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AN INTEGRATIVE APPROACH BETWEEN GAME THEORY AND PARETO FRONTIER CONCEPTS FOR THE TRANSBOUNDARY WATER RESOURCES ALLOCATIONS: Case of the Euphrates and Tigris

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**AN INTEGRATIVE APPROACH BETWEEN GAME THEORY AND PARETO
FRONTIER CONCEPTS FOR THE TRANSBOUNDARY WATER RESOURCES
ALLOCATIONS:
Case of the Euphrates and Tigris**

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ABSTRACT

In the transboundary water resources allocation issues, there has been so far very limited progress made in terms of allocation techniques. This study introduces a composite water resources allocation approach that integrates game theory and Pareto frontier technique over the case of the Euphrates and Tigris. The proposed approach searches an acceptable solution set over the Pareto frontier surface via game theory based core constraints. The base model to generate the Pareto Frontier Surface is the Euphrates and Tigris River Basin Model, which is a linear programming model maximizing net economic benefits while optimally allocating scarce water resources in the basin. Results show that i) game theory provides a determinative backbone for an efficient and effective use of Pareto Frontier Surface and ii) upstream countries have upper hand position due to the geographic context.

Keywords: Linear programming; Multi-objective programming; Game theory; Pareto frontier surface; Transboundary water resources allocation; the Euphrates and Tigris.

1. INTRODUCTION

Today, as we see impacts of the global warming and observe symptoms of the global climatic change, *rational and equitable* use of water resources has become a daunting task among multiple competing parties. This issue is further exacerbated considering that transboundary water resources do not acknowledge country borders (Dellapenna, 2007). Worldwide, there are 261 transboundary surface water resources basins (Dinar et. al., 2007), a crucial one of which is the Euphrates and the Tigris River Basin (ETRB). Because of their critical geographic location and historic context, both rivers have been a source of life in the Mesopotamia. The Euphrates and the Tigris are two separate rives until their confluence near

Basra, where they become a single river before reaching to the Persian Gulf. Today, the rivers are connected by the Tharthar Canal much before Basra.

Although academic researches have been extensively conducted, allocation of scarce water resources remains as an issue to be solved in the world. So far an agreed framework is yet to be developed. The reasons for that can be attributed to the unique complex characteristics of each basin. Every basin has accumulated geological, geographic, historic, social, and economic characters that may require specific treatments that do not fit in a generic legal and procedural framework.

This paper, after a short literature review, presents the Euphrates and Tigris River Basin Model (ETRBM) with various system and decision constraints to encompass the economic and game theoretic approaches. Afterward, in the model application section, a series of analyses are pursued to present the country impacts to overall performance of the basin-wide resources uses and allocation via marginal impact and compensation concepts. In the conclusion section, a short evaluation of findings and new research directions are provided.

2. LITERATURE

Literature on the transboundary water resources allocation can be classified into two broad categories: *descriptive* studies covering legal and political aspects of the topic and *quantitative* studies that covers technical aspects of various allocation issues. This study can be categorized more on the technical, specifically, modeling aspects of the literature.

The basic modeling studies are on the optimal allocation of scarce water resources among multiple uses and parties: Though being not in the transboundary water resources literature, Flinn & Guise (1970), Booker & Young (1994), Mahan et al. (2002) and Becker (1995) have made significant contributions to the modeling literature. Booker & Young (1994) is a critical one that models a river (Colorado River) similar to the ETRB.

One of the first transboundary water resource allocation model dates back to 1969 by Rogers with his studies on the Ganges. Later, in 1993, Rogers outlined the basic modeling concepts (Pareto frontier, game theory) that can be used for the allocation of scarce water resources. Later, Dinar & Wolf (1994a, 1994b) and Wu & Whittington (2006) studied the Middle East-North Africa water problems such as the Nile River; Kampragou et. al. (2007) and Eleftheriadou & Mylopoulos (2008) worked on the River Nestos/Mesta; Kucukmehmetoglu (K, 2002, 2009), Kucukmehmetoglu & Guldman (K-G, 2004, 2010) have pursued researches on the Euphrates and the Tigris Rivers.

From the earlier modeling studies, we found that grand coalition provides the highest net economic benefits as compared to various forms of sub-coalition benefits. In this process, one or some of the parties are required to give up her or their benefits for the higher grand coalition net economic benefits. However, in this process the estimated variables in the grand coalition do not provide sufficient information to attract the contributing disadvantaged parties. In K-G (2004) the focus was on the game theoretic aspects of the transboundary water resources allocation, and in K-G (2010) the focus was on the trilateral Pareto tradeoff among the basin countries. Beyond these studies, this study provides improvements in i) selecting the valid extent of Pareto frontier tradeoff surface that countries compete, and ii) determining the necessary amount of compensation to attract or convince the influential parties to take part in grand coalition. This study obtains the dual solutions of the ETRBM and finds the necessary marginal values of defined decision constraints presented in the coming modeling section. These marginal impacts of country or subgroup of countries on the grand net economic benefits are measured and visually presented in the model application section.

3. MODEL USED

The Euphrates and Tigris River Basin Model (ETRBM) is a three-country, two-river, a single basin model. Among the basin counties (Turkey, Syria, Iraq), Turkey has an upper hand position due to her upstream geographic location and as a nearly 90% of Euphrates and half of the Tigris River water contributor. As can be seen in Figure 1, the ETRBM contains 45 supply (15, 7, 22 of them are respectively in Turkey, Syria, Iraq) and 63 demand nodes (24, 16, 23 of them are respectively in Turkey, Syria, Iraq), and three inter-basin links (from j to j : 28→14, 31→16, and 21→12). Among demand nodes, 37 are agricultural and the remaining 26 are urban demand nodes. Linear programming (LP) based optimization takes place while allocating scarce water resources for the benefit of agricultural and urban uses considering the water conveyance costs. During this process, energy is generated via the water releases from upstream supply node to downstream supply nodes, which are dams and reservoirs.

