might not know the strategies that his opponents are able to play. The analysis of strategic choices under these circumstances has not been explored in the current literature, but it is this kind of analysis that decision-makers may be most anxious to have.

Last, the influence of the game-theoretical approaches on water resource problems has so far been rather limited, not to mention the area of water conflicts in international rivers. Aside from the fact that negotiators and politicians often lack the training in economics to for them to fully appreciate the benefits of using game-theoretical models, game-theoretical solutions need to be interpreted with great care, and their equity implications should be assessed fully. It is important to note that efficiency gains only constitute one set of criteria employed by riparian countries.

To make game-theoretical approaches more applicable for policy purposes, attention should be directed to several key barriers of cooperation; they are, namely, information asymmetry, uncertainty, and unidirectional externality. *Information asymmetry* results from the fact that riparian countries generally have differential access to information due to their geographic locations or data processing abilities, and in many cases, it might be in their best interest to withhold such information from other riparian countries. *Uncertainty* also plays an important role because it is not uncommon in international river basins that both the supply and demand for water for the future is uncertain. and consequently, it would be difficult for a riparian to commit to certain allocation schemes in such situations. *Unidirectional externality* implies that the countries controlling the sources of water (often the upstream riparian countries) normally hold the dominant positions in water negotiation, and in comparison, downstream countries lack the necessary leverage to balance against the demand made by upstream riparian countries. In addition, while most studies typically assume transferable utility, which requires income to be redistributed freely among riparian countries, such assumption might not make sense in cases where side payments among countries are not politically feasible. This dissertation seeksto make a contribution to the literature by examining the effects of asymmetric information, uncertainty and unidirectional externality on cooperative solutions.

1.3 Objectives and Organizations

The Nile basin provides a unique opportunity for the study of international water conflicts in this dissertation. First, the challenges faced by the Nile basin riparians are the familiar ones for other major international rivers. The population in the basin has increased by 250% in the last fifty years, and it will double over the next 25 years. In order to sustain population growth of such magnitude, all of the 10 riparian countries are embarking on ambitious plans to increase food production by using Nile water. A cursory look at the irrigation schemes planned by these countries indicates that the water deficit for the basin can easily be over 20 billions cubic meters annually (Kliot, 1994). Second, driven by the severe consequences of the potential water crises and the urgent needs to resolve the water conflicts, the Nile riparian countries are ready to launch an unprecedented quest for innovative solutions to water conflicts. More than ever before, the leaders of these countries are prepared to engage in discourse that can lead to water-sharing agreements and cooperative schemes for the Nile. Third, with access to new information and our involvement in the Nile Basin Initiative launched by several international organizations, we are in a unique position to interact with some key policy makers in the area and respond to problems with immediate practical implications.

Within the context of the Nile basin, we will examine several policy issues dealing with water conflicts in international rivers. First of all, while the benefits of cooperation in international rivers may be apparent and unambiguous, the causes and nature of barriers to such cooperation are not well understood. As a result, decisions responding to the immediate needs may quickly become inadequate as a sequence of new events unfolds. Prudent decision-making should be aimed at creating appropriate institutions to sustain cooperation in the long run. Second, while the arguments of cooperation often stem from efficiency considerations, the current policy discussion about water allocation in international rivers has been largely dominated by arguments based on various versions of "fairness." Here, we argue that some game-theoretical solutions may serve as convergence points between equity and efficiency because of the equity considerations embedded in these solutions. Third, international organizations are likely to play a more important role in conflict resolution in international rivers, but so far the efficiency and equity implications of their involvement have not been fully understood. In the dissertation, we will show how the involvement of international organizations may affect the outcome of allocation games among riparian countries.

Chapter 2 consists of three parts. The first part depicts conflicts in the Nile basin through an analysis of the hydrology and economy of the basin. In the second part, we present the Nile Economic Optimization Model (NEOM)—a model based on systems analysis and economic optimization—and assess benefits of cooperation in the Nile basin. We will show how the water would be best utilized from the point of view of maximizing the overall economic benefits for the whole basin. While acknowledging various political obstacles to cooperation, we show that economic costs of foregoing cooperative initiatives can be quite expensive. In the last part, we introduce two applications of the NEOM and show how the economic optimization model can be used to aid the decision-making process. In particular, we will measure the potential costs to the whole basin when various political constraints--such as existing water allocation agreements or minimum (or maximum) water withdrawal for one or more riparian countries--are imposed. In addition, illustrative examples are provided to show how the economic optimization model can be used in evaluating key capital investment projects in the Nile.

From Chapter 3 on, we start to look at the allocation of benefits among riparian countries. We apply the economic theory of the core to identify negotiation boundaries for each riparian country. Knowing the negotiation boundaries is important for both riparian countries and international organizations, because it would afford them a quick way to evaluate proposals put forth by other riparian countries. Knowledge of the core can help them save political resources because it allows them to focus on the range where successful resolution is more likely. In Chapter 3 we will also analyze proposals based on a variety of proportionality rules and to evaluate whether or not these proposals fall into the core of the game. Finally, we calculate Shapley value and Nucleolus of the Nile water allocation game and discuss how these solutions might be relevant to decision-makers of individual riparian countries.

The effects of imperfect and incomplete information on conflict resolution are the main subjects of Chapter 4. In the first section, we consider a multi-year economic optimization model to characterize the situation where the future water availability is uncertain. Specifically, we will use different sequences of hydrological data to represent the variation of water availability over time and analyze how each country's negotiation powers might change. In the second section, we consider the case where the value of water for irrigation is uncertain for all riparian countries and analyze how the core would change. In the last section, we evaluate the impacts of uncertainty in water resources development projects on the negotiation powers of individual riparian countries.

Chapter 5 is aimed at assessing the role of international organizations in conflict resolution in international rivers. While the involvement of international organizations in international water conflicts is critical, the efficiency and equity implications of such involvement are not well understood. In the Nile basin, for example, if international organizations restrain themselves from financing disputed projects in upstream countries, this is no different than conferring a veto power to downstream countries. On the other hand, the upstream countries may not have enough incentive to participate in any negotiation unless they are convinced that development assistance for financing of projects will not be forthcoming in the absence of any agreement among riparian countries. Through our case study of the Nile Basin, we assess the role of international organizations in conflict resolution as lending institutions and deal brokers.

Finally, in the concluding chapter we discuss the implications of our study for cooperation and negotiation for the Nile basin. We also offer some insights on how the analytical tools such as the ones presented in this dissertation can help to enrich policy discussion of conflict resolution for international water conflicts.

Chapter 2 Measuring the Economic Benefits of Cooperation: An Economic Optimization Model for the Nile Basin

Cooperation may mean that a downstream riparian country must trust its upstream neighbor(s) to restore its irrigation water; or it may require a riparian country to forego its rights to divert water for consumptive purposes because such water yields higher economic return elsewhere. Not surprisingly, such cooperative behaviors are likely to be challenged by the political reality facing most riparian countries. Sovereignty over a basic resource such as water and the desire to achieve food self-sufficiency are often driving considerations for riparian countries and these considerations can easily pre-empt any initiative for cooperation. In addition, while the benefits from cooperation may not materialize until far into the future, the political costs of arranging cooperation are of immediate nature, entailing high political risks that leaders of individual riparian countries might hesitate to take. The high political costs of cooperative initiatives imply that, unless the economic gains from cooperation are large enough, cooperation in international rivers will be very difficult to achieve.

Perhaps an important factor accounting for the lack of success in cooperation in international rivers is that the magnitude of potential gains from cooperation is largely unknown for many international rivers. As a result, riparian countries may have an incomplete or even inaccurate knowledge of the cooperative opportunities, and consequently water conflicts in international rivers have often been mistakenly perceived as zero-sum games, for which one riparian country's gains are necessarily another riparian country's losses. In order for cooperative initiatives to move forward, the first and foremost task is to measure the economic benefits of cooperation.

In the Nile basin, the ten riparian countries sharing the river face a challenge that is familiar to other major international rivers. On one hand, water available in the Nile basin cannot meet the demands of riparian countries; but on the other hand, significant benefits from harnessing the resource have yet to materialize due to lack of cooperation among key riparian countries. In this chapter, we will use the Nile Economic Optimization Model (NEOM)—a model based on systems analysis and economic optimization—to assess the economic implications of different investment strategies faced by the Nile riparians.

2.1 Nile Basin: Its Hydrology, Economy and Water Conflicts

A. Nile Hydrology

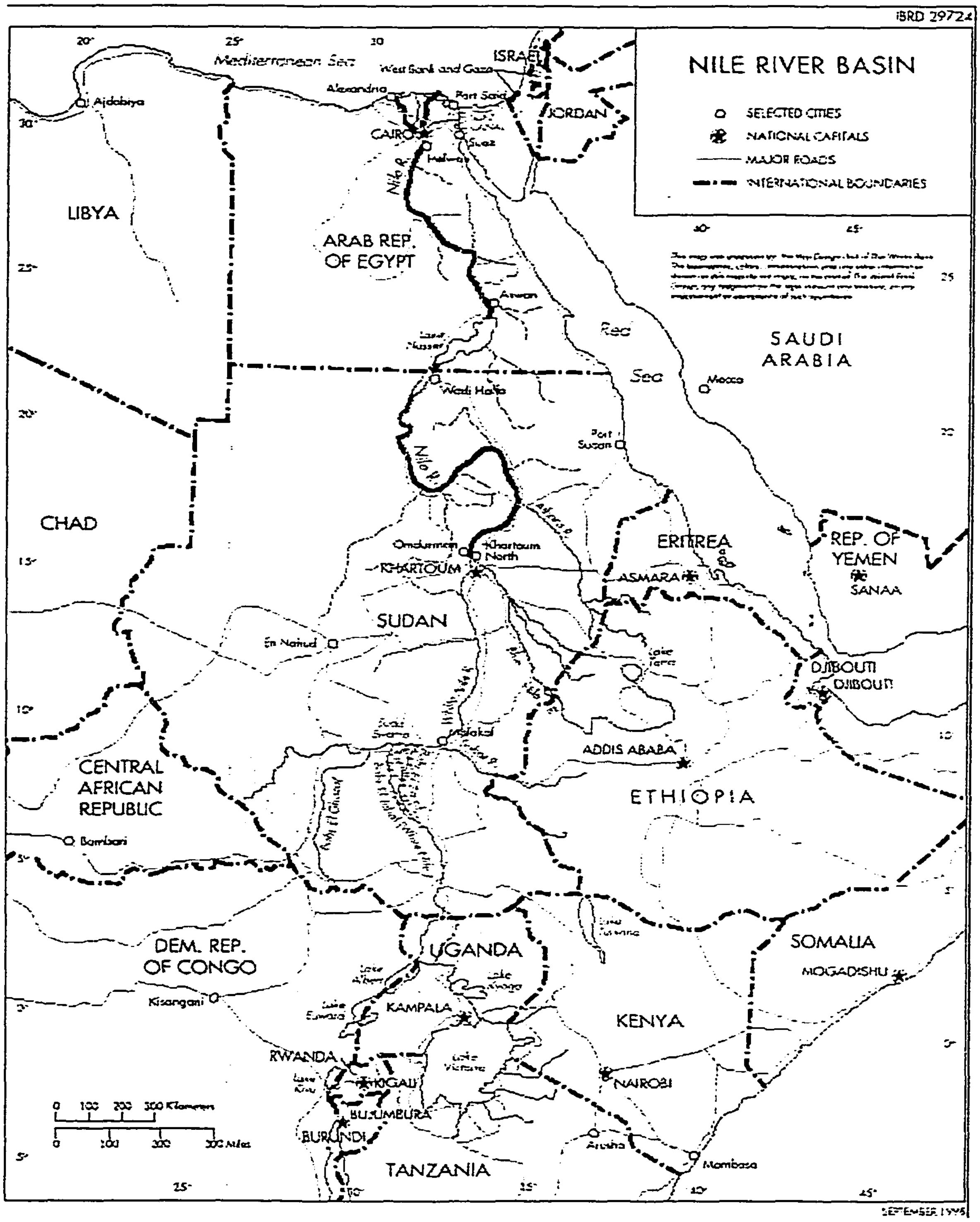
While a more detailed discussion of the Nile hydrology should be best left to work of other disciplines, the barriers and opportunities of cooperation in the Nile basin cannot be fully understood without some knowledge of its hydrology. Here we provide a brief account of some essential hydrological features of the Nile basin.

Measured at 6,700 km, the Nile is the longest river in the world. The Nile is also among the international river basins with the biggest number of riparian countries. It is shared by ten countries: Egypt, Sudan, Ethiopia, Uganda, Kenya, Tanzania, Burundi, Rwanda, Democratic Republic of Congo and Eritrea. Figure 2-1 shows a map of the Nile basin.

The Nile basin includes two large rivers, the White Nile and the Blue Nile. The White Nile originates from the Kagera River, which drains the mountains of Burundi and Rwanda. It flows into Lake Victoria, which is shared by Tanzania, Kenya and Uganda. Since 1953, the outflow and lake level of Lake Victoria have been controlled by Owen Falls dam, which not only provides electricity for Uganda but also bestows some storage capacity to fulfill the irrigation needs of downstream riparian countries. After Owen Fall dam, the river passes through Lake Kyoga and Lake Albert, while it crosses from Uganda to the Republic of Congo. The White Nile enters Sudan at the Sudd region: a vast plain of open land, rivers and swamps. One critical feature of the Sudd region is that the evaporation in this area greatly exceeds rainfall, and as a result, outflow from Sudd only accounts for about half of the inflow. The huge evaporation loss of the Sudd region has given rise to an ambitious engineering endeavor known as Jonglei Canal to bypass the swamps in order to reduce losses. The construction of the canal began in 1978 but was halted after Southern Sudanese rebels (SPLA) took over the region.

After the Sudd, the White Nile receives runoff from the Sobat, whose tributaries drain the southwestern part of the Ethiopian highlands, and then it continues its course to Jebel Aulia dam, located 40 km upstream of Khartoum—the capital city of Sudan—where the White Nile meets the Blue Nile. The dam was initially constructed to provide Egypt with additional water supplies for summer irrigation, but the construction of Aswan High Dam made the dam unnecessary. The only purpose of the dam now is to raise the water level for pump irrigation schemes along the While Nile, but the evaporation losses for the dam are quite high.

Figure 2-1 Map of the Nile basin

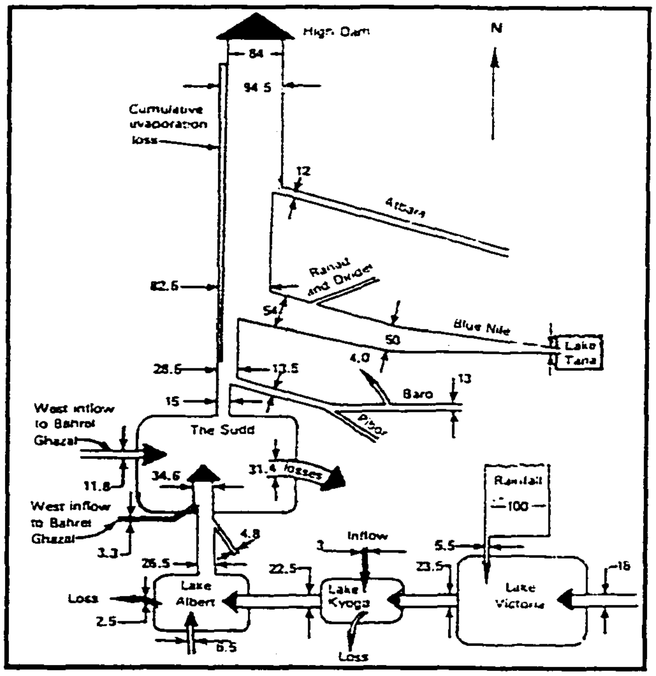


Source: The World Bank, 1999

The source of the Blue Nile is in the Ethiopian highlands. The Blue Nile originates at Lake Tana, lying 1,829 meters above the sea level. From Lake Tana the river drops 50 meters while it cuts a deep canyon through the Ethiopian highlands. After its exit to Sudan plateau at an altitude of 490 meters, the slope of the river turns flat. Two small dams have been built in Roseires (near the border of Ethiopia and Sudan) and Sennar to provide Sudan with both irrigation water and hydropower. In between Sennar and Wad-Maani, two important tributaries—Dinder and Rahad—join the Blue Nile.

From Khartoum, the united river becomes the Main Nile and is joined by its last tributary—Atbara River, which drains the northern portion of Ethiopian highlands and part of Eritrea. The Khashm el Girba reservoir was built on the upper Atbara to store the runoff from the river for irrigation purpose, but the considerable amount of siltation has greatly reduced its storage capacity. From the mouth of Atbara to the Mediterranean Sea, the Nile receives no additional water source. The Main Nile enters Egypt at Lake Nasser, and two main storage dams in the Nile—the old Aswan dam and Aswan high dam—have been built by the Egyptians in 1902 and 1971. After Aswan, the river reaches the Nile valley and continues its course to Cairo. At 24 kilometers north of Cairo, the Nile is divided into two branches: one flowing to the northeast while the other flowing to the northwest, where both are emptied into the Mediterranean Sea.

Figure 2-2 Inflows and losses in the upper Nile basin



Source: EXWAP Water Master Plan, Egyptian Ministry of Irrigation (1979)

Figure 2-2 shows the contributions of the different sources of water in the Nile basin as well as the evaporation losses in different parts of the basin. Ethiopia is the most important contributor of the Nile flows. With a combined 72 billion m^3 from Blue Nile, Atbara and Sobat, Ethiopia alone contributes to 85% of the total Nile discharge. The remaining water inflows are from the Equatorial countries, which contribute about 14% of the total Nile discharge.

Table 2-1 shows the percentage of the Nile basin in each riparian country. Although its contribution to the flow of the Nile is negligible[1], Sudan possesses the largest area of the Nile basin, and a large portion of river itself. It has 1,500 kilometers in the Main Nile, 800 kilometers in the White Nile and 780 kilometers in the Blue Nile. Ethiopia ranks second for its share in the Nile basin. It possesses large portion of the Blue Nile (with 700 kilometers) and Atbara (with 400 kilometers). Egypt has about 10% of the Nile basin area and possesses 1,300 kilometers of the Main Nile, but it contributes no water to its flow. The only major riparian country from the Equatorial countries (Uganda, Kenya, Tanzania, Burundi, Rwanda and Congo) is Uganda, with 7.7% of the basin, 40% of Lake Victoria and 600 kilometers of the Upper Nile basin.

Table 2-1 Individual country share in the Nile basin

Country	Area per country (km^2)	Percentage of area (%)
Sudan	1,900,000	62.7%
Ethiopia	368,000	12.1%
Egypt	300,000	9.9%
Uganda	232,000	7.7%
Tanzania	116,000	3.8%
Kenya	55,000	1.8%
Republic of Congo	23,000	0.8%
Rwanda	21,500	0.7%
Burundi	14,500	0.5%

Source: Kloit, Nurit (1994) *Water Resources and Conflict in The Middle East*, New York: Routledge.

The uneven distribution of the contribution by different riparian countries to the Nile flow stems from the differences in their climate conditions. Egypt and some parts of Sudan have a very dry climate with precipitation less than 200 mm a year. The Sudan and small part of Ethiopia have another type of dry climate--a steppe type (BS) with rainfall ranging from 200 to 400 mm a year. The other three climate types--the tropical rainforest climate, the tropical savannah climate and the highland climate—cover a large part of Ethiopia and the Equatorial states, as they annually receive a

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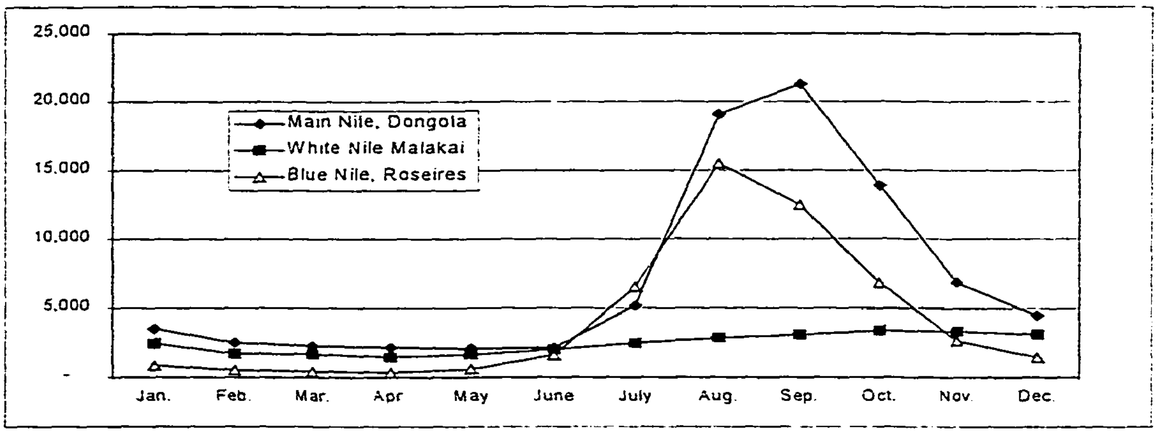
[1] Sudan's contribution would be negative if taking account of the high evaporation loss in the Sudd area.

rainfall level between 1,400 mm and 1,800 mm, and as a result, these regions serve as the sources of the Nile. The disparity in climate conditions determines both the water dependency as well as the current irrigation pattern of a particular riparian country. For example, while rain-fed irrigation is currently the predominant irrigation pattern in Ethiopia highlands, it is nearly impossible in Egypt.

Aside from the disparity of climate conditions in the Nile basin, there are great variations of discharge for the Nile basin in both intra-year and inter-year. Figure 2-3 shows the average monthly fluctuations from 1912 to 1973. Of special interest here is the very large variation for the Blue Nile discharge: the lowest month reaches 0.37 billion m^3 while the highest month has inflow of 15.5 billion m^3. Compared to the Blue Nile discharge, the discharge of the White Nile is much more evenly distributed and it only varies between 1,650 million m^3 and 3,402 million m^3. Historically this was fortunate for the irrigation schemes in downstream riparian countries, as the inflow from the White Nile can be utilized to meet the irrigation demand during the months when the Blue Nile discharges are the lowest.

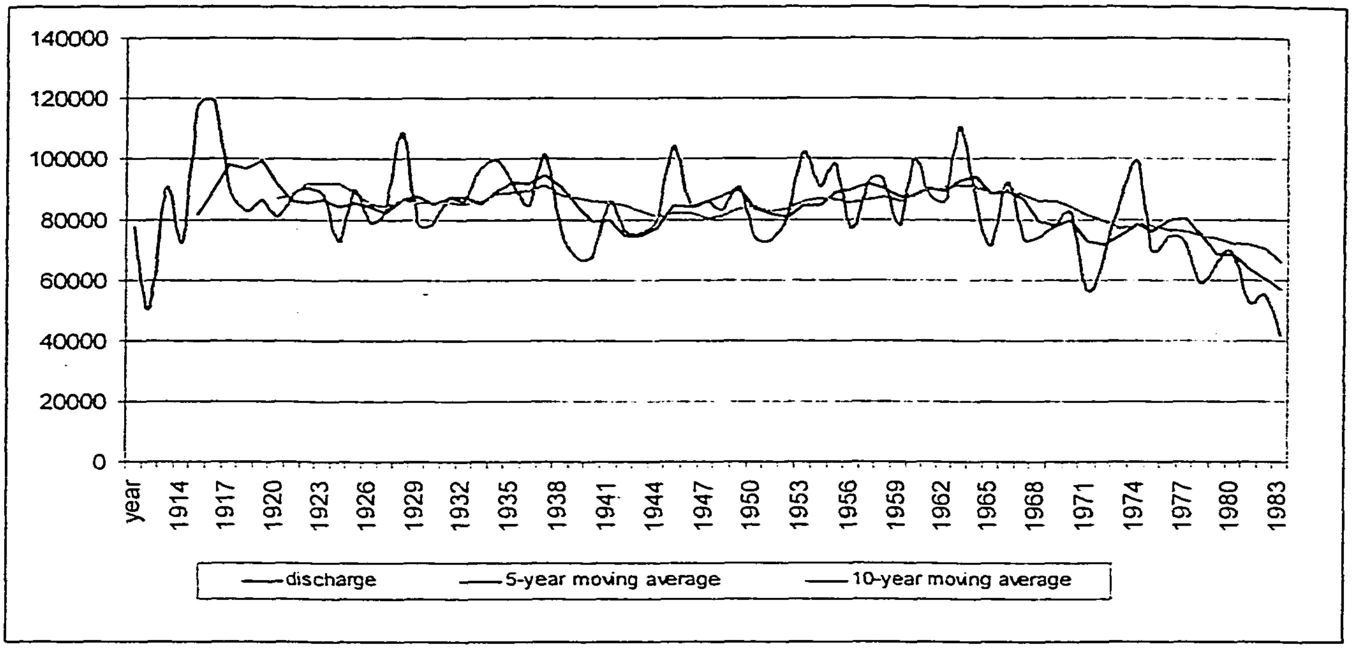
Figure 2-3 Monthly and annually discharges of the Nile (1912-1973)



Source: Shahin, Mamdouh (1985) *Hydrology of the Nile Basin*, Amsterdam: Elsevier.

Figure 2-4 compares the discharges at Dongola for the year 1912 to 1984. Two features from this graph are worth pointing out. The first is the magnitude of inter-year variation of river flow. From 1912 to 1984, the standard deviation of the river flow is about 14.7 billion m^3, approximately 20% of the mean annual discharge. In addition, the dramatic fall in the annual discharge in the 1970's and 80's (as reflected in the 5-year and 10-year moving average of the annual discharge) has led researchers to question some earlier assumptions about the water availability of the Nile. Some scientists believe that the reduction of water discharge in the Nile might be in part due to the global climate changes, although clear evidence of such assertion is yet to be found.

Figure 2-3 The Main Nile average flow at Dongola: 1912-84



Source: Shahin, Mamdouh (1985) *Hydrology of the Nile Basin*, Amsterdam: Elsevier;

The inter-year and intra-year variations in Nile flow, plus the differences in climate conditions in different parts of the basin, serve as driving forces of the hydro-politics of the Nile basin. Because of the high fluctuations of seasonal and annual flows in the Nile, storage facilities are key to the control of the Nile flow, and subsequently, their construction and operation have been subjects of tension throughout history while posing numerous dilemmas for engineers as well as political leaders. For instance, although the existence of the Aswan High Dam may have saved Egypt in the Sahara drought of the 80's because Egypt was able to store excess water from previous flood years at the dam, the dam also has some severe social and economic implications. Because of the adverse climate condition, the Aswan High Dam annually loses about one eighth of total mean flow of the river through evaporation, an appreciable amount given the potentially tight balance between demand and supply for the water in the future. The hydrological facts of the Nile basin pose many challenges as well as several opportunities for any cooperative schemes.

B. The Economies of the Nile Basin

With the exception of Egypt, the Nile riparian countries are among the poorest in the world. Table 2-2 shows some social and economic indicators of the ten riparians of the Nile basin. The social indicators clearly show that many of these countries are struggling to provide basic health and education services for the population. The per capita GNP in each of the Nile riparian countries is extremely low, averaging about 5% of most European countries. The share of agriculture as percentage of GDP indicates that the economies of the Nile basin rely heavily on the agricultural sectors and thus their economies are vulnerable to factors contributing to fluctuations in the agricultural sectors. In addition, civil wars and droughts have also plagued some riparian countries. Sudan, for example, which was considered as the potential "bread basket" of the Arab world two decades ago, finds itself spending one half of the value of its exports on food imports alone, due to prolonged civil wars and droughts in the country.

Table 2-2 Selected social and economic indictors for Nile riparian countries

	GNP per capita (in US$)	*GNP per capita growth rate, 1976-1986*	*GNP per capita growth rate, 1987-1997*	*Agriculture/GDP*	*Life expectancy*	*Access to safe water*	*Illiteracy*
Burundi	140	3.9%	-1.2%	53.3%	42	58%	55%
Congo	110	0.8%	-6.5%	57.9%	51 -		28%
Egypt	1200	6.4%	4.6%	17.7%	66	84%	47%
Eritrea	230			9.3%	51	7%	
Ethiopia	110	-0.3%	2.5%	55.5%	43	26%	65%
Kenya	340	4.5%	2.5%	28.8%	52	45%	21%
Rwanda	210	51%	4.5%	37.5%	40		37%
Sudan	290	-0.3%	4.3%	36%	55	60%	47%
Tanzania	210		3.6%	47.3%	48	49%	28%
Uganda	330		7.1%	43.7%	42	42%	36%

Source: 1999 World Development Indicators CD-ROM, World Bank.

Another distinct feature common to all Nile riparian countries is rapid population growth. Table 2-3 presents some harsh facts in this regard. The population of almost all Nile riparian countries is projected to double in the next 50 years (in the cases of Ethiopia and Uganda, it is expected to triple). The ranking in population will alternate as some countries' growth rates are higher than others'. For example, while Ethiopia's population today is still lower than that of Egypt by a small margin, Ethiopia is expected to have a population of approximately 136 million by the year 2025, or 36% percent higher than the population forecast for Egypt for the same year. As the population in the Nile basin will more than double in the next fifty years, constraints imposed by the availability of natural resources such as land and water will remain difficult to overcome. In some major riparian countries, there are clear signs that the rate of population growth has outpaced the agricultural growth. Hence, it is obvious that the population needs to rely upon food imports more and more. Ethiopia's cereal imports and food aid in cereals, for example, has increased almost ten-fold from 1974 to 1990.

Table 2-3 Population growth in the Nile basin

	1950	*1998*	*2025*	*2050*	*1950-2050*
Burundi	2,456	6,589	12,341	16,937	590%
Congo,	12,184	49,208	105,925	164,635	1251%
Egypt	21,834	65,675	95,766	115,480	429%
Eritrea	1,140	3,548	6,504	8,808	673%
Ethiopia	18,434	62,111	136,288	212,732	1054%
Kenya	6,265	29,020	50,202	66,054	954%
Rwanda	2,120	6,528	12,981	16,937	699%
Sudan	9,190	28,526	46,850	59,947	552%
Tanzania	7,886	32,189	62,436	88,963	1028%
Uganda	4,762	21,318	44,983	66,305	1292%
Nile Basin	86,271	304,712	574,276	816,798	847%
AFRICA	223,974	778,484	1,453,899	2,046,401	814%
WORLD	2,523,878	5,929,839	8,039,130	9,366,724	271%

Source: Source: 1999 World Development Indicators CD-ROM, World Bank.

On the other hand, the development potential in many of these countries is largely untapped due to unstable political situation or financial constraints. Sudan, for example, despite its excellent potential to increase its agricultural production, only irrigates about 14% of its cropland, and it has yet to fully utilize its share of the Nile water based on the 1959 agreement.

Table 2-4 Land areas and land use in selected Nile basin countries

	Area (in thousand hectares)	Cropland	Share of irrigated land as percentage of cropland
Egypt	99,545	5,700	98%
Sudan	237,500	12,499	14%
Ethiopia	110,100	13,930	1%

Source: Said, Rushdi (1993) *The River Nile: Geology Hydrology and Utilization*, Pergamon Press.

The development potential of Ethiopia has been hampered by financial diffficulties and unstable political conditions. According to a study done by the US Bureau of Reclamation in 1964, the potential hydropower projects along the Blue Nile could offer some of the best economic returns of any hydropower projects in the world (Whittington and Guariso, 1987). It is estimated by the same study that a total of 1,284 million feddans of land is irrigable. The initial capacity of the proposed dams can reach 175 billion m^3 with an installed hydropower generation of 31,335 GWH. However, more than thirty years later, only one of the 33 proposed projects has been completed.

C. Water Conflicts in the Nile Basin

The main source of conflicts among the Nile riparian countries is the fact that the water currently available in the Nile basin cannot meet the requirements of irrigation plans on the drawing boards of riparian countries. As population is increasing rapidly throughout the basin, several major riparian countries are planning to dramatically increase their irrigation schemes in order to meet the demands for such population growth. In Egypt, for instance, the government plans to irrigate an additional 5 million acres by 2025, which means that an additional 20 billion m^3 of water will be required. In Sudan, which currently uses less water than its share specified in the 1959 agreement, the irrigation and hydropower projects considered by the government would demand an additional 12 billion m^3 water on top of its current allocation (Knott and Hewett, 1994). As for Ethiopia, while it uses almost no water from the Nile at present, it could use perhaps 20-30 billion m^3 of water from the Nile (Abate, 1993). In view of the fact that the Nile's annual discharge is pretty much used in its entirety by Egypt and Sudan at present, the water deficit of the Nile basin could exceed 40 billion m^3 without taking into consideration of the additional water required by the equatorial states.

In addition, the water conflicts in the Nile basin are also fueled by a sheer contrast between contribution and utilization of water by different riparian countries. The pattern of climate determines the dependency of riparian countries on the waters from the Nile. For example, while Egypt contributes none to the flows of the Nile, it depends upon the Nile for 97% of its water supply and it currently uses more than 80% of the Nile water. Meanwhile, Ethiopia contributes 85% of the water flow in the Nile basin, yet it has not received any of that water for irrigation (see Table 2-5). As Ethiopia's population is forecast to be twice as large as that of Egypt, such an allocation pattern is not likely to be sustainable in the future. Historically, Egyptians have made the claim that Ethiopia and other Equatorial countries do not need the water from the Nile because they have plenty of alternative supply sources, and Egypt has perceived any water resource development projects in these upstream countries as a direct threat to its national security.

Table 2-5 The contribution and utilization by Nile riparian countries

Country	Contribution to River Flow (% of Total)	Usage of Water (% of the Total)
Egypt	0	80
Sudan	1	18.5
Ethiopia	85	1.0
Equatorial Sates	14	0.5

Furthermore, lack of international agreements over the use of the Nile water also contributes to water conflicts in the region. As in other major international rivers, the existing international agreements over the utilization of the Nile water do not provide appropriate legal basis to cope with the differences among the riparians on water allocation. For example, the 1959 water agreement has been the legal basis for water allocation between Egypt and Sudan. Based on the agreement, 55.5 billion m^3 and 18.5 billion m^3 water were allocated to Egypt and Sudan respectively while there was no water reserved for the upstream countries. Not surprisingly, Ethiopia, which controls 85% of the source of the Nile, has never ratified the agreement, and neither have the equatorial states.

Non-water issues greatly complicate the resolution of the water conflicts. Interstate relations among Nile riparian countries have been overshadowed by colonial legacies, superpower rivalry in the Cold War era, and political upheavals (Elhance, 1999). Due to the strategic importance of Egypt to the British colonizers, the development of water resources in the Nile basin during the 19th century and early part of the 20th century had concentrated almost exclusively on the goal of satisfying Egypt's water needs, and had held little regard for the interests of other riparian countries. In addition, the political upheavals in the Blue Nile basin have made it difficult for Sudan and Ethiopia to jointly exploit the great potential of water resources in the Blue Nile. While Sudan has been accused by Ethiopia of supporting the newly independent Eritrea in its war against Ethiopia, it has criticized Ethiopia for helping the Southern Sudan anti-government rebels (Soffer, 1999).

