MULTI-OBJECTIVE PROGRAMMING FOR THE ALLOCATION OF TRANS-BOUNDARY WATER RESOURCES:
The Case of the Euphrates and Tigris

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Abstract. The allocation of water in a multi-country river system necessarily involves conflicting objectives, where increasing water benefits to one country may entail losses to other countries. This paper presents the formulation and application of a multi-objective linear programming model, where each objective represents the benefits to a country from using water for agriculture, urban consumption, and energy production, net of conveyance costs. This model is applied to the Euphrates and Tigris river basin, with the three objective functions representing the net water benefits to the three riparian countries – Turkey, Syria, and Iraq. The model is used to delineate the set of non-inferior solutions (Pareto frontiers), where no individual country benefits can be increased without reducing the benefits of at least another country. These Pareto frontiers, and the underlying water resources allocations, are graphically displayed and analyzed under different scenarios related to river flow, electricity price, and agricultural productivity. The trade-offs between the three benefits are assessed, providing the basis for possible compromises among the three countries.

Keywords: Water Resources, Economic Benefits, Multi-Objective Programming, Pareto Frontier.

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1. INTRODUCTION

There has been an ongoing competition over the control of water resources in the Euphrates and Tigris basin. Increasing population pressures and long-term development expectations have triggered tensions and conflicts among the riparian countries. In particular, Turkey has started implementing an ambitious project, the Southeastern Anatolia Development Project (GAP), to eliminate regional socio-economic disparities by utilizing water resources in the basin, especially for agriculture and electricity production. Due to their upstream geographical positions, the GAP investments by Turkey have been regarded by both Syria and Iraq as threats to their welfare and aspirations.

To analyze these conflicts, Kucukmehmetoglu and Guldmann (K-G) (2004) have developed the Euphrates and Tigris River Basin Model (ETRBM). This model assumes that the basin will be completely developed in the year 2040, and provides optimal allocations of water among the riparian countries under various scenarios. The ETRBM optimizes the use of basin resources without accounting for country power. In reality, each country has a separate objective function, and some countries may have more weight than others, due to their political, economic, or geographical characteristics. An alternative approach is to find water allocations where no one country can be made better off without making some other country worse off, i.e., the Pareto Frontier Surface (PFS). All the points on the PFS represent the set of non-inferior solutions/allocations.

This paper presents a multi-objective programming model generating Pareto frontiers representing the tradeoffs among country net economic benefits, under various scenarios related to 1) annual tributary flow, 2) energy price, and 3) country agricultural productivity. The remainder of the paper is organized as follows. Section 2 consists of a literature review. The modeling methodology is presented in Section 3. Applications are described in Section 4. Section 5 concludes the paper.

2. LITERATURE REVIEW

A first stream of literature involves models based on the spatial price equilibrium framework developed by Samuelson (1952), and on its quadratic programming version later developed by Takayama and Judge (1964). Flinn & Guise (1970) applied this approach to a hypothetical water resources allocation problem. Vaux and Howitt (1984) applied the model to a real-world problem for California water resources in a market context. Booker & Young (1994) considered a similar model for the Colorado River basin within riparian (Arizona, Utah, New Mexico, Colorado, Nevada) and non-riparian (California) states of the US and Mexico. Dinar & Wolf (1994), focusing on the Nile, tested the potential advantage of international water trade among Israel, Egypt, the West Bank, and the Gaza Strip. Finally, Mahan, Horbulyk, and Rowse (2002) developed a model for Southern Alberta to best utilize regional water resources.

A second stream of literature focuses on the allocation of scarce water resources among cooperating or conflicting parties, using game theory methods. Rogers (1969) showed the potential economic benefits of common development strategies in the Ganges basin through a coalition between East-Pakistan and India. When East-Pakistan broke away from Pakistan as an independent state (Bangladesh), Rogers (1993) reformulated the issue in a three-country allocation framework (Nepal, Bangladesh, and India). Dinar & Wolf (1994) listed the most meaningful coalition scenarios among the four parties, and then evaluated the economic benefits obtained under these scenarios. Dufournaud & Harrington (1990) brought a temporal dimension into the game theory framework, considering both the spatial and temporal pattern of costs and benefits from river development. K-G (2004), after building the Euphrates and Tigris River Basin Model (ETRBM), an optimization model, applied cooperative game theory concepts to search for possible coalitions in the Euphrates and Tigris basin.