This paper initially presents the basic model (ETRBM) with its structural constraints (K, 2002; K-G, 2004) and makes elaboration via additional constraints in order to measure game theory based country decisions on the generated Pareto Frontier Surface (K-G, 2010) showing country net economic benefit tradeoffs. The model is introduced in three sequential steps. In the *first* step, there is an introduction of basic model (ETRBM). In the *second* step, there is a short review of methodology used in multi-objective programming (MOP) study and the process of generating Pareto frontier surface. In the *last* step, the game theory constraints,

which are based on individual and subgroup rationalities, are used to measure the marginal impacts of unilateral and bilateral country choices to the overall performance of grand coalition benefits.

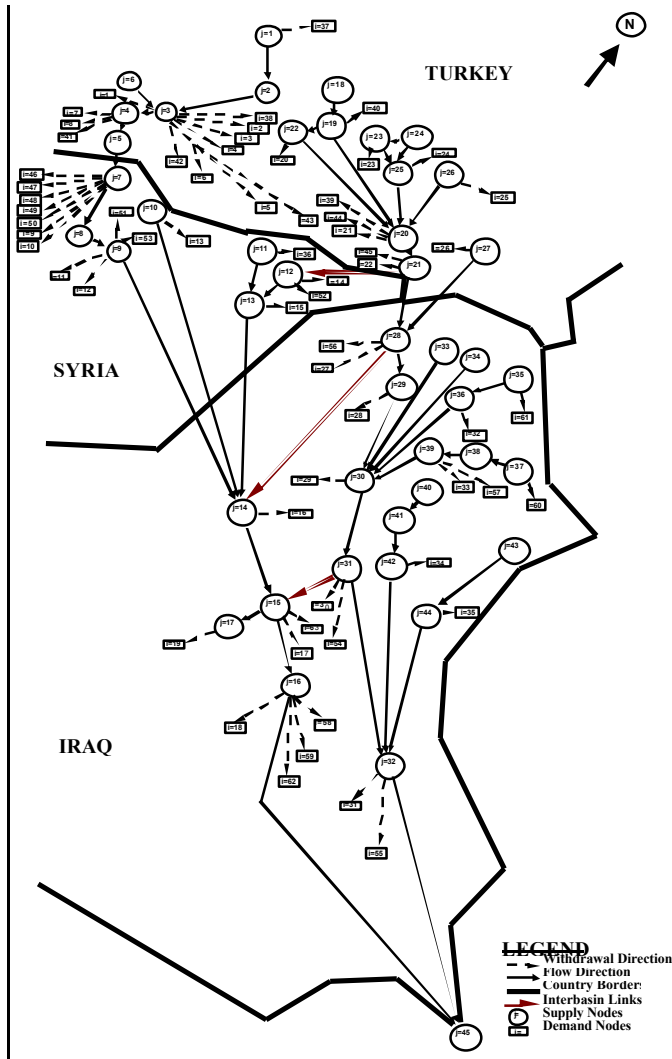


Figure 1. The Network Structure of the ETRBM [Kucukmehmetoglu (2002 p.96), Kucukmehmetoglu and Guldmann (2004 p.786).]

An overview of the ETRBM (K, 2002; K-G, 2004, 2010), various system and decision constraints are presented as follows:

Objective Function: Objective function of the ETRBM in K (2002) is presented in two different but equivalent Equations (1a) and (1b). The *first* one (Eq. 1a) maximizes the net economic benefit derived from two main sources: 1) withdrawals, which are consumptive for agriculture and urban uses, and 2) energy generations (consumptions) from water releases (pump) to the downstream nodes from head losses (gains for inter/intra basin transfers). In the same equation, the first two lines consider benefits from agriculture ($\sum_{i \in ag} V_{ag} \cdot \sum_j W_{ji}$) and

urban ($\sum_{i \in ur} V_{ur} \cdot \sum_j W_{ji}$) withdrawals minus their associated water conveyance costs ($\sum_{j, i \in ag} C_{ag} \cdot D_{ji} \cdot W_{ji} + \sum_{j, i \in ur} C_{ur} \cdot D_{ji} \cdot W_{ji}$) respectively. The third line ($\sum_{j, l} P_e \cdot E_{jl} \cdot Q_{jl}$) is designed to measure the benefit (cost) of energy generation (consumption) from water releases (pumps) between reservoirs. It also accounts for inter-basins water conveyances from the Euphrates to the Tigris. In the function, energy benefits are converted into cost of energy via negative sign. The summation of all benefit and cost categories constitute the objective function (*NEB i.e. NEB_{TSI}*) of the ETRBM. The *second* function, presented in Equation (1b), is designed to computationally separate country benefits with weight multipliers (WG_T, WG_S, WG_I), which can vary 0 to 1. In order to obtain the same net economic value from Equations (1a) and (1b), weights are required to be nonzero and equal for the three countries. Later on, those weights are used to generate Pareto Frontier Surfaces and to include and exclude country or countries from game theory objective functions. The remaining 3 functions presented in Equations (1c)-(1e) are the country details of apportioned Equations (1a) and (1b) with their country subsets.