In the absence of cooperative management for the Nile basin, unilateral developments have proceeded in some key riparian countries, and this will further cloud the future of regional cooperation. Egypt has begun with preparation work for its New Valley project in the Western

Desert, which would require an additional 5-10 billion m^3 of water annually once completed. Although Egypt claims that it can meet its water requirement by using the existing water supplies more efficiently, the potential of such saving might be best reserved to serve as cushion for Egypt if it is forced to reduce the current water usage level in order to accommodate the demand from upstream countries (Waterbury and Whittington, 1999). For its part, Ethiopia has also planned to develop micro-dams in the Blue Nile basin for the sake of exploiting its irrigation potential. Both of these unilateral development schemes might not be desirable outcomes from basin-wide point of view, and once completed, would have consequences far into the future and create additional obstacles for the cooperation among riparian (Waterbury and Whittington, 1999).

The following summarizes the claims, concerns and positions of three riparian countries:

Egypt

- Egypt insists that colonial agreements are binding on the upstream countries;
- Egypt maintains that the status quo established by the 1959 Nile Waters Agreement should be outside the scope of future water allocation agreements;
- Egypt holds the position that Ethiopia's share should be minimal because it has other sources of water.

Sudan

- Although its alliance with Egypt has helped to secure its water supplies, Sudan has an interest in building coalition with upstream riparian countries;
- Sudan would have to settle several internal conflicts such as the one with Southern Sudanese rebels before the benefits of any wetland projects can be materialized.

Ethiopia

- Ethiopia states that it does not ratified any Nile water agreements concluded by the colonial powers of the time;
- Ethiopia has never ratified the 1959 agreement, and claiming that it does not take into consideration the needs of upstream countries:
- Ethiopia maintains that it should be entitled to use the Nile water to develop its total irrigable area;
- Ethiopia argues that more thorough research is necessary to identify its water needs before it can commit to Egypt and Sudan for any amount of water.

D. Opportunities for Cooperation in the Nile Basin

The massive potential water deficit for the Nile basin should not mask the fact that, as in many other international rivers in conflict, there are plenty of opportunities for riparian countries to jointly develop the basin's water resources and to resolve conflicts. From early last century on, attention has been given to measures that can increase the water supplies by building large-scale river regulation facilities along the Nile. Such attempts have been manifested clearly by the Century Storage Scheme proposed by Hurst more than half a century ago. It called for the construction of four projects: 1) an over-year storage reservoir at Lake Albert combined with a regulator on Lake Victoria; 2) a canal bypassing the Sudd swamps; 3) over-year storage in Lake Tana; 4) an additional seasonal storage reservoir on the Main Nile in the region between Atbara and Wadi Halfa (Whittington and Guariso, 1983). Because the projects proposed by the Century Storage Scheme are located in many different riparian countries, the construction of these projects requires joint efforts of almost all of the key riparian countries. In the second half of the last century, conditions for such joint development have not been afforded by international politics in that period. Instead, unilateral development of Nile water resources has prevailed. For example, the Aswan High Dam was constructed for the sole purpose of providing Egypt with greater security regarding its water supplies, at the expense of significant evaporation losses for the whole basin.

Table 2-6 Proposed projects and potential benefits

Project	Hydropower Production (Installed capacity in MW)	Water Savings (in billion m3)
Blue Nile Storage Projects	5700 MW	4
Wetland Projects (Jonglei I and II, Machar Marshes and Gahzal projects)	-	11
Demolition of Jebel Aulia dam	-	3
White Nile reservoirs (Lake Albert and lake Kioga)	-	-
White Nile hydropower stations	2300 MW	-

As the demand for the Nile water continues to increase, the benefits promised by a basin-wide development plan such as Century Storage Scheme can no longer be overlooked. In recent years, several projects aiming at increasing the water supply of the Nile have been considered by both the

Nile riparian countries and the international organizations (see Table 2-6 for a list of selected projects).

The proposed Blue Nile storage projects are located in Ethiopia, and they include reservoirs (dams) in Lake Tana, Mandaire, Mabil, Karadobi and Border. These projects will 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 will be reduced if water is stored in Blue Nile dams where the climate conditions are more favorable. Wetland projects consist of Jonglei I, Jonglei II, Machar Marshes and Gahzal projects. Jonglei I calls for the construction of a canal from Jonglei to Bahr-el-Zeraf to allow the While Nile flow to bypass the Sudd area. It is estimated that Jonglei I would increase 3.8 billion m^3 in water supplies. Jonglei II would double the capacity of Jonglei I, and reduce evaporation loss 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, while the Gahzal projects consist of a series of reservoirs and diversion canals. These projects combined would induce water savings in the order of 4 billion m^3. The demolition of Jebel Aulia would yield water saving about 3 billion m^3. Two storage facilities in Lake Kioga and Lake Albert, and six power stations are also considered. It is expected that the total installed capacity of these power stations will reach 2300 MW. If all of these projects are completed, the yield of the Nile will increase by 18 billion m^3 of water, which can significantly reduce the potential water deficit. Of course a massive capital outlay would be required to complete these projects, and the expected benefits from the projects would have to be compared with their costs.

Measures focusing on demand-side management have also been proposed. The global water shortages are partially due to the fact that water has not been treated as an economic resource. As a result, inefficient uses of water are prevalent around the world. In Egypt, charging the users of water based on the water's true economic value has been proposed as an important means of combating the water shortage problems.

Some innovative institutional mechanisms have also been discussed in the literature. Whittington, Waterbury and McClelland (1995) explore the potential benefits of establishing regional water markets once property rights are assigned through a new Nile water agreement. Given the high costs of developing additional water supply sources in Egypt and the relatively low value of water for Ethiopia for irrigation purposes (Abate, 1994), the potential trading of water between these two countries might greatly boost the overall water usage efficiency. Linking water issues with non-water issues may be another important way to deal with the unidirectional externalities experienced in international rivers (see, for example, Bennett, Ragland, and Yolles, 1998). So far, the ten riparian countries in the Nile basin have had very little international trade among themselves (see Table 2-7). The large amount of hydropower that can be generated through the proposed projects in upstream Nile riparians (Ethiopia and Uganda) may provide the much needed energy source for downstream countries to expand agricultural production, and such trading may provide incentives for upstream countries to extract less water (Whittington, Waterbury and McClelland, 1995).

Table 2-7 International trades of Nile riparian countries (in millions of US$)

	Burundi	*Congo, DR*	*Egypt*	*Eritrea*	*Ethiopia*	*Kenya*	*Rwanda*	*Sudan*	*Tanzania*	*Uganda*
All imports	157.7	760	14643	134.4	1167	2631	171.8	777.6	1425.5	738
Import from:										
Burundi	-	2	-	-	-	10	1	-	6	-
Congo, DR	3	-	1	-	-	16	1	-	2	0.1
Egypt	0.1	1	-	-	24	79	-	3	2	7
Eritrea	-	-	-	-	-	-	-	-	-	-
Ethiopia	-	-	6	2	-	47	-	1	1	-
Kenya	6	2	4	-	0.1	-	1	2	12	8
Rwanda	2	3	1	-	-	38	-	-	40	1
Sudan	-	-	64	2	1	46	0.1	-	6	2
Tanzania	5	1	1	-	-	150	-	-	-	2
Uganda	1	-	-	-	-	186	1	-	9	-
Sub-Total	17.1	9	77	4	25.1	572	4.1	6	78	20.1
% of total imports	10.84%	1.18%	0.53%	2.98%	2.15%	21.74%	2.39%	0.77%	5.47%	2.72%

Source: IMF, Direction of Trade Statistic Yearbook, 1997 and UN COMTRADE database

The efforts towards cooperation in Nile Basin have been expanded during the recent years. In December 1992, an inter-governmental organization called Tecconile (Technical Committee for the Promotion of the Development and Environmental Protection of the Nile Basin) was formed among six of the 10 Nile riparians—Egypt, Sudan, Tanzania, Uganda, Congo and Rwanda. The Tecconile has focused on technical aspects of water resource development in the basin. Concurrently, conferences known as Nile 2002 series have been held annually since 1993, with the goal of sharing scientific research by technical experts from each of the Nile basin countries. Although Ethiopia, Eritrea and Kenya are not full-fledged members of the Tecconile and Nile 2002, they take part in the conferences as observers. In May 1995, a breakthrough in cooperation on the Nile Basin was achieved when the water ministers of most of the Nile basin countries—including Egypt and

Ethiopia—agreed to form a panel of experts that would be charged with developing a basin-wide framework that aimed to provide "equitable and efficient allocation of water" by water sharing.

2.2 The Nile Economic Optimization Model

A. Model Formulation

Water conflicts in the Nile basin has stirred great interests in utilizing analytical tools to evaluate the benefits of cooperation in the Nile basin. Economic optimization models based on a single country or several riparian countries and basin-wide optimization model based solely on hydrological data have been developed in the past, and these studies have greatly enriched the policy discussion on the issue (see, for example, Whittington and Guariso, 1983; Whittington and Guariso, 1987; Georgakakos and Klohn, 1997; Georgakakos at el., 1998). However, so far there has not been a basin-wide economic optimization model for the whole Nile basin. The economic optimization model developed in this dissertation aims to fill this gap. The followings describe the objective functions and main constraints of the model.

The objective function of the model is to maximize the total benefits of water allocation to irrigation and hydropower generation summed over all riparian countries and over a 12-month period. Assume that the economic value of water for irrigation takes a fixed value, the mathematical formulation of the objective function can be expressed:

$$Maximize \sum_{c} \{ \sum_{i,c} P_{w}^{i,c} \sum_{t} Q_{t}^{i,c} + \sum_{i,c} P_{e}^{i,c} \sum_{t} KWH_{t}^{i,c} \}$$

where $P_w^{i,c}$ is economic value of water for irrigation at site i for country c (in US\$/m^3), $Q_t^{i,c}$ is 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\$/KWH), and $KWH_t^{i,c}$ is the hydropower generated at site i for country c in month t.

Alternatively, if we assume that the economic value of water for irrigation does not take a fixed value and that such value is defined by non-linear demand functions for individual riparian countries, the objective function of the model can be modified as:

$$\mathit{Maximize}\ \sum_{c}\{[\alpha_c \sum_{i,c}\sum_{t} Q_t^{i,c} + \frac{\beta_c}{1+\upsilon_c}(\sum_{i,c}\sum_{t} Q_t^{i,c})^{1+\upsilon_c}] + \sum_{i,c} P_e^{i,c} \sum_{t} KWH_t^{i,c}\}$$

where the economic value of water for irrigation for country c is described as

$$P_c = \alpha_c + \beta_c * (\sum_{i,c}\sum_{t} Q_t^{i,c})^{v_c}$$

The main constraints of the model are the followings:

1. Continuity Constraints for Reservoir Nodes

$$S_{t+1}^i = S_t^i + I_t^i + (1 - EV_t^{j-i})R_t^j - (e_t^i - r_t^i)[a^i + b^i(\frac{S_t^i + S_{t+1}^i}{2})] - Q_t^{i,c} - R_t^i$$

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

2. Continuity Constraints for Intermediate Nodes

$$(1 - EV_t^{j-i})R_t^j + I_t^i = R_t^i + Q_t^{i,c}$$

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

3. Storage Capacity Constraints for Reservoir Nodes

$$S_{Min}^i \le S_t^i \le S_{Max}^i$$

4. Irrigation Water Withdrawal Pattern

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

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

5. Hydropower Generation Equalities

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

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

6. Hydropower Generation Capacity Constraints

$$KWH_t^{i,c} \le CAP^{i,c}$$

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

7. Non-negativity Constraints

$$S_t^i, R_t^i, Q_t^i, KWH_t^{i,c} \ge 0$$

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

where S_t^i is reservoir storage for reservoir i in month t, I_t^i is the inflow, R_t^i is the release (or the outflow), EV_t^{j-i} is the percentage of evaporation loss for water flowing from site j (j indicates immediate nodes before site i and can be more than one) to site i, e_t^i is the evaporation rate, r_t^i is the rain rate, a^i and b^i are the constant and the slope of the area storage relation of the reservoir[2], S^i_{Min} and S^i_{Max} are the minimum and maximum storage for the reservoir, $Q^{i,c}$ is the irrigation withdrawal for irrigation site i in October, δ^i_t is the coefficients of irrigation withdrawal for site i in month t in relation to irrigation withdrawal for site i in October, η is the unit conversion constant, $f(S^i_t, S^i_{t+1})$ is a 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. Table 2-8 summarizes the decision variables and input data for the model.

Table 2-8 A list of Decision variables and input Data

Decision Variables:

S^i_t - reservoir storage
R^i_t - release(or outflow)
$Q^{i,c}_t$ - withdrawal for irrigation
$f(S^i_t, S^i_{t+1})$ - average storage productive head
KWH^i_t - electricity generated at site i in period t

Input Data:

$P^{i,c}_w$ - economic value of water for irrigation for country c
$P^{i,c}_e$ - electricity price for hydropower for country c
I^i_t - Inflow
a^i - Contant for the area storage relationship
b^i - Slope for the area storage relationship
S^i_{Min} - Mininum storage for reservoir i
S^i_{Max} - Maximum storage for reservoir i
δ^i_t - Irrigation coefficients for irrigation site i
r^i_t - rain rate for site i
e^i_t - evporation rate for site i
EV^{j-i}_t - percentage of evaporation losses for the flow from j to i
η - Unit conversion constant for hydropower generation
ε - Hydropower efficiency

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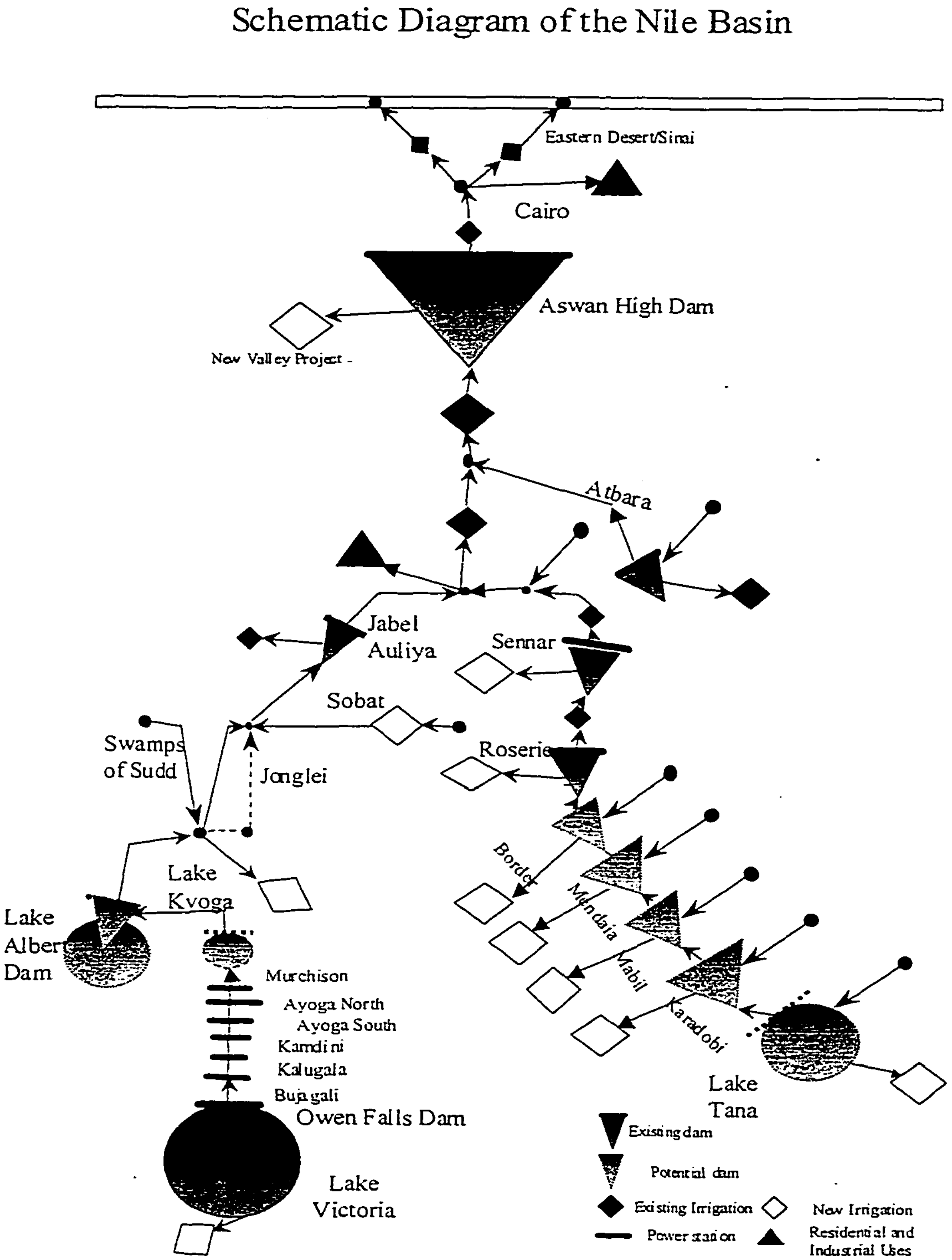
[2] The evaporation losses for the reservoir are determined by the function $(e^i_t - r^i_t)[a^i + b^i(\frac{S^i_t + S^i_{t+1}}{2})]$

Figure 2-4 Schematic diagram of the Nile basin for NEOM



B. Model Description

The model operates on a monthly basis over a period of a year for the average inflow to determine the combination of monthly releases from a specified set of Nile hydropower generation facilities and 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 optimization model is solved with the GAMS software. Figure 2-4 shows how the Nile system is represented in the economic optimization model. The water resources network is assumed to constitute of a series of nodes and links between these nodes.

Information regarding the physical representation (elevation, storage and installed capacity) of the proposed reservoirs and (or) power stations are treated as inputs to the model. Table 2-9, 2-10 and 2-11 show the set of the configuration of the physical characteristics of the proposed reservoirs and (or) power stations that is used by the study.

Table 2-9 Scale and capacity of the proposed Blue Nile reservoirs

	Lake Tana	Karadobi	Mabil	Mendaia	Border
Max Level (m)	1787.6	1156.0	910.6	743.6	575.0
Max Storage (BCM)	13.8	34.2	14.1	16.7	10.8
Min Level (m)	1783.8	1041.0	837.8	724.8	563.4
Min Storage (BCM)	2.3	3.9	3.2	11.4	6.3
Designed Capacity (MW)	50	113	100	135	100

Source: Georgakakos, Aris ed. al. (1998) *Decision Support System for the Blue Nile*, School of Civil and Environmental Engineering, Georgia Tech.

Table 2-10 Capacity of the proposed White Nile power stations

	Kalagala	Murchison	Bujagali	Ayago South	Ayaho North	Kamdini
Designed head (m)	73.5	23.0	84.0	25.0	28.0	57.5
Designed Capacity (MW)	450	642	320	234	304	180

Source: Georgakakos, Aris, 1999.

Table 2-11 Scale of the proposed White Nile reservoirs

	Lake Albert	Lake Kyoga
Max Level (m)	1034.0	624.0
Max Storage (BCM)	20.4	176.0
Min Level (m)	1030.0	619.0
Min Storage (BCM)	5.4	145.9

Source: Georgakakos, Aris ed. al. (1998) *Lake Victoria Decision Support System*, School of Civil and Environmental Engineering, Georgia Tech.

Other main input data for the model are inflow, evaporation rate, rainfall rate and irrigation withdrawal patterns, as well as the value of water for irrigation and the value of hydropower. As in other economic optimization models, the results of our model will be critically dependent upon the input data we use, and thus one should proceed with care when interpreting the results. This is especially critical for the economic input data, because they are subject to much greater uncertainty than other input data.

The first such economic input data is the value of irrigation water in the Nile basin. Since irrigation is part of the production process, the economic value of irrigation water is determined by the prices of commodities produced from irrigation, prices of resources used to produce these commodities and characteristics of water supply, as well as the method and procedure for delivering the water. While there is more information available on downstream riparian countries, such information is largely unknown for some major upstream riparian countries such as Ethiopia and Sudan. Based on international experience, the value of water for irrigation users is typically in the range of US$ 0.01-0.25 per cubic meter (Briscoe, 1996; Briscoe, 1998).

There have been a few attempts to determine the economic value of water for irrigation in the Nile basin. Based on calculation by Whittington and Guariso (1983), the economic value for water in Egyptian agriculture was between $0.01- 0.17 per cubic meter in the 1970s.. Some recent studies based on CGE models are able to establish a narrower band for the value. For example, using the results of a CGE model of Egyptian agriculture, Lofgren (1996) reports an economic value of water for Egyptian irrigation users ranging from US$ 0.018- 0.036 per cubic meter; independently, Robinson and Gehlhar (1995) show that the shadow price for water for agricultural water supply in Egypt is in the order of US$ 0.003- 0.047 per cubic meter. For illustrative purposes, we arbitrarily assume that the economic value of irrigation in our baseline cases is US$ 0.05 per cubic meter for all riparian countries. Sensitivity analysis will be used to show the sensitivity of the results to these assumptions.

Another economic input data that could have significant impacts on model results is the value of water for electricity production. According to Gibbons (1986), the value of one KWH's worth of water removed from hydropower production is defined as the long run marginal cost of the alternative electricity production method (thermal, nuclear or others) subtracting the cost of producing the hydropower forgone. In the Nile basin, the long run marginal costs of thermal power range from US$ 0.038/KWH for gas turbine generation in Egypt to US$ 0.15-0.2/KWH for thermal generation in Ethiopia (The World Bank, 1999). Table 2-12 displays the range of long run marginal cost of alternative generation method for selected Nile riparian countries. In this study in the base case, we assume that the value of water for hydropower generation is US$ 0.07/KWh for our baseline cases.

Table 2-12 Long-run marginal cost of thermal generation in selected Nile riparian countries

Country	Type of Power	Long-run marginal cost (US$/KWh)
Egypt	Gas	0.038
Ethiopia	Thermal	0.15-0.2
Kenya	Coal	0.09
Rwanda	Gas	0.19
Tanzania	Gas	0.074

Source: The World Bank (1999) *Opportunities for Power Trade in the Nile Basin* (draft final report).

In order to run the model, we will specify a specific configuration indicating whether or not a particular water control infrastructure is built, as well as user values of water for irrigation and hydropower. For cases where different political constraints are considered, minimum or maximum water requirements for each country are also to be specified. In addition, the total amount of water available over the course of the year may also be specified (i.e., whether the water resources managers would operate the control structures during an average, high, or low hydrological year). The results of the model can be used not only to measure the economic benefits of cooperation, but also to examine the effects of different infrastructure investments and economic consequences of imposing different constraints.

Although there are 10 riparian countries in the Nile basin, they are not equally affected by the flow of the river. For example, the water claims from the countries such as Burundi, Rwanda, Democratic Republic of Congo and Eritrea are likely to be small, hence including every riparian individually in the analysis would unnecessarily complicate our analysis. Instead, Uganda, Tanzania, Kenya, Burundi, Congo, and Rwanda are assumed to form a single coalition (termed "Equatorial States"). In addition, Eritrea is not included in the model.

C. Limitations of the Model

Due to the preliminary nature of our study, limitations of the study should be discussed explicitly before results of the model can be presented and interpreted. The followings summarize the limitations of the model:

- Costs of infrastructure investments are not included.
- Optimal timing and sequencing of infrastructure investments are not addressed.
- Environmental losses resulting from infrastructure investments are not included.
- Economic benefits of flood control are not included.
- Economic value of water in irrigated agriculture in riparian countries is uncertain; economic value of hydroelectricity is uncertain.
- Hydrological uncertainty is not considered.
- Hydrological input is limited to a single year (e.g., mean, low, or high hydrological year).
- Neither water quality considerations nor sediment transport are addressed in the model formulation.
- Groundwater/surface water interrelationships are ignored.
- Uganda, Tanzania, Kenya, Burundi, Congo, and Rwanda are assumed to form a single coalition (termed "Equatorial States"). Eritrea is not included in the model.

The long list of limitations certainly suggests that any "solution" from the optimization model should not be taken at its face value. In fact, even if the limitations listed above are completely eliminated, any "optimal solution" defined by economic criterion might still be sub-optimal when other non-economic factors are taken into consideration. Our intention is to capture some of the trade-offs for the whole basin as well as for individual riparian countries when different strategies and policies are weighted against each other.

In the meantime, one should not be discouraged by the fact that critical information necessary for such modeling exercises to be more informative may not exist at present time. In our view, optimization models not only offer a good way to organize the information available to us, they also offer useful insights into the question of what are the information barriers for conflict resolution processes.

D. Economic Benefits of Full Cooperation

In order to measure the economic benefits of cooperation, we first calculate the economic benefits under two cases: the *status quo* and full cooperation. Under the status quo, no proposed infrastructure is built and irrigation water allocated to individual riparian countries roughly reflects the current allocation pattern[3]. Under the full cooperation case, all proposed infrastructures (Blue Nile projects, White Nile Reservoirs, White Nile power projects, wetland projects and the modification of Jebel Aulia Dam) will be completed and operated in such a way to optimize the total economic benefits for the whole basin. Table 2-13 presents the comparison between the *status quo* and full cooperation, assuming the value water for irrigation is US$0.05 per m^3 and value for hydropower is $0.07 per KWH. Costs of infrastructure investments are not included, and thus the total economic benefits are the gross benefits rather than the net benefits.

Table 2-13 Economic benefits of full cooperation

	Status Quo		Full Cooperation	
Water Withdrawal for Irrigation	BCM	Economic Value (in million US$)	BCM	Economic Value (in million US$)
Ethiopia	1	$ 50		
Sudan	12	$ 600	33	$ 1,625
Egypt	54	$ 2,700	51	$ 2,569
Equatorial States	2	$ 100		
Total	69	$ 3,450	84	$ 4,194
Hydropower Generation	GWH	Economic Value (in million US$)	GWH	Economic Value (in million US$)
Ethiopia			37684	$ 2,638
Sudan	1612	$ 113	2442	$ 171
Egypt	6335	$ 443	5408	$ 379
Equatorial States	1284	$ 90	15895	$ 1,113
Total	9231	$ 646	61429	$ 4,300
Total Economic Value per country	share (%)	Economic Value (in million US$)	share (%)	Economic Value (in million US$)
Ethiopia	1%	$ 50	31%	$ 2,638
Sudan	17%	$ 713	21%	$ 1,796
Egypt	77%	$ 3,134	35%	$ 2,948
Equatorial States	5%	$ 190	13%	$ 1,113
Total	100%	$ 4,087	100%	$ 8,494

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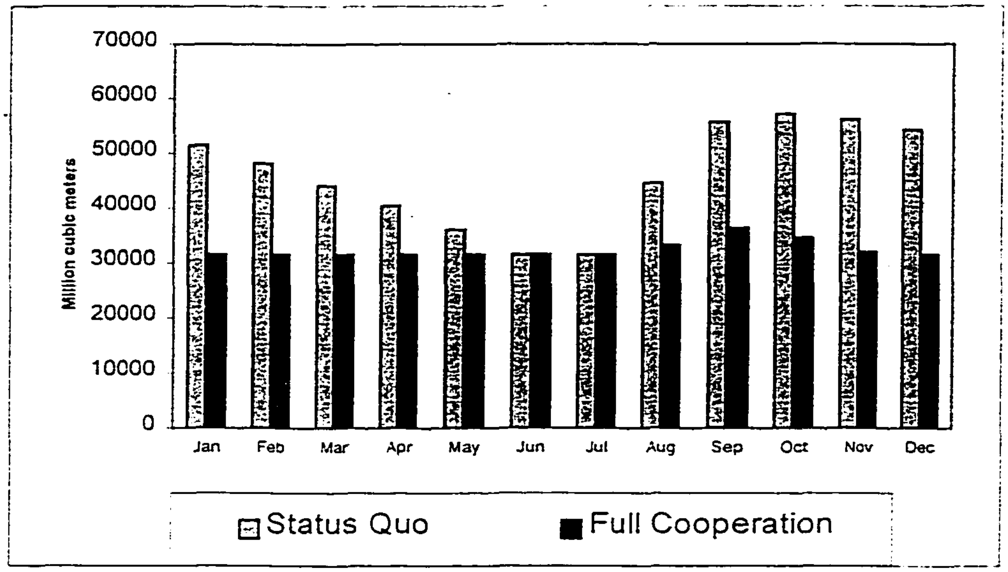
[3] Although Sudan is allocated 18.5 billion m^3 of water under the 1959 Water Allocation Agreement, it is currently using significantly less that amount due to its deteriorating agricultural sector.

Both the amount of irrigation water and hydropower production will be increased significantly if full cooperation in the Nile basin is achieved. An additional 15 billion m^3, or 20% of the average annual discharge of the basin, can be made available to the Nile riparian countries primarily due to the wetland projects and modification of the Jebel Aulia Dam. Storage requirements at the Aswan High Dam can be reduced noticeably (see Figure 2-5), indicating that the under the case of full cooperation evaporation losses at the Aswan High Dam can be cut down to a minimum (the storage at Aswan High Dam is equal to or slightly above the level of dead storage).

Figure 2-5 Storage requirement for the Aswan High Dam*



*The dead storage for the Aswan High Dam is 31600 million m^3.

While the gains in irrigation water may have been well anticipated since the days when the century storage plan was first construed more than half a century ago, the greatest gains of full cooperation lie in the realization of hydropower production potential. As we can see from the table, once the five Blue Nile dams and White Nile power stations are completed, an additional 52,000 GWH of electricity will be made available to the grids of the Nile basin countries.

Perhaps the dramatic increase in hydropower production from the Nile basin (a six-fold increase over the *status quo*) under the full cooperation case warrants some explanations as to when there would be sufficient demand for such increase in electricity production. First of all, a significant capital outlay is required to complete all the proposed projects for the full cooperation case, and it would probably take at least two decades to put them in place even with the most optimistic projection (Abate, 1994). Second, although at present the electricity consumption in the Nile basin countries is quite low, demand for electricity for the countries in the Nile basin will increase by 270% by the year 2020. Assuming 10% of power losses due to transmission, an additional production of 180,000 GWH is required to meet such a demand. While the additional 52,000 GWH of electricity generated in the case of full cooperation represents an appreciable amount indeed comparing to the current consumption, there should be sufficient demand in the future. Third, while our model results suggest that the increase in electricity production would concentrate on Ethiopia and the Equatorial States, Table 2-14 indicates that the majority of the increase in the demand for electricity will be in Egypt and that power trading will be critical to the realization of the full cooperation case.

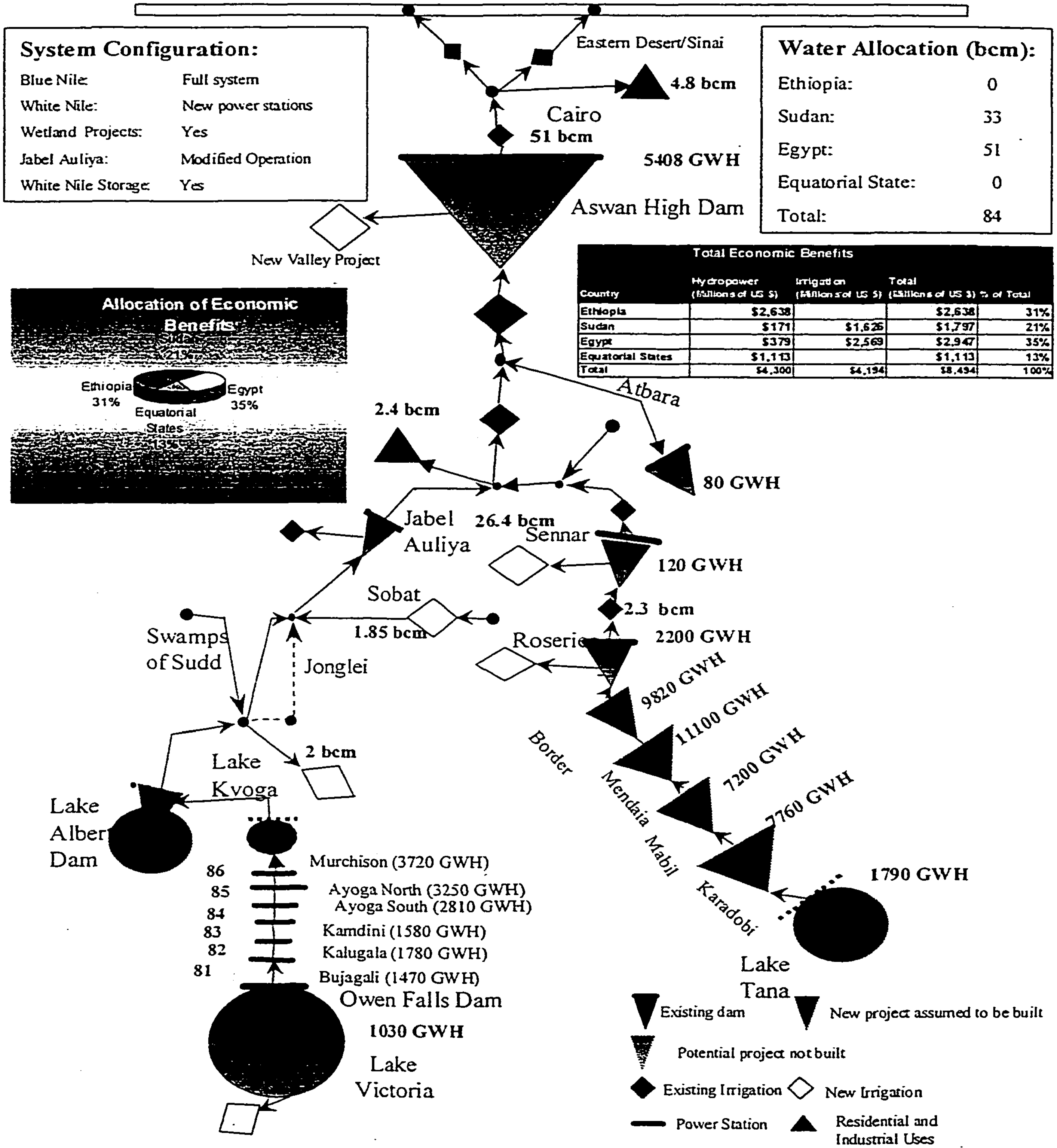
Table 2-14 Current consumption and demand forecast for electricity in the Nile basin

	Burundi	Congo	Egypt	Eritrea	Ethiopia	Kenya	Rwanda	Sudan	Tanzania	Uganda	Total
Average Annual Growth Rate	2.5% (1985-1997)	17.4% (1980-1988)	5.2% (1988-1997)	1.0% (1983-1992)	7.2% (1980-1995)	4.0% (1992-1997)	6.2% (1985-1992)	2.7% (1985-1996)	7.0% (1980-1996)	11.2% (1986-1997)	
Current Consumption											
Access to electricity(%)	2.1%	5.7%	100.0%	n.a.	10.0%	8.0%	4.0%	8.0%	7.0%	5.0%	
per capita electricity use (KWH)	18	132	896	43	27	130	28	38	53	36	
Total (GWH/year)	108	113	52,778	171	1,478	3,650	224	2,320	1,698	870	63,372
Demand Forecast											
2005 (GWH/year)	150	290	80,467	251	2,527	5,723	408	3,670	4,166	1,252	98,904
2020 (GWH/year)	251	800	191,222	518	5,523	13,800	961	8,712	9,009	3,551	234,445

Source: The World Bank (1999) Opportunities for Power Trade in the Nile Basin (draft final report).