3. MODELING METHODOLOGY

3.1 OVERVIEW

In order to present the theoretical framework of this research, it is assumed that a river basin encompasses two countries, Country I downstream and Country II upstream. These two countries gain economic benefits, NEB_I and NEB_{II}, from the use of basin water resources for energy, urban, and agricultural purposes.

Consider first the nature of water resources utilization. There are three cases regarding the availability of slack water resources. The *first* one is the ***starting case,*** wherein there is a significant amount of slack (unused) resources and no shortage of water. In Figure 1, point O represents such a case. Potential water resources can be tapped to contribute to the economy of both countries. The second case is the ***improvement case,*** where the countries use the potential resources for their own net economic benefits. In Figure 1, the area OAXB is the set of cases where improvements for both countries may take place. The third case is the ***frontier*** case, where countries use all available resources (no slack). On this frontier, any increase in one country's net economic benefits results in a decrease in the other country's net economic benefits. In Figure 1, the frontier represented by the arc AXB is the set of solutions where no one country can be made better off without making the other worse off, and is called the Pareto Frontier (PF).

In Figure 1, points A and B correspond to the maximum gains achieved by country I and II, respectively, while the other country retains its initial benefits. The obtained PF is not limited to the arc between point A and B, and could extend to points C and D, or even beyond points C and D. Currently, the riparian countries of the Euphrates and Tigris basin, are still in the *improvement* phase. It is assumed that a Pareto Optimal (PO) solution will be reached by the year 2040.

The non-inferior solution set (PF) can be obtained via two different methods: 1) *Weighting method*, in which each country net economic benefit is assigned a weight, and the aggregate weighted benefits are maximized. Using a large number of weights combinations will generate many frontier points (curve PF). 2) *Constraint method*, in which one country net economic benefit is maximized subject to constraining the minimum net economic benefits of the other country. The frontier may vary, depending upon the exogenous parameters. The PF_2 and PF_3 curves in Figure 2 represent changes in system parameters, as compared to PF_1.

Figure 1 Pareto Frontier

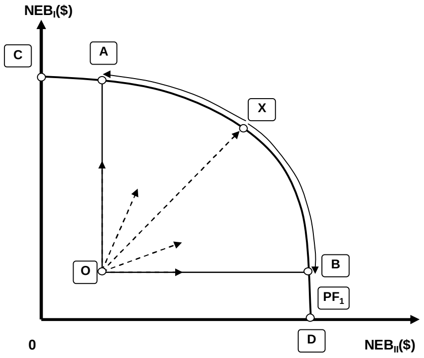
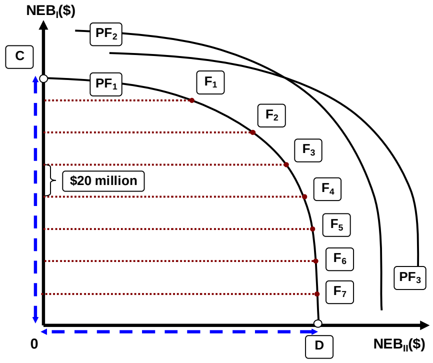


Figure 2 Changes in Pareto Frontier



3.2. BASIC OPTIMIZATION MODEL: THE EUPHRATES AND TIGRIS RIVER BASIN MODEL (ETRBM)

The Euphrates and Tigris rivers follow two separate basins before their confluence near Basra to form the Shatt al-Arab, which flows into the Persian Gulf. The ETRBM closely reflects, in network form, the E-T basin physical structure, incorporating supply reservoirs and centers of water demand throughout the basin. It includes 63 demand (*i*) and 45 supply (*j*) nodes. The supply nodes (either dam or confluence of tributaries) provide water for both urban and agricultural uses, and each demand node is assumed to be served by only one supply node, the most accessible one. There are three inter-basin links, all from the Tigris to the Euphrates, with one already built (the Tharthar Canal). Of the 63 *demand* nodes, 37 are agricultural nodes, and 26 urban nodes. More details on this network are available in K-G (2004).