System Constraints: Equations (2)-(4) define the model's basic *system constraints*. Equation (2) is prepared for continuity in the river system and controls system *in* and *out* balances for each node j . On the *right* hand side, there are tributary inflows (T_j), water coming from upstream nodes ($\sum_i Q_{ij}$), and return flows from various withdrawals ($\sum_i RF_{ij} \cdot \sum_j W_{ji}$). On the *left* hand side, there are water withdrawals ($\sum_i W_{ji}$), water releases to the downstream nodes ($\sum_i Q_{ji}$), and evaporation losses (EL_j). As presented in Equation (2), both left and right hand sides are required to fulfill the equality condition. Equations (3)-(4) limit withdrawals and prevent excessive consumptions due to the linear nature of the objective function. The same equations can be easily modified to set policy decision for least withdrawals for each demand i .

Pareto Frontier Surface (PFS) Generator Constraints (K-G, 2010): Equations (5) and (6) are the constraints designated for a separate optimization run given the objective function (Eq. 1b) and system constraints (Eq. 2-4). During the process of maximization, while weight multipliers for Turkey and Syria ($WG_T=0$ and $WG_S=0$) are set to be zero to make them null at the objective function, but leaving multiplier for Iraq different from zero (such as $WG_I=1$), the constraints in Equations (5) and (6) controls the lower bound of those two country net economic benefits. Procedurally, after an iterative maximization process subject to the varying a grid value constraints which are set regarding the Figure 2 ($CNEB_T^*$ and $CNEB_S^*$), a set of associated Iraqi net economic benefits (NEB_I) are generated to form three party non-

dominated tradeoff surface (Pareto Frontier Surface). At the PFS, all marginal impacts of countries to each other are negative.

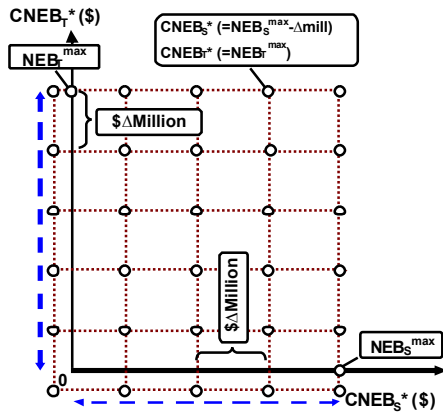


Figure 2. Benefit grids for the generation of Pareto Frontier Surface (K-G, 2005)

Decision Constraints: Basin countries may come together and assemble various forms of coalitions. These coalitions can be categorized and named as *unilateral*, *subgroup*, and *grand* coalitions. In a river basin, significance of a coalition formation depends largely on geographic and hydrologic characteristics of the basin. Upstream countries are more likely to have advantageous positions regarding higher level of annual precipitations. Meanwhile downstream countries are more likely to have advantageous positions regarding plain lands, most of which are potentially productive agricultural lands. Figure 3 succinctly summarize the strategies may evolve in the ETRB between/among Turkey, Syria, and Iraq by considering the geographic and hydrologic contexts of the ETRB.

Figure 3a presents the grand coalition unifying all countries as if they are a single country. The maximum value net economic benefit is achieved from this scenario. In an optimization framework, NEB (i.e. NEB_{TSI}) is achieved from the maximization of Equation (1a) or (1b) with an equal weight ($WG_T=WG_S=WG_I=1$) subject to only the basic system constraints (Eq. 2-4).

Figure 3b presents the sequential moves of individual countries with respect to their individual rationalities. The upstream country Turkey is the main source of precipitation in the ETRB. After optimal utilization of the water in Turkey, the unused and return flow waters are used in Syria and then similarly in Iraq. In each step, mathematically, the same optimization process is proceeded by using the same Equations (1a) or (1b) subject to Equations (2)-(4). But this time difference takes places at the objective function that irrelevant (other countries not a part of optimization) components of objective function is multiplied by

zero weight. The necessary parametric adjustments are considered exogenously for the relevant subsets. To illustrate, while maximizing NEB_T , the weight for Turkey is assumed to be one ($WG_T=1$), and weights for Syria and Iraq are assumed to be zero ($WG_S=WG_I=0$). The parameters for the country having zero weights are set to be zero except return flows and water releases from upstream/to downstream nodes. The obtained benefits are codified as NEB^*_T , $NEB^*_{S/T}$, $NEB^*_{I/T\&S}$ due to sequential i.e. conditional moves.

Figure 3c presents bilateral subgroup coalition formations behaving like a single country. The remaining country keeps individual rationalities given the subgroup formation. These individual rationalities are slightly different from the earlier rationalities. Because, two-country coalitions may affect the third country in such a way that impacts may be significantly different from the earlier single country sequential strategies. To illustrate, Iraq is affected from Turkey-Syria coalition rather than first Turkey's then Syria's strategic unilateral moves. It is noteworthy that Turkey is immune from the Syria-Iraq coalition due to her geographic upstream position. The optimization process is similar to the individual optimization. But this time weights for subgroup members are different from zero (preferably 1). The third country or subgroup countries, regarding the geographic positions in the basin, either gets the return flows and water releases from the upstream or releases them to the downstream countries. The necessary parametric adjustments are considered exogenously for the relevant subsets. The obtained benefits are codified as NEB^*_{TS} , $NEB^*_{I/TS}$, $NEB^*_{T/SI}$, $NEB^*_{SI/T}$, $NEB^*_{TI/S}$, $NEB^*_{S/TI}$.

From a series of optimization results regarding the game theoretic strategies, a set of minimum and maximum attainable benefits for individuals, subgroups, and grand coalition are obtained. From these results, a series of valid ranges of benefits are derived for individuals, subgroups coalition formations, and they are further utilized in the model application section to pursue sensitivity analyses. Equations (7)-(12) are the constraints designed to measure the impacts of individual and subgroup rationality decisions on the overall performance of grand optimization. Among those Equations (7)-(9) are for the least expected benefits of the basin countries from any optimization run. Those minimum values are incrementally and iteratively altered as a lower bound to be able to see their impacts on estimated NEB (i.e. NEB_{TSI}) values. Equations (10)-(12) are used to pursue the similar analyses for the bilateral coalitions. These analyses provide marginal value impacts of lower bound constraints on the objective values. Those values later can be used as a source of least compensation needed to the disadvantaged party for higher NEB .