In economic terms, evaluating the value of irrigation water at US$0.05 per m^3 and value the hydropower at US$0.07 per KWH, the gross annual economic benefits of utilizing the Nile water can be more than doubled if full cooperation is achieved. Most of the increases in economic benefits are from the increases in hydropower production; and in comparison, the increases in the economic benefits from irrigation are moderate. More importantly, the economic gains are much more evenly distributed among the Nile riparian countries—Ethiopia and the Equatorial states can claim 44% of the economic gains created through the full cooperation—without diverting any water from the system for irrigation purposes.

Figure 2-6 Water Allocation and Economic Benefits
under Full Cooperation



System Configuration:

Blue Nile:	Full system
White Nile:	New power stations
Wetland Projects:	Yes
Jabel Auliya:	Modified Operation
White Nile Storage:	Yes

Water Allocation (bcm):

Ethiopia:	0
Sudan:	33
Egypt:	51
Equatorial State:	0
Total:	84

Total Economic Benefits

Country	Hydropower (Millions of US $)	Irrigation (Millions of US $)	Total (Millions of US $)	% of Total
Ethiopia	$2,638		$2,638	31%
Sudan	$171	$1,626	$1,797	21%
Egypt	$379	$2,569	$2,947	35%
Equatorial States	$1,113		$1,113	13%
Total	$4,300	$4,194	$8,494	100%

Figure 2-6 gives a more detailed description of the water allocation and hydropower generation for the full cooperation case. Noticeably, Egypt's New Valley project did not receive any water if the economic value of water in the New Valley is the same as the old land (US$ 0.05 per m^3). Despite the high evaporation losses expected in the Aswan High Dam, it is more efficient from the systems point of view for the water to flow through the Aswan High Dam in order to capturing the benefits from hydropower. In addition, Sudan will receive the majority of its irrigation water from the Blue Nile rather than that from the White Nile.

Perhaps as expected, Egypt is the only country that would suffer some losses when moving from *status quo* to full cooperation, because under the status quo it benefits the most from the inability of other riparian countries to utilize the water of the Nile basin. Of course, the water allocation between Egypt and Sudan can be shifted dramatically if different values of irrigation water or hydropower are assumed. Table 2-15 shows how the optimal water allocation would change under different values for hydropower price while the economic value of water for irrigation is kept at US$ 0.05 per cubic meter. As the value for hydropower increases, the irrigation water allocated to Egypt under the systems optimization will increase dramatically, indicating that the benefits from the hydropower generation in the Aswan High Dam will exceed the losses from evaporation when the value for hydropower increases.

Table 2-15 Sensitivity analyses for variation in the value for hydropower (full cooperation)

Value for Hydropower (US$ per KWH)	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
Water Withdrawal for Irrigation (bcm)								
Ethiopia	0	0	0	0	0	0	0	0
Sudan	84	80	72	71	39	33	6	4
Egypt	0	0	13	17	46	51	74	76
Equatorial States	6	6	0	0	0	0	0	0
Total	90	86	85	88	85	84	80	80

Note: The economic value of water for irrigation is kept at US$ 0.05 per cubic meter.

Similar sensitivity analyses can be conducted for variation in economic value of water for irrigation, and the results are shown in Table 2-16. Again, Egypt would receive all the irrigation water if the economic value of water for irrigation is very low (less than US$ 0.03 per m^3), because the benefits from hydropower generation in Aswan High Dam becomes relatively more important compared to the benefits from irrigation. Such importance will decrease gradually as the economic value of water for irrigation increases.

Table 2-16 Sensitivity analyses for variation in economic value of water for irrigation (full cooperation)

Value for Irrigation Water (US$ per m³)	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
Water Withdrawal for Irrigation (bcm)								
Ethiopia	0	0	0	0	0	0	0	0
Sudan	0	0	4	33	54	70	71	72
Egypt	69	75	76	51	32	17	16	14
Equatorial States	0	0	0	0	0	0	0	3
Total	69	75	80	84	86	87	87	89

Note: The economic value for electricity is kept at US$ 0.07 per KWH.

Table 2-17 Sensitivity analysis of both value of hydropower and value of irrigation water

	Value for Hydropower (US$ per KWH)	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
Value for Irrigation Water (US$ per m³)									
0.02	Water Withdrawal for Irrigation (bcm)								
	Ethiopia	0	0	0	0	0	0	0	0
	Sudan	71	31	2	0	0	0	0	0
	Egypt	[illegible]	53	77	73	70	69	69	69
	Equatorial States	0	0	0	0	0	0	0	0
	Total	88	84	79	73	70	59	69	69
0.03									
	Ethiopia	0	0	0	0	0	0	0	0
	Sudan	82	71	36	4	2	0	0	0
	Egypt	5	17	48	76	77	75	71	70
	Equatorial States	3	0	0	0	0	0	0	0
	Total	90	88	84	80	79	75	71	70
0.04									
	Ethiopia	0	0	0	0	0	0	0	0
	Sudan	84	75	71	37	7	4	2	0
	Egypt	0	11	17	47	73	76	77	76
	Equatorial States	6	3	0	0	0	0	0	0
	Total	90	89	88	85	80	80	79	76
0.05									
	Ethiopia	0	0	0	0	0	0	0	0
	Sudan	84	80	72	71	39	33	6	4
	Egypt	0	0	13	17	46	51	74	76
	Equatorial States	6	6	0	0	0	0	0	0
	Total	90	86	85	88	85	84	80	80
0.06									
	Ethiopia	0	0	0	0	0	0	0	0
	Sudan	83	84	82	74	71	54	36	31
	Egypt	0	0	4	14	17	32	48	53
	Equatorial States	8	6	3	0	0	0	0	0
	Total	91	90	89	88	88	86	84	84
0.07									
	Ethiopia	0	0	0	0	0	0	0	0
	Sudan	83	84	81	75	74	71	58	37
	Egypt	0	0	3	10	14	17	29	47
	Equatorial States	8	6	6	0	0	0	0	0
	Total	91	90	90	85	88	88	87	84
0.08									
	Ethiopia	0	0	0	0	0	0	0	0
	Sudan	83	83	84	80	74	71	71	64
	Egypt	0	0	0	4	12	17	17	23
	Equatorial States	8	8	6	0	0	0	0	0
	Total	91	91	90	84	86	88	88	87
0.09									
	Ethiopia	0	0	0	0	0	0	0	0
	Sudan	83	83	84	83	82	72	71	71
	Egypt	0	0	0	1	5	14	17	17
	Equatorial States	8	8	6	6	3	3	0	0
	Total	91	91	90	90	90	89	88	88

We also conduct a sensitivity analysis when both the economic value for hydropower and value for electricity are allowed to vary, and the results are shown in Table 2-17.

Given any value for irrigation water, Egypt's share of irrigation water will increase as value for hydropower becomes higher; while Sudan's share will decrease. However, the rate of change will differ for different value for irrigation water. For example, as the value for hydropower increases, Sudan's allocation water will change from 71 billion m^3 to 0 when value for irrigation water is US$ 0.02 per cubic meter, but it will only change from 83 billion m^3 to 71 billion m^3 if value for irrigation water is set at 0.09 per cubic m^3. This result suggests that, when the value for irrigation water is higher the additional benefits from hydropower generation in Aswan High Dam resulting from an increase in the value for hydropower becomes less favorable compared to the evaporation losses in the dam.

When the value of water for irrigation is low and the value of hydropower is high, Egypt will receive the majority of the irrigation water, but as value for irrigation water increases, Egypt's share will decrease even when the value for hydropower is high.

While the model allocates equatorial states small amount of water for irrigation either when the economic value of water for irrigation is very high or hydropower price is very low, it is never justifiable from the systems point of view to allocate any water for Ethiopia for irrigation purposes over the range of economic value of irrigation water and value of hydropower. The model would allocate water to Ethiopia only if the economic value for irrigation in Ethiopia is much higher than that in the downstream riparian countries, or if its electricity price is lower than those in other riparian countries.

2.3 The Economic Optimization and Scenario Analysis

While full cooperation in the Nile basin may create significant economic benefits compared to the *status quo*, it should be pointed out that the case of full cooperation is only one of the possible scenarios for the future. As a matter of fact, full cooperation may encounter the greatest challenges in reality.

An important dimension of scenario analysis is the evaluation of capital investment projects. Because of the political and financial constraints, capital investment required to implement the full cooperative schemes will not be available at once, and decision-makers will have to choose among different projects. The scenario analysis conducted in this section should shed some light in this regard.

Another dimension of scenario analysis is the assessment of the effects of the absence of one or more riparian countries in cooperative schemes. Key riparian countries may be absent from the negotiation process or cooperative schemes because of political unrest or internal conflicts. In addition, it is not necessary that cooperative schemes with more riparian countries would yield more desirable outcomes because the additional benefits brought about by including these riparian countries might not justify the additional political costs incurred.

The ten scenarios used in our analysis are defined based on the status of five types of capital investment projects, namely, Blue Nile projects, Wetland projects, White Nile hydropower projects, the modification of Jebel Aulia and White Nile storage projects. The description for each scenario is given in Table 2-18.

Table 2-18 Scenario definitions

	Blue Nile Projects	Wetland Projects (Jonglei, Marchar, Ghazal)	White Nile Hydropower Projects	Jebel Aulia	White Nile Storage projects
Scenario 1: Baseline	None	Existing Conditions	Existing Conditions	Current Operation	None
Scenario 2	LakeTana/ Mabil/Border	Existing Conditions	Existing Conditions	Current Operation	None
Scenario 3	Full System	Existing Conditions	Existing Conditions	Current Operation	None
Scenario 4	None	Yes	Existing Conditions	Current Operation	None
Scenario 5	Full System	Existing Conditions	Full System	Modified Operation	Yes
Scenario 6	None	Existing Conditions	Full System	Current Operation	None
Scenario 7	Full System	Yes	Existing Conditions	Modified Operation	Yes
Scenario 8	None	Yes	Full System	Modified Operation	Yes
Scenario 9	Full System	Yes	Existing Conditions	Modified Operation	None
Scenario 10	Full System	Yes	Full System	Modified Operation	Yes

The first scenario is the baseline case, for which no proposed infrastructure is built. However, the baseline case differs from the *status quo* we discussed earlier on an important account: while in the *status quo* case the current allocation pattern for irrigation water is preserved by imposing irrigation withdrawal constraints in the model, there is no constraint for the baseline case regarding the use of irrigation water. The last scenario, Scenario 10, is the case for full cooperation, the results of which have been shown in the previous section. For this scenario, we assume that all proposed infrastructures (Blue Nile projects, White Nile Reservoirs, White Nile power projects, wetland projects and the modification of Jebel Aulia Dam) will be completed.

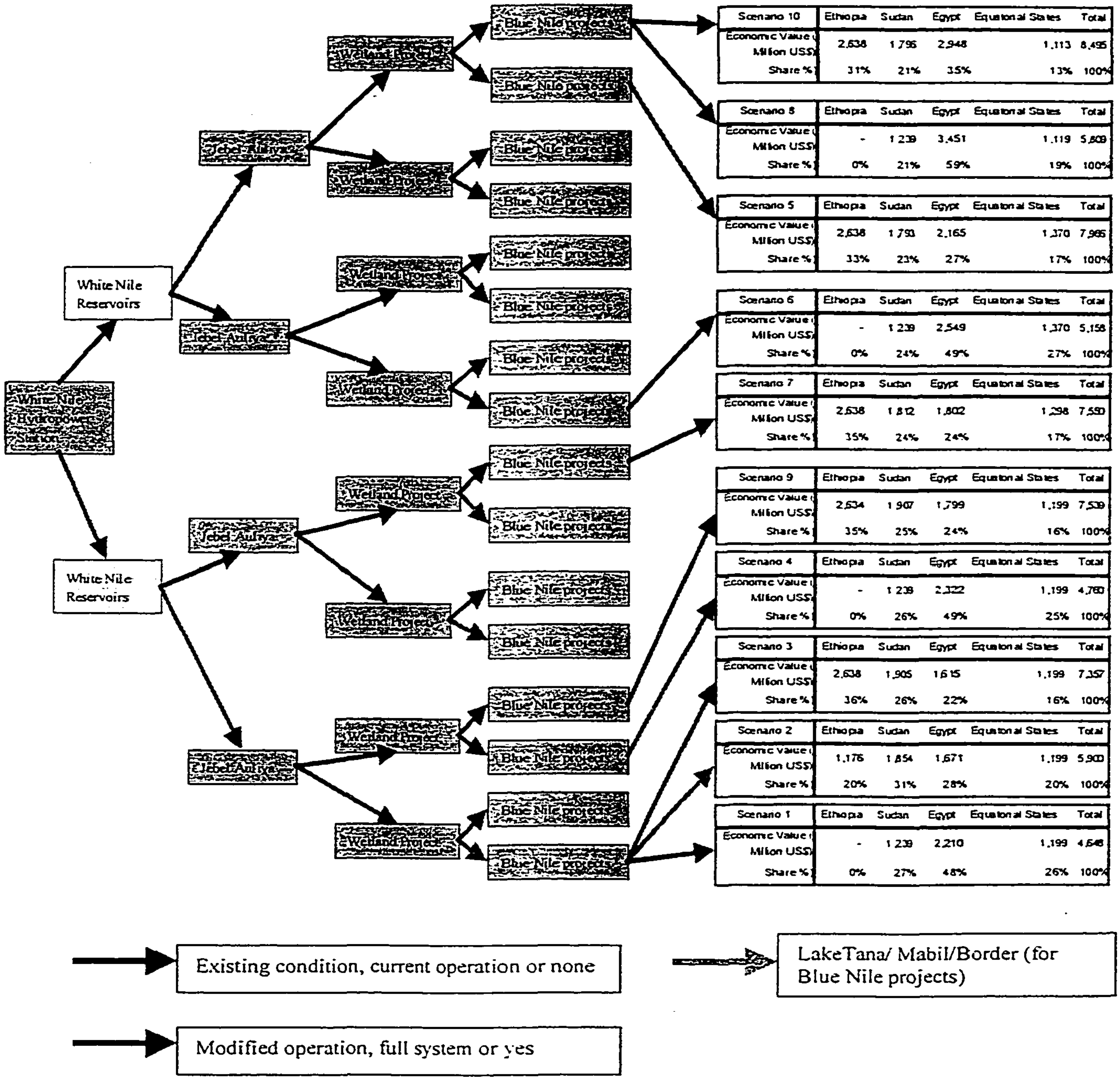
Between the baseline case and the full cooperation, there are several partial cooperative schemes that might be of interest to decision-makers in the Nile basin, and they are represented by Scenario 2 through 9. The comparison of Scenario 1 through 3 shows the economic gains and implications of the Blue Nile projects when all other proposed projects are not in place. In contrast, the comparison between Scenario 8 and Scenario 10 will enable us to understand the economic benefits of these projects when all other projects are completed. Our objective here is to evaluate the economic benefits of the Blue Nile projects and how they might change the allocation pattern for irrigation water.

Given the importance of the wetland projects in increasing the amount of irrigation water for the Nile basin and controversies regarding these projects, we designed Scenarios 4 and 5 to evaluate the economic benefits of the wetland projects. Scenario 4 is the case when none of the proposed projects except the wetland projects is completed while Scenario 5 is the case when all other proposed projects are built but wetland projects are not in place. The results of Scenario 4 can be compared with those of the baseline case in order to evaluate the economic benefits of the wetland projects when none of other proposed projects are completed, and at the meantime, the results of Scenario 5 can be compared to those of the full cooperation case to evaluate the economic benefits of the wetland projects when all other projects are in place.

Scenarios 6 and 7 can be used to show how important the White Nile power stations are to the optimal water allocation of the whole basin. In Scenario 6 none of the proposed projects except the White Nile power stations are completed, and in Scenario 7, all the proposed projects except the White Nile power stations are built. Again, two pairs of comparison, i.e.,*Scenario 1-Scenario 6* and *Scenario 7-Scenario 10*, can be established to evaluate the economic impacts of the White Nile power stations.

Lastly, Scenario 8 and 9 depict the system behaviors when some key riparian countries are absent from the cooperative schemes. Some riparian countries may participate in the negotiation process or cooperative schemes because of political unrest or internal conflicts. In fact, a cooperative scheme with all riparian countries may not always be the most probable outcome because the extra benefits brought about by incorporating additional riparian countries into the cooperative schemes might not justify the additional political costs incurred. It is important to understand the underlying economic implications of bringing in additional riparian countries to the cooperative schemes before any sound judgment can be rendered in this regard. Scenarios 8 and 9 are construed to serve this purpose. Scenario 8 is the case for which all countries but Ethiopia take part in the cooperation; while Scenario 9 is the case where all riparian countries but Uganda take part in the cooperation. Figure 2-7 provides an overview of the allocation of economic benefits for Ethiopia, Sudan, Egypt and the Equatorial States under the ten scenarios in a decision tree format. The remainder of this section will present the results of these scenario analyses in more details and will elaborate on their implications for the optimal utilization of the Nile basin.

Figure 2-7 A decision tree representation of the scenario analysis



Scenario 10	Ethiopia	Sudan	Egypt	Equatorial States	Total
Economic Value (Million US$	2,638	1,796	2,948	1,113	8,495
Share %	31%	21%	35%	13%	100%

Scenario 8	Ethiopia	Sudan	Egypt	Equatorial States	Total
Economic Value (Million US$	-	1,239	3,451	1,119	5,809
Share %	0%	21%	59%	19%	100%

Scenario 5	Ethiopia	Sudan	Egypt	Equatorial States	Total
Economic Value (Million US$	2,638	1,793	2,165	1,370	7,965
Share %	33%	23%	27%	17%	100%

Scenario 6	Ethiopia	Sudan	Egypt	Equatorial States	Total
Economic Value (Million US$	-	1,239	2,549	1,370	5,158
Share %	0%	24%	49%	27%	100%

Scenario 7	Ethiopia	Sudan	Egypt	Equatorial States	Total
Economic Value (Million US$	2,638	1,812	1,802	1,298	7,550
Share %	35%	24%	24%	17%	100%

Scenario 9	Ethiopia	Sudan	Egypt	Equatorial States	Total
Economic Value (Million US$	2,634	1,907	1,799	1,199	7,539
Share %	35%	25%	24%	16%	100%

Scenario 4	Ethiopia	Sudan	Egypt	Equatorial States	Total
Economic Value (Million US$	-	1,239	2,322	1,199	4,760
Share %	0%	26%	49%	25%	100%

Scenario 3	Ethiopia	Sudan	Egypt	Equatorial States	Total
Economic Value (Million US$	2,638	1,905	1,615	1,199	7,357
Share %	36%	26%	22%	16%	100%

Scenario 2	Ethiopia	Sudan	Egypt	Equatorial States	Total
Economic Value (Million US$	1,176	1,854	1,671	1,199	5,900
Share %	20%	31%	28%	20%	100%

Scenario 1	Ethiopia	Sudan	Egypt	Equatorial States	Total
Economic Value (Million US$	-	1,239	2,210	1,199	4,648
Share %	0%	27%	48%	26%	100%

A. Economic Benefits of the Blue Nile Projects

Table 2-19 shows the benefits of Blue Nile projects. Both the amount of water available for irrigation and hydropower production will increase as these reservoirs (dams) are added to the system, and the total economic value for the basin will increase by 58% when all five reservoirs/dams are constructed. Comparing Scenario 2 and the baseline case, the additional hydropower benefits brought about by the three Blue Nile reservoirs (Lake Tana, Mabil and Border) are about US$ 1,150 millions, while the total extra benefits attributable to the three dams is US$ 1,251 millions. The difference between the two, approximately US$ 100 millions annually, is due to the savings from shifting the storage from Aswan High Dam to these Blue Nile reservoirs. As shown by difference between Scenario 2 and 3, the benefits from such savings will stop to increase when two additional reservoirs, Mandaire and Karadobi, are constructed, suggesting that the benefits of water savings can be obtained in full once the three reservoirs are built.

Table 2-19 Economic benefits of Blue Nile projects

	Baseline		*Scenario 2*		*Scenario 3*	
Water Withdrawal for Irrigation	bcm	Economic Value (in million US$)	bcm	Economic Value (in million US$)	bcm	Economic Value (in million US$)
Ethiopia	0	$ -	0	$ -	0	$ -
Sudan	23	$ 1,125	34	$ 1,682	35	$ 1,733
Egypt	38	$ 1,898	29	$ 1,441	28	$ 1,392
Equatorial States	24	$ 1,189	24	$ 1,189	24	$ 1,189
Total	84	$ 4,211	86	$ 4,311	86	$ 4,314
Hydropower Generation	GWH	Economic Value (in million US$)	GWH	Economic Value (in million US$)	GWH	Economic Value (in million US$)
Ethiopia	0	$ -	16797	$ 1,176	37689	$ 2,638
Sudan	1632	$ 114	2451	$ 172	2451	$ 172
Egypt	4464	$ 312	3286	$ 230	3192	$ 223
Equatorial States	156	$ 11	156	$ 11	156	$ 11
Total	6252	$ 438	22690	$ 1,588	43488	$ 3,044
Total Economic Value per country	Share (%)	Economic Value (in million US$)	Share (%)	Economic Value (in million US$)	Share (%)	Economic Value (in million US$)
Ethiopia	0%	$ -	20%	$ 1,176	36%	$ 2,638
Sudan	27%	$ 1,239	31%	$ 1,854	26%	$ 1,905
Egypt	48%	$ 2,210	28%	$ 1,671	22%	$ 1,615
Equatorial States	26%	$ 1,199	20%	$ 1,199	16%	$ 1,199
Total	100%	$ 4,649	100%	$ 5,899	100%	$ 7,358

An interesting finding one may conclude from the results in Table 2-19 is that Sudan's irrigation needs would be given more weight as more dams/reservoirs are added to the Blue Nile. For example, water allocated to Sudan increases from 23 billion m^3 to 34 billion m^3 when Lake Tana, Mobil and Border dams are in operation, and such allocation will further increase to 35 billion m^3 if two additional dam, Mandaira and Karodobi, are added. Sudan's hydropower production will also be boosted from 1632 to 2451 GWH, because the decreased intra-year variations of the Blue Nile flows resulting from the existence of the Blue Nile dams will be beneficial to the electricity production at Roseires and Sennar.

B. Economic Benefits of Wetland Projects

Table 2-20 Economic benefits of wetland projects

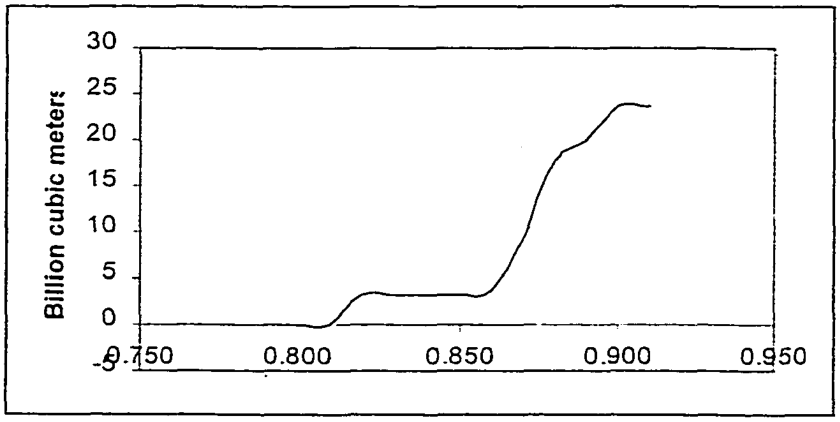
	Baseline		*Scenario 4*		*Scenario 5*		*Scenario 10*	
Water Withdrawal for Irrigation	bcm	Economic Value (in million US$)	bcm	Economic Value (in million US$)	bcm	Economic Value (in million US$)	bcm	Economic Value (in million US$)
Ethiopia	0	$ -	0	$ -	0	$ -	0	$ -
Sudan	23	$ 1,125	23	$ 1,125	32	$ 1,623	33	$ 1,625
Egypt	38	$ 1,898	40	$ 1,996	38	$ 1,877	51	$ 2,569
Eqyuatorial States	24	$ 1,189	24	$ 1,189	8	$ 393	0	$ -
Total	84	$ 4,211	86	$ 4,309	78	$ 3,892	84	$ 4,194
Hydropower Generation	GWH	Economic Value (in million US$)	GWH	Economic Value (in million US$)	GWH	Economic Value (in million US$)	GWH	Economic Value (in million US$)
Ethiopia	0	$ -	0	$ -	37692	$ 2,638	37682	$ 2,638
Sudan	1632	$ 114	1622	$ 114	2432	$ 170	2443	$ 171
Egypt	4464	$ 312	4671	$ 327	4111	$ 288	5408	$ 379
Eqyuatorial States	156	$ 11	156	$ 11	13969	$ 978	15895	$ 1,113
Total	6252	$ 438	6449	$ 451	58204	$ 4,074	61428	$ 4,300
Total Economic Value per country	Share (%)	Economic Value (in million US$)	Share (%)	Economic Value (in million US$)	Share (%)	Economic Value (in million US$)	Share (%)	Economic Value (in million US$)
Ethiopia	0%	$ -	0%	$ -	33%	$ 2,638	31%	$ 2,638
Sudan	27%	$ 1,239	26%	$ 1,239	23%	$ 1,793	21%	$ 1,796
Egypt	48%	$ 2,210	49%	$ 2,322	27%	$ 2,165	35%	$ 2,948
Eqyuatorial States	26%	$ 1,199	25%	$ 1,199	17%	$ 1,370	13%	$ 1,113
Total	100%	$ 4,649	100%	$ 4,760	100%	$ 7,966	100%	$ 8,494

The economic benefits of wetland projects are shown in Table 2-20. Maybe surprising to the proponents of the wetland projects, these projects appear effective in changing the water allocation pattern only if other proposed investment projects are in place, when the irrigation value is valued at US$0.05 per m^3 and hydropower priced at US$0.07 per KWH. While the wetland projects can increase the amount of water by 2 billion m^3 measured at Egypt (Baseline scenario vs. Scenario 4), they do not change the fact that water from Lake Victoria may be best utilized if it does not leave Lake Victoria basin.

The wetland projects will have bigger impacts when they are combined with other projects. The annual gross economic benefits of the wetland projects are US$ 535 millions (the net difference between Scenario 5 and Scenario 10) once other projects are in place, representing an increase of 7% over the case without these projects. It is clear that, if equatorial states aggressively expand their irrigation schemes around the Lake Victoria area, the benefits of the wetland projects would be less.

We conducted a sensitivity analysis to see in what circumstances the wetland projects might be more beneficial. We incrementally changed the value of irrigation water for the equatorial states for Scenario 4, and charted the amount of the water allocated to the equatorial states against the ratio of the value of irrigation water for the equatorial states to that of downstream countries. The results are shown in Figure 2-8. With the construction of wetland projects, the model will not allocate water to equatorial states if the value of irrigation in the equatorial states is less than 80% of the irrigation value in downstream countries. If the value of irrigation water in the equatorial states is more than 90% of that of Sudan and Egypt, the water from Lake Victoria will find its highest return without flowing downstream.

Figure 2-8 Sensitivity analysis of value of irrigation for the equatorial states



C. Economic Benefits of White Nile Power Stations

The White Nile power stations have not received much attention in current literature regarding the water development in the Nile basin. Although these projects cannot increase the yield of water flow of the Nile, they have profound impacts on how water should be best allocated. Table 2-21 provides some interesting and perhaps surprising insights.

Table 2-21 Economic Benefits of White Nile power stations

	Baseline		*Scenario 6*		*Scenario 7*		*Scenario 10*	
Water Withdrawal for Irrigation	bcm	Economic Value (in million US$)	bcm	Economic Value (in million US$)	bcm	Economic Value (in million US$)	bcm	Economic Value (in million US$)
Ethiopia	0	$ -	0	$ -	0	$ -	0	$ -
Sudan	23	$ 1,125	23	$ 1,125	33	$ 1,641	33	$ 1,625
Egypt	38	$ 1,898	44	$ 2,193	31	$ 1,557	51	$ 2,569
Equatorial States	24	$ 1,189	8	$ 393	26	$ 1,296	0	$ -
Total	84	$ 4,211	74	$ 3,711	90	$ 4,494	84	$ 4,194
Hydropower Generation	GWH	Economic Value (in million US$)	GWH	Economic Value (in million US$)	GWH	Economic Value (in million US$)	GWH	Economic Value (in million US$)
Ethiopia	0	$ -	0	$ -	37692	$ 2,638	37684	$ 2,638
Sudan	1632	$ 114	1622	$ 114	2441	$ 171	2443	$ 171
Egypt	4464	$ 312	5086	$ 356	3501	$ 245	5408	$ 379
Equatorial States	156	$ 11	13969	$ 978	36	$ 3	15895	$ 1,113
Total	6252	$ 438	20677	$ 1,447	43670	$ 3,057	61430	$ 4,300
Total Economic Value per country	Share (%)	Economic Value (in million US$)	Share (%)	Economic Value (in million US$)	Share (%)	Economic Value (in million US$)	Share (%)	Economic Value (in million US$)
Ethiopia	0%	$ -	0%	$ -	35%	$ 2,638	31%	$ 2,638
Sudan	27%	$ 1,239	24%	$ 1,239	24%	$ 1,812	21%	$ 1,796
Egypt	48%	$ 2,210	49%	$ 2,549	24%	$ 1,802	35%	$ 2,948
Equatorial States	26%	$ 1,199	27%	$ 1,370	17%	$ 1,298	13%	$ 1,113
Total	100%	$ 4,649	100%	$ 5,158	100%	$ 7,550	100%	$ 8,494

The difference between the baseline and Scenario 6 is that in the latter the White Nile power stations are added. With the White Nile power stations, the model allocates most of the White Nile discharge from Lake Victoria to downstream countries even if the evaporation losses at Sudd stand at 50%. However, it cannot do so without some trade-offs. While the total hydropower increases by about 14,000 GWH, or more than 200% over the baseline case, the benefits from the increased hydropower production would have to be discounted by the losses of 10 billions m^3 in water which could otherwise available for irrigation. It is important that these evaporation losses to be taken into consideration when evaluating the benefits of the White Nile power stations.

Scenario 7 highlights the importance of White Nile power stations in the cooperation. Without White Nile power stations, water from Lake Victoria basin should be best utilized by the equatorial states even when wetland projects are completed. However, the large evaporation losses we've seen from the comparison between baseline and scenario 6 will not be at present here, because the wetland projects are in place. Our results demonstrate an interesting relationship between wetland projects and White Nile power stations: without White Nile power stations, wetland projects will not be very effective; without wetland projects, the benefits from White Nile power stations will have to be discounted heavily by the evaporation losses at the Sudd. Such interdependency might suggest that these two projects should be bundled together when different investment projects are considered.

Besides the equatorial states (Uganda, in particular), Egypt may benefit the most from the construction of the White Nile power stations. Once the water passes through the White Nile power stations, it is optimal for water to continue its flow until reaching Aswan High Dam, and thus Sudan would gain little from the addition of the White Nile power stations, regardless of whether or not other regulation facilities are in place. In fact, the total benefits for Sudan may actually decrease after these stations are added (See Table 2-16 for details). From the Egyptian perspective, a good strategy for alleviating concerns over the potential irrigation withdrawal in the equatorial states might be to assist these countries in the expansion of their hydropower facilities.

D. Economic Implications of Partial Cooperation

As stated earlier, full cooperation may not be the most probable outcome. In fact, it may not necessarily be the most desirable outcome. Under certain circumstances, the extra benefits brought about by incorporating additional riparian countries into the cooperative schemes might not justify the additional political costs incurred. The cases with or without some riparian countries are particularly relevant in practice because bringing additional riparian countries on-board might induce conflict of interest among different countries in the initial cooperative scheme. However, it is important to understand the underlying economic implications of bringing in additional riparian countries to the cooperative schemes before any sound judgment can be rendered in this regard. Scenario 8 and 9 are designed to serve this purpose. Scenario 8 is the case for which all countries but Ethiopia take part in the cooperation; while Scenario 9 is the case where all riparian countries but Uganda take part in the cooperation.

Table 2-22 shows that, while the construction of the Blue Nile projects will dramatically increase the economic benefits (exclusively hydropower) for Ethiopia, the extra benefits of these projects for the other three parties—Egypt, Sudan and the equatorial states—are rather modest if side payments would not be used to reallocate economic benefits among riparian countries. For example, excluding the huge increase in benefits for Ethiopia, the extra benefits of Blue Nile dams to the rest of the riparian countries are only in the order of 45 millions annually

Table 2-22 Cooperation w/o Ethiopia and cooperation w/o the Equatorial States

	Scenario 8		*Scenario 9*		*Scenario 10*	
Water Withdrawal for Irrigation	bcm	Economic Value (in million US$)	bcm	Economic Value (in million US$)	bcm	Economic Value (in million US$)
Ethiopia	0	$ -	0	$ -	0	$ -
Sudan	23	$ 1,125	35	$ 1,735	33	$ 1,625
Egypt	60	$ 2,996	31	$ 1,554	51	$ 2,569
Equatorial States	0	$ -	24	$ 1,189	0	$ -
Total	82	$ 4,121	90	$ 4,477	84	$ 4,194
Hydropower Generation	GWH	Economic Value (in million US$)	GWH	Economic Value (in million US$)	GWH	Economic Value (in million US$)
Ethiopia	0	$ -	37625	$ 2,634	37684	$ 2,638
Sudan	1622	$ 114	2452	$ 172	2442	$ 171
Egypt	6499	$ 455	3510	$ 246	5408	$ 379
Equatorial States	15985	$ 1,119	156	$ 11	15895	$ 1,113
Total	24106	$ 1,687	43743	$ 3,062	61429	$ 4,300
Total Economic Value per country	Share (%)	Economic Value (in million US$)	Share (%)	Economic Value (in million US$)	Share (%)	Economic Value (in million US$)
Ethiopia	0%	$ -	35%	$ 2,634	31%	$ 2,638
Sudan	21%	$ 1,239	25%	$ 1,907	21%	$ 1,796
Egypt	59%	$ 3,451	24%	$ 1,799	35%	$ 2,948
Equatorial States	19%	$ 1,119	16%	$ 1,199	13%	$ 1,113
Total	100%	$ 5,808	100%	$ 7,539	100%	$ 8,494

In comparison, the impacts of including the Equatorial States in cooperation are of different characteristics. The Equatorial States may not benefit from such cooperation if they are able to fully capture the irrigation potentials around the Lake Victoria sub-basin. In fact, turning from Scenario 9 to full cooperation, the net benefits for the Equatorial States would be negative because it would lose its irrigation water while gaining from hydropower production. Egypt can strengthen its position significantly by obtaining better economic return when the Equatorial States are on-board. In fact, Egypt is the only country that would gain from such move (Sudan will see a slight decrease in its benefits when the Equatorial States are included. It indicates that the Equatorial States' participation in the cooperative scheme would be particularly important for Egypt; and it would be in Egypt's best interest to secure Equatorial States membership in any cooperative scheme even if it may have to compensate them for such participation.