The ETRBM is a linear programming model designed to maximize the total net benefits of the three riparian countries – Turkey, Syria, and Iraq – subject to resources, water balance, and usage constraints. The net benefits are the gross benefits derived from agricultural, urban, and energy uses of the water in the basin at the various demand nodes, minus the water transportation costs from supply to demand nodes and over inter-basin links. The model accounts for the fundamental trade-off between off-stream water withdrawal for agricultural and urban uses, and on-stream electricity production. The basic model is made of Equations (1) – (4):

Maximize

$$\begin{aligned} NEB = {} & \sum_{i\in ag} V_{ag} \cdot \sum_j W_{ji} - \sum_{j,\, i\in ag} C_{ag} \cdot D_{ji} \cdot W_{ji} + \sum_{i\in ur} V_{ur} \cdot \sum_j W_{ji} \\ & - \sum_{j,\, i\in ur} C_{ur} \cdot D_{ji} \cdot W_{ji} + \sum_{j,l} P_e \cdot E_j \cdot Q_{jl} \\ & - [(Q_{28,14} \cdot C_{ss} \cdot D_{28,14}) + (Q_{31,16} \cdot C_{ss} \cdot D_{31,16}) + (Q_{21,12} \cdot C_{ss} \cdot D_{21,12})] \end{aligned} \qquad (1)$$

Subject to

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

$$Min_{ag} \cdot S_i \le \sum_j W_{ji} \le Max_{ag} \cdot S_i \qquad \forall\ i \in ag \qquad (3)$$

$$Min_{ur} \cdot S_i \le \sum_j W_{ji} \le Max_{ur} \cdot S_i \qquad \forall\ i \in ur \qquad (4)$$

The indices, variables and parameters are defined in the Appendix. The total net economic benefit, NEB, is the sum of (1) the net benefits of water usage to agriculture, $\sum_{i\in agr} V_{ag}.(\sum_j W_{ji}) - \sum_{j,\, i\in agr} C_{ag}.D_{ji}.W_{ji}$, (2) the net benefits of water usage to urban centers $\sum_{i\in urb} V_{ur}.(\sum_j W_{ji}) - \sum_{j,\, i\in urb} C_{ur}.D_{ji}.W_{ji}$, and (3) the total energy benefits $\sum_{j,l} P_e.E_j.Q_{jl}$, net of total inter-basin link costs $(Q_{28,14}.C_{ss}.D_{28,14}) + (Q_{31,16}.C_{ss}.D_{31,16}) + (Q_{21,12}.C_{ss}.D_{21,12})$.

Equation (2) represents the water balance constraint at node *j*. The water inputs to supply node *j* are the tributary inflows T_j, the return flows from the upstream withdrawals, taken as the sum of the products of return flow rates and withdrawals at node *i*, $\sum_i RF_{ij} \cdot (\sum_j W_{ji})$, and water from upstream nodes *l* to *j*, $\sum_l Q_{lj}$. On the other hand, water leaving node *j* is allocated to reservoir evaporation EL_j, water withdrawal for agricultural and urban uses $\sum_i W_{ji}$, and water release to downstream nodes $\sum_l Q_{jl}$.

The parameter S_i is a measure of the size of demand node i (either urban or agriculture), and Min_{ag}, Min_{ur}, Max_{ag}, Max_{ur} represent minimum usage rates – to sustain agricultural and urban activities – and maximum usage rates – to prevent excessive withdrawals, leading constraints (3) and (4).

The data used to calibrate the ETRBM are detailed in K-G (2004).

3.3. PARETO FRONTIER BY THE WEIGHTING METHOD

The ETRBM assumes that every country has equal weight in the process of estimating total net benefits. That solution is of course on the PF. Defining the net economic benefits as NEB_t for Turkey, NEB_s for Syria, and NEB_i for Iraq, we obtain:

$$\text{Maximize} \qquad F = NEB_t + NEB_s + NEB_i \tag{11}$$

where:

$$\begin{aligned} NEB_t = {} & \sum_{i\in ta} V_{ta} \cdot \sum_j W_{ji} - \sum_{j,\, i\in ta} C_{ta} \cdot D_{ji} \cdot W_{ji} \\ & + \sum_{i\in tu} V_{tu} \cdot \sum_j W_{ji} - \sum_{j,\, i\in tu} C_{tu} \cdot D_{ji} \cdot W_{ji} \\ & + \sum_{j\in st,l} P_e \cdot E_j \cdot Q_{jl} \end{aligned} \tag{12}$$