Data and Assumptions: The ETRBM is built up on an extensive data base and various system assumptions. For the details, please refer the relevant dissertation and published articles (K, 2002, 2009; K-G, 2004, 2010).

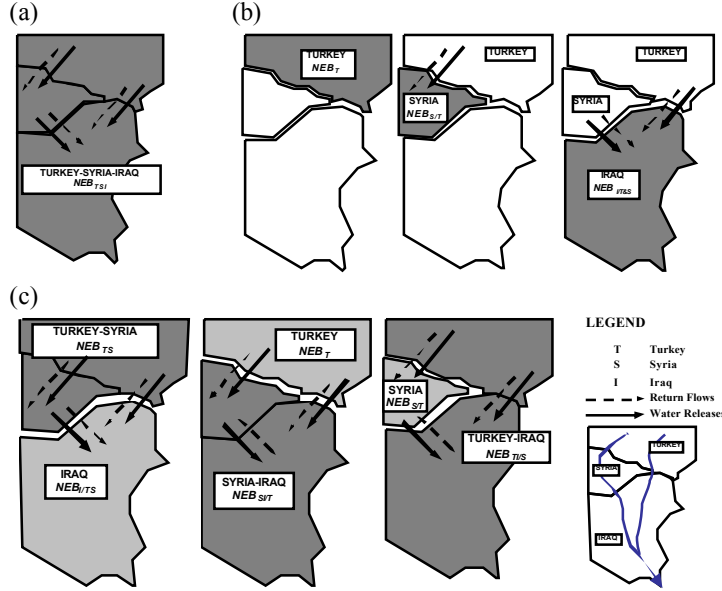


Figure 3. The various country interactions under different configurations of independence and cooperation: (a) grand coalition; (b) individual action; (c) bilateral coalition. (Adopted from Kucukmehmetoglu, 2009).

Maximize Objective Function:

Net Economic Benefit:

$$NEB = \sum_{i \in ag} V_{ag} \cdot \sum_j W_{ji} - \sum_{j, i \in ag} C_{ag} \cdot D_{ji} \cdot W_{ji} + \sum_{i \in ur} V_{ur} \cdot \sum_j W_{ji} - \sum_{j, i \in ur} C_{ur} \cdot D_{ji} \cdot W_{ji} + \sum_{j, l} P_e \cdot E_{jl} \cdot Q_{jl} \quad (1a)$$

equivalently (assuming $WG_T = WG_S = WG_I = 1$)

$$NEB = WG_T \cdot NEB_T + WG_S \cdot NEB_S + WG_I \cdot NEB_I \quad (1b)$$

where:

$$NEB_T = \sum_{i \in ta} V_{ta} \cdot \sum_j W_{ji} - \sum_{j, i \in ta} C_{ta} \cdot D_{ji} \cdot W_{ji} + \sum_{i \in tu} V_{tu} \cdot \sum_j W_{ji} - \sum_{j, i \in tu} C_{tu} \cdot D_{ji} \cdot W_{ji} + \sum_{j \in st, l} P_e \cdot E_{jl} \cdot Q_{jl} \quad (1c)$$

$$NEB_S = \sum_{i \in sa} V_{sa} \cdot \sum_j W_{ji} - \sum_{j, i \in sa} C_{sa} \cdot D_{ji} \cdot W_{ji} + \sum_{i \in su} V_{su} \cdot \sum_j W_{ji} - \sum_{j, i \in su} C_{su} \cdot D_{ji} \cdot W_{ji} + \sum_{j \in ss, l} P_e \cdot E_{jl} \cdot Q_{jl} \quad (1d)$$

$$NEB_I = \sum_{i \in ia} V_{ia} \cdot \sum_j W_{ji} - \sum_{j, i \in ia} C_{ia} \cdot D_{ji} \cdot W_{ji} + \sum_{i \in it} V_{it} \cdot \sum_j W_{ji} - \sum_{j, i \in it} C_{it} \cdot D_{ji} \cdot W_{ji} + \sum_{j \in si, l} P_e \cdot E_{jl} \cdot Q_{jl} \quad (1e)$$

Subject to:

Basic system constraints

$$\sum_j W_{ji} + \sum_l Q_{jl} + EL_j = \sum_i RF_{ij} \cdot (\sum_j W_{ji}) + T_j + \sum_l Q_{jl} \quad \forall j \quad (2)$$

$$\sum_j W_{ji} \leq Max_{ag} \cdot S_i \quad \forall i \in ag \quad (3)$$

$$\sum_j W_{ji} \leq Max_{ur} \cdot S_i \quad \forall i \in ur \quad (4)$$

Pareto Frontier Surface (PFS) generator constraints

$$NEB_T \geq CNEB_T^* \quad (5)$$

$$NEB_S \geq CNEB_S^* \quad (6)$$

Decision Constraints

Individual rationality constraints:

$$NEB_T \geq \min(NEB_{T/S}^*, NEB_{T/SI}^*) = NEB_T^{*min} + incr \quad (7)$$

$$NEB_S \geq \min(NEB_{S/T}^*, NEB_{S/IT}^*) = NEB_S^{*min} + incr \quad (8)$$

$$NEB_I \geq \min(NEB_{IT\&S}^*, NEB_{ITS}^*) = NEB_I^{*min} + incr \quad (9)$$

Subgroup rationality constraints:

$$NEB_T + NEB_S \geq NEB_{TS}^* + incr \quad (10)$$

$$NEB_T + NEB_I \geq NEB_{TI/S}^* + incr \quad (11)$$

$$NEB_S + NEB_I \geq NEB_{SIT}^* + incr \quad (12)$$

Indices

i : demand nodes (1 to 63)