2.4 Economic Optimization and Political Constraints

Another critical aspect of our analysis is the consideration of a variety of political constraints. For example, a riparian country may request a predetermined withdrawal target be satisfied before it would consider any cooperative scheme; or several riparian countries may insist that certain water allocation patterns be observed in any new agreement regarding water allocation.

Political constraints may have important implications for optimization models. On one hand, optimisation models ignoring political constraints are expected to meet harsh resistance. On the other hand, political constraints are different from the laws of nature, and under certain circumstances, they can be removed with certain costs. In this section, we examine the economic implications of imposing several political constraints to the model.

The first constraint we consider here is the 1959 agreement. Egypt has repeatedly claimed that it would not negotiate its water allocation established through the 1959 agreement. However, the 1959 Nile waters Agreement leaves out seven other riparian states, including Ethiopia, where much of the Nile Water originates. Conditions of the riparian countries have changed dramatically since the agreement was signed. Hence, the strategies of all riparian countries will have to adapt to these changes. Table 2-23 shows how imposing the constraint will impact the results of the model.

Table 2-23 Economic costs of the 1959 Agreement

	Scenario 7: no constraint		*Scenario 7: constrained*		*Scenario 10: no constraint*		*Scenario 10: constrained*	
Water Withdrawal for Irrigation	bcm	Economic Value (in million US$)	bcm	Economic Value (in million US$)	bcm	Economic Value (in million US$)	bcm	Economic Value (in million US$)
Ethiopia	0	$ -	0	$ -	0	$ -	0	$ -
Sudan	33	$ 1,641	16	$ 800	33	$ 1,625	33	$ 1,625
Egypt	31	$ 1,557	51	$ 2,550	51	$ 2,569	51	$ 2,569
Equatorial States	26	$ 1,299	19	$ 954		$ -		$ -
Total	90	$ 4,497	86	$ 4,304	84	$ 4,194	84	$ 4,194
Hydropower Generation	GWH	Economic Value (in million US$)	GWH	Economic Value (in million US$)	GWH	Economic Value (in million US$)	GWH	Economic Value (in million US$)
Ethiopia	37692	$ 2,638	37692	$ 2,638	37684	$ 2,638	37684	$ 2,638
Sudan	2441	$ 171	2448	$ 171	2442	$ 171	2443	$ 171
Egypt	3501	$ 245	5447	$ 381	5408	$ 379	5410	$ 379
Equatorial States	36	$ 3	416	$ 29	15895	$ 1,113	15895	$ 1,113
Total	43670	$ 3,057	46003	$ 3,220	61429	$ 4,300	61432	$ 4,300
Total Economic Value per country	Share (%)	Economic Value (in million US$)	Share (%)	Economic Value (in million US$)	Share (%)	Economic Value (in million US$)	Share (%)	Economic Value (in million US$)
Ethiopia	35%	$ 2,638	35%	$ 2,638	31%	$ 2,638	31%	$ 2,638
Sudan	24%	$ 1,812	13%	$ 971	21%	$ 1,796	21%	$ 1,796
Egypt	24%	$ 1,802	39%	$ 2,931	35%	$ 2,948	35%	$ 2,948
Equatorial States	17%	$ 1,301	13%	$ 983	13%	$ 1,113	13%	$ 1,113
Total	100%	$ 7,553	100%	$ 7,524	100%	$ 8,494	100%	$ 8,494

Once all the proposed Nile projects are in place, the constraints imposed by the 1959 agreement will have much greater implications for equity than for efficiency. Take Scenario 7, for example. The total economic losses attributable to the agreement are US$ 29 million annually, a small amount compared to the size of the total benefits of utilizing the Nile water. However, once the constraints are imposed, the benefits accruing to Sudan and the equatorial countries are reduced considerably (Sudan would incur a loss amounting to 50%, while this loss is 20% for the equatorial states). Meanwhile, Egypt would be in a position to turn these losses to its advantage.

Another interesting set of political constraints that are of immediate political implications for Nile cooperation is the irrigation withdrawal targets claimed by upstream riparian countries, particularly by Ethiopia. Table 2-24 shows the economic implications of imposing such constraints to the model. We consider three cases of imposing the constraints: the "low withdrawal" is for the case in which Ethiopia diverts 5 billion m^3, the "medium withdrawal" is when Ethiopia demands 10 billion m^3, and the "high withdrawal" is when Ethiopia sets the withdrawal target at 20 billion m^3.

Table 2-24 Economic costs of downstream withdrawal targets (Ethiopian withdrawal)

		Scenario 3: no constraint		*Scenario 3: Low withdrawal*		*Scenario 3: Midium withdrawal*		*Scenario 3: High withdrawal*
Water Withdrawal for Irrigation	bcm	Economic Value (in million US$)	bcm	Economic Value (in million US$)	bcm	Economic Value (in million US$)	bcm	Economic Value (in million US$)
Ethiopia	0	$ -	5	$ 250	10	$ 500	20	$ 1,000
Sudan	35	$ 1,733	31	$ 1,555	29	$ 1,433	24	$ 1,179
Egypt	28	$ 1,392	27	$ 1,330	24	$ 1,218	20	$ 1,000
Equatorial States	24	$ 1,189	24	$ 1,189	24	$ 1,189	24	$ 1,189
Total	86	$ 4,314	86	$ 4,323	87	$ 4,339	87	$ 4,367
Hydropower Generation	GWH	Economic Value (in million US$)	GWH	Economic Value (in million US$)	GWH	Economic Value (in million US$)	GWH	Economic Value (in million US$)
Ethiopia	37689	$ 2,638	36666	$ 2,567	35469	$ 2,483	33303	$ 2,331
Sudan	2451	$ 172	2445	$ 171	2437	$ 171	1930	$ 135
Egypt	3192	$ 223	3072	$ 215	2865	$ 201	2489	$ 174
Equatorial States	156	$ 11	156	$ 11	156	$ 11	156	$ 11
Total	43488	$ 3,044	42339	$ 2,964	40927	$ 2,865	37878	$ 2,651
Total Economic Value per country	Share (%)	Economic Value (in million US$)	Share (%)	Economic Value (in million US$)	Share (%)	Economic Value (in million US$)	Share (%)	Economic Value (in million US$)
Ethiopia	36%	$ 2,638	39%	$ 2,817	41%	$ 2,983	47%	$ 3,331
Sudan	26%	$ 1,905	24%	$ 1,726	22%	$ 1,603	19%	$ 1,314
Egypt	22%	$ 1,615	21%	$ 1,545	20%	$ 1,419	17%	$ 1,174
Equatorial States	16%	$ 1,199	16%	$ 1,199	17%	$ 1,199	17%	$ 1,199
Total	100%	$ 7,358	100%	$ 7,286	100%	$ 7,204	100%	$ 7,018

Comparing the "no constraint" and "high withdrawal" cases, Ethiopia would gain US$ 693 millions while Egypt and Sudan combined would lose US$ 1,122 millions, resulting in a total system loss of US $340 millions. Not only water allocation for Egypt and Sudan would be reduced by the amount of Ethiopia withdrawal, hydropower production in these two countries would also suffer from significant losses.

In addition to the effects on the system as a whole and on other riparian countries, the irrigation withdrawal constraints for Ethiopia also have important implications to the country itself. Ethiopia will benefit from irrigation when certain withdrawal targets are imposed, but its benefits from hydropower will be reduced. Table 2-25 shows such trade-off for Ethiopia.

Table 2-25 Economic implications of the irrigation withdrawal of Ethiopia

	Three Blue Nile dams (Lake Tana/Mabil/Border)			All five Blue Nile dams		
	No withdrawal for Ethiopia	High Withdrawal for Ethiopia	Difference	No withdrawal for Ethiopia	High Withdrawal for Ethiopia	Difference
Irrigation Water (BCM)	0	20	20	0	20	20
Hydropower Production (KWH)	16799	12799	-4000	37684	33303	-4381
Economic Benefits (in million US$)	1176	1896	720	2638	3331	693

As we can conclude from the table, Ethiopia's benefits from imposing a higher withdrawal targets will decrease if more Blue Nile dams are built, because the losses from hydropower will be greater. This result suggest that a compelling reason for Egypt and Sudan for having more development along the Blue Nile is that, once these projects are in place, the political costs for Ethiopia to decrease its irrigation withdrawal targets might be actually lowered because gains from hydropower can partially offset the losses from irrigation.

2.5 Concluding Remarks

Cooperation in international rivers has rarely taken place in reality, and such lack of success is partially due to the fact that the magnitude of potential gains from cooperation is largely unknown for most international rivers, and riparian countries may have an incomplete or even inaccurate knowledge of cooperative opportunities. As a result, water conflicts in international rivers have often been mistakenly perceived as zero-sum games, where there might be plenty of opportunities for win-win solutions.

Results of the economic optimization in this chapter clearly show that there might be some win-win solutions for water conflicts in the Nile basin if full cooperation can be achieved. With the completion of the Blue Nile storage projects, wetland projects, White Nile power stations and the modification of the Jebel Aulia, additional 15 billion m^3, or 20% of the average annual discharge of the basin, can be made available to the Nile riparian countries. In addition, additional 52,000 GWH of electricity will be made available to the grids of the Nile basin countries. Since most of the increases in economic benefits are from the increases in hydropower production, and such increase will be concentrated on Ethiopia and the Equatorial States, the economic gains are much more evenly distributed among the Nile riparian countries. Ethiopia and the Equatorial States can dramatically increase their benefits of utilizing the Nile water without diverting any water from the system for irrigation purposes.

The Blue Nile projects will significantly increase the benefits accrued to Ethiopia. It is also beneficial from a systems point of view since the additional storage capacity in the Blue Nile will allow the water storage to shift from the Aswan High Dam to the Blue Nile dams and thus to reduce evaporation losses. Once more Blue Nile storage facilities are in place, the political costs for Ethiopia to decrease its irrigation withdrawal targets might be actually lowered because gains from hydropower can partially offset the losses from irrigation.

Another interesting finding from our analysis is the relationship between wetland projects and White Nile power stations. Without the White Nile power stations, wetland projects will not be very beneficial; without wetland projects, the benefits from White Nile power stations will have to be discounted heavily by the evaporation losses at the Sudd. Such interdependency might suggest that these two projects should be bundled together when different investment projects are considered.

The two main existing users of the Nile water—Egypt and Sudan—are found to be affected differently by different infrastructure projects. For example, Sudan's irrigation needs would be given more weight once Blue Nile storage projects are in place while Egypt may benefit handsomely from the construction of the White Nile power stations.

Lastly, while the model results show that water from the Lake Victoria basin should be best utilized by the equatorial states in absence of White Nile power stations, it is not justifiable from the systems point of view to allocate any water for Ethiopia for irrigation purposes under almost all scenarios and reasonable ranges of the economic value for water.

Chapter 3 Economic Incentives for Cooperative Behaviour

Identifying win-win solutions for water conflicts involves several challenging tasks. The first is to determine what the appropriate reference point should be for each riparian country. While it might be convenient to think of the *status quo* as a reference point, a comparison based on the *status quo* can be misleading. For example, given the fact that the upstream riparian countries of the Nile basin are currently using very little water from the Nile, any upside incremental change in their water uses resulting from a potential water allocation agreement may represent a significant improvement over the *status quo*, and thus may be perceived as a "win" for them. However, from the perspective of these riparian countries, it could not be a "win" unless the benefits allocated to them are more than what they would have achieved on their owns. In our view, the more appropriate reference point for comparison purposes should be what each riparian country could have achieved without participating in any cooperative scheme. Another demanding task is to determine the allocation of benefits among riparian countries. Negotiation may breakdown not because there is no win-win solution, but because there are too many of them, and there is no guiding principle to reconcile the differences in the preferences of riparian countries over different solutions. It is apparent that the economic gains from system optimisation will mean very little to individual riparian countries unless appropriate institutions are in place to guarantee the economic incentives for them to embrace cooperative initiatives.

Determination of the economic incentives for individual riparian countries in water allocation negotiation is the main subject of this chapter. The advances in modern game theory have provided a set of tools that can be applied to characterize and measure such incentives. For example, the concept and the theory of the core can be used to determine the economic incentives necessary to induce cooperative behaviors of all riparian countries by taking into consideration their relative hydrological positions, economic returns of non-cooperative behaviours as well as their ability to form partial coalitions with other riparian countries. Through the analysis in this chapter, we will setup a cooperative game-theoretical framework for water allocation negotiation for the Nile basin, and show how such a framework might be useful in the negotiation process.

In addition, several game-theoretical solutions such as the Shapley value and the nucleolus will be presented. The game-theoretical solutions in cooperative game theory can serve as some logical focal points where efficiency and equity considerations may converge. For example, solution concepts such as *Shapley value* and *nucleolus* are rooted in some normative notions of justice, and yet at the same time the principles of economic efficiency can be preserved. We will demonstrate how these solution concepts might be relevant to the potential water allocation negotiation for the Nile basin.

3.1 A Game-Theoretical Framework for the Nile Basin

Facing present or potential water conflicts in international rivers, riparian counties typically have four types of strategies to choose from: negotiating with co-riparian countries, unilaterally creating new facts, making threats of violence or simply taking no action. Too often, riparian countries have decided to overlook the potential benefits of settling their difference through negotiation and cooperation, and instead to engage in activities that would further deteriorate the situation. For example, in light of the uncertainties surrounding the future allocation of the Nile water, both Ethiopia's micro-dam strategies and Egypt's New Land Reclamation project may be perceived by many as an attempt to create new facts that could significantly change the landscape for future negotiation among the Nile riparians (Waterbury and Whittington, 1999).

Although these decisions may lead to counter-productive measures and sub-optimal results for the whole basin, justifications for such decisions may easily be found from an individual country's perspective. For example, no action can be a good strategy for a particular riparian country as long as the opportunity costs of delaying action can be offset by the benefits from holding the options of taking actions in the future. The success of a particular allocation scheme will critically depend on whether or not there exist sufficient incentives for each riparian country to act cooperatively.

A. Determinants of Economic Incentives

Economic incentives for cooperation are first determined by the hydro-strategic position of a particular riparian country. The better the country's 'hydro-strategic' position, the less interest it has in reaching a water-sharing agreement (Wolf, 1996), and thus more incentives are required to guarantee its presence in negotiation or cooperation. For instance, other things being equal, Ethiopia would have very little incentive in reaching water-sharing agreements with upstream countries since most of the Nile water originates from that country. In contrast, Egypt may have the strongest incentive to establish water-sharing agreements with upstream riparian countries to secure its long-term water supply.

The incentives necessary for inducing cooperative behaviours are also determined by how well a riparian country can do if it acts independently. This factor is somewhat related to the hydro-strategic position of a riparian country, but it is also confined by the economic and financial conditions of that country. For example, if a riparian country does not have the financial resources to launch large-scale water resource development projects within its territory, it may find itself in a weaker position in negotiation as it would have to depend on the assistance of other countries or international organizations in developing these projects. On the other hand, a riparian country that has sufficient means to withstand extreme events caused by uncertainty may be rewarded in negotiation for such capability. For example, although Egypt cannot control the sources of the Nile water, the Aswan High Dam offers multiyear storage capacity for the country, and it might be in a better position than Sudan because it has the means to withstand adverse events such as floods and droughts.

Lastly, economic incentives are also determined by the ability of riparian countries to form strong alliances with other countries. For a riparian country that can secure the bulk of its share through some partial coalitions with one or more riparian countries, the additional benefits resulting from full cooperation may appear to be less important.

Because of the symmetric nature of the problem, ensuring the incentives for other riparian countries will also constrain the maximum share a particular country can demand, essentially setting the upper bound for the potential negotiation. For instance, the maximum benefits Ethiopia can potentially demand is the total economic benefits of cooperation minus the total of the minimum incentives provided for rest of the riparian countries; otherwise one or a few countries would defect from the cooperative scheme. Too often, negotiation ends prematurely because one or a few riparian countries have unrealistic expectations about the potential share that it can seek through negotiation or political manoeuvre.

B. Cooperative Game Theory and Water Allocation Games

Cooperative game theory can be applied to identify the economic incentives necessary for riparian countries to embrace cooperative initiatives. The concept of the core can be used to establish the negotiation boundary by taking into consideration their relative hydrological positions, economic returns of non-cooperative behaviors, as well as their ability to form partial cooperative schemes with other riparian countries.

In order to define a cooperative game for the water allocation negotiation for the Nile basin adequately, we first need to introduce several concepts. A typical cooperative 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 of the game.

Although there are 10 riparian countries in the Nile basin, they are not equally affected by the flow of the river. For example, the water claims from the countries such as Burundi, Rwanda, Democratic Republic of Congo and Eritrea are likely to be small, hence including every riparian as an independent player in the game would unnecessarily complicate our analysis. In the allocation game described here we consider four players—Egypt, Sudan, Ethiopia and the Equatorial States. The Equatorial States can be viewed as a stable decision-making entity established among equatorial states, mostly for the benefits of Uganda, Kenya and Tanzania. In addition, although one might envision a situation where there are multiple interest groups at work for each of the four players—for instance, Ethiopia farmers and hydropower companies might have a conflict of interest in utilizing water—we simplify the matter by assuming that these four players can make decisions for maximizing their total economic benefits.

Each player in the game has three actions to choose from: act independently, join the full cooperation scheme that includes all players, or form some partial coalitions with one or a few other players[1]. Coalitions are the subsets of players that are able to make a binding agreement (Friedman, 1986). Coalitions with only one member represent the situation where players act independently. For the Nile allocation game, coalitions such as (Egypt), (Sudan), (Ethiopia) and (*Equatorial States*) are of this nature. The coalition with all players in the game is full cooperation, and we denote the case by (Egypt-Sudan-Ethiopia-*Equatorial States*). The coalitions

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[1] Since a particular country can form different partial coalitions with different players, one might argue that there are several actions available for each player in terms of forming partial coalitions.

with more than one member but less than the total number of players are all partial coalitions of the game. Some examples of partial coalitions for the game are (Egypt-Sudan), (Sudan-Ethiopia), or (Egypt-Sudan-Ethiopia). *In this section, we limit our attention to cases for which no partial coalition is permitted, and by doing so we only measure the effects of the first two determinants of the economic incentives, namely, hydro-strategic positions of riparian countries and how well they can do on their own.* We will relax this restriction in the next section.

The characteristic functions will differ based on whether or not players can make side payments to each other. If side payments are allowed in the game, there is a scalar valued function, v(K), for each coalition with K members. The v(K) here can be interpreted as the maximum payoff for this coalition. For games where side payments are not allowed, v(K) denotes the set of all payoff vectors u^K that the coalition K can achieve, and it satisfies the condition $u^K_i \geq u_i$, u^K_i being the payoff for player *i* in the coalition and u_i being the payoff *i* can achieve on its own. Given the lack of clearly defined rights for water in international rivers, side payments as allocation mechanisms among riparian countries may encounter harsh resistance from the countries that have to make the side payments.

However, excluding the possibility of side payments will force us to speculate on how benefits will be divided among riparian countries in any partial coalition, a procedure that might be too arbitrary at this stage of analysis. In addition, while side payments are not common, they are certainly not entirely impossible. In fact, in the Nile basin Egypt and Uganda had an agreement regarding the operation of Owen Fall Dam, which specifies that payment be made from Egypt to Uganda if the dam were operated to benefit Egypt at the expenses of Uganda. Side payments may also take other forms. For example, a riparian country may be able to provide a certain amount of electricity for free or for a low price to other riparians as a means of side payments; or side payments can be made in the form of technical and financial assistance for developing water resources projects. In our analysis, we consider both the cases with side payments and the cases without them.

C. The Definition of the Core

The core of the game can be defined after the three elements of the cooperative game are specified. The core of a game is a set of all payment vectors u^K, such that $\Sigma\, u^K_i \leq v(I)$ and

$\Sigma(i \subseteq I)\ u^K_i \geq v(S)$, *I* being the grand coalition with all players and S being the set of all possible coalitions except the grand coalition. For the allocation games for international rivers, the core represents economic incentives necessary to bring riparian countries into the cooperative scheme. The first condition, $\Sigma\ u^K_i \leq v(I)$, makes sure that the summation of benefits for riparian countries will be less than the total benefits available for allocation; and the second condition, $\Sigma(i \subseteq I)\ u^K_i \geq v(S)$, guarantees that each riparian country will do better by participating in the full cooperation scheme than by acting unilaterally or by forming partial coalition.

Two facts are worth mentioning with regard to applying the concept of the core to the water allocation negotiation for international rivers. The first is that many allocations may belong to the core, and within the economic theory of the core, there is no guidance to suggest that one allocation in the core is better than another. The second is that the core may not exist for some allocation games. An empty core would imply that there is no allocation that would provide the economic incentives for all riparian countries to participate in the full cooperation scheme.

Since we rule out the possibility of partial coalitions in this section, there are only five possible coalitions for the Nile allocation game. They are, namely, (Egypt), (Sudan), (Ethiopia), (*Equatorial States*), and (Egypt-Sudan-Ethiopia-*Equatorial States*). For the case in which Ethiopia acts independently, we assume that Ethiopia would build Lake Tana Dam on its own, and it would unilaterally develop irrigation schemes to maximize its own total benefits (hydropower benefits plus irrigation benefits). For the coalition (*Equatorial States*), we assume that the White Nile power stations would not be in place, and the *Equatorial States* would demand a large quantity of irrigation water when maximizing its total benefits. As for Egypt and Sudan, we assume that if they both act independently, Sudan would divert irrigation water in the amount as specified in the 1959 Agreement (about 18.5 billion m^3) despite the increased water uses in the upstream riparian countries[2], and any remaining water would be for the use of Egypt.

Table 3-1 shows the benefits and water allocations for four players under these different coalitions. We need to emphasize that the costs of building infrastructure in the full cooperation cases are not included, and thus benefits are gross rather than the net.

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[2] Sudan will be in better position than Egypt here if all countries act independently because it can divert water before the water can reach Egypt.

Table 3-1 No cooperation and full cooperation

No Cooperation				***Full Cooperation***			
	Irrigation water (bcm)	Hydropower generation (GWH)	Total Economic Value (in million US$)		Irrigation water (bcm)	Hydropower generation (GWH)	Total Economic Value (in million US$)
Ethiopia	11	745	$ 592	**Ethiopia**	0	37682	$ 2,948
Sudan	16	1225	$ 886	**Sudan**	33	2443	$ 1,796
Egypt	34	4007	$ 1,963	**Egypt**	51	5408	$ 2,638
Equatorial States	24	118	$ 1,232	**Equatorial States**	0	15895	$ 1,113
Total	85	6095	$ 4,673	**Total**	84	61428	$ 8,494

As we pointed out earlier, the reference point we employ here is not the status quo, rather it is based on an assumption as to what each riparian country could achieve on its own when there were no cooperation. For example, while in the *status quo* Ethiopia and the Equatorial States have used very little water for irrigation purposes, we assume that without cooperation in the Nile basin they could withdraw a significant portion of the Nile water for irrigation. Although such a reference point offers a better basis for comparison purposes, it also critically depends upon several assumptions. For example, the benefits for the Equatorial States would have been much smaller if we assume that the future political or financial conditions would restrain its ability to reach the maximum level of benefits. Therefore, while assumptions used in our analysis might reflect our knowledge of the situation at present, they can only be regarded as educated guesses at best.

Given the set of assumptions, Egypt, Sudan and Ethiopia would incur significant losses if full cooperation could not be achieved. Without considering the costs of building new infrastructures, the total benefits available for allocation is significantly less in the case of players acting alone than in the case of full cooperation. In fact, moving from no cooperation to full cooperation, the total economic benefits for the whole basin can be increased by 82%.

Based on the definition of the core given earlier, the core[3] of the game consists of the set of allocations that meet the following conditions:

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[3] Although strictly speaking the core of a game is defined when all the potential coalitions are in existence, in our model we consider an interpretation that, if a potential coalition can not be formed, the total benefits for players in the "coalition" are simply the sum of the benefits the players can obtain independently. From this interpretation, all the potential coalitions are in existence, although some of them do not bring extra benefits.

P(Egypt) ≥ 1963[4]; P(Sudan) ≥ 886; P(Ethiopia) ≥ 592; P(Equatorial States) ≥ 1232;
P(Egypt) + P(Sudan) + P(Ethiopia) + P(Equatorial States) ≤ 8494

We cannot display the sphere of the core graphically since it requires four dimensions to do so. However, one can find the boundary of the core by solving four constrained maximization problems, one for each player of the game. The objective function for the maximization problem for each players is P(i), i = Egypt, Sudan, Ethiopia, *the Equatorial States*, the benefits can be allocated for the specific player, and the constraints are the conditions for the core as shown in the box above. Table 3-2 displays the lower and upper bounds of the benefits that can be allocated to each player, and their comparison with the allocation based on the full cooperation. These bounds can be viewed as the boundary of the core of the game.

Table 3-2 Boundary for the core of the allocation game without partial coalitions

	Lower Bound	**Upper Bound**
Country	Economic Value (in million US$)	Economic Value (in million US$)
Ethiopia	$ 592	$ 4,413
Sudan	$ 886	$ 4,707
Egypt	$ 1,963	$ 5,784
Equatorial States	$ 1,232	$ 5,053

The lower bounds of the core reflect the "bottom line" for all players in negotiation; and a player will not have incentive to stay with the cooperative scheme if its share from such endeavor is less than the lower bound. For example, *The Equatorial States* would not participate in the cooperative scheme if there is no transfer payment from other players, since the lower bound for *the Equatorial States* (US$ 1,232 millions) is greater than the share it can obtain from the full cooperation without transfer payment (US$ 1,113 millions). The upper bounds of the core reflect a set of maximum allocations 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.

Despite Ethiopia's strong hydro-strategic position, the negotiation power of the country will be dampened if it can not capitalize on its hydropower potential on its own. This is clearly manifested by the relative small value of the lower bound for the country.

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[4] P(i) denotes benefits allocated to country i in full cooperation scheme.

One may notice that the bands between the lower and upper bounds are quite large for all four players of the game. It is not surprising partially because we have not considered the cases involving partial coalitions; and partially because there are substantial differences in terms of total economic benefits between the case for no cooperation and the one for full cooperation. When there is no possibility for partial coalitions, each player is essentially granted veto power over cooperation—no benefit from full cooperation can be retained if any one of the players decides to block the grand coalition. Because of such veto power in negotiation, each player can potentially demand *all* excess benefits from the cooperation. In such a case, the upper bound for a particular player is simply the total benefits of full cooperation minus the summation of the lower bounds for rest of the players.

A word of caution should be offered before the results of analysis can be interpreted. It should be noted that the core might be very sensitive to assumptions that we make with regard to the system configuration for different coalitions, and that the results of analysis should not be taken at face value. For example, we would have found a different core if we had assumed that the Ethiopia would build several dams instead of one dam on its own.

3.2 Cooperative Strategies under the Presence of Partial Coalitions

Depending on one's take on several assumptions we made in the last section, different readers might find different elements presented in the last section to be unrealistic; however, no one would be truly convinced that there would be no possibility for partial coalitions in the Nile allocation game. While this assumption serves the purpose of decomposing the effects of determinants of economic incentives, we relax it from this section on.

A. Rationale for Forming Partial Coalitions

Riparian countries in international rivers may form partial coalitions for a variety of reasons. First of all, they form partial coalitions because they might share the same goals with each other. In Nile basin, for example, neither Egypt nor Sudan contributes much to the flow of the river, and thus they share the common interest of securing their water supplies against the increasing pressure from upstream countries. Therefore, they have an incentive to form a united front in dealing with upstream countries.

Riparian countries also form coalitions to explore the comparative advantages among them. For example, Sudan and Ethiopia may be good partners for each other if they join forces to develop the water resources in Blue Nile: Ethiopia may be able to provide cheaper power for Sudan, while the proceeds from the sales of such power may allow Ethiopia to import food to meet the demands of its growing population.

Perhaps another compelling reason for partial coalitions is that it is much easier to form partial coalitions than to reach full cooperation among all riparian countries. Establishing full cooperation not only takes considerably more political resources, it is also more time-consuming. Riparian countries might be interested in forming partial coalitions because they cannot afford the delay associated with getting all riparian countries on board. In addition, it may make sense for certain key riparian countries to form a dominant coalition and then gradually add more members to it until full cooperation is achieved.

While partial coalitions may help to simplify and facilitate the bargaining process in a typical multilateral negotiation context, the rigidity of some pre-existing partial coalitions may also hinder the prospects of reaching a more comprehensive agreement when more members join the coalitions, because the structures of these existing coalitions might not be compatible with the demands of new members, and some rival coalitions may emerge to deadlock the negotiation process. One of the prevalent challenges faced by negotiators and politicians alike in dealing with water conflicts in international rivers is to design the negotiation process in such a way that the creation of cooperative or winning coalitions is enhanced while the chances of blocking coalitions are minimized.

An important point should be made before we discuss any partial coalition for the Nile allocation game. A partial coalition will have an impact on the game even if it is only potential. In many cases, it is the ability to make *threats* of forming alternative partial coalitions rather than the actual existence of such coalitions that will have impacts on the ultimate results of an allocation game. Countries with the prospect of developing multiple coalitions with different players are often better positioned in negotiation because they are able to make credible threats of breaking off the grand coalitions or some other partial coalitions. To this end, a particular riparian country might attempt to create an impression that it is simultaneously making moves towards forming alliances with different co-riparian countries, despite of the fact that these alliances might be mutually exclusive to each other, or that it is not its true intention to create these coalitions.

In this section, we consider several partial coalitions for the Nile allocation game and discuss how the formation of these coalitions will change the core of the game. Four partial coalitions are selected because of their great practical implications for the Nile basin. They are: 1) coalition between Egypt and Sudan, 2) coalition between Sudan and Ethiopia, 3) coalition among Egypt, Sudan and Ethiopia, and 4) coalition among Egypt, Sudan and the Equatorial States. We will evaluate the effects of these partial coalitions both individually and jointly.

B. Egypt-Sudan Coalition

The Egypt-Sudan coalition is appealing to both countries because of their similar geopolitical positions in the Nile basin: both heavily relying on the Nile water and both contributing little to its sources. The coalition would allow them to establish a unified front to deal with claims from upstream riparian countries. Such stance is stated clearly in language found 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 water usage of downstream riparian countries in the Nile basin not only because Sudan possesses the biggest area of the Nile basin, but also because Sudan is among the poorest countries in the world. On the other hand, Sudan may be convinced that it can secure its water supplies only by taking advantage of Egypt's strong political, economic and military positions in the area. A coalition between them will offer Egypt and Sudan much better chances to block any upstream water development projects that might jeopardize their existing uses, especially when external financing from international organizations is involved.

These two countries also have much to gain from joint development in the While Nile. Since they are upstream countries of the basin, projects such as wetland projects or modification of Jebel Aulia do not involve any other riparian countries but themselves. We assume that the coalition between Egypt and Sudan would lead the completion of the wetland projects and the modification of Jebel Aulia dam.

With the presence of Egypt-Sudan coalition, the conditions for the core of the game are shown in the box below. While the sum of the benefits for the two countries when they act independently is US$ 2,849 millions, the Egypt-Sudan coalition can provide a total benefit of US$ 3,062 millions that can be allocated between them.

$P(\text{Egypt}) \geq 1963$; $P(\text{Sudan}) \geq 886$; $P(\text{Ethiopia}) \geq 592$; $P(\text{Equatorial States}) \geq 1232$;
$P(\text{Egypt}) + P(\text{Sudan}) \geq 3062$;
$P(\text{Egypt}) + P(\text{Sudan}) + P(\text{Ethiopia}) + P(\text{Equatorial States}) \leq 8494$

Compared with the core conditions discussed in the last section, the only change made here is adding an additional condition, "$P(\text{Egypt}) + P(\text{Sudan}) \geq 3062$". This condition implies that the sum of the benefits allocated for Egypt and Sudan *in full cooperation case* needs to be at least US$ 3,062 millions[5], otherwise Egypt and Sudan will block the full cooperation by forming a bilateral coalition from which they *jointly* would receive a higher return[6]. Table 3-3 presents the core of the game when this new condition is added.

Table 3-3 Core under the presence of Egypt-Sudan coalition[7]

	Maximizing Ethiopia	*Maximizing Sudan*	*Maximizing Egypt*	*Maximizing the Equatorial States*
Country	*Economic Value (in million US$)*	*Economic Value (in million US$)*	*Economic Value (in million US$)*	*Economic Value (in million US$)*
Ethiopia	$ 4,180	$ 592	$ 592	$ 592
Sudan	$ 1,119	$ 4,707	$ 886	$ 886
Egypt	$ 1,963	$ 1,963	$ 5,784	$ 2,196
Equatorial States	$ 1,232	$ 1,232	$ 1,232	$ 4,820

The relative bargaining powers of Egypt and Sudan appear to be on the rise if the only partial coalition in the game is the Egypt-Sudan coalition, while they decline for Ethiopia and *the Equatorial States*. A quick comparison between Table 3-3 and Table 3-2 reveals that while both the lower and upper bounds for Egypt and Sudan remain the same, the upper bounds for both Ethiopia and *the Equatorial States* have decreased when the Egypt-Sudan coalition is considered. The upper bound for Ethiopia changes from US$ 4416 millions to US$ 4183 millions, and for *the Equatorial States* it changes from US$ 5053 to 4820 millions. Both Ethiopia and *the Equatorial States* would still possess the veto power to the full cooperation, but with the presence of Egypt-

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[5] The benefit of wetland projects and modification of Jebel Aulia will not be as big as many might believe because we assume that the Equatorial States will divert significant amount of water from the White Nile.

[6] As we stated early, we do not specify how the economic gains would be distributed between the two countries in the bilateral coalition.

[7] One might notice the way we describe the core in the table is a little different from the one as in Table 3-2. Although we can continue to refer to the lower bounds and upper bounds of the each player, there will be lower bound and upper bound for each partial coalition considered. Therefore, we directly present the four extreme allocations to avoid any potential confusion.

Sudan coalition, the premium from such veto power has declined. They can no longer (potentially) claim all the excess benefit from full cooperation because they have to allocate enough shares to Egypt and Sudan so they will not block the full cooperation by forming a bilateral coalition.

C. Sudan-Ethiopia Coalition

Although the Egypt-Sudan coalition will increase the negotiation powers for both countries, this coalition may not be as unshakable as Egypt might want it to be. From the perspective of Sudan, construction of more Blue Nile storage facilities would enable it to expand its irrigation system more rapidly because water stored in these locations will be delivered by gravity flow and pumping expenses will be kept at minimum. New Blue Nile development can also protect the Sudan's existing reservoirs (Roseires, Sennar, Khashm el-Girba) better from further siltation. Furthermore, the electricity generated from the proposed Blue Nile power stations in Ethiopia may provide Sudan with cheaper power necessary to expand its irrigation schemes along the Blue Nile. Lastly, given the growing environmental opposition and concerns over the local Nilotic people currently residing in the Sudd area, the completion of wetland projects, one of the key elements of a potential Egypt-Sudan coalition, is likely to be prolonged.