$$\begin{aligned} NEB_s = {} & \sum_{i\in sa} V_{sa} \cdot \sum_j W_{ji} - \sum_{j,\, i\in sa} C_{sa} \cdot D_{ji} \cdot W_{ji} \\ & + \sum_{i\in su} V_{su} \cdot \sum_j W_{ji} - \sum_{j,\, i\in su} C_{su} \cdot D_{ji} \cdot W_{ji} \\ & + \sum_{j\in ss,l} P_e \cdot E_j \cdot Q_{jl} - (Q_{21,12} \cdot C_{ss} \cdot D_{21,12}) \end{aligned} \tag{13}$$

$$\begin{aligned} NEB_i = {} & \sum_{i\in ia} V_{ia} \cdot \sum_j W_{ji} - \sum_{j,\, i\in ia} C_{ia} \cdot D_{ji} \cdot W_{ji} \\ & + \sum_{i\in iu} V_{iu} \cdot \sum_j W_{ji} - \sum_{j,\, i\in iu} C_{iu} \cdot D_{ji} \cdot W_{ji} \\ & + \sum_{j\in si,l} P_e \cdot E_j \cdot Q_{jl} - (Q_{28,14} \cdot C_{ss} \cdot D_{28,14}) - (Q_{31,16} \cdot C_{ss} \cdot D_{31,16}) \end{aligned} \tag{14}$$

st(j) are the supply nodes in Turkey, *ss(j)* the supply nodes in Syria, *si(j)* the supply nodes in Iraq, *ta(i)* the agricultural demand nodes in Turkey, *tu(i)* the urban demand nodes in Turkey, *sa(i)* the agricultural demand nodes in Syria, *su(i)* the urban demand nodes in Syria, *ia(i)* the agricultural demand nodes in Iraq, and *iu(i)* the urban demand nodes in Iraq.

A set of Pareto-admissible (non-inferior) solutions can be obtained by maximizing a weighted ($W_k \geq 0$, at least one $W_k > 0$) sum of the benefits, as illustrated in Equation (15):

$$\text{Maximize} \qquad G = W_t \cdot NEB_t + W_s \cdot NEB_s + W_i \cdot NEB_i \tag{15}$$

The ETRBM can be easily adapted to the weighting method, as the basic model constraints remain the same, and the only reformulation is for its objective function. Selecting a large number of weight combinations, and solving the new model for each of them, will generate a large number of Pareto-admissible solutions, points on the Pareto Frontier Surface (PFS). However, these solutions are not necessarily homogenously distributed throughout the frontier surface, and there is no way of controlling this distribution.

3.4. PARETO FRONTIER BY THE CONSTRAINT METHOD

A Pareto-admissible solution can also be generated by maximizing the benefit of one country, while setting lower bounds for the other two countries' benefits. Assume that the net economic benefits of Iraq (NEB_i) are maximized, and let $CNEBt^*$ and $CNEBs^*$ be the lower bounds on Turkey's and Syria's benefits, respectively. The model to be solved is then:

$$\text{Maximize} \quad NEB_i \tag{16}$$

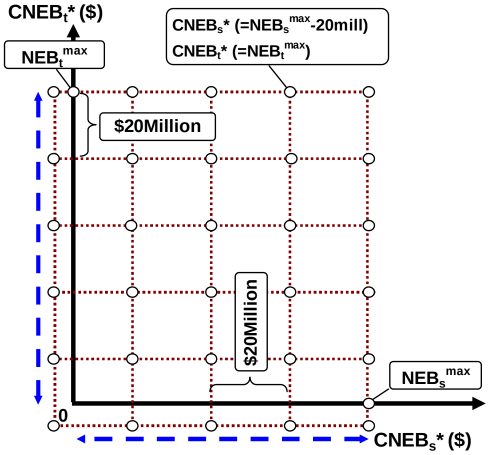
$$\text{Subject to} \quad NEB_t \geq CNEB_t^* \tag{17}$$

$$NEB_s \geq CNEB_s^* \tag{18}$$

As with the weighting method, the ETRBM can be easily adapted to the constraint method by reducing its objective function to the net economic benefits of Iraq (NEB_i) and by adding constraints (17) and (18). The reason for selecting NEB_i as the objective function is that, based on the geography of the basin, Iraq is at the receiving end of the impacts of upstream country decisions. Note that a solution is Pareto-admissible *only if both constraints are binding*. At points where the constraints are binding, the dual values of constraints (17) and (18) measure the impacts of Turkish and Syrian changes in their minimum net economic benefits ($CNEB_t$, $CNEB_s$) on Iraqi net economic benefits (NEB_i), and are necessarily negative. In the following, these dual values are noted $MNEB_{it}$ and $MNEB_{is}$.