J & l : supply nodes (1 to 45)

ag : set of agricultural demand nodes

ur : set of urban demand nodes

$st(j)$, $ss(j)$, $si(j)$: the supply nodes in Turkey, Syria, and Iraq, respectively

$ta(i)$, $sa(i)$, $ia(i)$: the agricultural demand nodes in Turkey, Syria, and Iraq, respectively

$tu(i)$, $su(i)$, $iu(i)$: the urban demand nodes in Turkey, Syria, and Iraq, respectively

Variables

NEB : total benefit net of transportation costs (\$))

NEB_T , NEB_S , NEB_I : Country NEB for Turkey, Syria, and Iraq

Q_{jl} : inter-nodal flow (node j to node l) (Mm^3)

W_{ji} : water transferred from supply node j to demand node i

Parameters

C_{ag} :	agricultural water transport unit cost	(\$ per Mm^3 -km)
C_{ur} :	urban water transport unit cost	(\$ per Mm^3 -km)
V_{ag} :	agriculture water unit value	(\$ per Mm^3)
V_{ur} :	urban water unit value	(\$ per Mm^3)
C_{ss} :	internodal water transport unit cost	(\$ per Mm^3 -km)
D_{ji} :	distance from supply node j to demand node l	(km)
D_{jl} :	distance from supply node j to supply node l	(km)
P_e :	energy price for electricity	(\$ per MWh)
E_{jl} :	electric generation (consumption) rate for node j dam	(MWh per Mm^3)
Max_{ag} :	maximum agricultural consumption rate	(Mm^3 per ha)
Max_{ur} :	maximum urban consumption rate	(Mm^3 per inhabitant)
EL_j :	reservoir evaporation loss at supply node j	(Mm^3)
RF_{ij} :	return flow rate from demand node i to supply node j	
S_i :	size of demand node i (hectare for agricultural nodes, inhabitants for urban nodes)	
T_j :	tributary inflow at node j	(Mm^3)
WG_T , WG_S , WG_I :	weights (0-1) assigned to Country Turkey, Syria, and Iraq respectively	
$incr$:	externally attributed increments to make sensitivity analyses	

4. MODEL APPLICATIONS

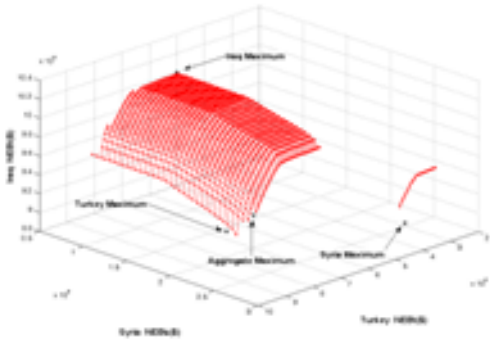
This study is an elaborated and integrated version of K-G (2004) and (2010). The used model takes the scenario in K-G (2010) which is the one generating the most extensive Pareto Frontier Surface (PFS) among the scenarios outlined in earlier version of K-G (2004). The basic parameters are i) the total drainage basin flow (TDF), which is set minimum (59,800 Mm^3); ii) energy price in the basin (\$25Mwh), and iii) upstream countries has marginally

more productive agricultural lands than the downstream countries (productivity multipliers are 1.2, 1.0 and 0.8 for Turkey, Syria and Iraq, respectively).

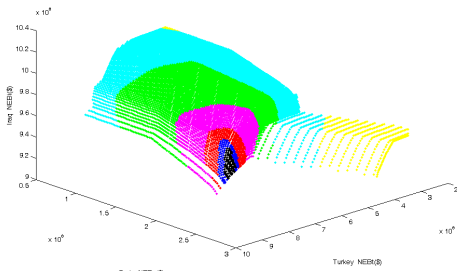
Generating the Pareto Frontier Surface (PFS)

By the repeated maximization of Equation (1b) subject to Equations (2)-(4) and for the incrementally altered lower bound values in Equations (5)-(6), a series of non-dominated points are obtained to generate the Pareto Frontier Surface (PFS). Figures 4a-4c are generated to present the form and characters of the PFS. On the PFS, each point shows a three-country non-dominated single run optimization result where no one can be better off without making others worse. In Figure 4a, on the PFS, there are achievable maximums by the countries and aggregate maximum benefit as in K-G (2010). In Figure 4b, on the same PFS, but this time by denser points, the changes in aggregate net economic befits (sum of the three country net economic benefits) are presented via graduated colors. The darker the color the higher is the

a)



b)



c)

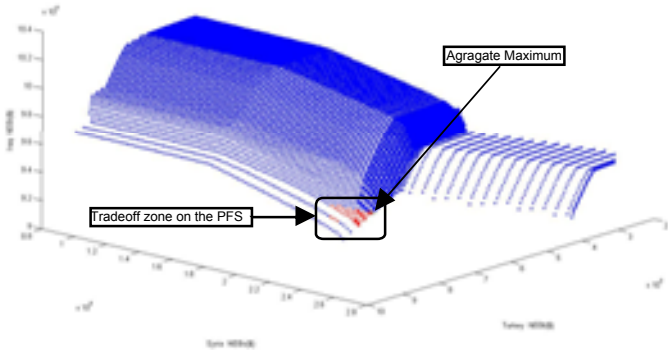


Figure 4. Three-Dimensional PFS: a) Country and aggregate maximum benefits on the PFS (K-G, 2010), b) Changing aggregate benefits on the PFS, and c) Game theory based three-party trade-off region on the PFS

aggregate net economic benefits. The same surface shows that while approaching to the county extremes, the aggregate total country net economic benefits on the PFS fall farther away from the aggregate net economic benefit. Figure 4c presents the valid country benefit zone in red by considering game theory based individual and subgroup the strategies outlined in Figure 3. In the next section, the tradeoffs and associated marginal impact analyses are presented for the area in red in Figure 4c.