By forming alliance with Sudan, Ethiopia may be better positioned in seeking international financing of its Blue Nile projects, or the two countries might be able to pool their resources together to develop Blue Nile projects for the benefits of both countries. Another important consideration for Ethiopia is that, with Sudan on board, the 1959 Agreement between Egypt and Sudan—a critical barrier to a new Nile allocation scheme—may finally be cleared.

We assume that with Sudan-Ethiopia coalition two more dams—Mabil and Border—can be constructed[8], and the maximization of the benefits in this way for the two countries would yield a total return of US$ 2,506 millions, a significant increase from the sum of the benefits they receive by acting independently. The conditions of the core can be expressed as follows:

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[8] Although a potential Sudan-Ethiopia coalition will allow the two countries to use more water for irrigation purposes, we limit our attention to cases where Egypt would still be able to receive at least 34 billion m3, and the potential benefits of Sudan-Ethiopia coalition come from shifting irrigation water usage from Ethiopia to Sudan and from the additional hydropower generated in Mabil and Border, and not from diverting more water from the Blue Nile.

$P(\text{Egypt}) \geq 1963$; $P(\text{Sudan}) \geq 886$; $P(\text{Ethiopia}) \geq 592$; $P(\text{Equatorial States}) \geq 1232$;
$P(\text{Sudan}) + P(\text{Ethiopia}) \geq 2502$;
$P(\text{Egypt}) + P(\text{Sudan}) + P(\text{Ethiopia}) + P(\text{Equatorial States}) \leq 8494$

Table 3-4 shows the core under the presence of Sudan-Ethiopia coalition. Similar to the findings displayed in Table 3-3, relative bargaining positions for Sudan and Ethiopia, the two countries that can form a mutually beneficial coalition, are strengthened, while they are weakened for Egypt and *the Equatorial States*. In addition, because the coalition between Sudan and Ethiopia will result in significant improvement from the case of which they act independently, the upper bounds for Egypt and *the Equatorial States* decrease substantially (Egypt from US$ 5784 to 4756 millions and the Equatorial State from US$ 5053 to 4025 millions) so that Sudan and Ethiopia have sufficient incentives to maintain their presence in the grand coalition.

Table 3-4 Core under the presence of Sudan-Ethiopia coalition

	Maximizing Ethiopia	*Maximizing Sudan*	*Maximizing Egypt*	*Maximizing the Equatorial States*
Country	*Economic Value (in million US$)*	*Economic Value (in million US$)*	*Economic Value (in million US$)*	*Economic Value (in million US$)*
Ethiopia	$ 4,413	$ 592	$ 592	$ 592
Sudan	$ 886	$ 4,707	$ 1,914	$ 1,914
Egypt	$ 1,963	$ 1,963	$ 4,756	$ 1,963
Equatorial States	$ 1,232	$ 1,232	$ 1,232	$ 4,025

We can also jointly consider the effects of the presence of both Egypt-Sudan and Sudan-Ethiopia coalitions, since it is the *potential* rather than existence of coalition that would matter to the game in a cooperative framework. To find out the core for the game under the presence of both coalitions, we can revise the conditions for the core such that both coalitions are considered. The new core for the game is depicted in Table 3-5.

Table 3-5 Core under the presence of both Egypt-Sudan and Sudan-Ethiopia coalitions

	Maximizing Ethiopia	*Maximizing Sudan*	*Maximizing Egypt*	*Maximizing the Equatorial States*
Country	*Economic Value (in million US$)*	*Economic Value (in million US$)*	*Economic Value (in million US$)*	*Economic Value (in million US$)*
Ethiopia	$ 4,180	$ 592	$ 592	$ 592
Sudan	$ 886	$ 4,707	$ 1,914	$ 1,914
Egypt	$ 2,196	$ 1,963	$ 4,756	$ 1,963
Equatorial States	$ 1,232	$ 1,232	$ 1,232	$ 4,025

Not surprisingly, Sudan becomes the biggest winner due to its abilities to form coalitions with both Egypt and Ethiopia. All other three players—Egypt, Ethiopia and *the Equatorial States*—will incur a relative loss of negotiation power when compared to the case of which no partial coalition is allowed.

D. Egypt-Sudan-Ethiopia Coalition

Another potential coalition that has received considerable attention in the political arena is the coalition among Egypt, Sudan and Ethiopia. Since the Blue Nile projects do not *affect the Equatorial States*, all potential oppositions to the Blue Nile projects will be removed under the presence of Egypt-Sudan-Ethiopia coalition, and thus Blue Nile projects can be developed in full. The potential benefits of such coalition will arise from additional hydropower generation, water saving by shifting storage from Aswan High Dam to Blue Nile dams, irrigation water usage shift from Ethiopia to downstream riparian countries, and the joint management of both White and Blue Nile flows. For those who believe the current alliance between Egypt and Sudan is hard to be broken because of the political economy of the basin, the Egypt-Sudan-Ethiopia coalition might present a viable extension rather than a dramatic shift. In addition, given the difficulties of bringing all riparian countries into a grand coalition, the Egypt-Sudan-Ethiopia coalition might be a solid alternative to grand coalition. The following box reflects the necessary changes in the conditions for the cores when this coalition is considered. The results are presented in Table 3-6.

$P(\text{Egypt}) \geq 1963$; $P(\text{Sudan}) \geq 886$; $P(\text{Ethiopia}) \geq 592$; $P(\text{Equatorial States}) \geq 1232$;

$P(\text{Egypt}) + P(\text{Sudan}) \geq 3062$;

$P(\text{Sudan}) + P(\text{Ethiopia}) \geq 2506$;

$P(\text{Egypt}) + P(\text{Sudan}) + P(\text{Ethiopia}) \geq 6331$[9];

$P(\text{Egypt}) + P(\text{Sudan}) + P(\text{Ethiopia}) + P(\text{Equatorial States}) \leq 8494$

Table 3-6 Core of the game under the presence of Egypt-Sudan-Ethiopia coalition

	Maximizing Ethiopia		*Maximizing Sudan*		*Maximizing Egypt*		*Maximizing the Equatorial States*	
Country	*Economic Value (in million US$)*		*Economic Value (in million US$)*		*Economic Value (in million US$)*		*Economic Value (in million US$)*	
Ethiopia	$	4,180	$	592	$	592	$	592
Sudan	$	1,119	$	4,707	$	1,914	$	1,914
Egypt	$	1,963	$	1,963	$	4,756	$	3,825
Equatorial States	$	1,232	$	1,232	$	1,232	$	2,163

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[9] To maximize the total combined benefit for Egypt, Sudan and Ethiopia would yield US$ 6331 millions.

With the presence of Egypt-Sudan-Ethiopia coalition, as well as the coalition between Egypt and Sudan and the coalition between Sudan and Ethiopia, Sudan's bargaining power rises further as reflected by the increase of its lower bound: it increases from US$ 886 to 1119 millions. The relative powers of Egypt and Ethiopia have also been improved in comparison to those of *the Equatorial States*. The upper bound for *the Equatorial States* declines dramatically (the upper bound for *the Equatorial States* is reduced by half to US$ 2,163 millions). *The Equatorial States* becomes the biggest loser of the game because it cannot form any mutually beneficial coalition in any of the cases we considered so far. With the presence of Egypt-Sudan-Ethiopia coalition, the veto power of *the Equatorial States* to block the grand coalition is considerably restricted: the potential Egypt-Sudan-Ethiopia coalition can retrieve the bulk of excess benefits of the grand coalition. Another important finding when we go through the results from Table 3-2 to Table 3-6 is that the range for the core is narrowed when more partial coalitions are considered, or narrowed at least for some players (*the Equatorial States* in this case).

E. Egypt-Sudan-Equatorial States Coalition

The last potential coalition we consider here is the one among Egypt, Sudan and the Equatorial States. While in recent years more attention has been directed towards implications of development projects in Blue Nile, the potential of joint development of the White Nile and the Main Nile was a key to the management of the basin for some early practitioners. For example, the century storage scheme proposed by Hurst called for the construction of two river regulating facilities in the White Nile, the Jonglei Canal, an over-year reservoir in Lake Tana and additional seasonal storage reservoir on the Main Nile (Whittington and Guariso, 1983).

The potential of an Egypt-Sudan-Equatorial States has certainly been taken notice by leaders of these countries. In 1991, four equatorial states, Tanzania, Uganda, Congo and Rwanda, along with Egypt and Sudan formed an inter-governmental organization called Tecconile (Technical Committee for the Promotion of the Development and Environmental Protection of the Nile Basin) to foster the exchange of information and joint development of the Nile basin.

The following box shows the conditions for the computation of the core of the water allocation when Egypt, Sudan and Equatorial States can form a partial coalition, and the core of the game is presented in Table 3-7.

$P(\text{Egypt}) \geq 1{,}963$; $P(\text{Sudan}) \geq 886$; $P(\text{Ethiopia}) \geq 592$; $P(\text{Equatorial States}) \geq 1{,}232$;

$P(\text{Egypt}) + P(\text{Sudan}) + P(\text{Equatorial States}) \geq 5{,}312$;

$P(\text{Egypt}) + P(\text{Sudan}) + P(\text{Ethiopia}) + P(\text{Equatorial States}) \leq 8{,}494$

Ethiopia's relative negotiation power would decrease as it is the only riparian country to be left out of the coalition. This is clearly reflected in the decline of the up bound for Ethiopia from US$ 4,413 millions to 3182 millions. All other three players, including the Equatorial States, can increase their relative negotiation powers with the presence of the coalition among the three players.

Table 3-7 Core of the game under the presence of Egypt-Sudan-Equatorial States coalition

	Maximize Ethiopia	*Maximize Sudan*	*Maximize Egypt*	*Maximize Others*
	Economic Value (in millions US$)	Economic Value (in millions US$)	Economic Value (in millions US$)	Economic Value (in millions US$)
Ethiopia	3182	592	592	592
Sudan	2117	4707	886	886
Egypt	1963	1963	5784	1963
Others	1232	1232	1232	5053
Total	8494	8494	8494	8494

A quick summary of the last two sections brings upon three important lessons for the analysis of the conflict resolution for international rivers. The first is that riparian countries that are able to form multiple mutually beneficial coalitions with other riparian countries will be in a better position in the negotiation. The second is that incorporating more partial coalitions into the game can help to narrow the ranges of potential feasible allocation. The last point is that, since individual riparian countries would gain from the potential of forming partial coalitions with other riparian countries, it is in the interest of each riparian country to engage in activities that may convince the other participants that they are exploring the possibilities of potential coalitions even though creating such coalitions may not be their true intention.

3.3 The Core of the Nile Allocation Game

A. A Summary of Assumptions

In the light of the introduction and preliminary analysis in last two sections, we can now proceed with computing the core of the game. We start the process by specifying the configuration for each potential coalition in the game. Besides the coalitions we have considered so far, there are potentially 7 other coalitions for the games: Egypt-Ethiopia, Sudan-*Equatorial States*, Ethiopia-*Equatorial States*, Egypt-*Equatorial States*, Egypt-Sudan-*Equatorial States*, Sudan-*Equatorial*-Ethiopia and Egypt-*Equatorial States*-Ethiopia. We assume that for all coalitions including *the Equatorial States* (except for bilateral coalition between Ethiopia and *the Equatorial States*, for which we assume there will be no improvement from the case of which each player acts independently) the While Nile hydropower and storage projects will be completed. We also assume that three Blue Nile dams (Lake Tana, Mabil and Border) will be in place for any coalition that involves Ethiopia and either Egypt or Sudan. Furthermore, we assume that wetland projects and modification of Jebel Aulia will be completed for any coalition involving both Egypt and Sudan. Table 3-8 summarizes a set of assumptions for different coalitions in the game.

Table 3-8 Assumption for all potential coalitions.

Coalition	Blue Nile Projects	Wetland Projects (Jonglei, Marchar, Ghazal)	White Nile Hydropower Projects	Jebel Aulia	While Nile Storage projects
Egypt-Sudan	Lake Tana	Yes	None	Modified Operation	None
Ethiopia-Sudan	LakeTana/ Mabil/Border/	Existing Conditions	None	Current Operation	None
Ethiopia-Egypt	LakeTana/ Mabil/Border/	Existing Conditions	None	Current Operation	None
Egypt-Equatorial States	Lake Tana	Existing Conditions	Full System	Current Operation	Yes
Sudan-Equatorial States	Lake Tana	Existing Conditions	Full System	Current Operation	Yes
Ethiopia-Equatorial States	Lake Tana	Existing Conditions	None	Current Operation	None
Egypt-Sudan-Ethiopia	Full System	Yes	None	Modified Operation	None
Egypt-Sudan-Equatorial States	Lake Tana	Yes	Full System	Modified Operation	Yes
Egypt-Equatorial States-Ethiopia	Lake Tana /Mabil/Border	Existing Conditions	Full System	Current Operation	Yes
Ethiopia-Sudan-Equatorial States	LakeTana /Mabil/Boder	Existing Conditions	Full Systems	Current Operation	Yes
Full Cooperation	Full System	Yes	Full System	Modified Operation	Yes

Given the large number of the assumptions we have to make, perhaps it is appropriate for us to offer some explanations. First of all, an important part of this research is to build some analytical tools that are accessible to policy makers, and ideally, we hope that the task of specifying assumptions would be left to actual users of the tools. Therefore, in this sense any assumption we employ here is for illustrative purposes. Second, we have made a deliberate attempt to link the project development with the number of riparian countries in a particular coalition. The bigger the size of a coalition, the more development projects in the coalition. Third, constraints have been imposed on the upstream riparian countries such that, unless they cooperate with one or more downstream riparian countries, infrastructure development in these countries will be limited.

Since seven additional coalitions will be considered, the conditions for the core can be set by adding one condition for each of the seven coalitions based on the results of maximization problems with the new added coalitions. The seven additional conditions for determining the core are expressed in the box below. Table 3-9 presents the core of the game.

$P(\text{Egypt}) + P(\text{Ethiopia}) \geq 3711$;
$P(\text{Ethiopia}) + P(\text{Equatorial States}) \geq 1824$;
$P(\text{Egypt}) + P(\text{Equatorial States}) \geq 3795$;
$P(\text{Sudan}) + P(\text{Equatorial States}) \geq 2267$;
$P(\text{Egypt}) + P(\text{Sudan}) + P(\text{Equatorial States}) \geq 5312$;
$P(\text{Sudan}) + P(\text{Ethiopia}) + P(\text{Equatorial States}) \geq 4485$;
$P(\text{Egypt}) + P(\text{Equatorial States}) + P(\text{Ethiopia}) \geq 5443$

B. The Core of the Game

Table 3-9 Core the Nile allocation game

	Maximizing Ethiopia	*Maximizing Sudan*	*Maximizing Egypt*	*Maximizing the Equatorial States*
Country	*Economic Value (in million US$)*	*Economic Value (in million US$)*	*Economic Value (in million US$)*	*Economic Value (in million US$)*
Ethiopia	$ 3,182	$ 1,648	$ 592	$ 592
Sudan	$ 886	$ 3,051	$ 2,661	$ 1,914
Egypt	$ 2,260	$ 2,063	$ 4,009	$ 3,825
Equatorial States	$ 2,166	$ 1,732	$ 1,232	$ 2,163
Total	$ 8,494	$ 8,494	$ 8,494	$ 8,494

By comparing Table 3.6 (when only three coalitions are considered in the game), a noticeable change is that the range for the allocation is narrowed considerably after all potential partial coalitions are taken into account. Sudan's bargaining power is shown to decline (from the case in Table 3-6) as other coalitions without Sudan are incorporated into the calculation of the core. In general, the core with smaller ranges spells good news for negotiators, because the task of settling the differences among countries may be easier because a smaller set of alternatives are now feasible. It can help the negotiators to focus on other important issues and thus expedite the negotiation process. On the other hand, however, the sizes of range are still pretty large for some riparian countries, leaving undesired sizable space for political manoeuvre. For instance, Sudan's allocation may range from 886 to 3051 millions while the upper bound for Egypt is about 2 times above its lower bound. Additional tools will be needed to augment the analysis so that the core could be more informative for policy purposes.

Moving from the core of the game to a final allocation scheme acceptable by all players would require appropriate negotiation process and necessary external assistance. The final allocation attained will reflect each country's political, military and diplomatic strengths. However, the information revealed through the core of the game is still of critical value. Some allocation schemes might be temporarily acceptable to riparian countries because of the present political situation or some emergent events, but these allocations are not likely to be sustainable if they do not fall into the core of the game.

While 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 coming into life because it is hard to yield any appreciable excess benefit for those two parties forming such an alliance. In the next chapter, we will show that the allocation game can become more interesting when the chances of forming certain coalitions are uncertain to riparian countries.

3.4 The Core and Conflict Resolution for Water Conflicts in International Rivers

A. Importance of the Core in Conflict Resolution

The knowledge of the core of the game can be useful in assisting decision-makers or negotiators in dealing with water conflicts in international rivers. First of all, the core can be applied to identify the boundary of potential agreement among riparian countries. Such boundary is known as "*negotiation set*" (Luce and Raiffe, 195), or the *contract zone* (Bacharach and Lawter, 1981), or *bargaining arena* (Kennedy et al., 1981) in the literature. Too often, riparian countries are found far apart in their demands at the negotiation table because the reasonable ranges of such demands are unknown to them. Establishing the negotiation boundary through the analysis of the core would expedite the search for the ultimate allocation schemes and the limited political or economic resources can be best spent to focus on key differences, rather than to justify allocations that may be located outside the core.

Second, the knowledge of the core can contribute to the long-term stability of allocation schemes reached by riparian countries. A water agreement may serve some particular political (economic) purposes on an *ad hoc* basis, but it is unlikely to be sustained if fundamental economic rational is absent. Hence, the boundary identified by the core can be used as a test for economic incentive *that any proposed allocation scheme would have to pass.* If a particular allocation falls into the core, then we can be sure that no riparian country can gainfully deviate from the grand coalition; otherwise the allocation will not be sustainable in the long term. The knowledge of the core can be also used to test the readiness of riparian countries for serious negotiation. Until the expectation of all riparian countries with regard to potential demands is located inside the core, the political conditions for serious negotiation may not be in place.

Third, individual riparian countries can also draw some valuable insights from the core itself. For each riparian country, an interesting way to evaluate the core is to see how it would fare when the benefits of each of the other co-riparian countries are maximized[10]. For example, Ethiopia can only achieve its minimal level of payoffs when the benefits of either Egypt or *the Equatorial States* are maximized, while Ethiopia can secure more benefits when Sudan's benefits are maximized, (see Table 3-8 for details). From Sudan's point of view, it fares the worst when Ethiopia's benefits are maximized, which indicates the potential contribution of Sudan to the Ethiopian cause is quite limited, and in fact, such contribution is entirely replaceable by Egypt. Such analysis can help an individual riparian country to determine its relative bargaining power when a particular co-riparian country is the dominant player[11].

Finally, knowledge of the core can help one understand the behaviour of riparian countries, and to anticipate their potential moves. Redford (1977) characterizes negotiation as a sequence of moves in which the adversaries attempt to arrive at a favorable agreement. Negotiation moves can be communicative or structural: a communicative move informs the opponents of either the truth or deception about preferences or intentions of the player, whereas a structural move is an overt action, commitment, or proposal. Since a country's bargaining power will be strengthened by the potential of having alliance with other riparian countries, we may expect to see more communicative moves from the key Nile riparian countries with regard to forming potential

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[10] This is essentially how core is reported as shown in various tables in Section 3.2.

[11] If a particular country is the dominant player of the allocation game, then the allocation that maximize its economic benefits will be given more weight in deciding the final allocation scheme.

alliances with other riparian countries, and the underlying motives for such moves should be interpreted with care.

To illustrate how the concept of the core can be applied in a real negotiation among riparian countries, we consider several allocation proposals based on some popular notions of equity and justice, and assess whether or not they meet the requirements of providing economic incentives for all riparian countries.

B. Water Allocation Proposals Based on Absolute Equality

We consider three types of proposals here. The first type of proposal focuses on the absolute equality of the allocation, and we consider two cases denoted by Proposal 1 and 2. Proposal 1 calls for an *equal* distribution of the excess economic benefits from cooperation among Egypt, Sudan, Ethiopia and *the Equatorial States*. Since the total excess benefits are US$ 3,824 millions (8497 minus 4673), Egypt, Sudan, Ethiopia and *the Equatorial States* would each get a fourth of the benefits which is worth of US$ 956 millions. Table 3-10 shows the payoffs for individual players as well as those for the partial coalitions under this allocation proposal. The first column of Table 3-10 lists all potential coalitions (including single member coalitions, partial coalitions, and grand coalition); the second column states the requirement of the core for the particular coalition. Finally, the last two columns calculate the accrued gains for the particular coalition under the proposal.

Table 3-10 Proposals focusing on absolute equality

Coalition	*Core Requirements*	*Proposal 1*	*Proposal 2*
(Ethiopia)	P(Ethiopia) ≥ 592	*$ 1,547*	*$ 1,866*
(Sudan)	P(Sudan) ≥ 886	*$ 1,841*	*$ 2,160*
(Egypt)	P(Egypt) ≥ 1963	*$ 2,918*	*$ 3,237*
(Equatorial States)	P(Equatorial States) ≥ 1232	*$ 2,187*	*$ 1,232*
(Ethiopia, Sudan)	P(Ethiopia) + P(Sudan) ≥ 2506	$ 3,389	$ 4,025
(Sudan, Egypt)	P(Sudan) + P(Egypt) ≥ 3062	$ 4,760	$ 5,396
(Ethiopia, Equatorial States)	P(Ethiopia) + P(Equatorial States) ≥ 1824	$ 3,735	$ 3,098
(Ethiopia, Egypt)	P(Ethiopia) + P(Egypt) ≥ 3711	$ 4,466	$ 5,102
(Sudan, Equatorial States)	P(Sudan) + P(Equatorial States) ≥ 2267	$ 4,029	$ 3,392
(Egypt, Equatorial States)	P(Egypt) + P(Equatorial States) ≥ 3795	$ 5,106	$ 4,469
(Sudan, Egypt, Ethiopia)	P(Sudan) + P(Egypt) +P(Ethiopia) ≥ 6331	$ 6,307	$ 7,262
(Sudan, Egypt, Equatorial States)	P(Sudan) + P(Egypt) +P(Equatorial States) ≥ 5312	$ 6,947	$ 6,628
(Sudan, Ethiopia, Equatorial States)	P(Sudan) + P(Ethiopia) + P(Equatorial States) ≥ 4485	$ 5,576	$ 5,257
(Ethiopia, Egypt, Equatorial States)	P(Ethiopia) + P(Egypt) + P(Equatorial States) ≥ 5443	$ 6,653	$ 6,334
Full cooperation	P(Sudan) + P(Egypt)+ P(Ethiopia) + P(Equatorial States)≤ 8494	$ 8,494	$ 8,494

It is apparent that Proposal 1 violates the core requirements because the combined benefits for Ethiopia, Sudan and Egypt, US$ 6,309 million, is less than the payoff for the three countries in forming the Egypt-Sudan-Ethiopia coalition (US$ 6,331 millions). In addition, the benefits allocated to *the Equatorial States* also exceed the maximum amount of benefits for *the Equatorial States* in the core, another indication that paying *the Equatorial States* an equal share of the excess benefits of cooperation will diminish the incentive of Ethiopia, Sudan and Egypt to move from a three-country coalition to the full cooperation. Two conditions are important in reaching this conclusion. The first is that the benefits of most key projects (Blue Nile projects, wetland projects and modification of Jebel Aulia) will be obtained once the Ethiopia-Sudan-Egypt coalition is formed; the second is that, once the While Nile power stations are built, it will be in the best interest of *the Equatorial States* itself to let the water pass through these stations, and thus its demand for irrigation water will be greatly reduced (see Chapter 2 for details).

Proposal 2 considers the situation where the excess of benefits is distributed equally among Egypt, Sudan and Ethiopia. The benefits for individual countries and different coalitions under the proposal are also shown in Table 3-11. It is easy to see that all core requirements are met and the allocation belongs to the core.

Such a proposal may be of particular interest to Egypt and Sudan, as it would allow them to better safeguard their current stakes in the system. Table 3-11 clearly shows this point. Compared with the allocation based on system optimisation (from Chapter 2), transfer payment from Ethiopia to the rest of the players is needed based on this proposal and the allocations to Egypt and Sudan will be boosted significantly[12].

Table 3-11 Transfer payment for Proposal 2

System Optimization		Proposal 2		Transfer Payment
Country	Economic Value (in million US$)	Country	Economic Value (in million US$)	(in million US$)
Ethiopia	$ 2,638	***Ethiopia***	$ 1,867	$ (771)
Sudan	$ 1,796	***Sudan***	$ 2,161	$ 365
Egypt	$ 2,948	***Egypt***	$ 3,238	$ 290
Others	$ 1,113	***Others***	$ 1,232	$ 119
Total	$ 8,494	***Total***	$ 6,631	

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[12] One of primary reasons Ethiopia would fare poorly in such an allocation proposal is due the fact that the benefits Ethiopia can secure on its own is quite low; thus if Ethiopia receives the equal share of the excess

The high value of transfer payments among riparian countries may make Proposal 2 less attractive for policy purposes. In fact, one severe drawback of the any proposal heavily relying upon the transfer payment among countries is that it might not be feasible to handle transfer payment in a context in which water rights cannot be determined. It is particularly difficult for countries that are required to make such payments to other countries because of political resistance. Therefore, more attention needs to be directed to proposals that do not rely on transfer payments.

C. Water Allocation Proposals Based on Proportionality Rules

The second type of proposals is based on some notions of proportionality in allocating benefits or amount of water. Given their deep roots in the social and cultural norm of our time, arguments based on proportionality principles are often compelling for riparian countries in negotiating for water allocation agreements for international rivers. For example, although equitable utilization does not mean equal share for all riparian countries, it is often widely accepted as fair when benefits or water rights are allocated based on *equal per capita shares*. In addition, the allocations of water may also be based on the amount of other resources such as the land each riparian country has. It is claimed that the 1959 agreement was based on the proportion of irrigated land between Egypt and Sudan: since the ratio of irrigated land for the two countries is roughly 3/1, Egypt would receive 3 times as much as Sudan's share (Said, 1992).
However, allocations based on simple proportionality principles might run in direct contradiction to the requirement of economic incentives necessary for bring a stable coalition. Here we compare the requirements of the core of the game to the two proposals based on simple proportionality principles: one based on population and the other based on land. To simplify the matter, we only consider the allocation of irrigation water among Egypt, Sudan and Ethiopia and we assume that the benefits from hydropower generation would accrue to the respective countries in which these power facilities are located. As for *the Equatorial States*, we assume that it would maximize its total benefits and thus would withdraw about 7 billion m^3 of water for irrigation purposes. Proposal 3 calls for the remaining water or benefits to be distributed among Egypt, Sudan and Ethiopia based on future populations of the three countries. Table 3-12 shows the projected population for the three countries and their corresponding share based on this proposal. Since Ethiopia has other water supply sources besides the Nile, we only count its population that

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benefits as Egypt and Sudan, it will be required to give up some of its gains in hydropower as side payments.

is located in the Nile basin, rather than the country's total population. Egypt and Sudan, on the other hand, do not have other significant water supply sources and their whole population depends on water from the Nile. The water allocation for these three countries under this proposal clearly indicates that population growth in the Nile basin will likely to have significant impact on the Nile allocation game. Today, the Ethiopia's population within the Nile basin is about 38% of that of Egypt, but in 2050, this ratio will increase to 69%.

Table 3-12 Proposal 3—water allocation proportional to population

	Total Population	*Basin population*	*Share*	*Water allocation (BCM)*
Egypt	115480	115480	45%	36
Sudan	59947	59947	23%	19
Ethiopia	212732	79900	31%	25
Total	388159	255327	100%	79

In Proposal 4, we consider the case where water is allocated based on each country's irrigable land *available* for development in the foreseeable future. The irrigation land we consider here is not the same as the existing irrigation land, nor is it the total cropland for the country. The figure we use reflects the best scenario in each riparian country's own planning for the future development. Egypt has currently utilized virtually all of its total cropland, and thus its total irrigation land will be essentially the same as it is today. Sudan currently irrigates about 1.9 million ha and it has long-range projects aiming to increase irrigated lands to 3.37 million ha. As for Ethiopia, its irrigation land may include 900,000 hectares in the Blue Nile basin and 1.5 million hectares in the Sobat basin. Table 3-13 depicts the water allocation for the three riparian countries under this proposal. Under Proposal 4, although water allocated to Ethiopia will not be as high as in the case of Proposal 3, it is still a considerable amount given the volume of the average yield of the river. Sudan would be able to claim more water for its irrigation system because it possesses large areas that might be fit for irrigation.

Table 3-13 Proposal 4—water allocation proportional to available irrigation Land

	Irrigation Land	*Share*	*Water Allocation (BCM)*
Egypt	5700	50%	39
Sudan	3368	29%	23
Ethiopia	2400	21%	17
Total	11468	100%	79

The results of the analysis are shown in Table 3-14. Both proposals fail the test of the core requirements. Since Ethiopia currently uses almost no water from the Nile, re-allocating the Nile water based on either population or land resources would dispense a significant portion of the river flow for the country. While Sudan's share of water increases under both proposals, Egypt's water use will be dramatically reduced from its current level, and it may no longer have incentives for staying in the grand coalition. Another noticeable feature about these proposals is that they could not reach the full potential of the grand coalition because the total benefits would be below US$ 8,494 millions. This is due to the fact that irrigation water is predetermined, rather than being determined by the economic principle of maximizing system returns.

Table 3-14 Proposals based on some proportionality rules, without benefit transfers

Coalition	***Core Requirements***	***Proposal 3***	***Proposal 4***
(Ethiopia)	P(Ethiopia) ≥ 592	***$ 3,476***	***$ 3,263***
(Sudan)	P(Sudan) ≥ 886	***$ 1,030***	***$ 1,738***
(Egypt)	P(Egypt) ≥ 1963	***$ 2,137***	***$ 1,739***
(Equatorial States)	P(Equatorial States) ≥ 1232	***$ 1,371***	***$ 1,371***
(Ethiopia, Sudan)	P(Ethiopia) + P(Sudan)≥ 2506	$ 4,506	$ 5,001
(Sudan, Egypt)	P(Sudan) + P(Egypt) ≥ 3062	$ 3,167	$ 3,477
(Ethiopia, Equatorial States)	P(Ethiopia) + P(Equatorial States)≥ 1824	$ 4,847	$ 4,634
(Ethiopia, Egypt)	P(Ethiopia) + P(Egypt) ≥ 3711	$ 5,613	$ 5,002
(Sudan, Equatorial States)	P(Sudan) + P(Equatorial States) ≥ 2267	$ 2,401	$ 3,109
(Egypt, Equatorial States)	P(Egypt) + P(Equatorial States) ≥ 3795	$ 3,508	$ 3,110
(Sudan, Egypt, Ethiopia)	P(Sudan) + P(Egypt) +P(Ethiopia) ≥ 6331	$ 6,643	$ 6,740
(Sudan, Egypt, Equatorial States)	P(Sudan) + P(Egypt) +P(Equatorial States) ≥ 5312	$ 4,538	$ 4,848
(Sudan, Ethiopia, Equatorial States)	P(Sudan) + P(Ethiopia) + P(Equatorial States) ≥ 4485	$ 5,877	$ 6,372
(Ethiopia, Egypt, Equatorial States)	P(Ethiopia) + P(Egypt) + P(Equatorial States) ≥ 5443	$ 6,984	$ 6,373
Full cooperation	P(Sudan) + P(Egypt)+ P(Ethiopia) + P(Equatorial States)≤ 8494	$ 8,014	$ 8,111

D. Water Allocation Proposals Based on Fixed Withdrawal Targets

The impetus for the third type of proposal comes from the consideration that upstream riparian countries may set pre-determined water withdrawal targets before they would participate in any negotiation for a new Nile water agreement. Such requests from those countries may not be dismissed lightly because these countries can unilaterally take actions that would directly affect downstream countries. In addition, since almost all water in the Nile basin originates from those upstream countries (Ethiopia and Equatorial States), it my have merits to meet the targets of those countries on equity ground because of their contribution to the flows of the Nile. Here we select two such proposals. Proposal 5 is based on the median withdrawal targets for both Ethiopia and *the Equatorial States*, and under this proposal Ethiopia would demand 10 billions m^3 and *the Equatorial States* 5 billion m^3. Proposal 6 is for the scenario that Ethiopia would request 15 billions m^3 while *the Equatorial States* 10 billions m^3. Since we will continue to assume no transfer payment, we also need specify how Egypt and Sudan will deal with such requests. We assume that Egypt and Sudan would agree to reduce their existing water allocation (Egypt 55.5 and Sudan 18.5), and the ratio of the deduction for the two countries will be based on the ratio of their current allocation[13]. Table 3-15 shows the results of the analyses.

Proposal 5 is in the core, as all conditions for the core are satisfied. Ethiopia will enjoy a significant increase in irrigation water while all players still have enough incentives to stay with the cooperative. However, if the target for Ethiopia's irrigation water usage continues to rise, as shown by Proposal 6, such incentives will diminish quickly, and in the scenario of high irrigation water target for both Ethiopia and *the Equatorial States*, the rest of players would be better off defecting from the grand coalition. While it is important to analyse situations where individual countries might carry some rigid demands that are not to be altered, it will be *irrational* for these countries to forego all the benefits resulting from cooperating with other riparian countries. In addition, countries may effectively position themselves in setting up conditions for negotiation, and they know too well that compromise is unavoidable in reaching final agreement with other countries.

Table 3-15 Proposals based on fixed withdrawal targets for Ethiopia and *the Equatorial States*

Coalition	***Core Requirements***	***Proposal 5***	***Proposal 6***
(Ethiopia)	P(Ethiopia) ≥ 592	***$ 2,267***	***$ 3,152***
(Sudan)	P(Sudan) ≥ 886	***$ 1,605***	***$ 759***
(Egypt)	P(Egypt) ≥ 1963	***$ 2,568***	***$ 2,790***
(Equatorial States)	P(Equatorial States) ≥ 1232	***$ 1,894***	***$ 1,367***
(Ethiopia, Sudan)	P(Ethiopia) + P(Sudan)≥ 2506	$ 3,872	$ 3,911
(Sudan, Egypt)	P(Sudan) + P(Egypt) ≥ 3062	$ 4,173	$ 3,549
(Ethiopia, Equatorial States)	P(Ethiopia) + P(Equatorial States)≥ 1824	$ 4,161	$ 4,519
(Ethiopia, Egypt)	P(Ethiopia) + P(Egypt) ≥ 3711	$ 4,835	$ 5,942
(Sudan, Equatorial States)	P(Sudan) + P(Equatorial States) ≥ 2267	$ 3,499	$ 2,126
(Egypt, Equatorial States)	P(Egypt) + P(Equatorial States) ≥ 3795	$ 4,462	$ 4,157
(Sudan, Egypt, Ethiopia)	P(Sudan) + P(Egypt) +P(Ethiopia) ≥ 6331	$ 6,440	$ 6,701
(Sudan, Egypt, Equatorial States)	P(Sudan) + P(Egypt) +P(Equatorial States) ≥ 5312	$ 6,067	$ 4,916
(Sudan, Ethiopia, Equatorial States)	P(Sudan) + P(Ethiopia) + P(Equatorial States) ≥ 4485	$ 5,766	$ 5,278
(Ethiopia, Egypt, Equatorial States)	P(Ethiopia) + P(Egypt) + P(Equatorial States) ≥ 5443	$ 6,729	$ 7,309
Full cooperation	P(Sudan) + P(Egypt)+ P(Ethiopia) + P(Equatorial States)≤ 8494	$ 8,334	$ 8,068

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[13] Although the 1959 Agreement specifies that Egypt and Sudan would share equally the additional water available to the system resulting from completion of potential water conservation projects, it does not specify how deficit of water will be shared between the two riparian countries when more water is to be used by upstream riparian countries.