Figure 3 illustates the procedure for obtaining constraint values ($CNEB_t^*$ and $CNEB_s^*$) for Equations (17) and (18). Based on the range of benefits derived by using the weighting method, the maximum Turkish benefit $NEB_t^{\max}$ is divided into increments of \$20 million, and $CNEB_t^*$ is set as equal to each of these values. The Syrian range is subdivided in the same way, and $CNEB_s^*$ is progressively increased while solving model (16) – (18). When constraints (17) and (18) become binding, the Pareto frontier starts being generated.

Figure 3: Generation of Grids and Intersection Points for Constraint Method



4. MODEL APPLICATION

4.1. SCENARIOS

Both the *weighting* and *constraint methods* are implemented under 18 different scenarios that combine three different annual flow regimes (**I**:T=59.8, **II**:T=81.9, **III**:T=92.6 Bm^3), two energy prices (**1**:P_e=\$0/MWh, **2**:P_e=\$25/MWh), and three different patterns of agricultural productivity in the three riparian countries (**A**:T=1.2,S=1,I=0.8; **B**:T=1,S=1,I=1; **C**:T=0.8,S=1,I=1.2). These scenarios are coded as presented in Table 1. For instance, **BII2** refers to agricultural productivity **B (**T=S=I=1), flow **II** (T=81.9 Bm^3), and energy **2 (**P_e=\$25/ MWh). These scenarios are based on earlier research reported in K-G (2004).

In order to delineate benefit ranges on the Pareto frontier surfaces (PFS), country net benefits are weighted by a large number of weight combinations. A 3-dimensional grid of weights is created, where weights are altered by small increments and always sum up to 3. Initially, in order to obtain a clear view of the PFS, a large number of weight scenarios were used; however, the obtained PFS points were not homogeneously distributed over the PFS. Therefore, the model was solved over 4 different weight combinations: the *first* one assumes that all countries have equal weights (1 for all countries); the three other combinations involve assigning a weight of 3 to one country, and weights of 0 to the other two countries. Thus, the upper bounds of country net benefits and ranges can be estimated, that will provide the basis for specifying the incremental values (by \$20 million step) to be used in the constraint method.

Table 1: Scenarios

Country Productivity Weights		**I: Minimum Flow** (59.8 Bm3)		**II: Average Flow** (81.9 Bm3)		**III: Maximum Flow** (92.6 Bm3)	
		1: $P_e = \$0$	**2: $P_e = \$25$**	**1: $P_e = \$0$**	**2: $P_e = \$25$**	**1: $P_e = \$0$**	**2: $P_e = \$25$**
A	Turkey 1.2	**AI1**	**AI2**	**AII1**	**AII2**	**AIII1**	**AIII2**
	Syria 1.0						
	Iraq 0.8						
B	Turkey 1.0	**BI1**	**BI2**	**BII1**	**BII2**	**BIII1**	**BIII2**
	Syria 1.0						
	Iraq 1.0						
C	Turkey 0.8	**CI1**	**CI2**	**CII1**	**CII2**	**CIII1**	**CIII2**
	Syria 1.0						
	Iraq 1.2						

4.2. RESULTS

4.2.1. WEIGHTING METHOD

There are several purposes for using this method: (1) to determine the maximum attainable system-wide benefits ($NEB_t+NEB_s+NEB_i$), when assigning the same weight to each country; (2) to obtain the maximum attainable country benefit by using the available resources, completely favoring one country at the expense of the two others; (3) to measure the difference between these two benefits for each country; and (4) to obtain benefits ranges to establish PFS grids

The top left quadrants of Tables 2 and 3 present country net economic benefits with equal and extreme weights, respectively. Table 2 also provides the sum of country benefits. The top right quadrants represent, first, percent changes in benefits resulting from inclusion of energy into the model (the first three columns), and, second, the percent changes in benefits resulting from changes in the annual total tributary flows from benchmark II (the last four columns). The bottom left quadrants present the percent changes in net economic benefits due to changes in agricultural productivity, as compared to benchmark B. The absolute and percent differences between the top left quadrants of Tables 2 and 3 are summarized in Table 4.