Results by Decision Constraints regarding Game Theory Strategies:

Initially, game theory based individual and subgroup rationality behaviors are observed via separate optimization runs. The grand coalition results are obtained by the maximization of Equation (1a) or (1b) subject to Equations (2)-(4). The other individual and subgroup strategy results, which are coded by “*” in Equation (7)-(12), are obtained from separate optimization runs considering the countries’ associated relevant subsets (K-G, 2004). In this process, again mathematically Equation (1b), in which there are Equations (1c)-(1e), is maximized subject to Equations (2)-(4) by considering the individual or subgroup coalition strategies. The obtained results are presented in Table 2.

Table 2 shows that the maximum achievable benefit in the basin is $\$2,096,296 \times 10^3$. It is interesting that Turkey’s minimum economic benefit is achieved in this scenario. If Turkey as an upstream county goes alone, she can achieve higher net economic benefit ($\$904,893 \times 10^3$). This shows that by participating into the grand coalition Turkey loses $\$18,654 \times 10^3$ benefit for the higher grand coalition benefit (NEB_{TST}). This amount roughly shows the quantity of compensation needed for unilaterally behaving Turkey to take part in the grand coalition. Subgroup coalition rationalities may enable Turkey request more than $\$18,654 \times 10^3$. In contrast, if both Syria and Iraq prefer to go alone, both countries attain lower net economic benefits ($\$242,343 \times 10^3$ and $\$923,729 \times 10^3$ respectively) as compared to the benefits in the grand coalition ($\$258,713 \times 10^3$ and $\$951,343 \times 10^3$ respectively). It is clear that being in a grand coalition in the basin is beneficial to the downstream countries. While Turkey’s net economic benefit is decreasing, Syria and Iraq’s net economic benefits increase. Table 2 provides us attainable not only country minimum and maximum benefits, but also subgroup country benefits and their ranges (Figure 4c). Those minimum and maximum benefits in Table 3 are used to determine valid ranges to perform sensitivity analyses. Those ranges are further subdivided into \$1 million incremental values to determine the constraint values in Equations (7)-(12). In those equations, if a constraint value is set to zero, that constraint is externally set to be not binding and neutral one. For each incremental value, a separate

optimization run (maximization of Equation 1b subject to Equations 2-4 and relevant one of the Equations 7-12) is performed and obtained marginal values are summarized in the second column of Table 3 by the computed ranges.

Table 2. Individual, subgroup, and grand coalition benefits from the ETRBM applications to estimate core, (TDF = 59,800 Mm³; \$10³).

Coalitions	Turkey	Syria	Iraq	Bilateral	Total
Individual (T,S,I)	$NEB_T = 904,893^{**}$	$NEB_{ST} = 242,343^{***}$	$NEB_{IT&S} = 923,729^{****}$		$NEB_{T,S,I} = 2,070,965$
Subgroup (TS, I)			$NEB_{ITS} = 940,642^*$	$NEB_{TS} = 1,151,900^*$	$NEB_{TS,I} = 2,092,542$
Subgroup (TI, S)		$NEB_{STI} = 235,166^{**}$		$NEB_{TIS} = 1,833,961^*$	$NEB_{TIS} = 2,069,127$
Subgroup (T, SI)	$NEB_{TSI} = 904,893^{**}$			$NEB_{SIT} = 1,166,072^*$	$NEB_{T,SI} = 2,070,965$
Grand (TSI)	$NEB_{TSI} = 886,239^*$	$NEB_{S/TSI} = 258,713^*$	$NEB_{I/TSI} = 951,343^*$		$NEB_{TSI} = 2,096,296^*$

* $NEB_T^{min} = NEB_T = NEB_{TSI} = 904,893$; ** $NEB_S^{min} = NEB_{STI} = 235,166$; *** $NEB_I^{min} = NEB_{IT&S} = 923,729$.
 * Requires a separate optimization run via the ETRBM adjusted to the forms of coalitions regarding the principles identified in Figure 3.
 * Country net economic benefits obtained in the body of grand coalition.

As can be seen from the ranges of the marginal value impacts of country or country-group constraints in Table 3, the binding constraints are the only Turkey's or Turkey-Syria coalition's constraints defined in Equations (7) and (10). The unbinding Turkey-Iraq coalition constraint can be attributed to the geographic location of Syria between Turkey and Iraq. The Turkey's unilateral impact may reach to -4.2 that every \$1 increase in Turkish net economic benefit results in \$4.2 decrease in grand optimization net economic benefit. Though, there are similar impacts of Turkey-Syria coalition, their ranges are much narrower than Turkey's unilateral move. The reason for that is Turkey-Syria coalition uses the larger potentials of basin resources than Turkey alone, and return flows and water releases to Syria has positive indirect effects on Iraq's benefit.