In our analysis of different proposals in this section, our intention is not to provide any conclusive argument for or against certain proposals. One should be aware that the detailed calculation shown in this section might shift dramatically if different assumptions were made. Instead, we attempt to illustrate the potential of using the information embedded in the core for decision-makers facing different courses of actions. In fact, our interactive training tools developed with methods discussed in this section can allow users to conduct such analysis with any number of potential proposals that are of interest to them.

3.5 Game-Theoretical Solutions to Water Allocation Problems

In addition to the core, cooperative game theory has much more to contribute to conflict resolution in international rivers. For example, several game–theoretical solutions are found to be useful to serve as focal points for negotiation. Here we describe and compute two such solutions: nucleolus and Shapley value, and discuss their implications for the Nile allocation game.

A. The Nucleolus

The nucleolus is the allocation that has the lexicographically smallest associated excesses. For an allocation (X_a, X_b, X_c), $V(R)-\Sigma(X_i)$ for *i* can be viewed as the objection raised by a coalition R against this allocation, and *nucleolus* chooses the payoff that minimizes the maximum objection, that is,

$$\underset{Xi}{Min}\{\underset{R}{Max}[V(R)-\sum_{i\in R}Xi]\}$$

To understand the underlying rationale for such a solution, suppose an arbitrator is called upon to decide on the share allocated to each player of the game. $V(R)-\Sigma(X_i)$, the excess of a coalition (X_a, X_b, X_c), is regarded by the arbitrator as undesirable[14], and his job is to decrease the excesses of the various coalitions as much as possible (Maschler, 1992). Nucleolus can be found when the highest excess is as low as possible (or in other words, when the lowest excess is as high as possible).

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[14] A coalition with high positive excess will gain a lot by departure and the defection is still less liable if the excess is smaller.

It is of special interest to point out that the nucleolus solution is consistent with Rawls' notion of "the veil of ignorance," that is, it is the allocation that might be preferred if no player knows his or her future identity (Loehman, 1995). Rawls postulates that, since people are not aware of their personal interests and future identities, they might want to maximize the net benefits obtained from the worst possible outcome that can happen. In fact, Rawls assumes that everybody would act in such a way as if he were absolutely sure that, whatever he did, the worst possible outcome of his action would obtain, and thus, the value of any possible action will wholly dependent on the worst possible outcome, regardless of how small its possibility. Obviously the allocation based on Rawls' theory would give absolute priority to the interests of the most disadvantaged social group.

Computationally, nucleolus can be found by solving a linear programming problem. In the Nile allocation game, the min-max problem given above can be formed mathematically as follows:

Objective Function:
Maximize a
Constraints:
$a \le P(\text{Ethiopia}) - 592;$
$a \le P(\text{Sudan}) - 886;$
$a \le P(\text{Egypt}) - 1963;$
$a \le P(\text{The Equatorial States}) - 1232;$
$a \le P(\text{Ethiopia}) + P(\text{Sudan}) - 2506;$
$a \le P(\text{Egypt}) + P(\text{Sudan}) - 3062;$
$a \le P(\text{Ethiopia}) + P(\text{The Equatorial States}) - 1824;$
$a \le P(\text{Egypt}) + P(\text{Ethiopia}) - 3711;$
$a \le P(\text{Sudan}) + P(\text{The Equatorial States}) - 2267;$
$a \le P(\text{Egypt}) + P(\text{The Equatorial States}) - 3795;$
$a \le P(\text{Egypt}) + P(\text{Sudan}) + P(\text{Ethiopia}) - 6331;$
$a \le P(\text{Egypt}) + P(\text{Sudan}) + P(\text{The Equatorial States}) - 5312;$
$a \le P(\text{Sudan}) + P(\text{Ethiopia}) + P(\text{The Equatorial States}) - 4485;$
$a \le P(\text{Egypt}) + P(\text{Ethiopia}) + P(\text{The Equatorial States}) - 5443;$
$P(\text{Egypt}) + P(\text{Sudan}) + P(\text{Ethiopia}) + P(\text{The Equatorial States}) \le 8494;$

Using the GAMS linear programming solver to solve the above optimisation problem[15], the nucleolus of this allocation game is shown in Table 3-15. It is apparent that*the Equatorial States* would receive some special attention in the nucleolus. *The Equatorial States* is the most disadvantaged player in the game because once the White Nile power stations are built it would volunteer sending water downstream even if no restriction were imposed on its behaviour. Table

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[15] It is not easy to give a general formula to calculate the nucleolus, and as a result, mathematics software with optimization algorithm is often used for calculation.

3-16 clearly shows this point. There would be large benefit transfer from Egypt and Sudan to *the Equatorial States*.

Table 3-16 Nucleolus of the Nile allocation game

	System Optimization	Nucleolus Allocation	Benefit Transfer
Country	Economic Value (in million US$)	Economic Value (in million US$)	Economic Value (in million US$)
Ethiopia	$ 2,638	$ 2,716	$ 78
Sudan	$ 1,796	$ 1,517	$ (279)
Egypt	$ 2,948	$ 2,563	$ (385)
Equatorial States	$ 1,113	$ 1,698	$ 585

One of the critiques of the nucleolus is that it only pays attention to excess benefits of a coalition, but does not consider the size of the coalition (the number of players in a given coalition). The per capita nucleolus, a variant of nucleolus, is proposed to solve this problem. In computing per capita nucleolus[16], we replace $V(R)-\Sigma(X_i)$ with $(V(R)-\Sigma(X_i))/r$, r being the size of the coalition R. Using this new formulation, the per capita nucleolus of the game is (1366, 2353, 3311, 1465) for Ethiopia, Sudan, Egypt and *the Equatorial States*, respectively. The per capita nucleolus gives more weight to Egypt and Sudan while Ethiopia and *the Equatorial States* will receive less favourable treatment. Ethiopia's share will be reduced significantly because we assume that the benefits it can achieve on its own are quite small.

Nucleolus can be a very useful solution when applied to international water conflicts. First of all, nucleolus may be appealing to riparian countries when an arbitrator is called upon to decide on the final allocation, but they are not sure about the preferences of the arbitrator about the allocation. Second, the nucleolus is necessarily contained in the core and thus it ensures the economic incentives automatically. Third, the nucleolus (especially per capita nucleolus) tends to equalize the claims of all riparian countries, and thus the solutions might be closer to a proposal for equalizing the excess benefits for all players.

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[16] It might be confusing to call it "per capita nucleolus" because r represents the number of players in the coalition rather than the population in the demographic sense.

B. The Shapley Value

Another point solution that has important practical implications to water conflicts is the*Shapley value*. The Shapley value is the only solution that satisfies all three conditions: 1) the value of the game to a player is the same because each player has equal probability weight; 2) the individual values to the players in the game sum to the value of the whole game; and 3) the value of two games taken together is the sum of the values of each game considered separately. These three conditions are termed symmetry, carrier and additivity axiom, respectively. Symmetry implies equal treatment for players with identical roles and addivitity implies that the Shapley value is efficient. The Shapley value can be computed with the following formula:

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

, where N is any finite carrier of v.

To interpret the above formula for computing the Shapley value, one can think of players in N randomly ordered as (player1, player2,..), 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!. Therefore, the Shapley value of player *i* is an average of his marginal benefits from all coalitions, including the empty set.

The Shapley value represents a distinct 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 for measuring the strength of each player in the game, based on the strength of the coalitions of which he is a member and of those he is not a member. Because it imposes equal treatment of players who make the same contribution in the game, Shapley value is often used as a benchmark of fairness.

The following box explains the computation of the Shapley Value for the Nile allocation game.

P(Ehiopia)	=(1/4)*(592-0) + (1/12)*(2506-886) + (1/12)*(1824-1232) + (1/12)*(3711-1963) +(1/12)*(6331-3062)+(1/12)*(4485-2267)+ (1/12)*(5443-3795) +(1/4)*(8497-5312) =US$ 1868 millions
P(Sudan)	=(1/4)*(886-0) + (1/12)*(2506-596) + (1/12)*(3082-1963) + (1/12)*(2267-1232) +(1/12)*(6331-3711)+(1/12)*(4485-1824)+ (1/12)*(5312-3795) +(1/4)*(8497-5443) =US$ 1888 millions
P(Egypt)	= (1/4)*(1963) + (1/12)*(3082-886) + (1/12)*(3711-592) + (1/12)*(3795-1232) +(1/12)*(6331-2506)+(1/12)*(5312-2267)+ (1/12)*(5443-1824) +(1/4)*(8497-4485) =US$ 3022 millions
P(The Equatorial States)	=(1/4)*(1232-0) + (1/12)*(1824-592) + (1/12)*(2267-886) + (1/12)*(3795-1963) +(1/12)*(5312-3082)+(1/12)*(4485-2506)+ (1/12)*(5443-3711) +(1/4)*(8497-6331) =US$ 1716 millions

Although Ethiopia and the Equatorial States contribute to all of the flow of the Nile basin, the significance of this contribution will be balanced by unique contribution made by upstream riparian countries based on our assumptions. For example, we have assumed in any coalition without Egypt's presence, the modification of the Jebel Aulia, wetland projects in the White Nile and at least two reservoirs in the Blue Nile will not be completed. Because of such contribution, and the fact that Egypt is able to obtain a high level of economic benefits on its own, Egypt will be entitled to a sizable share from the cooperation despite the fact that it does not contribute to the flow of the river.

Sudan's contribution is similar to that of Egypt, because based on our assumption, the modification of Jebel Aulia, wetland projects, and at least two dams in Blue Nile will not be completed without its presence in the coalition. However, because the benefits that Sudan can achieve on its own is less that that of Egypt, the marginal contribution of Sudan to any coalition with the presence of both Sudan and Egypt will be less than that of Egypt based on the formula to compute the Shapley value.

Perhaps one of the most unrealistic aspects of the Shapley value solution in water allocation games is the assumption of symmetry. Symmetry implies that any coalition with the same number of players will have same probability to be formed and each player will have same probability of joining these coalitions. In a typical water allocation game, there are several factors that might make some coalitions easier to form than others. For example, Egypt-Sudan coalition might be more likely to be formed than coalitions such as Egypt-Ethiopia or Ethiopia-The Equatorial States. Due to some specific political constraints, there may even be zero probability for some coalitions. In addition, the order players entering a particular coalition or grand coalition may not be absolutely random. For example, it is less likely for Egypt to be the last player to join the grand coalition than *the Equatorial States* or Ethiopia. Lastly, lack of symmetry can also arise when players have different bargaining abilities or diplomatic resources.

Generalized (or weighted) Shapley value is proposed to deal with the problems by dropping the symmetry assumption. The formula for calculating the generalized Shapley value is:

$$\phi_i = \sum_{S \subset N} r_i(S)[v(S) - v(S-i) \quad \text{where } r_i(S) \text{ are weights satisfying} : \sum_{i \in T} \sum_{T \subset S} r_i(S) = 1$$

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 get extremely complicated as different people may assign different weights based on their knowledge and belief. For illustration purpose, we specify a scenario for which the following assumptions are implied:

a) Egypt and Sudan are more likely to be involved in some kind of coalitions and thus there is less chance for both of them to act unilaterally;
b) There is no possibility for The Equatorial States to form any bilateral coalition with other players;
c) Either Ethiopia or The Equatorial States is likely to be the last to join the grand coalition and there is no chance that either Egypt or Sudan would be the last to join the grand coalition.

Table 3-17 Probability weights for Shapley and generalized Shapley value

(Coalition S-I)I	*Shapley*	*Genalized Shapley*	*(Coalition S-I)I*	*Shapley*	*Genalized Shapley*
Egypt			**Ethiopia**		
(Egypt)	0.250	0.200	(Ethiopia)	0.250	0.300
(Sudan)Egypt	0.083	0.300	(Egypt)Ethiopia	0.083	0.000
(Ethiopia) Egypt	0.083	0.000	(Sudan) Ethiopia	0.083	0.100
(Equatorial Statess) Egypt	0.083	0.000	(Equatorial Statess) Ethiopia	0.083	0.000
(Sudan-Ethiopia) Egypt	0.083	0.500	(Egypt-Sudan) Ethiopia	0.083	0.200
(Sudan-Equatorial States) Egypt	0.083	0.000	(Sudan-Equatorial Statess) Ethiopia	0.083	0.000
(Ethiopia-Equatorial States) Egypt	0.083	0.000	(Egypt-Equatorial Statess) Ethiopia	0.083	0.000
(Sudan-Ethiopia-Equatorial States) Egypt	0.250	0.000	(Egypt-Sudan-Equatorial Statess) Ethiopia	0.250	0.400
Sudan			**Equatorial States**		
(Sudan)	0.250	0.200	(Equatorial States)	0.250	0.300
(Egypt)Sudan	0.083	0.300	(Egypt)Equatorial States	0.083	0.000
(Ethiopia) Sudan	0.083	0.300	(Sudan) Equatorial States	0.083	0.000
(Equatorial States) Sudan	0.083	0.000	(Ethiopia) Equatorial States	0.083	0.000
(Egypt-Ethiopia) Sudan	0.083	0.200	(Egypt-Sudan) Equatorial States	0.083	0.100
(Ethiopia-Equatorial States) Sudan	0.083	0.000	(Sudan-Ethiopia) Equatorial States	0.083	0.000
(Egypt-Equatorial States) Sudan	0.083	0.000	(Egypt-Ethiopia) Equatorial States	0.083	0.000
(Egypt-Ethiopia-Equatorial States) Sudan	0.250	0.000	(Egypt-Sudan-Ethiopia) Equatorial States	0.250	0.600

Table 3-17 gives a comparison of the probability weights between Shapley value and generalized Shapley value. For the first column of the table, the coalitions in parenthesis indicate the coalition preceding *i*.

Based on the probability weights given in the table, the generalized Shapley value can be calculated and the results are shown in Table 3-18. At the outset, it might be somewhat surprising to see that the bargaining powers of Egypt and Sudan valued by the generalized Shapley value seem to decline after we give prominent treatment to Egypt-Sudan coalition—the shares for both Egypt and Sudan decrease significantly in comparison to the Shapley value. On the other hand, although Ethiopia and *the Equatorial States* cannot join the grand coalition until after Sudan and Egypt are both in, their relative negotiation powers have increased. These results might be due to the fact that Egypt-Sudan coalition's performance will be mediocre if White Nile power stations are not built—which can only happen when *the Equatorial States* is brought in. In addition, Ethiopia and *the Equatorial States*' position as the last marginal players may help enhance their bargaining powers—the marginal player can literally hold up the grand coalition unless it is compensated handsomely.

Table 3-18 Shapley value and generalized Shapley value

	Shapley Value		Generalized Shapley Value	
Country	Economic Value (in million US$)	Share (%)	Economic Value (in million US$)	Share (%)
Ethiopia	$ 1,868	22%	$ 2,267	27%
Sudan	$ 1,888	22%	$ 1,605	19%
Egypt	$ 3,022	36%	$ 2,568	31%
Others	$ 1,716	20%	$ 1,894	23%

The above analyses of nucleolus and Shapley value point to several interesting common threads. First of all, the roles of the Equatorial States in the Nile allocation game need to be carefully re-examined. Contrary to a common belief that their involvement will be less critical and the emphasis should be placed on potential alliance in the Blue Nile, they will play an important role in achieving the benefits through projects in the White Nile because irrigation interests around Lake Victoria would severely damage the potential gains of system optimisation. Our results from the computation of both the nucleolus and Shapley value suggest that the large compensation for their involvement may be justified. Second, although Ethiopia's contribution to the whole system as the most important source of the Nile's flow is non-replaceable, the game-theoretical solutions presented here imply that Ethiopia's claim to a large quantity of irrigation water after Blue Nile projects are completed would not be warranted. The analyses of the Shapley value and generalized Shapley value indicate that substantial transfer payments are due for Ethiopia if the benefits of cooperation are allocated based on the marginal contributions of each country to different coalitions. Third, the allocations for Egypt and Sudan are in-line with the original allocations under the system optimisation and are relatively stable when different equity principles are applied[17].

On the other hand, however, differences between the Shapley value and nucleolus of the game are large enough to deserve some special attention to reconcile them. Such differences may be well 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 coalitions, whereas the Shapley value grants all coalitions equal status. The Shapley value and the nucleolus also differ in their relationship with the core of the game. The nucleolus is derived from core-minded thinking, and thus automatically belongs to the core; whereas the Shapley value is derived from reasonable-set thinking, and if the Shapley value is located inside the core, then it does so more by accident than by design.

C. An Assessment of Game-Theoretical Solutions

Common sense tells us that social life is full of situations where we have to weigh different social values against each other and must find morally and politically acceptable trade-offs between them: here decision-makers and negotiators have to reconcile multiple versions of equity and justice, not only the ones reflected in Shapley value and nucleolus, but also the various versions of equitable allocations discussed in the last section. When differences are large and means of settling such differences are relatively few, disputes over different principles of equitable distribution may create gridlock for a negotiation process.

Prudent analysis may help alleviate such anxiety by articulating differences underlying the different solutions or proposals. The real question here, as Maschler (1992) stated, is not about whether or not a particular solution is good or bad, but rather trying to identify the circumstances under which it is appropriate and to learn the insights coming out of it. We can start the process by evaluating different solutions under several criteria that might hold appeal for most people.

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[17] The only exception is the case for per capita nucleolus, which calls for much larger share to be allocated for Egypt and Sudan.

The first criterion we want to employ is the core. As we stated earlier, the core represents the economic incentive necessary for each riparian country to participate in cooperation. While the nucleolus automatically belongs to the core, there is nothing in the theoretical construct to guarantee that the Shapley value would be inside the core. Solutions or proposals that are not inside the core ought to be revised before they can be seriously considered in the negotiation or political processes.

The second criterion is the magnitude of the differences between these solutions and current positions of riparian countries. Given the fact we have four players here and the core involves a set of complex relationships between (among) different players, it will be a formidable task to sort out the positions of each player. We simplify the matter by looking at a potential focal point for discussion—splitting-the difference for each of the four players. Based on the maximum and minimum value for each player as shown in the core of the game (Table 3-9), splitting the difference would yield an allocation as shown in Table 3-19. We will then compute the differences between this allocation and each of the solutions or proposals and to see which one would be closer to this hypothetical focal point.

Table 3-19 A hypothetical focal point for the Nile water allocation game

	Maximizing Ethiopia	*Maximizing Sudan*	*Maximizing Egypt*	*Maximizing the Equatorial States*	Splitting the Differences
Country	*Economic Value (in million US$)*	*Economic Value (in million US$)*	*Economic Value (in million US$)*	*Economic Value (in million US$)*	*Economic Value (in million US$)*
Ethiopia	$ 3,182	$ 1,648	$ 592	$ 592	$ 1,846
Sudan	$ 886	$ 3,051	$ 2,661	$ 1,914	$ 1,925
Egypt	$ 2,260	$ 2,063	$ 4,009	$ 3,825	$ 3,064
Equatorial States	$ 2,166	$ 1,732	$ 1,232	$ 2,163	$ 1,660

Another useful criterion to assess different solutions is the *propensity to disrupt*. Player *i*'s propensity to disrupt is defined as the ratio of how much the rest of players would lose if *i* refused to cooperate to how much player *i* itself would lose if it refused to cooperate. For example, in the Nile allocation game, Ethiopia's propensity to disrupt can be calculated as "P(Egypt) + P(Sudan) + P(The Equatorial States) – v(Egypt-Sudan-The Equatorial States)," the losses other three players would incur, is divided by "P(Ethiopia) – v(Ethiopia)," the losses for Ethiopia if it refused to cooperate (this part of the sentence is not clear). It is clear that the higher a player's *propensity to disrupt*, the more negotiation power the player would have in the game.

Table 3-20 depicts the comparison of nucleolus, per capita nucleolus, Shapley value and generalized Shapley value evaluated against each of the three criteria.

All of the four game-theoretical solutions evaluated above satisfy the requirements of the core, and thus the economic incentives necessary for inducing cooperative behaviours are provided by all these solutions. Measured by the sum of the absolute value of the differences between the solutions analysed and the allocations associated with the focal point, there are large variations among the four solutions, ranging from US$ 205 for the Shapley value to US$ 1820 for the nucleolus. Such high differences normally signal the presence of big winner(s) and big loser(s), and thus might face heavier resistance in implementation. Generalized Shapley value fares better with relatively lower overall propensity to disrupt. However, if an individual country's propensity to disrupt is the focus of concern, the per capita nucleolus will be the least favoured by Ethiopia and The Equatorial States, but be most favored by Egypt and Sudan. The nucleolus will give the least reason for Ethiopia to defect, but the tendency of disrupting the grand coalitions is highest for Egypt and Sudan; the generalized Shapley value assigns the highest benefits for the Equatorial States and as a result its propensity to disrupt is the lowest for this solution.

Table 3-20 An assessment of game-theoretical solutions

	Allocation	Core requirements	Difference to the focal point	Propensity to disrupt
Solution				
1. Nucleolus		**Satisfied**		
Ethiopia	2718		872	0.22
Sudan	1517		408	2.44
Egypt	2563		501	1.11
Equatorial States	1699		39	1.00
2. Per capita nucleolus		**Satisfied**		
Ethiopia	1366		480	2.35
Sudan	2353		428	0.48
Egypt	3311		247	0.34
Equatorial States	1465		195	3.00
3. Shapley value		**Satisfied**		
Ethiopia	1869		23	0.99
Sudan	1888		37	1.12
Egypt	2976		88	0.58
Equatorial States	1717		57	0.83
4. Generalized Shapley value		**Satisfied**		
Ethiopia	2267		421	0.45
Sudan	1605		320	1.79
Egypt	2568		496	0.98
Equatorial States	1894		234	0.16
5. The Hypothetical Focal Point		**Satisfied**		
Ethiopia	1846		-	1.07
Sudan	1925		-	1.08
Egypt	3064		-	0.53
Equatorial States	1660		-	1.18

3.5 Concluding Remarks

A critical barrier to cooperation in international rivers is that there is no clear rule to allocate gains from cooperation among riparian countries. As a result, the economic gains from cooperation may mean very little to individual riparian countries if the economic incentives for riparian countries to participate in the cooperative schemes are not guaranteed. Throughout this chapter, we have shown that game-theoretical concepts can help to identify such incentives.

While the knowledge of the core of the game does not allow us to pin down a solution to water conflicts, it nevertheless helps us to exclude allocations that should never to be considered, and thus to narrow down the solution set. The core is based on some simple yet surprisingly powerful rules. For example, an allocation in which a riparian country receives less than what it can achieve on its own will never be a part of the solution; or two riparian countries in the grand coalition must be allocated combined benefits that exceed what they can achieve by forming a partial coalition of their owns. We are able to establish boundaries of allocation for the Nile water allocation game.

Our analysis of the core of the game also suggests that the riparian countries that are able to form multiple mutually beneficial coalitions with other riparian countries would be in a better position in the negotiation. In fact, since individual riparian countries would gain from the potential of forming partial coalitions with other riparian countries, it is in the interest of each riparian country to engage in activities that may convince the other participants that they are exploring the possibilities of potential coalitions, even though creating such coalitions may not be their true intention.

Our analysis of the game-theoretical solutions also leads to some interesting findings. First of all, the large differences among game-theoretical solutions clearly indicate that different solutions will likely appeal to different riparian countries. For example, Ethiopia would definitely prefer the nucleolus solution while Egypt would like the per capita nucleolus the best. While it is unlikely that riparian countries would establish their positions in negotiation based on these game-theoretical solutions, the logic embedded in these solutions may enter negotiation process one way or another.

Second, the fact that the benefits for Ethiopia and *the Equatorial States*' increase significantly when moving from the Shapley value to the generalized Shapley value suggests that riparian countries can actually benefit from being the last to join the cooperation. In this case, Ethiopia and the Equatorial States' position as the last marginal players may help enhance their bargaining power—the marginal player can literally hold up the grand coalition unless it is compensated handsomely.

Third, the Shapley value closely matches the hypothetical focal point established by splitting the differences for the core of the game, and it also offers relatively low propensity to disrupt for all players. In addition, the benefits allocated to the two upstream riparian countries are close to the results of the optimal allocation under full cooperation. These features may make the Shapley value an attractive solution concept for further consideration.

Lastly, under almost all game-theoretical solutions Ethiopia is required to make transfer payments to other riparian countries if it is to obtain all the benefits of hydropower production in the Blue Nile in the full cooperation case. While such transfer payments may not be politically feasible, water withdrawal for Ethiopia for irrigation purposes would not be justified under any game-theoretical solution concept.

Chapter 4 Coping with Uncertainty in Cooperation

Due to the stochastic nature of meteorological processes and incomplete knowledge about the demographic, economic, technical and political conditions in the future, riparian countries face many uncertainties in negotiation. Consequently, their behaviours may not be the same as in the deterministic cases. So far in our analysis we have ignored the effects of uncertainty on cooperation among riparian countries. For example, we have based our analysis on the hydrological data for a mean year for the Nile basin, while the actual flows of the river historically are subject to a great deal of fluctuation. In addition, we have assumed that some investment projects would be in place once certain coalitions are formed, while in reality the prospect of building these projects may be dampened or boosted by the unfolding of a series of unexpected future events.

Although such simplifications were necessary for us to focus on some of the most critical aspects of the water allocation game, analysis that disregards uncertainty completely may encounter numerous difficulties in finding its way to useful policy advice. For example, *hydrological uncertainty* may change the dynamics of the allocation game because the problem of allocating the benefits from utilizing water in international rivers differs from other resource allocation problems on a critical account: the quantity of the resource itself is uncertain. Apart from that, the *uncertainty of the economic value* of using water in different riparian countries can also become an important factor in the game because as we have seen from previous analysis, the differences on economic value of water among riparian countries can determine how water should be optimally utilized.

Contrary to what many people may believe, *uncertainty may not necessarily become a barrier to cooperation.* While uncertainty may create a commitment problem for riparian countries, it can also generate additional incentives for riparian countries to cooperate with each other, as it would be in the interests of these countries to join forces in order to reduce the adverse impacts of uncertainty. For example, the construction of the Blue Nile reservoirs will become more important to Sudan's irrigation schemes when fluctuations in the Blue Nile flows are taken into consideration. The over-year storage in these reservoirs will be critical to secure the annual water usage for Sudan.

Perhaps another added value of incorporating uncertainty in our analysis is to understand the value of obtaining better information. For example, although fluctuations in hydrological and meteorological processes such as evaporation, rainfall and temperature are imminent, improvement in water resource planning can be achieved through better measurement and more accurate forecasts of hydrological variables. The uncertainty in the value of water in irrigation and hydropower can also be reduced when more and better information from all riparian countries is collected and comprehensive analysis conducted. From the perspective of cost-benefit analysis, the costs of collecting better information and conducting more comprehensive analysis can be compared against the gains from the better information. We can then determine if better information would result in greater return for the whole system.

Coping with uncertainty in cooperation also means that implementation would be a critical part of any water agreement in international rivers. On one hand, monitoring efforts ought to be emphasized in order to carry out any agreement; on the other hand, agreement should be structured in such a way that it can be sustained mostly by self-enforcing mechanisms. In addition, when riparian countries differ in their accesses to some critical information, one of the most challenging aspects of cooperation has to do with structuring agreements so that riparian countries would find it in their best interest to truthfully reveal the information.

The extensive treatment of uncertainty—especially hydrological uncertainty—in water resources planning and management is not the subject of this research. In the field of hydrological engineering, sophisticated models (such as various dynamic adaptive control models) have been developed to deal with hydrological uncertainty. While these comprehensive models are more suited to provide better guidance for real-time operation of river regulation facilities, the focus of this analysis is to determine how uncertainty would change the relative negotiation power among riparian countries and how their strategies impacted.

4.1 Hydrological Uncertainty and Cooperation

A. Hydrological Uncertainty in the Nile Basin

Water allocation problems differ from other resource allocation problems on a critical account: the amount of resource available for allocation is uncertain. Scientific innovations (e.g., satellite imaging technology) and developments in better measurement certainly would help in obtaining better information, but due to the stochastic nature of meteorological processes such as evaporation, rainfall, and temperature, the quantity of water available for allocation will never be known with certainty in advance.

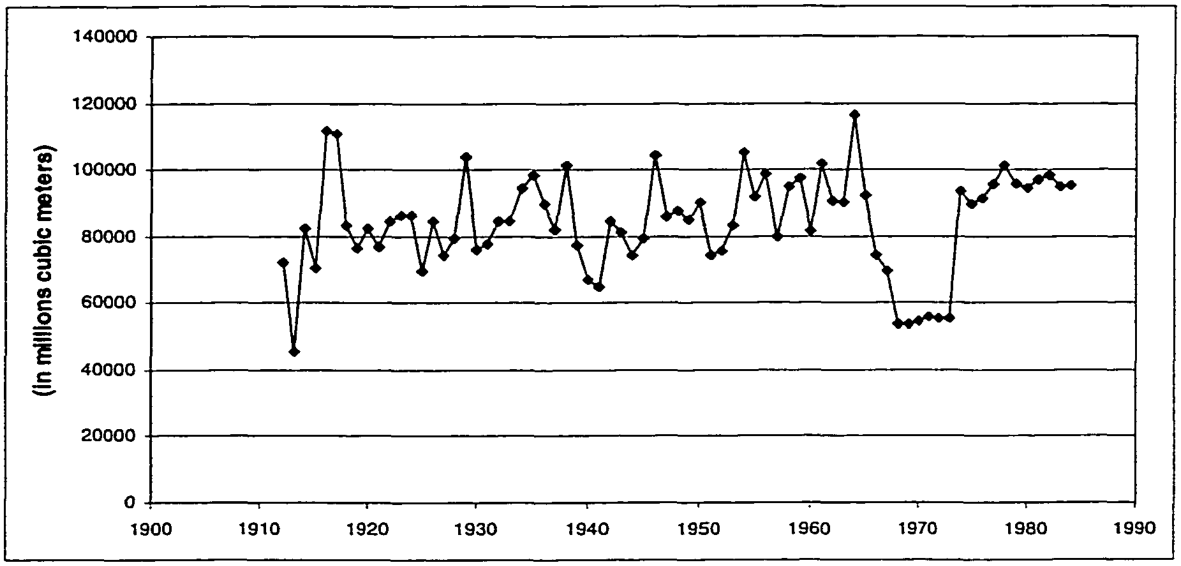
Hydrological uncertainty can have significant impacts on the dynamics of water allocation games in international rivers. First of all, hydrological uncertainty may change the relative negotiation power of riparian countries because such uncertainty may have different impacts on different riparian countries. For example, countries (Sudan, for example) that have fewer means to withstand the adverse effects of extreme events may also have to pay for such inability in the allocation games.

Hydrological uncertainty also implies that model results from using average values of hydrological inputs (inflow, rainfall, etc.) might be biased. Loucks, Stedinger and Haith (1984) point out that models based on average or mean values of inputs such as streamflow tend to overestimate system benefits while underestimate the costs and losses. Such biases might be due to the facts that evaporation losses from inter-year storage in river regulation facilities might not be accounted for in the annual model that assumes average inflow, and that the benefits from hydropower tend to fluctuate and thus the value of firm power will decrease when hydrological uncertainty is considered.

Finally, hydrological uncertainty may change the outlook of some capital investment projects. For example, for a river basin subject to a high level of inter-year variation ins streamflow, river regulating facilities provide benefits for both inter- and intra-year allocation of water, but models based on a single year hydrological input data often ignore the benefits of inter-year allocation. It is entirely possible that a project could turn from being economically unjustified to economically sound when the benefits from inter-year allocation are taken into consideration.

The discussion of hydrological uncertainty and water allocation games is especially relevant for the Nile basin. Table 4-1 shows the fluctuations of the Nile basin based on river flow at Khartoum. The standard deviation of the river flow is about 14.7 billion m^3, or approximately 20% of the mean annual discharge. The hydrological uncertainty for the Nile basin is even more pronounced, as there is unsatisfactory data on some of the hydrological features and contradictory data on other features.

Figure 4-1 Main Nile Annual Flows: 1912-1984



B. Multi-Year Economic Optimization Model

To examine the effects of hydrological uncertainty on the Nile water allocation game, we consider a multi-year model (five-year) for which the objective function can be expressed as follows:

$$Maximize \sum_{p}^{\varphi} \sum_{y} (1-r_p)^{y-1} [\sum_{i} IVy^{i}_{y,p} \sum_{y,t} Q^{i}_{y,t} + \sum_{j} ELV^{j}_{y,p} \sum_{y,t} KWH^{j}_{y,t}]$$

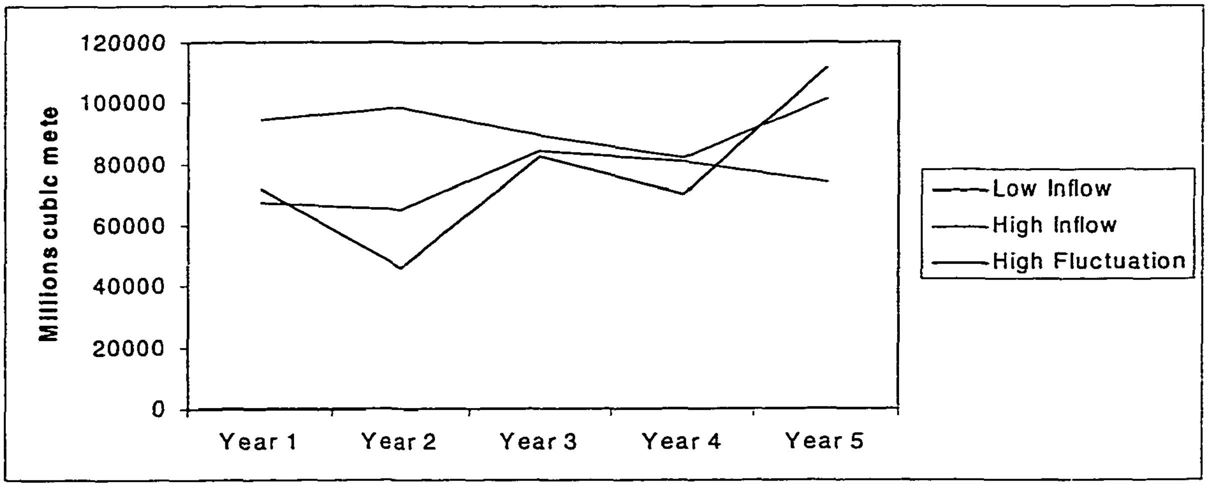
where φ represents a particular coalition considered (it may be full cooperation or partial coalitions involving one or several players), r_p is the discount rate for country p, $IV^{i}_{y,p}$ is the value of water for irrigation for site *i* for country *p* in year y, $Q^{i}_{y,t}$ is the quantity of water withdrawn for irrigation use in site *i* in year *y* and time period *t*, $ELV_{y,p}^{j}$ is the value for hydropower for power station *j* for country *p* in year *y*, and $KWH_{y,t}^{j}$ is hydropower generated in station *j* in year *y* and time period *t*. The model constraints are the same as in the annual model, except there will be a total of 60 periods (5X12) instead of 12 periods in the annual model. The model operates on a monthly basis over a period of five years. It will determine the combination of monthly releases from a specified set of Nile hydropower generation facilities and the monthly abstractions at specified sets of irrigation schemes that will generate the greatest total economic benefits for a particular coalition of the game.