The Case of Equal Country Weights

The first three columns of the top right quadrant of Table 2 show that, although every country is affected differently, all countries derive positive net economic benefits from including energy in the optimization ($P_e = \$0/\text{MWh} \rightarrow \$25/\text{MWh}$). The largest economic gain goes to Turkey, due to its high terrain and upstream position in the basin. However, downstream countries also benefit from water use for hydroelectric power production.

The last four columns of the top right quadrant of Table 2 show that increasing annual tributary flows (59.8→81.9→92.6Bm^3) also has positive effects on all counties. When electricity generation is ignored (P_e=\$0/MWh), the downstream country of Iraq is the major beneficiary. On the other hand, when considering energy benefits (P_e=\$25/MWh), Turkey gains significantly because the additional water resources are used for both energy generation and other consumptive uses.

Because the net benefit of Iraq is mainly derived from agriculture, changes in agricultural productivity patterns affect mainly Iraq, which has a downstream location, and a significant amount of agricultural land in the basin; therefore, the productivity impact in Iraq is especially prominent when energy is considered (P_e=\$25/MWh). When energy is ignored (P_e=\$0/MWh), the shift from the higher Turkish agricultural productivity to the higher Iraqi productivity in a seesaw fashion is clearly reflected in the changes in net economic benefits.

Table 2: Net Economic Benefits Using Equal Weights (\$10^6)

	Country	**Minimum Flow**		**Average Flow**		**Maximum Flow**	
		P_e =\$0	**P_e =\$25**	**P_e =\$0**	**P_e =\$25**	**P_e =\$0**	**P_e =\$25**
A	**NEB_t**	412.4	886.2	413.7	1168.2	414.3	1297.9
	NEB_s	167.3	258.7	178.8	302.8	182.1	327.2
	NEB_i	829.7	951.3	997.7	1129.3	1053.3	1200.1
	SUM	**1409.4**	**2096.3**	**1590.1**	**2600.3**	**1649.7**	**2825.2**
B	**NEB_t**	277.7	810.0	328.1	1088.8	328.5	1217.9
	NEB_s	159.6	249.6	166.1	302.0	175.1	326.4
	NEB_i	1101.7	1259.5	1348.7	1527.6	1447.0	1632.5
	SUM	**1539.0**	**2319.0**	**1842.9**	**2918.3**	**1950.5**	**3176.7**
C	**NEB_t**	165.5	788.9	226.6	1067.6	239.4	1199.4
	NEB_s	153.0	251.7	171.8	302.0	175.1	326.4
	NEB_i	1449.2	1544.2	1751.0	1906.0	1858.6	2040.4
	SUM	**1767.7**	**2584.8**	**2149.4**	**3275.6**	**2273.0**	**3566.2**

	Country	**Minimum Flow**		**Average Flow**		**Maximum Flow**	
		P_e =\$0	**P_e =\$25**	**P_e =\$0**	**P_e =\$25**	**P_e =\$0**	**P_e =\$25**
(A-B) %	**ΔNEB_t**	48.5	9.4	26.1	7.3	26.1	6.6
	ΔNEB_s	4.8	3.7	7.6	0.3	4.0	0.3
	ΔNEB_i	-24.7	-24.5	-26.0	-26.1	-27.2	-26.5
	ΔSUM	**-8.4**	**-9.6**	**-13.7**	**-10.9**	**-15.4**	**-11.1**
(C-B) %	**ΔNEB_t**	-40.4	-2.6	-31.0	-1.9	-27.1	-1.5
	ΔNEB_s	-4.1	0.9	3.4	0.0	0.0	0.0
	ΔNEB_i	31.5	22.6	29.8	24.8	28.4	25.0
	ΔSUM	**14.9**	**11.5**	**16.6**	**12.2**	**16.5**	**12.3**

	Country	**Minimum Flow**	**Average Flow**	**Maximum Flow**	**P_e =\$0**		**P_e =\$25**	
		(2-1) %	**(2-1) %**	**(2-1) %**	**(I-II) %**	**(III-II) %**	**(I-II) %**	**(III-II) %**
A	**NEB_t**	114.9	182.4	213.3	-0.3	0.1	-24.1	11.1
	NEB_s	54.7	69.4	79.7	-6.4	1.9	-14.6	8.1
	NEB_i	14.7	13.2	13.9	-16.8	5.6	-15.8	6.3
	SUM	**48.7**	**63.5**	**71.3**	**-11.4**	**3.7**	**-19.4**	**8.7**
B	**NEB_t**	191.7	231.8	270.8	-15.4	0.1	-25.6	11.9
	NEB_s	56.4	81.9	86.4	-3.9	5.4	-17.4	8.1
	NEB_i	14.3	13.3	12.8	-18.3	7.3	-17.6	6.9
	SUM	**50.7**	**58.4**	**62.9**	**-16.5**	**5.8**	**-20.5**	**8.9**
C	**NEB_t**	376.7	371.2	401.1	-27.0	5.6	-26.1	12.3
	NEB_s	64.5	75.8	86.4	-10.9	1.9	-16.7	8.1
	NEB_i	6.6	8.9	9.8	-17.2	6.1	-19.0	7.1
	SUM	**46.2**	**52.4**	**56.9**	**-17.8**	**5.8**	**-21.1**	**8.9**