Table 3. Marginal impact analyses for the constraints derived from game theory application

Source of Marginal Impact	Marginal Value Impact on Grand Coalition Benefits (\$10 ³ NEB_{TOT})		Valid Eq. for Sensitivity Analysis
	Computed Range of Marginal*	Range of the Constraint (Min – Max)	
Unilateral Impacts			
Turkey (NEB_T)	0 – -4.2	886,239 – 904,893	Eq. (7)
Syria (NEB_{ST} or S/STI)	0	235,166 – 258,713	Eq. (8)
Iraq ($NEB_{IT&S}$ or I/TS)	0	923,729 – 951,343	Eq. (9)
Subgroup Impacts			
Turkey-Syria (NEB_{TSI})	0 – -0.76	(904,893+235,166) – (899,531+252,369)	Eq. (10)
Turkey-Iraq (NEB_{TIS})	0	(904,893+923,729) – (896,192+937,769)	Eq. (11)
Syria-Iraq (NEB_{SIT})	0	(235,166+923,729) – (242,343+923,729)	Eq. (12)

* Derived from $dNEB_{TOT}/dNEB_i$ i refers to any country or a group of countries.

Figure 5-8 are prepared only for binding constraints that are Equations (7) and (10). Those binding constraint values and associated marginal impacts, and country and grand optimization benefits are used to prepare the following figures. On the horizontal axis there are the numeric values of constraints (NEB_T^* and NEB_{TS}^*).

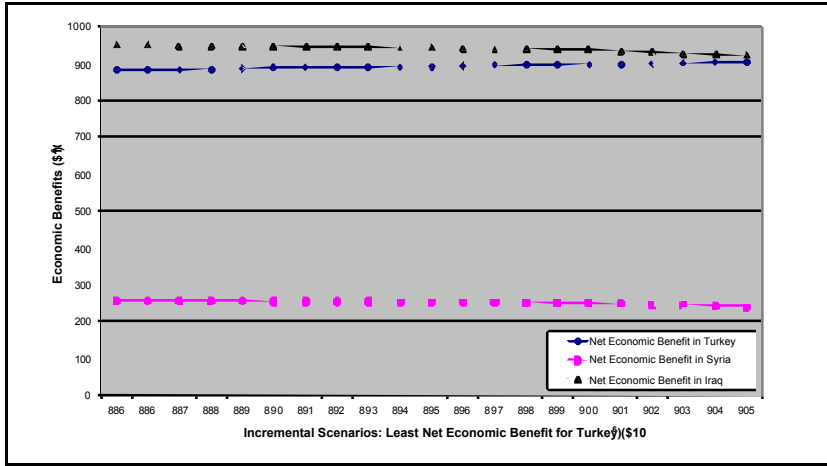


Figure 5. Grand coalition benefits by country (Turkey, Syria, and Iraq) given the NEB_T^*

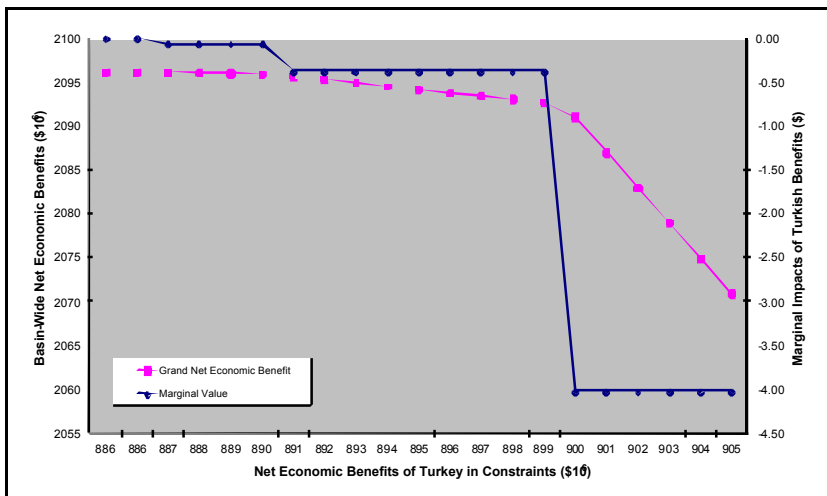


Figure 6. Grand coalition benefits given NEB_T^* and marginal value impacts of NEB_T^* on grand coalition

Figure 5 and 6 is prepared for Turkey’s binding constraint by Equation (7). Figure 5 shows the tradeoff between Turkish versus Syrian and Iraqi net economic benefits in the body of grand optimization. While Turkish net economic benefit is increasing, the grand optimization benefit decreases, and naturally do the components of grand optimization (Syrian and Iraqi benefits). When constraint value is set $NEB_T^* = 886,239 \times 10^3$, Turkey’s net economic benefit constraint is not binding; therefore, its marginal value impact on the grand optimization benefit is zero (Figure 6). That means any lower benefit value constraint of Turkey does not have any effect on the grand optimization benefit, NEB_{TSI} . Figure 6 clarifies this tradeoff in terms of marginal value impacts and changes in the marginal values. The staircase decrease in marginal values is the outcome of discrete choices encountered by the nature of linear programming. Turkey’s maximum impact for each unit \$ of net economic benefit increase to the grand optimization reaches to \$-4.2.

Figures 7 and 8 are prepared for binding Turkey-Syria coalition constraint values used in Equation (10). Figure 7 shows the tradeoff between Turkish-Syrian coalition and Iraqi net

economic benefits in the grand optimization. In Figure 7, while Turkish-Syrian coalition net economic benefit is increasing, grand optimization benefit decreases. When constraint values are set between $NEBS_{TS}^* = \$1,146 \times 10^3$ and $\$1,152 \times 10^3$, those constraints are not binding, therefore, their marginal value impacts on the grand optimization benefit is zero (Figure 8). That means any lower benefit value constraint of Turkey-Syria coalition does not have any effect on the grand optimization benefit, NEB_{TSI} . Figure 8 provides the tradeoff in terms of marginal value impacts and changes in the marginal values. The staircase decrease in marginal values is the outcome of discrete nature of linear programming. Turkey-Syria coalition's impact on to the grand optimization for each unit \$ of net economic benefit increase may maximally reach to \$-0.76.