Sensitivity analysis is used to examine the effects of different hydrological inflows on cooperation. Specifically, we use different types of hydrological inflows as inputs and compare results of analysis.

Based on the historical hydrological data for the Nile basin, three types of five-year sequences of hydrological inflows are chosen for our analysis, they are, namely, low inflow, high inflow, and high fluctuation inflow. Figure 4-2 shows the three types of sequences in more details.

1934-1938	Sequence of five high years
1940-1944	Sequence of five low years
1912-1916	Sequence of five high fluctuation years

Figure 4-2 Three Five-year Sequences of Inflows for the Nile Basin



The model then can be run with different sequences of inflows as inputs and results are compared. Although our analysis continues to be based upon a deterministic model, the use of different sequences of hydrological inflows in the model will not only allow us to determine the benefits from the inter-year allocation of water, but also helps us to analyze the effects of different hydrological inputs on the water allocation game.

The first step of our analysis is to determine the economic benefits of cooperation when different types of hydrological sequences are used. Several additional assumptions are needed in addition to assumptions we've set up in Chapter Two. For illustrative purpose, we assume the discount rate for all riparian countries to be 6%, and values for irrigation and hydropower for all riparian countries continue to be US$ 0.05 per cubic meter and US$ 0.07 per KWH.

C. Results of Analysis

A difficult but important task involves setting up assumptions for different riparian countries for the cases that they act alone. It differs from the annual model in which there is only one sequence of inflows. We assume that under the case of non-cooperation two upstream players—Ethiopia and the Equatorial states—would maximize their own benefits without any constraints. We also assume that Sudan can extract its allocation in the amount specified in the 1959 agreement when the water flow is below the mean annual flow (consequently, Egypt is assumed not to be not able to obtain its share in the 1959 Agreement). Essentially, we make the assumption that Sudan can take the advantage of its unique geographic position in the Nile basin (it can withdraw water from the system before the flow reaches Egypt).

Table 4-1 Benefits of Cooperation under Hydrological Uncertainty

	Low inflow	High inflow	High Fluctuation
	Economic Value (in million US$)	Economic Value (in million US$)	Economic Value (in million US$)
No cooperation			
Ethiopia	$ 1,820	$ 2,490	$ 2,012
Sudan	$ 4,438	$ 4,680	$ 4,459
Egypt	$ 8,525	$ 11,405	$ 9,324
Others	$ 4,852	$ 5,179	$ 4,559
Total	***$ 19,635***	***$ 23,754***	***$ 20,354***
Full cooperation			
Total	***$ 35,586***	***$ 43,977***	***$ 37,835***
Difference (%)	***81%***	***85%***	***86%***

Table 4-1 displays the benefits of cooperation under different hydrological sequences of inflows. Not surprisingly, the benefits of cooperation as measured by the percentage difference between non-cooperation and full cooperation are greatest for the high fluctuation case. This implies that the benefits from inter-year reallocation of water provided by the proposed river regulating facilities are the most evident in case of high fluctuation. On the other hand, when water becomes relatively abundant, as in the case of high inflow; the percentage increase in benefits for cooperation is the smallest among the three.

The results also indicate that the statement by Loucks, Stedinger and Haith (1984) may not be relevant for the Nile basin. The results of the annual model based on a mean hydrological year do not appear to be very different from the cases when hydrological uncertainty is considered. The percentage increase from non-cooperation to cooperation is 82% (See Chapter 3) for the annual model, and it ranges from 81% to 86% for the multi-year model. This might be due to the fact that we have used total hydropower rather than firm power in calculating the benefits for hydropower generation.

The second step of our analysis here is to analyze the impacts of hydrological uncertainty on the allocation patterns among different riparian countries. We computed two benchmark game-theoretical solutions—the nucleolus and the Shapley value—to see how these values would change as different hydrological sequences are used. It should be pointed out that, in conducting this exercise, our goal is not to suggest some specific allocation results from the game-theoretical solutions. Instead, we want to use these game-theoretical solutions as a sort of indicator, through the change of which we can infer whether or not the distribution of negotiation power among riparian countries is altered. For consistency, we continue to employ the assumptions displayed in Table 3-7 to specify each coalition. Table 4-2 and 4-3 show the results of analysis for the computation of the nucleolus and the Shapley value.

Table 4-2 The Nucleolus under hydrological uncertainty

Nucleolus	Low inflow		High Inflow		High Fluctuation	
Country	Economic Value (in million US$)	% of total	Economic Value (in million US$)	% of total	Economic Value (in million US$)	% of Total
Ethiopia	$ 6,603	19%	$ 13,398	30%	$ 10,806	29%
Sudan	$ 8,160	23%	$ 8,347	19%	$ 7,696	20%
Egypt	$ 12,247	34%	$ 14,229	32%	$ 12,474	33%
Others	$ 8,574	24%	$ 8,003	18%	$ 6,858	18%
Total	$ 35,584	100%	$ 43,977	100%	$ 37,834	100%

Several observations can be made from these tables. First of all, the allocation among the four players appears to be relatively robust across different hydrological inflows. This is especially true for the Shapley value, where the biggest change is for the Equatorial states, from 18% in high inflow to 24% in the low inflow. It indicates that for the water allocation game at hand hydrological uncertainty will not have significant bias towards one or a few riparian countries. For an international river basin that fluctuates as much as the Nile, such robustness will undoubtedly have positive impacts on the negotiation process.

Table 4-3 Shapley value under hydrological uncertainty

Shapley Value	Low inflow		High Inflow		High Fluctuation	
Country	Economic Value (in million US$)	% of total	Economic Value (in million US$)	% of total	Economic Value (in million US$)	% of Total
Ethiopia	$ 6,240	18%	$ 9,367	21%	$ 7,668	20%
Sudan	$ 8,165	23%	$ 10,303	23%	$ 9,288	25%
Egypt	$ 12,673	36%	$ 16,421	37%	$ 13,792	36%
Others	$ 8,508	24%	$ 7,885	18%	$ 7,086	19%
Total	$ 35,586	100%	$ 43,976	100%	$ 37,834	100%

Second, measured by both nucleolus and Shapley value, the share of Egypt is affected very little by the hydrological uncertainty. However, in absolute term, the change can be quite substantial for the country in some cases. For example, moving from low inflow to high inflow, the Shapley value for Egypt changes from 12,673 to 16,421, or 30% of increase, while system overall only increase by 23%.

Finally, measured by both nucleolus and Shapley value, the relative negotiation powers for Ethiopia are the highest for the sequence of high inflow and the lowest for the low inflow, while it is the exactly the opposite for the Equatorial states. This might be due to the fact that the level of fluctuation in the Blue Nile does not coincide with that in the White Nile, and as a result, the amount of changes from low inflow to high inflow might be different for White Nile and Blue Nile. In the low inflow case when the decrease of inflow in the Blue Nile is much greater than that in the White Nile, the importance of the equatorial states as main contributors of the White Nile water has been particularly emphasized.

4.2 Uncertainty on Economic Value of Water and Cooperative Behaviors

Regarding the potential cooperation among the three riparian countries in the Euphrates-Tigris River, Okyayuz—the late minister of Turkey—made the following remarks:

> "If, for example, it is found that the growing of cotton is more profitable in Iraq than in Syria or in Turkey, then the growing of cotton should be left to the Iraqis. Then, Turkey could grow beans and then buy cotton from Iraq, which in its turn could buy beans from Turkey."

Okyayuz's remarks show that the politicians can be well aware of the political implications of the differences of the economic value of water in different parts of a river basin. To implement such an idea, however, a difficult question must be answered: how to determine the profitability of using water in different parts of an international river? From the point of view of a water allocation game among several riparian countries, an even more difficult issue might be how to get different countries to reach a common understanding of what the values should be for different parts of the river.

Several factors suggest that the economic value of water may be highly uncertain. First of all, while the existing information might be available to estimate the economic value of water for countries that are currently using water from the international rivers, the value of water is highly uncertain for riparian countries that have yet to utilized much water in the past. In the Nile basin, for example, the information necessary for determining the value for irrigation in Ethiopia and the equatorial states is virtually non-existent, and as a result, the value for irrigation for these riparian countries is highly uncertain.

Second, due to methodological issues, the value of water is also difficult to determine even if information on water usage is relatively complete. For example, while the economic value of water is closely related to the prices of both inputs (land, labor, etc.) and outputs (agricultural products or electricity), these prices might not truly reflect market value, and are to large extent determined by the national policies of different riparian countries. In addition, the quality of the estimation of the value of water is also determined by whether or not water can be linked to the overall economy of the nation, and whether or not social benefits of using water can be assessed.

Third, the length of planning horizon can also have negative impacts on how accurately the economic value of water can be determined. The water allocation games in international rivers typically involve medium to long-term planning horizon, and technical breakthroughs (bio-agriculture, for instance) can change the landscape of valuation dramatically and render previous valuation results irrelevant.

While the uncertainties mentioned above might be reduced by carrying out extensive research, water allocation games are likely to involve strategic uncertainty, which is more difficult to deal with. In a "perfect" world of modelling, information is known to all countries at all times, but in reality, the access to information is bound to differ from country to country. Restricting information to negotiation partners can clearly become a strategic asset for riparian countries, because they can selectively reveal the information they have on the value of water, or even misrepresent the value of water if doing so would help them to strengthen their negotiation powers. Such strategic uncertainty will have critical impacts on our results of analysis.

In this section, we will analyze how the relative negotiation power of riparian countries will be affected by the change in the value of water. We will also examine several sensible strategies for riparian countries if uncertainty in the value for water is likely to be prevalent. We will show that under some circumstances some riparian countries may benefit from such uncertainty, and therefore not revealing true information becomes a dominant strategy for them.

Our analysis will proceed in three steps. In the first step, we assume that while the exact value of water for irrigation is uncertain, the value for irrigation nevertheless would be the same across riparian countries. In the second step, we relax the assumption that irrigation value is the same in all Nile riparian countries, and we allow it to differ for different riparian countries. In the last step, we analyze the implications of uncertainty in economic value of water for the allocation games.

Table 4-4 The Shapley value under different values of irrigation water

	Value for Irrigation water=US $ 0.01/m^3		Value for Irrigation water=US $ 0.02/m^3		Value for Irrigation water=US $ 0.03/m^3		Value for Irrigation water=US $ 0.04/m^3		Value for Irrigation water=US $ 0.05/m^3	
Country	Economic Value (in million US$)	% of total	Economic Value (in million US$)	% of total	Economic Value (in million US$)	% of Total	Economic Value (in million US$)	% of total	Economic Value (in million US$)	% of total
Ethiopia	$ 1,458	27%	$ 1,539	25%	$ 1,614	23%	$ 1,711	22%	$ 1,844	22%
Sudan	$ 1,349	25%	$ 1,501	24%	$ 1,644	24%	$ 1,812	24%	$ 1,952	23%
Egypt	$ 1,689	31%	$ 1,974	32%	$ 2,293	33%	$ 2,629	34%	$ 2,970	35%
Equatorial States	$ 996	18%	$ 1,165	19%	$ 1,337	19%	$ 1,521	20%	$ 1,727	20%
Total	$ 5,492	100%	$ 6,179	100%	$ 6,888	100%	$ 7,673	100%	$ 8,493	100%

	Value for Irrigation water=US $ 0.06/m^3		Value for Irrigation water=US $ 0.07/m^3		Value for Irrigation water=US $ 0.08/m^3		Value for Irrigation water=US $ 0.09/m^3		Value for Irrigation water=US $ 0.10/m^3	
Country	Economic Value (in million US$)	% of total	Economic Value (in million US$)	% of total	Economic Value (in million US$)	% of Total	Economic Value (in million US$)	% of total	Economic Value (in million US$)	% of total
Ethiopia	$ 1,950	21%	$ 2,061	20%	$ 2,180	20%	$ 2,284	19%	$ 2,421	19%
Sudan	$ 2,140	23%	$ 2,337	23%	$ 2,516	23%	$ 2,732	23%	$ 2,943	23%
Egypt	$ 3,327	36%	$ 3,687	36%	$ 4,058	37%	$ 4,419	37%	$ 4,753	37%
Equatorial States	$ 1,922	21%	$ 2,128	21%	$ 2,337	21%	$ 2,540	21%	$ 2,747	21%
Total	$ 9,339	100%	$ 10,213	100%	$ 11,091	100%	$ 11,975	100%	$ 12,864	100%

Table 4-4 shows that the allocation pattern across riparian countries is surprisingly robust to the different values of irrigation when the values are the same for all riparian countries. Sudan's allocation, for example, is virtually unchanged as the value of irrigation turns from US $ 0.01 to 0.1, and the share of equatorial states also change very little (from 18% to 21%). Egypt's relative negotiation power will be strengthened as value for irrigation becomes higher, while Ethiopia's position becomes weakened. This is hardly surprising because Ethiopia draws its benefit most from hydropower generation while Egypt draws it from irrigation, and the relative weights of the irrigation benefits in the total benefits will increase as the value of water for irrigation becomes higher.

A desirable feature displayed in Table 4-4 is that as the value for the resources increases, the absolute value of allocation for all riparian countries increases—no player is suffering from growth. To some extent, this confirms the attractiveness of the Shapley value as a potential solution guide because it satisfies the monotonicity property: that is, when the resources themselves, or when the value of resources increases, the utility of no players would decrease. Another game-theoretical solution—the nucleolus—also displays this property (Table 4-5). Measured by the share of the different riparian countries, nucleolus is even more robust than the Shapley value, while the changes of share do not have a clear trend as in the Shapley value.

Table 4-5 The Nucleolus under different values of Irrigation Water

	Value for Irrigation water=US $ 0.01/m^3		Value for Irrigation water=US $ 0.02/m^3		Value for Irrigation water=US $ 0.03/m^3		Value for Irrigation water=US $ 0.04/m^3		Value for Irrigation water=US $ 0.05/m^3	
Country	Economic Value (in million US$)	% of total	Economic Value (in million US$)	% of total	Economic Value (in million US$)	% of Total	Economic Value (in million US$)	% of total	Economic Value (in million US$)	% of total
Ethiopia	$ 1,698	31%	$ 1,949	32%	$ 2,203	32%	$ 2,464	32%	$ 2,718	32%
Sudan	$ 1,231	22%	$ 1,277	21%	$ 1,334	19%	$ 1,409	18%	$ 1,517	18%
Egypt	$ 1,679	31%	$ 1,863	30%	$ 2,079	30%	$ 2,318	30%	$ 2,563	30%
Equatorial States	$ 884	16%	$ 1,091	18%	$ 1,272	18%	$ 1,482	19%	$ 1,699	20%
Total	$ 5,492	100%	$ 6,180	100%	$ 6,888	100%	$ 7,673	100%	$ 8,497	100%

	Value for Irrigation water=US $ 0.06/m^3		Value for Irrigation water=US $ 0.07/m^3		Value for Irrigation water=US $ 0.08/m^3		Value for Irrigation water=US $ 0.09/m^3		Value for Irrigation water=US $ 0.10/m^3	
Country	Economic Value (in million US$)	% of total	Economic Value (in million US$)	% of total	Economic Value (in million US$)	% of Total	Economic Value (in million US$)	% of total	Economic Value (in million US$)	% of total
Ethiopia	$ 2,856	31%	$ 2,995	29%	$ 3,138	28%	$ 3,273	27%	$ 3,416	27%
Sudan	$ 1,754	19%	$ 2,003	20%	$ 2,174	20%	$ 2,363	20%	$ 2,578	20%
Egypt	$ 2,815	30%	$ 3,068	30%	$ 3,407	31%	$ 3,736	31%	$ 4,048	31%
Equatorial States	$ 1,914	20%	$ 2,146	21%	$ 2,370	21%	$ 2,603	22%	$ 2,820	22%
Total	$ 9,339	100%	$ 10,212	100%	$ 11,089	100%	$ 11,975	100%	$ 12,862	100%

The results above are based on the assumption of the same value of water for all riparian countries display several desirable properties, such as robustness and monotonicity. However, it is highly unlikely that the value of water for irrigation will be the same for all riparian countries, and therefore, a better alternative might be to relax this assumption. In this part of the analysis, we allow the value of water for irrigation to be different for different riparian countries.

We assume that the value of water in irrigation for riparian countries ranges from US$ 0.04 to US $0.08, and to simplify our analysis, we consider two polar cases where riparian countries either take the lowest value or the highest value of the water used for irrigation. In Case 1, upstream players (Ethiopia and the Equatorial states) will take the value of US$ 0.08 while downstream players (Egypt and Sudan) take the value of US $0.04. In the second case, upstream players are assumed to have the low value of water for irrigation while the downstream players have the high value. Both the nucleolus and the Shapley value are calculated for these cases.

Table 4-6 Shapley value and nucleolus under different values of Irrigation Water

	Shapley value				Nucleolus			
	upstream 0.08; downstream 0.04		upstream 0.04; downstream 0.08		upstream 0.08; downstream 0.04		upstream 0.04; downstream 0.08	
Country	Economic Value (in million US$)	% of total	Economic Value (in million US$)	% of total	Economic Value (in million US$)	% of Total	Economic Value (in million US$)	% of total
Ethiopia	$ 2,326	27%	$ 2,035	18%	$ 3,814	44%	$ 2,642	24%
Sudan	$ 1,942	22%	$ 2,792	25%	$ 1,077	12%	$ 2,501	23%
Egypt	$ 2,474	28%	$ 4,331	39%	$ 1,758	20%	$ 4,069	37%
Equatorial States	$ 1,989	23%	$ 1,933	17%	$ 2,081	24%	$ 1,879	17%
Total	$ 8,731	100%	$ 11,091	100%	$ 8,730	100%	$ 11,091	100%

If downstream players have higher values of water for irrigation, then the share allocated to these players would be greater as one can conclude from the two game-theoretical solutions. The combined share of Sudan and Egypt will increase from 50% to 64% measured by the Shapley value, and it will increase from 32% to 60% in the case of nucleolus. This result clearly indicates that riparian countries have strong incentives to misrepresent the value of water if the results of system analysis are to be used in the negotiation.

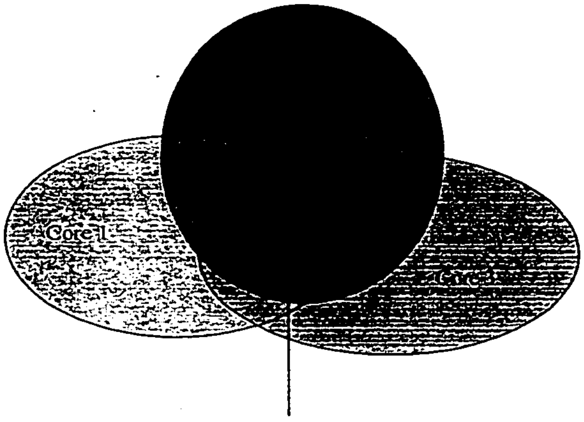
Riparian countries' tendency to misrepresent the value of water has significant impacts on the water allocation game considered here. In fact, it might be possible that the value of water could become a disputed issue in negotiation, if the results of systems optimization and game-theoretical models are to be taken more seriously.

On the other hand, even if the incentive bias of riparian countries in representing the value they estimated for the value of water can be corrected by some cleverly designed mechanisms, the value of water may still be uncertain based on factors we mentioned earlier, such as methodology issues or sudden technology innovations. In the third part of our analysis, we consider the situation where uncertainty regarding the value of water is unavoidable.

In the Nile water allocation game, we consider a case where riparian countries know that the value of water for irrigation ranges from US$ 0.04 to US$ 0.08 but they cannot pin down the exact value, either for themselves or for other riparian countries. This actually might be a very convincing case for many international rivers due to lack of necessary information.

Corresponding to each set of possible values estimated for irrigation water for the four players, a core can be calculated. Thus, there will be innumerable cores for the game since there are innumerable potential sets of values for irrigation water. We make a proposition; since riparian countries are not certain about the value of water they would be interested in searching an agreement that will fall into the core *under all circumstances*. Figure 4-1 shows how this proposition would work graphically.

Figure 4-1 "Core" of all cores for water allocation game under uncertain value



Actually, we do not need to compute every core associated with every possible combination of values for different riparian countries, because the share allocated to a particular coalition would tend to peak when the members of the coalition have highest values for water and non-members have the lowest value. Therefore, we simply compare several polar cases for which a riparian country either takes the highest value (US$ 0.08) or the lowest value (US$ 0.04) for irrigation. Since there are four players in the game, there are 16 different combinations for which players either take the highest value or the lowest value. We then compute the core of the game for all the 16 cases, and Table 4-7 shows the "core" of the cores, or the negotiation zone that that falls into all the 16 cores of the game.

A significant finding from Table 4-7 is that the negotiation zone is considerably narrowed after the uncertainty in the value of water is taken into consideration. The share for Sudan ranges from 16% to 26% (the same boundary for the case under certainty is 10% to 36) from and for Egypt from 28% to 40% (in the case of certainty it is from 27% to 47%). For the Equatorial states, the share will be set at 25% regardless of which players' benefits are maximized. Compared to both nucleolus and Shapley value estimated for the cases where the value is certain, the share for the Equatorial states actually gets a significant boost from the uncertainty.

Table 4-7 Core of the Nile water allocation game

Core of the game under certainty				
	Maximize Ethiopia	*Maximize Sudan*	*Maximize Egypt*	*Maximize Others*
Ethiopia	37%	19%	7%	7%
Sudan	10%	36%	31%	23%
Egypt	27%	24%	47%	45%
Others	25%	20%	14%	25%
Core of the game under uncertainty				
	Maximize Ethiopia	*Maximize Sudan*	*Maximize Egypt*	*Maximize Others*
Ethiopia	31%	22%	11%	11%
Sudan	16%	26%	25%	25%
Egypt	28%	28%	40%	40%
Others	25%	25%	25%	25%

In essence, the core displayed in Table 4-6 ensures that the least share each player can expect is the worst they can get under the situation for which the distribution of values is the most preferable for them. This can also be viewed as some sort of mutually provided insurance among the players.

Our analysis shows that considering value of uncertainty actually can draw riparian countries closer by narrowing down the negotiation zone. It is especially encouraging for conflict resolution for the Nile basin, as the uncertainty in the economic value of water might be unavoidable for the near future.

4.3 Uncertainty in Capital Investment Projects

The dynamics of the water allocation games may also change due to the uncertainty on the prospects of some key capital investment projects. The potential benefits from these capital investment projects may account for a large part of total benefits, and without them both absolute value and the share of individual riparian countries may change. In addition, capital investment projects often have greater impacts on the countries where they are located.

The uncertainty in the realization of capital investment projects may come from several sources. First of all, the proposed projects may not be put in service because of certain adverse future side effects of the projects may become overwhelming concerns and thus kills the project completely.

For example, damming rivers was once considered to be an unavoidable path of development for many developing countries with good hydropower potential. In recent years, however, the negative effects of building dams on the environment have become an important consideration, and the idea of damming rivers is no longer as popular as it was several decades ago.

Second, the external financing of investment projects can also be put on hold when the projects can no longer fit the investment profiles of the funding or donor organizations. Capital investment projects in international rivers often require substantial amounts of funding from multilateral organizations whose lending policies are often subject to heavy scrutiny in the international communities, and therefore, there are great deal of uncertainty about the prospects of investment projects when such funding is involved.

Finally, political circumstance can also shift suddenly and support for an investment project may disappear quickly. In the Nile basin, for example, the construction of the Jonglei project, once considered as an important element of the cooperative scheme between Sudan and Egypt, was disrupted when Sudanese Liberation Army took over the Southern Sudan in 1978. Since then, the construction of the project has never been resumed.

The question we attempt to address in this section is how the uncertainty in developing capital investment projects may change the ways the water allocation games are played. We select two investment projects for our analysis: wetland projects and White Nile power stations. Wetland projects are selected because despite the large water savings promised by the projects, the projects continue to be controversial, and it is highly uncertain whether or not the proponents of these projects can amass enough political support to move the projects forward. We select White Nile power stations because of their importance to the dynamics of water allocation game. We have already seen in Chapter Two that White Nile stations have a critical role in determining the behaviors of both the system and key White Nile riparians. Through this analysis, we will show how important these projects are in determining the allocation patterns for riparian countries.

Table 4-8 Shapley value and nucleolus for investment projects under uncertainty

	Shapley Value: with both wetland and white Nile Power stations		Shapley Value without wetland Projects		Shapley value without While Nile Power projects		Shapley value without both	
Country	Economic Value (in million US$)	% of total	Economic Value (in million US$)	% of total	Economic Value (in million US$)	% of Total	Economic Value (in million US$)	% of total
Ethiopia	$ 1,844	22%	$ 1,847	23%	$ 1,849	24%	$ 1,849	25%
Sudan	$ 1,952	23%	$ 1,754	22%	$ 1,713	23%	$ 1,666	22%
Egypt	$ 2,970	35%	$ 2,771	35%	$ 2,730	36%	$ 2,683	36%
Equatorial States	$ 1,727	20%	$ 1,594	20%	$ 1,260	17%	$ 1,277	17%
Total	$ 8,493	100%	$ 7,966	100%	$ 7,552	100%	$ 7,475	100%

	Nucleolus: with both wetland and white Nile Power stations		Nucleolus without wetland Projects		Nucleolus without While Nile Power projects		Nucleolus without both	
Country	Economic Value (in million US$)	% of total	Economic Value (in million US$)	% of total	Economic Value (in million US$)	% of Total	Economic Value (in million US$)	% of total
Ethiopia	$ 2,716	32%	$ 2,416	30%	$ 3,191	42%	$ 3,087	41%
Sudan	$ 1,517	18%	$ 1,489	19%	$ 1,036	14%	$ 1,036	14%
Egypt	$ 2,563	30%	$ 2,563	32%	$ 2,099	28%	$ 2,099	28%
Equatorial States	$ 1,697	20%	$ 1,498	19%	$ 1,227	16%	$ 1,252	17%
Total	$ 8,493	100%	$ 7,966	100%	$ 7,553	100%	$ 7,474	100%

Built upon the results of Chapter 3, sensitivity analysis is conducted based on whether or not wetland projects and White Nile power stations are built. Four cases are considered in the analysis: 1) with both wetland projects and White Nile power stations; 2) with wetland projects but without White Nile power station; 3) with White Nile power station but not wetland projects; and 4) without both wetland projects and White Nile power stations. We compute the two game-theoretical solutions for these four cases, and compare their differences. Table 4-8 shows the results of this analysis.

Although the wetland projects would provide a significant system saving in reducing the evaporation losses and would increase the system yield by 12 billions m^3 in annual basis, the projects actually have very little impact on the distribution of negotiation powers among riparian countries. For both nucleolus and Shapley value, the shares of different riparian countries change very little from Case 1 to Case 2. It is somewhat surprising, perhaps, that Sudan also won't suffer any loss in the share of benefits if chances of building wetland projects can never be materialized. The overall losses resulting from the absence of wetland projects have been relatively evenly distributed among the four players of the game.

The Shapley value for Case 1 and Case 3 (without White Nile power stations) also displays the similar pattern as seen in the analysis of wetland projects, indicating that White Nile power stations won't significantly change the distribution of negotiation powers. However, there are significant changes as measured by the nucleolus. For example, Ethiopia's share of benefits increases from 32% to 42% while shares of rest of the players turn downwards. Ethiopia's importance is seen increased as the benefits from the Blue Nile now carry heavier weights, and any coalition without Ethiopia will fare poorly.

4.5 Conclusions and Remarks

While uncertainty may create a commitment problem for riparian countries, it may not necessarily become a barrier to cooperation in international rivers. In fact, the allocation pattern appears to be relatively robust across different hydrological inflows. It indicates that for the water allocation pattern will not have significant bias towards one or a few riparian countries when the hydrological uncertainty is not accounted for.

Second, the negotiation zone established through the evaluation of the core of the game is considerably narrowed after the uncertainty in the value of water is taken into consideration. Some riparian countries (in this case, the Equatorial States) can even gain from such uncertainty as their negotiation powers will be strengthened.

Lastly, uncertainty may not necessarily change the relative negotiation powers among riparian countries. For example, the Shapley value and nucleolus of the game change marginally as hydropower uncertainty and investment uncertainty are taken into consideration. For an international river basin that fluctuates as much as the Nile, such robustness will undoubtedly have positive impacts on the negotiation process.

Chapter 5 International Organizations and Water Conflicts in International Rivers

International organizations have a long history of being involved in water resources development in many international river basins. For example, the United Nations was very active in promoting economic development activities in the Mekong basin as early as the end of the World War II. International organizations have also been long recognized as important third parties in resolving the water conflicts in international rivers. For example, during the period of 1951 to 1960, the World Bank played a critical role in resolving the water dispute between India and Pakistan over the use of Indus River. Its involvement eventually led to the 1960 Indus Water Treaty—one of the few examples of successful settlement of water conflicts in major international rivers.

Despite their importance, however, the efficiency and equity implications of the involvement of international organizations in water conflicts have not been explicitly explored in the literature. For example, the lending policies of international organizations such as the World Bank can be critical in shaping the outcomes of any negotiation among riparian countries. Traditionally, international organizations have adopted a policy of restraining from financing projects in disputed international rivers, but such practice in essence has conferred a veto power to downstream countries and thus has created a bias towards downstream riparian countries (Krishna, 1998). The fact that there is often more than one international organization involved in international rivers can also further complicate the matter if there is no coordination among them

In this chapter, the game-theoretical models, combined with the results of the systems optimization models, will be used to study the roles of international organizations in resolving water conflicts in international rivers. Although international water conflicts might be unique in many ways, the study of the roles of international organizations in resolving water conflicts may contribute to a better understanding of the roles of international organizations in international conflict resolution in general.

5.1 Roles and Challenges for International Organizations in Resolving Water Conflicts

The roles of international organizations in water conflicts have been continuously redefined and reshaped by the ever-changing political and economic environment as well as evolving characteristics of the international water conflicts themselves. Therefore, our discussion of the roles of international organizations is not necessarily limited to the past and present activities of international organizations. Instead, we focus on the emerging needs of conflict resolution in international rivers as well as functional areas where the involvement of international organizations may be most cost-effective.

First of all, international organizations can play an important role in the pre-negotiation stage of the negotiation process. Due to the fact that pre-negotiation normally does not bring direct and tangible results in the short-term, the involvement of international organizations in pre-negotiation has not received adequate attention, and in some cases such involvement may even be undervalued. This is unfortunate because in some international rivers, the hostilities among riparian countries can be so intense that considerable efforts are required for international organizations to persuade the parties just to talk to each other (Scheumann and Schittler, 1998). Even in situations where the relationship among riparian countries is more amicable, the demands of different countries can be so apart that no party perceives negotiation as a viable option. In the pre-negotiation stage, the main tasks of international organizations are to urge riparian countries in dispute to come to terms with the need to search for new solutions to the conflicts, and to convince them to make a formal commitment to negotiation.

In addition, the ability of international organizations to influence the process and outcome of conflict resolution in international rivers will be greatly strengthened when they are involved in financing key investment projects. The importance of the backing-up of financial resources and technical assistance is manifested clearly in the case of the World Bank's involvement in resolving conflicts in the Indus Basin. To seal the proposed treaty, Eugene Black, then President of the World Bank, convinced the USA, Canada, UK, West Germany, Australia and New Zealand to underwrite the water settlement at a cost of almost one billion US dollars. Without such efforts, the treaty would have not been agreed (Pittman, 1998). In international rivers where the lack of investment capital is a leading constraint for the realization of water resource projects, the involvement of international organizations in financing key water resource projects can broaden the choice sets of riparian countries, and thus turn a zero-sum game into a win-win solution.

Furthermore, international organizations can play an important role in addressing the information asymmetry problems. *Information asymmetry* results from the fact that riparian countries generally have differential access to information due to their geographic locations or data processing abilities. In some cases, it might be in their best interest to withhold such information from other riparian countries. Information asymmetry may hinder the negotiation or cooperation among riparian countries, because agreement will be hard to reach unless riparian countries establish some confidence in the credibility of information provided by other riparian countries. There is considerable scope for international organizations to intervene when information asymmetry problems are present. For example, international organizations can have a positive effect by developing the institutional framework within which critical information can be collected and shared among riparian countries. In addition, with international organizations as neutral outsiders on which all parties in the negotiation have built trust, an individual riparian country may reveal the true information and expedite the process for reaching an agreement.

Lastly, international organizations can step in as mediators or arbitrators in negotiations when such roles are called upon. International water conflicts have become so complex that alternative dispute resolution methods such as mediation and arbitration may become an important task for international organizations. These alternative dispute resolution methods can be used when no riparian in negotiation wishes to make any further concessions and the negotiation is deadlocked. As mediators, international organizations may undertake shuttle diplomacy between or among polarized parties, arrange group interactions among key disputants, and facilitate the negotiation process by providing technical assistance in explaining and clarifying the alternatives for the parties. As arbitrators, international organizations are required to render critical decisions to end the disputes, and thus their values, goals, strategies and tactics will be critical in shaping the outcomes of negotiation.

International organizations seeking more proactive roles in conflict resolution may also face several challenges, and how they would respond to these challenges will be essential.

First of all, although the ability to finance key investment projects in international rivers may offer international organizations some leverage in shaping desirable solutions to conflicts, the implications of the lending policies of these organizations have not been adequately analyzed. For example, while international organizations often require an extensive consultation process and sometimes approval from downstream riparian countries before any water resources development project in any upstream riparian country can be considered, the financing of water projects in downstream riparian countries often do not carry such requirements. It may be true that downstream countries cannot do any harm to upstream countries in terms of both quantity and quality of the river flow, but such development can effectively change the dynamics of negotiation in the future by creating new facts that may constrain upstream riparians. Krishna points out that the lending policies of the World Bank favor downstream riparians (Krishna, 1998).

Second, when many international organizations may be operating in any given international river at the same time, coordination among different international organizations can be a critical issue. Given the importance and the intensity of water conflicts in many international rivers as well the increasing needs for external financing, there is no lack of interest in the international community. In addition, regional projects and programs often require technical assistance and investment that may be well beyond the capacity of a single international agency (Hirji and Grey, 1998). However, different international organizations involved in the same water dispute may have their own agendas and institutional arrangements that may not be consistent with each other. For example, their priorities may be different from each other, or their ties with different riparian countries may differ. Consequently, when international organizations do not coordinate with each other, some riparian countries may be able to advance their interests by playing international organizations off against each other.

Third, international organizations and riparian countries may face a dual commitment problem. On one hand, riparian countries may face the danger that after they make negotiation moves that might be politically or economically costly to them, international organizations may renege on their financial commitments to the agreements reached, as they may re-prioritize their portfolios for one reason or another. On the other hand, international organizations might also be worried that, once the external financing is in place, certain riparian countries may renege on their commitments by not implementing the agreement reached.