The Case of Extreme Country Weights

The results derived with the extreme weighting scheme provide upper limits on the Pareto Frontier Surfaces (PFS), to be used as suggested in the two-country grid illustrated in Figure 3. Table 3 presents the maximum attainable country net benefits. These benefits are independent from each other, and therefore cannot be summed up in a meaningful way.

Table 3: Maximum Attainable Net Economic Benefits Using Single Country Extreme Weights (\$$10^6$)

	Country	Minimum Flow		Average Flow		Maximum Flow	
		P_e =\$0	P_e =\$25	P_e =\$0	P_e =\$25	P_e =\$0	P_e =\$25
A	NEB_t	412.4	904.9	413.7	1,173.5	414.3	1,303.2
	NEB_s	207.6	265.0	214.1	315.5	217.3	339.9
	NEB_i	946.2	1,029.1	1,042.8	1,182.6	1,082.9	1,247.6
B	NEB_t	329.3	850.1	330.1	1,118.2	330.4	1,247.7
	NEB_s	200.5	265.0	207.1	315.5	210.3	339.9
	NEB_i	1,232.1	1,314.7	1,410.2	1,545.8	1,484.0	1,648.8
C	NEB_t	253.1	817.3	253.4	1,085.0	253.5	1,214.2
	NEB_s	191.8	265.0	198.4	315.5	201.5	339.9
	NEB_i	1,519.4	1,601.3	1,777.5	1,915.6	1,885.1	2,050.2

	Country	Minimum Flow		Average Flow		Maximum Flow	
		P_e =\$0	P_e =\$25	P_e =\$0	P_e =\$25	P_e =\$0	P_e =\$25
(A-B) %	ΔNEB_t	25.2	6.4	25.3	4.9	25.4	4.5
	ΔNEB_s	3.5	0.0	3.4	0.0	3.3	0.0
	ΔNEB_i	-23.2	-21.7	-26.0	-23.5	-27.0	-24.3
(C-B) %	ΔNEB_t	-23.1	-3.9	-23.2	-3.0	-23.3	-2.7
	ΔNEB_s	-4.3	0.0	-4.2	0.0	-4.2	0.0
	ΔNEB_i	23.3	21.8	26.0	23.9	27.0	24.3

	Country	Minimum Flow	Average Flow	Maximum Flow	P_e =\$0		P_e =\$25	
		(2-1) %	(2-1) %	(2-1) %	(I-II) %	(III-II) %	(I-II) %	(III-II) %
A	NEB_t	119.4	183.7	214.6	-0.3	0.1	-22.9	11.1
	NEB_s	27.6	47.3	56.4	-3.0	1.5	-16.0	7.7
	NEB_i	8.8	13.4	15.2	-9.3	3.8	-13.0	5.5
B	NEB_t	158.2	238.8	277.6	-0.2	0.1	-24.0	11.6
	NEB_s	32.2	52.3	61.6	-3.2	1.5	-16.0	7.7
	NEB_i	6.7	9.6	11.1	-12.6	5.2	-15.0	6.7
C	NEB_t	222.9	328.2	379.0	-0.1	0.1	-24.7	11.9
	NEB_s	38.1	59.0	68.6	-3.3	1.6	-16.0	7.7
	NEB_i	5.4	7.8	8.8	-14.5	6.1	-16.4	7.0

Table 3 provides a picture similar to that of Table 2. Although every country receives positive net economic benefits, a positive energy value (P_e =\$25MWh) contributes the most to Turkey, due to its high country terrains and its high rainfalls (first three columns in the top right quadrant of Table 3). More water leads to larger net benefits for all countries; however, when energy generation is considered (P_e =\$25/MWh), the percent change in *NEB* is more prominent in Turkey than in the other countries; on the other hand, when energy generation is ignored (P_e =\$0/MWh), Iraq is the country prominently benefiting from water availability. However, when the energy price is positive (P_e =\$25/MWh), increased agricultural productivity loses its importance for Turkey, because in Turkey there is a significant tradeoff between energy generation and consumptive uses of water.