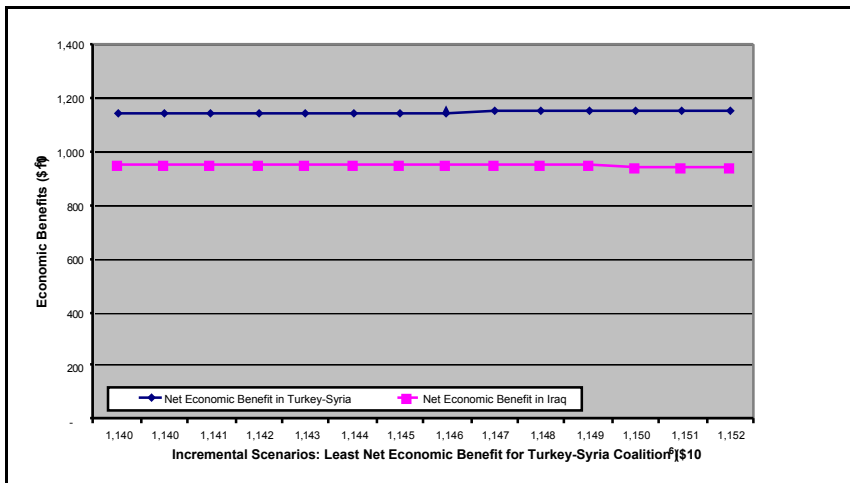


Figure 7. Grand coalition benefits by country and country groups (Turkey-Syria, and Iraq) given the NEB_{TS}^*

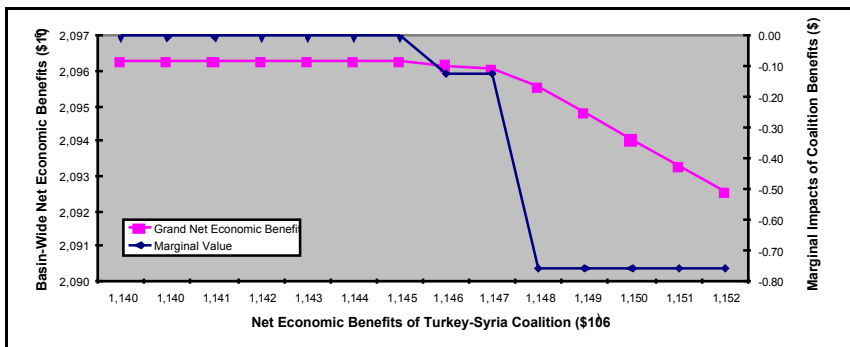


Figure 8. Grand coalition benefits given NEB_{TS}^* and marginal value impacts of NEB_{TS}^* on grand coalition

Table 3 and Figure 5-8 present that Turkey is the critical actor affecting grand optimization. This effect occurs in two ways: i) Turkey is the necessary partner to achieve higher grand optimization benefit; ii) Turkey's partnership requires Turkey's less withdrawal but at least equivalent compensation payments to Turkey from grand optimization partners. Figure 6 and 8 graphically present least compensation payments in marginal values.

It is noteworthy that the grand optimization benefit reaches the grand coalition benefit when none of the constraints are set to be binding (all equal to zero). In other words, grand coalition is a special case of grand optimization scenarios and generates the maximum net economic benefit in the basin.

5. CONCLUSION

This study introduces a composite water resources allocation approach that integrates game theory and Pareto frontier techniques over the case of the Euphrates and Tigris. The proposed approach analyzes the frontier zone and searches an acceptable solution set over the Pareto Frontier Surface via game theory based core constraints in the analyses. *First*, Pareto frontier surface is generated, *second*, the game theory based valid section of PFS is presented as a tradeoff zone, *third*, potential acceptable intervals for the country and subgroup coalitions are used for marginal impacts analyses on grand optimization of basin resources. The obtained marginal values have shown that there is a tradeoff between Turkish and grand optimization benefits. Similar tradeoff exist between Turkish-Syrian coalition and grand optimization benefits, but its impact is not as extensive as the Turkey's unilateral move. Turkey's impact comes from her upstream position in the ETRB, and her approach to grand optimization can be altered via a compensation mechanism. The least necessary compensation amounts can be seen from the marginal values and from the range of changes in Turkey's economic benefits. Marginal value impacts show only tradeoff between country and grand coalition, but, does not allocate extra benefits generated in the grand optimization. In order for that core analyses in K-G (2004, 2009) outline the principles of allocating those additional benefits. Finally, results show that i) game theory provides a determinative backbone for an efficient and effective use of Pareto Frontier Surface, ii) upstream countries have upper hand position due to the geographic context, iii) Turkey is the critical partner needs to be included into any form of coalition in the ETRB.

The prospective studies can be directed to i) collect detailed data to perform actual parametric policy analyses; ii) compensation frameworks do not encounter the secondary affects of country choices, which are the positive and negative local and regional economic-multipliers.

Finally, it is noteworthy to mention that these allocation and compensation framework are valid only for those isolated and competing countries. In reality, countries have other economic, business, and socio-cultural affiliations than the water resources issues. The larger cooperation in the other areas is less likely to have harsh water resources allocation issues. In

practice, countries should consider the advantage of building confidence and cooperation in other areas before solving the water resources. And then the results in this study and many others will guide parties towards better solutions. Geography puts Turkey into a naturally stronger position in the control of both rivers, but this capacity also gives Turkey to have a healthy and close relation with the riparian countries.

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