5.2 International Organizations and Capital Investment Projects

In the last section, we mentioned that the role of international organizations in dealing with international water conflicts would be strengthened when their involvement is backed up by their ability to arrange external financing for key investment projects. In the Nile basin, for example, there are ample opportunities for undertaking large scale water resource development projects that would create win-win solutions for some or all of the Nile riparians, but the countries in the Nile basin do not possess the necessary investment capital to implement all these projects without external assistance. Thus, the role of international organizations as lenders will be critical in the water allocation negotiation for the Nile basin. The following analysis attempts to illustrate how the external financing of capital investment projects may change the dynamics of the negotiation among riparian countries.

We start our analysis from a baseline case where the Lake Tana Dam is assumed to be the only new infrastructure in the system. We further assume that Ethiopia and the equatorial states (as a whole) would each withdraw 10 BCM of water for irrigation purposes, and that Egypt and Sudan would reduce their irrigation water usage accordingly. Table 5-1 displays the allocation of irrigation water, hydropower generation as well as the total economic benefits for four players considered (the water for irrigation is valued at US$ 0.05/m^3 and value of hydropower at US$ 0.07/KWH).

Table 5-1 Water Allocation, Hydropower Generation and Total Economic Benefits for Baseline Case

Country	Irrigation Water Allocation (BCM)	% of Total	Hydropower Hydropower (GWH)	% of Total
Ethiopia	10.0	13%	1,061	13%
Sudan	12.1	16%	1,280	15%
Egpyt	44.0	58%	5,088	61%
Equatorial States	10.0	13%	913	11%
Total	76.1	100%	8342	100%

	Total Economic Benefits			
Country	Hydropower (Millions of US $)	Irrigation (Millions of US $)	Total (Millions of US $)	% of Total
Ethiopia	$74	$500	$574	13%
Sudan	$90	$606	$695	16%
Egypt	$356	$2,200	$2,556	58%
Equatorial States	$64	$500	$564	13%
Total	$584	$3,806	$4,390	100%

Under this baseline case, Ethiopia and the equatorial states will proceed with their plans of expanding irrigation schemes, but the prospect of launching additional infrastructure development in these countries will be dampened as they won't be able to secure the external financing necessary. With its irrigation water withdrawal of 10 BCM, Ethiopia will derive most of its benefits from irrigation, and given that it has not used any water from the Nile at present, such increase in irrigation water will dramatically increase the total benefits for Ethiopia (See Chapter 2 for a comparison). Egypt and Sudan would have to reduce their uses of the Nile water to accommodate the increased uses in upstream riparian countries. Both the amount of irrigation water and hydropower generation will be reduced in Egypt and Sudan.

The water allocation negotiation in this case may be perceived as a zero-sum game. Any gains of Ethiopia and the equatorial states from increasing their shares of irrigation water will be at the expense of downstream riparian countries decreasing their uses; while the losses for downstream riparian countries can be reduced only when upstream riparian countries cut their irrigation uses. Table 5-2 clearly demonstrates this point. If Ethiopia were to cut its irrigation water use from 10 BCM to 5 BCM, the total economic benefits for the country would decrease by about 40% [1].

Table 5-2 Water Allocation, Hydropower Generation and Total Economic Benefits When the Target of Ethiopia Irrigation Water Withdrawal Is Reduced from 10 BCM to 5 BCM

	Irrigation		Hydropower	
Country	Water Allocation (BCM)	% of Total	Hydropower (GWH)	% of Total
Ethiopia	5.0	7%	1,787	19%
Sudan	13.5	18%	1,539	16%
Egpyt	47.0	62%	5,397	56%
Equatorial States	10.0	13%	913	9%
Total	75.5	100%	9635	100%

	Total Economic Benefits			
Country	Hydropower (Millions of US $)	Irrigation (Millions of US $)	Total (Millions of US $)	% of Total
Ethiopia	$125	$250	$375	8%
Sudan	$108	$676	$784	18%
Egypt	$378	$2,350	$2,728	61%
Equatorial States	$64	$500	$564	13%
Total	$674	$3,776	$4,451	100%

The dynamics of the water allocation negotiation will change when the external financing from international organizations are available for constructing additional infrastructure in the Blue Nile. Specifically, we assume that the Border Dam and Mabil Dam will be built in Ethiopia, but Ethiopia is required to make a concession by lowering its target of irrigation water from 10 BCM to 5 BCM. Table 5-3 shows the result of the analysis.

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[1] From the systems analysis point of view, this is not a strictly zero-sum game because the losses for Ethiopia will be less than the gains of downstream riparian countries.

Table 5-3 Water allocation, hydropower generation and total economic benefits with the construction of Border and Mabil dams

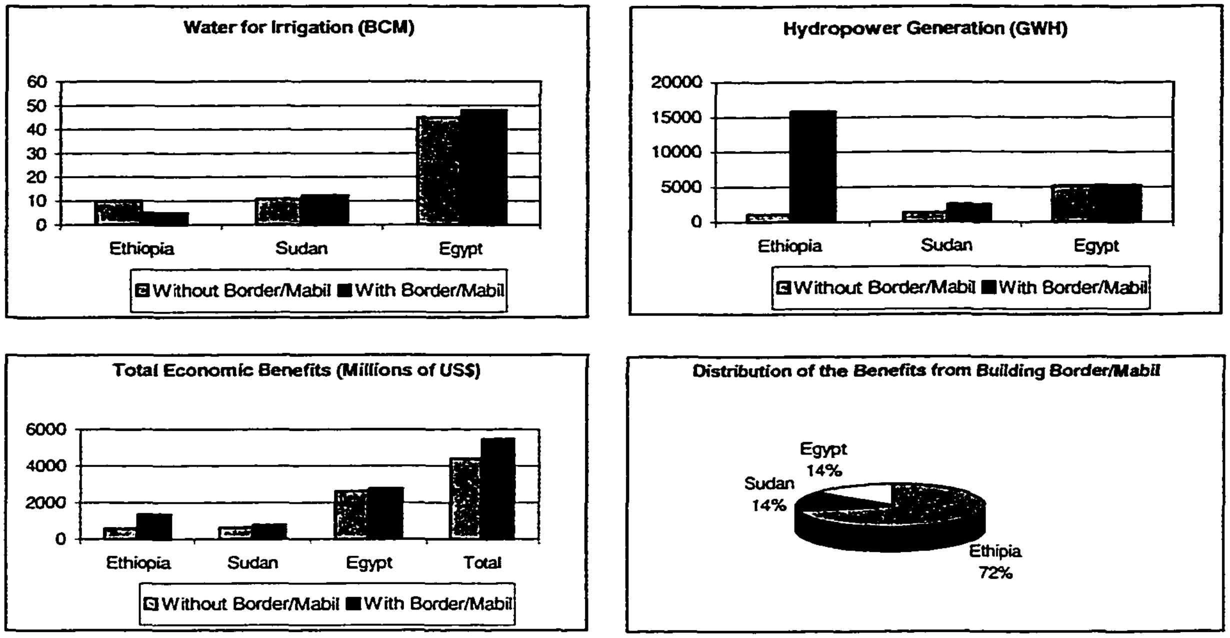
Country	Irrigation Water Allocation (BCM)	% of Total	Hydropower Hydropower (GWH)	% of Total
Ethiopia	5.0	7%	15,819	65%
Sudan	13.5	18%	2,448	10%
Egpyt	47.0	62%	5,163	21%
Equatorial States	10.0	13%	913	4%
Total	75.5	100%	24343	100%

	Total Economic Benefits			
Country	Hydropower (Millions of US $)	Irrigation (Millions of US $)	Total (Millions of US $)	% of Total
Ethiopia	$1,107	$250	$1,357	25%
Sudan	$171	$675	$846	15%
Egypt	$361	$2,350	$2,711	49%
Equatorial States	$64	$500	$564	10%
Total	$1,704	$3,775	$5,479	100%

The attractiveness of a potential agreement is apparent for Ethiopia. Although its use of irrigation water is cut in half, the total economic benefits for the country can increase by 80% due the significant increase in hydropower production. Egypt and Sudan will also benefit from such an agreement since both their irrigation water and hydropower production will be increased. In the case of Sudan, its hydropower production will be almost doubled as more river regulating facilities are added to the Blue Nile and Ethiopia's use of irrigation water decreases. This is clearly a win-win solution for the three riparian countries involved.

Figure 5-1 graphically shows how the nature of water allocation negotiation will change when additional Blue Nile development materializes through financing from international organizations. The involvement of international organizations will result in an increase of total gross economic benefits for the whole system in the order of one billion US dollars annually, without taking consideration the costs of infrastructures. The majority of the extra benefits will be allocated to Ethiopia (about 72%) in exchange for its concession to lower its use of irrigation water. The remaining benefits will be equally shared by Egypt and Sudan.

Figure 5-1 Comparison of irrigation water, hydropower generation, total economic benefits and distribution of benefits from having Border and Mabil Dams



Basically, the external financing provided by international organizations serves as a catalyst for turning a game originally regarded as a "zero-sum game" to a game for which a "win-win solution" can be found. The involvement of international organizations allows the focus of negotiation to shift from water allocation to benefit allocation for which ample opportunities exist for riparian countries in seeking joint gains.

The analysis above indicates that international organizations possess a great deal of leverage in shaping the negotiation processes in international rivers. However, it should be pointed out that the effectiveness of such involvement would critically depend upon a condition: riparian countries do not have the necessary funds to proceed with water resource development projects in their territories on their own. Such a condition may not be expected to last forever, and international organizations seeking more proactive roles in conflict resolution may encounter a window of opportunity in which they must act quickly.

International organizations may also face conflict of interests as they may be drawn to the process in multi-faceted roles. As lenders they may be more interested in developing projects that have the highest and quickest economic return, but as deal brokers they are required to focus on projects that have the most potential to lead to win-win solutions for key riparian countries.

5.3 Lending Policies of International Organizations and Conflict Resolution

The lending policies of international organizations in financing capital investment projects in international rivers in dispute will be critical in shaping the outcomes of the water allocation negotiation. The international organizations so far have been reluctant to finance the projects for international basins where no agreement among riparian countries is reached. The World Bank, for example, did not finance projects (Bhakra/Nangal proposed by India in 1949 and Lower Sind Barrage project proposed by Pakistan in 1950) because there was no agreement between the two riparians.

The international organizations' restraining from financing water resource projects in disputed river basins may enable some downstream riparian countries to use their objections to block upstream development. For example, in the face of Egyptian objections, the African Development Bank declined to lend Ethiopia funds for the development of sugar-cane plantations with water drawn from the Fincha Barrage (Shapland, 1995).

The common lending policy of international organizations of staying away from disputed river basins may not always be a wise course to follow. In our previous analysis, we have shown that one of the important factors determining a riparian country's negotiation power is how well the country can do on its own and the lending policies of international organizations are likely to have some effect on this factor. For illustrative purposes, we consider a case where international organizations have two lending policies to choose from for the proposed Blue Nile dams in Ethiopia. Under *Lending Policy A*, external financing of Border/Mobil dams are not available for Ethiopia unless it forms a coalition with one of the two downstream riparian countries—Egypt and Sudan; under *Lending Policy B*, external financing of Border/Mabil dams are available for Ethiopia even if downstream riparians may object. We calculated the cores of the game under these two lending policies and the results are presented in Table 5-4.

Table 5-4 Core of the game under two lending policies of international organizations

Lending Policy A: External financing is not available for Ethiopia to build Border/Mabil unilaterally				
	Maximize Ethiopia	***Maximize Sudan***	***Maximize Egypt***	***Maximize Others***
Ethiopia	**3185**	1648	**592**	**592**
Sudan	**886**	**3054**	2661	1914
Egypt	2260	**2063**	**4012**	3825
Equatorial States	**2166**	1732	**1232**	**2166**
Total	8497	8497	8497	8497

Lending Policy B: External financing is available for Ethiopia to build Border/Mabil unilaterally				
	Maximize Ethiopia	***Maximize Sudan***	***Maximize Egypt***	***Maximize Others***
Ethiopia	**3185**	1648	**1586**	**1586**
Sudan	**886**	**3054**	1667	920
Egypt	2260	**2063**	**4012**	3825
Equatorial States	**2166**	1732	**1232**	**2166**
Total	8497	8497	8497	8497

Ethiopia's relative negotiation power will increase under *Lending Policy B*. It can be shown clearly by the increase of the lower bound for Ethiopia in the core. Under *Lending Policy B*, Ethiopia will not entertain any offer for which it receives less than US$ 1,586 millions, the amount it can achieve without cooperating with other riparian countries. In comparison, the lower bound for Ethiopia in the core under *Lending Policy A* is only US$ 592 millions. Sudan's relative negotiation power will decline because the additional benefits it brings to the table for the Sudan-Ethiopia coalition (See Chapter 3 for its definition) will be minimal if Ethiopia can obtain external financing to build Border/Mabil dams on its own.

Perhaps a clearer indication of the decline of Sudan's relative negotiation power can be found by comparing the Shapley value of the game under different lending policies (see Table 5-5). Table 5-5 shows that not only the share allocated to Sudan will decrease under *Lending Policy B*, but the shares of Egypt and the equatorial states will also decrease. Ethiopia is the sole winner of the game under *Lending Policy A*.

Table 5-5 Shapley value of the Nile allocation game under two lending policies

	Lending Policy A : External financing is not avilable for Ethiopia to build Border/Mabil unilaterally		Lending Policy B : External financing is avilable for Ethiopia to build Border/Mabil unilaterally		
Country	Economic Value (in million US$)	Share (%)	Economic Value (in million US$)		Share (%)
Ethiopia	1,868	22%	$	2,117	25%
Sudan	1,889	22%	$	1,806	21%
Egypt	3,023	36%	$	2,940	35%
Equatorial States	1,717	20%	$	1,634	19%
Total	8,497	100%	$	8,497	100%

It is important to note that different lending policies of international organizations may benefit one or a particular group of riparian countries at the cost of other riparian countries and this may change the power balance of the negotiation. Therefore, the choices of lending policies are likely to have impacts on the outcomes of the water allocation games, and it is difficult for international organizations to maintain neutrality.

Given the impacts of the lending policies of international organizations on water allocation negotiation, perhaps a sensible strategy for international organizations to adopt is not to be locked in to a fixed or rigid position in their lending practice. On one hand, downstream riparian countries should not be entitled to deadlock external financing of projects in upstream riparian countries. On the other hand, upstream riparian countries should not always count on obtaining such financing if they do not make efforts to reach agreement with downstream riparian states.

Coordination among different riparian countries is also critical. For example, if there is no coordination, the availability of financing from different international organizations may easily upset the power balance among riparian countries and may decrease the attractiveness of a cooperative solution.

5.4 International Organizations and Information Asymmetry

The problems of information asymmetry are widely anticipated in water allocation negotiation. Riparian countries, in general, have differential access to information that is critical to the negotiation process, and in many situations it might be in their best interests to withhold or misrepresent such information in order to gain an advantage. For example, as we have seen from previous analysis, riparian countries generally have a tendency to overstate the value of irrigation water for their countries if economic benefits are the basis of water allocation (See Chapter 4 for details). In this analysis, we show that riparian countries may misrepresent the value of water when they are engaged in trading with other riparian countries, and that information asymmetry may lead to inefficient trading patterns. International organizations can play a positive role in correcting the information asymmetry problems and restoring efficient trading patterns.

Our analysis begins with a scenario for which all proposed infrastructures in the Nile basin are in place and water allocation agreement can only be reached such that specific amount of water will be allocated to individual riparian countries entering the agreement. We assume that Ethiopia would obtain all the benefits associated with the hydropower generated in the five new dams in the Blue Nile, and in addition, it is entitled to 5 BCM of water for irrigation. Egypt, on the other hand, will receive 55 BCM on an average annual basis. Suppose that after the water allocation agreement is reached Egypt and Ethiopia are interested in exploring the opportunities for trading of irrigation water that would be mutually beneficial to both sides.

On the surface, such trades in water are no different from trades of other economic goods: if the economic value of irrigation is higher in Egypt than in Ethiopia, then Ethiopia can sell the water to Egypt at an agreed-upon price of which both would benefit. However, our study of the system optimization models suggests that there are more issues to be considered. First of all, although Ethiopia would lose the economic benefits from irrigation if it chooses to sell its share of irrigation water, it can gain from hydropower production when an additional 5 BCM of water flows through its power stations. Second, the amount of water received at irrigation schemes in Egypt is less than the amount of water taken from Ethiopia because of evaporation losses. In fact, the 5 BCM available in Ethiopia will amount to only about 4.3 BCM measured in Egypt. Third, Egypt can also gain from hydropower production when additional water flows through the turbines in the Aswan High Dam, implying that Egypt might be willing to pay a price higher than its economic value for irrigation. In fact, if the economic value of irrigation water for Egypt is US\$ 0.05/m3, Egypt would be willing to pay up to US\$ 247 millions, or US\$ 0.053/m^3, for the 4.3 BCM that reaches its irrigation schemes. Table 5-6 shows the comparison of irrigation water and hydropower production for Ethiopia and Egypt under trade and no trade alternatives.

Table 5-6 Irrigation water and hydropower production: trade vs. no trade

	Egypt	Ethiopia
No Trade		
Water for Irrigation (BCM)	55	5
Hydropower (GWH)	5750	36500
Trade		
Water for Irrigation (BCM)	59.3	0
Hydropower (GWH)	6200	37700

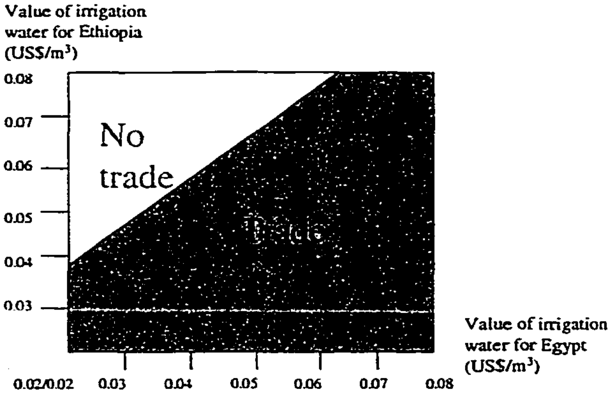
Of course, one should not expect the economic values of water for irrigation to always be US\$ 0.05/m^3 level for both riparian countries. In fact, they probably will not be equal to each other in most cases. Table 5-7 reports the calculation of the gains and losses for the two riparian countries under different values of irrigation water. It is not difficult to see that trading will be beneficial to both sides whenever the values of irrigation water are the same for Egypt and Ethiopia, as the gains of Egypt by trading exceed the losses of Ethiopia. The trading can take place even when the value for irrigation water is higher in Ethiopia. For example, losses to Ethiopia of not using the water for irrigation are about US$ 166 millions when its economic value for irrigation is US$ 0.05/m^3, but the gains for Egypt will amount to US$ 204 millions when its economic value for irrigation is US$ 0.04/m3, or 20% below that of Ethiopia.

Table 5-7 Total economic benefits of Ethiopia and Egypt under two scenarios

	Total Economic Benefits: Ethiopia			**Total Economic Benefits: Egypt**		
Value for irrigation water (US$/m^3)	With 5 BCM for irrigation (millions US$)	Without 5 BCM for irrigation (millions US$)	difference	Without additional 5 BCM for irrigation (millions US$)	With additional 5 BCM for irrigation (millions US$)	difference
0.02	2655	2639	-16	1503	1620	118
0.03	2705	2639	-66	2053	2213	161
0.04	2755	2639	-116	2603	2806	204
0.05	2805	2639	-166	3153	3399	247
0.06	2855	2639	-216	3703	3992	290
0.07	2905	2639	-266	4253	4585	333
0.08	2955	2639	-316	4803	5178	376

There is a certain range in which trading should not take place. For example, when the economic value of irrigation water is US$ 0.06/m^3 for Ethiopia and US $0.04/m^3 for Egypt, such trading will not be efficient because the losses of Ethiopia (US$ 216 millions) out-weight the gains of Egypt (US$ 204 millions). Figure 5-2 shows the details graphically as to when the trading should take place and when it should not as the economic value of irrigation water varies from US$ 0.02 to US$ 0.08 per cubic meter for both of these countries. The area in blue represents the range in which trading will be efficient and mutually beneficial for both countries.

Figure 5-2 Trading zone for Egypt and Sudan



The trading zone shown in Figure 5-2 is based on a critical assumption: that both riparian countries would truthfully reveal their true value at the time of the trading. However, since the terms of the trading will be based on the economic value of water for irrigation, both riparian countries would have a strong tendency to misrepresent such information when access to information is asymmetric. For example, Ethiopia may find that it is advantageous to declare a higher value; while Egypt may be tempted to claim a value that is lower than its true level.

Consider a situation where each riparian country knows its own true value of irrigation water but the other party only knows such value is uniformly distributed between US\$ 0.02 and US\$ 0.08/m^3. Therefore, Egypt will assume Ethiopia's willingness to accept as the 5 BCM of water is distributed uniformly between US\$ 16 millions and US\$ 312 millions; while Ethiopia believes that the Egypt's maximum willingness to pay for the water would be between US\$ 118 millions and US\$ 376 millions. The question here is what the dominant strategy for each riparian country would be as its true value of irrigation water is given.

Let b_{EGYPT} and $b_{ETHIOPIA}$ denote the willingness to pay declared by Egypt and willingness to accept claimed by Ethiopia at the time of the trading. If $b_{EGYPT} < b_{ETHIOPIA}$, trading would not occur and Ethiopia keeps the water; if $b_{EGYPT} > b_{ETHIOPIA}$, then the trading would take place and Egypt would pay $(b_{EGYPT} + b_{ETHIOPIA})/2$ to Ethiopia for the water. We then assume that b_{EGYPT} is an increasing function of v_{EGYPY}, the true maximum willingness to pay known to Egypt, and that $b_{ETHIOPIA}$ is an increasing function of $v_{ETHIOPIA}$, the true minimum willingness to accept known for Ethiopia.

Given a particular value for v_{EGYPY}, Egypt's net benefit for bidding b_{EGYPT} is $v_{EGYPT} - (\frac{b_{EGYPT} + b_{ETHIOPIA}}{2})$, and Egypt's optimal strategy can be regarded as the solution to the following maximization problem:

$$\underset{b_{EGYPT}}{Max} \int_{118}^{b_{EGYPT}} [v_{EGYPT} - (\frac{b_{EGYPT} + b_{ETHIOPIA}}{2})] dF_{ETHIOPIA}(b_{ETHIOPIA})$$

where $F_{ETHIOPIA}(b_{ETHIOPIA})$ is the probability that the bid by Egypt is greater than $b_{ETHIOPIA}$.

Similarly, Ethiopia's optimal strategy can be viewed as the solution for the following maximization problem:

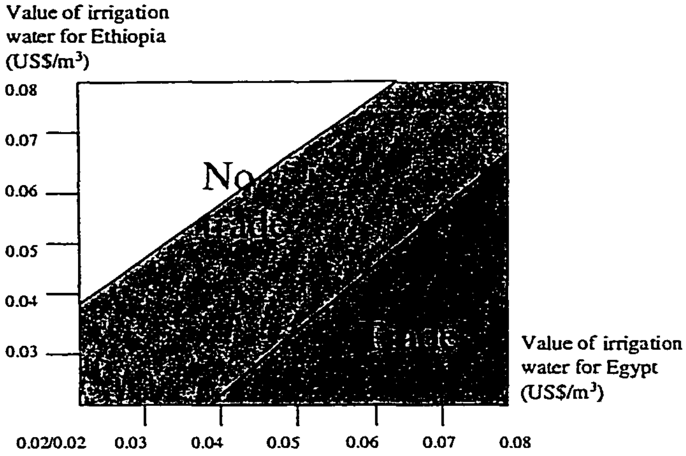
$$\underset{b_{ETHIOPIA}}{Max} \int_{b_{ETHIOPIA}}^{316} [(\frac{b_{EGYPT}+b_{ETHIOPIA}}{2}) - v_{ETHIOPIA}]dF_{EGYPT}(b_{EGYPT})$$

Suppose that a linear bidding function is used for both Egypt and Ethiopia, then the equilibrium of the game can be found by solving the two optimization problems jointly. Under the equilibrium of the game, the trading will not take place unless the following condition is met:

$$v_{EGYPT} > 168 + 0.8v_{ETHIOPIA}$$

It is obvious that many trading opportunities will not be realized when information asymmetry is present. For example, no trading can take place if the value of irrigation water in Egypt is less than US\$ 0.03/m^3, and no trading would occur if the irrigation value for Egypt is the same as that of Ethiopia. Figure 5-3 displays the trading zone for Ethiopia and Egypt under information asymmetry. The gray area in the graph represents the situation where the trading does not take place although it is efficient to trade.

Figure 5-3 Trading Zone for Ethiopia and Egypt under Information Asymmetry



The analysis above clearly demonstrates that information asymmetry can become an important barrier to negotiations and cooperation among riparian countries. International organizations can have a positive effect by dealing with the information asymmetry problems. For example, international organizations can help riparian countries to narrow down the information gaps by providing more reasonable estimates of the ranges of key economic input data such as economic value of irrigation and hydropower water. International organizations can also help riparian countries in developing an institutional framework within which critical information can be collected and shared among riparian countries. In many international rivers, systematic efforts towards collecting key information are still on the way. Consequently, collaboration among riparian countries in collecting and analyzing information can be an important step towards negotiation. In addition, international organizations may help riparian countries to draw up agreements that are robust with regard to attempts in misrepresenting the information.

Chapter 6 Conclusions

Although applications of systems analysis to water resource policy issues in international rivers have gained momentum in the last twenty years (see, for example, Whittington and Guariso, 1983; Whittington and Guariso, 1987; Fisher, 2000), there is little evidence that systems analysis has earned wide-spread acceptance among decision makers dealing with water conflicts in international rivers. Advances in mathematical techniques and developments in computational software (such as the GAMS) may have made the tools of systems analysis increasingly accessible, but they are unable to change the fact that the interests of decision makers may be inconsistent with the main focus of systems analysis. As Just et al (1998) point out, while the actions of decision makers are driven primarily by political pressures determined by distributional considerations, systems analysis has focused on efficiency gains and has paid insufficient attention to distribution and equity.

On the other hand, however, decision makers and negotiators of riparian countries are often ill equipped to make decisions in resolving conflicts in international rivers. For example, negotiators in riparian countries may not have adequate analytical tools to assess the impacts of different proposals put forth by their counterparts; or they may not possess sufficient information to develop their own plans and strategies in negotiation. Spector (1991) notes that, "international negotiators usually confront their counterparts only with their wits, instruction from their home government, and minimal background information developed by their staffs."

The acute water conflicts in international rivers call for new decision analytical tools that can respond to information and analytical needs of decision-makers and negotiators in resolving conflicts. Such tools should allow them to quickly diagnose the situation, to evaluate their own strategies and strategies of other parties, and to assess the impacts of different negotiation outcomes. Such tools should also help international organizations involved to determine their policies and strategies either in facilitating the negotiation process or in providing financial and technical assistance to riparian countries.

Through a case study of the Nile basin, this thesis has demonstrated that, game-theoretical approaches, combined with systems analysis techniques, can be applied to support the decision-making process in resolving international water conflicts. Key findings of our study and their implications to the Nile water allocation negotiation are summarized as the following[1]:

1) While water conflicts have often been perceived as "zero-sum" games in which one riparian country would have to lose in order for another riparian country to gain, our analyses indicate that water conflicts in the Nile basin are clearly not "zero-sum" games. If full cooperation in the Nile basin can be achieved, additional 15 billion m^3 of water—or about 20% of the average annual discharge of the basin—as well as 52,000 GWH of electricity can be made available to the Nile riparian countries. If we assume that the value of water for irrigation is US$0.05 per m^3 and value of hydropower is US$0.07 per KWH, such efficiency gains can amount to annual gross economic benefits that are more than the total economic benefits in the status quo. While riparian countries may be inclined to concentrate on distributional issues in negotiation, the large efficiency gains of cooperation suggest that more emphasis should be directed to achieving the efficiency gains when a new agreement for the basin is structured. Although extensive sensitivity analysis may be required to make some definite conclusions in this regard, our study offers some insights as to how the water should be best used in the basin (see Chapter 2). First of all, while our results show that water from Lake Victoria basin should be best utilized by the equatorial states in absence of the White Nile power stations, it is not justifiable from a systems point of view for Ethiopia to divert water for irrigation purposes. In addition, despite the high evaporation losses expected in the Aswan High Dam, Egypt's New Valley project will not receive any water if the economic value of water in the New Valley is the same as the old land. Lastly, Sudan will receive the majority of its irrigation water from the Blue Nile rather than from the White Nile.

2) While the potential adverse environmental impacts of wetland projects have received a lot of attention in policy debate of Nile water development, our analysis shows that such emphasis might not be warranted. Based on our scenario analysis in Chapter 2, the marginal benefits of the wetland projects do not appear to be substantial. Table 6-1 shows the marginal benefits of the wetland projects with or without other investment projects in place. One can conclude that

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[1] We want to remind our readers that since we have not explicitly consider the costs of infrastructure, our conclusion are drawn based on gross economic benefits rather than net economic benefits.

the most of benefits from development of the water resources can be captured without the wetland project, and that the negative ecological impacts associated with the wetland projects certainly should be become an obstacle for cooperation in the Nile basin.

Table 6-1 Marginal benefits of the wetland projects

	Without wetland projects	With wetland projects	Difference (in millions US$)	%
No other project is built	4679	4760	81	1.7%
All other projects are built	7966	8496	530	6.7%

3) Our results in Chapter 2 have shown that most of the extra benefits from cooperation may not come from irrigation, but from non-consumptive uses such as hydropower generation, and this may have profound implications to the negotiation. Traditionally, the basic allocation principle of all the agreements in international rivers has been a volumetric division of an average flow (Durth, 1998). Such allocation principle may be inappropriate in structuring the potential new agreement for the Nile because the majority of benefits comes from non-consumptive uses of water (hydropower generation) rather than from irrigation. Therefore, the goals of individual riparian countries should be to increase the benefits of water utilization rather than to maximize their water allocation. For example, the upstream riparian countries can get a significant boost in terms of the benefits of utilizing the water from the Nile in full cooperation even if they do not withdraw any water from the Nile for irrigation purposes. In the case of Ethiopia, if the Blue Nile projects are constructed, the annual economic benefits for Ethiopia from electricity production amount to US$ 47 per capita, or 43% of its GNP per capita in 1998.

4) The upstream water resources development projects are very important to the negotiation in the Nile basin. Without these projects, water saving projects such as the wetland projects and the modification of the Jebel Aulia may not be effective from a systems point of view (see Chapter 2). The fact that upstream riparian countries such as Ethiopia and the Equatorial States will probably have to rely on external financing to develop these projects may provide downstream riparian countries some bargaining powers in negotiation (see Chapter 3), and it

may also provide some leverage for international organizations in shaping the negotiation outcomes (see Chapter 5). Given the importance of the upstream water resources development projects in the negotiation, one could image that downstream countries and international organizations would want to include them in the potential new agreement as part of a packaged deal, under which the upstream riparian countries would limit their scope of irrigation expansion in exchange for the international support for their hydropower projects. In fact, the current conditions in the Nile basin should be viewed as a window of opportunity for reaching an equitable water allocation agreement among riparian countries, because as the upstream riparian countries become stronger both in political and economic terms in the future, the incentives for them to strike an agreement with downstream riparians may decrease.

5) Game-theoretical concepts such as the core can help decision makers and negotiators of riparian countries to better understand their strategic choices in negotiation. Despite large potential efficiency gains, there will be no cooperation if riparian countries have radically different views about the fair division of water or benefits. To form a basis for cooperation and negotiation, riparian countries must first concentrate on diminishing the difference between their perceptions of what is an equitable allocation (Durth, 1998). With knowledge of the core, we will be able to establish boundaries of allocation for the Nile water allocation negotiation. The knowledge of the core may also help one to interpret the behaviors of riparian countries in pre-negotiation and negotiation processes. For example, because a riparian country will be better positioned in negotiation if it can form multiple mutually beneficial coalitions with other riparian countries, it would be in the interest of each riparian country to engage in activities that may convince its counterparts that it is exploring the possibilities of potential coalitions, even though creating such coalitions may not be their true intention (see Chapter 3).

6) The analyses of game-theoretical solutions such as the Shapley value and the nucleolus can help decision makers and negotiators of riparian countries to understand the sources of their negotiation powers and how such powers may be affected when different circumstances arise. For example, the fact that the benefits for Ethiopia and *the Equatorial States*' increase significantly when moving from the Shapley value to the generalized Shapley value suggests that riparian countries may actually benefit from being the last to join the cooperation (Chapter 3). In addition, the Shapley value closely matches the hypothetical focal point

established by splitting the differences for the core, and also the benefits allocated to the two upstream riparian countries in the Shapley value are close to the results of the optimal allocation under full cooperation. These features may make the Shapley value an attractive solution concept for further consideration (See Chapter 3).

7) While uncertainty may create a commitment problem for riparian countries engaging in negotiation, it may not necessarily become a barrier to cooperation and negotiation. Uncertainties in areas such as hydrological information and investment projects may not necessarily alter the relative negotiation powers among riparian countries (see Chapter 4). Such robustness is encouraging for negotiation process. In fact, the uncertainty may actually expedite the negotiation process by narrowing the negotiation zone established through the evaluation of the core of the game (See Chapter 4).

In summarizing the findings of our research we have deliberately stayed away from results that might be very sensitive to many assumptions employed in our analyses, comprehensive analysis can be conducted on those aspects of problems that are of particular interest to the users. In addition, there are a variety of ways to modify and expand our models so that they can handle some specific tasks requested by the potential users. For example, attempts could be made to link the water in the Nile basin to the national economies of individual riparian countries through input-output models or computerized general equilibrium models. Once water is treated as a part of the overall system of the a national economy, analysis can be performed to assess the impacts of national economic policies as well as international trade patterns.

The framework established through this dissertation can also serve as a basis for designing gaming exercises for training purposes. One example of such games might be an interactive game for which each participant of a particular gaming session would represent a riparian country and would negotiate with each other over the terms of a potential agreement of water allocation. It can be designed to simulate an actual negotiation process in which decision makers and negotiators are required to make decisions in each period 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 gaming session, a score will be displayed for each participant of the game indicating the economic benefits obtained for the country she (or he) represents. Such gaming exercises may generate valuable insights for decision makers and negotiators in the pre-negotiation stage.

For analytical tools such as the ones presented in this thesis to be more useful to practitioners dealing with water conflicts in international rivers, a critical task is to enhance communication between the analysts and the users of the models. Analytical tools may fail to deliver their promise not because they are inaccurate or inadequate, but because the intended users of the analysis simply do not trust them. Analysts who want to contribute to the real problems of conflict resolution need to carefully select the venues through which the analytical tools are presented and delivered to the potential users. They should also work closely with such users, so that the analytical tools would no longer be viewed as a black-box, but instead, be used as a laboratory in which innovative ideas of conflict resolution are tested and nurtured.

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