Differences Between Equal and Extreme Weight Country Benefits

While the equally-weighted optimization results provide the maximum net economic benefits for the entire basin, the optimization results using extreme weights provide maximum country net economic benefits. Table 4 presents both the absolute and percentage differences between the left top quadrants of Tables 2 and 3.

In absolute value terms, the most extensive difference is for Iraq under scenarios AI1 and BI1, up to \$130Million. The smallest absolute change is for Turkey, when energy generation is ignored (P_e=\$0/MWh) and agricultural productivity favors Turkey (A).

In percentage terms, the largest deviations in benefits are observed under scenarios (AI1,BI1,CI1), that exclude energy (P_e=\$0/MWh) and assume minimum annual total tributary flows (59.8 Bm^3). When energy is included in the model, while utilizing its energy generation potential, Turkey releases significant amounts of water to downstream countries, which seems to significantly satisfy downstream country consumptive demands; therefore, when energy is considered, extreme country weights do not lead to significant deviations from the benefits obtained under equal weights (AI2, BI2, CI2, AII2, BII2, CII2, AIII2, BIII2, CIII2). The higher the energy value, the more water is supplied to downstream countries. Therefore, energy generation potentially alleviates allocation issues among the riparian countries.

Naturally, any increase in the annual water supply (I→II→III) results in lower percentage deviations. In all the scenarios where energy generation is ignored, Syria is the country that derives a significant increase in economic benefits. On the other hand, including energy reduces the percent deviations between the corresponding values in Tables 2 and 3.

Table 4: Difference Between Equally and Extremely Weighted Country Benefits ($\$10^6$)

Productivity Weights	**Country**	**Minimum Flow**				**Average Flow**				**Maximum Flow**			
		P_e=\$0		**P_e=\$25**		**P_e=\$0**		**P_e=\$25**		**P_e=\$0**		**P_e=\$25**	
		Δ	%	Δ	%	Δ	%	Δ	%	Δ	%	Δ	%
A	**NEB_t**	0.0	0.0	18.7	2.1	0.0	0.0	5.4	0.5	0.0	0.0	5.4	0.4
	NEB_s	40.4	24.1	6.3	2.4	35.4	19.8	12.7	4.2	35.2	19.3	12.7	3.9
	NEB_i	116.4	14.0	77.8	8.2	45.2	4.5	53.3	4.7	29.5	2.8	47.4	4.0
B	**NEB_t**	51.6	15.7	40.1	4.7	1.9	0.6	29.5	2.6	1.9	0.6	29.8	2.4
	NEB_s	40.9	20.4	15.5	5.8	41.0	19.8	13.5	4.3	35.2	16.7	13.5	4.0
	NEB_i	130.3	10.6	55.3	4.2	61.5	4.4	18.3	1.2	37.0	2.5	16.4	1.0
C	**NEB_t**	87.6	34.6	28.5	3.5	26.8	10.6	17.4	1.6	14.2	5.6	14.8	1.2
	NEB_s	38.8	20.2	13.3	5.0	26.6	13.4	13.5	4.3	26.4	13.1	13.5	4.0
	NEB_i	70.2	4.6	57.1	3.6	26.5	1.5	9.6	0.5	26.5	1.4	9.8	0.5

4.2.3. CONSTRAINT METHOD

There are two main purposes for using this method: (1) to visualize the PFS over which countries trade-off their benefits; (2) to measure the ranges of country benefits; and (3) to measure the marginal benefits over the PFS.

Following the methodology described in Section 3.4, the net economic benefits of Iraq, NEB_i, are maximized subject to satisfying minimum net benefits for Turkey, $CNEB_t^*$, and Syria, $CNEB_s^*$. After eliminating infeasible solutions or optimal solutions that are not located on the PFS (constraints 17 and/or 18 not binding), the remaining points are used to plot three-dimensional PFS surfaces. The total number of valid solutions on a PFS measures the extent of the trade-offs between Turkey and Syria while maximizing the net economic benefits of Iraq. The numbers of valid solution points are presented in Table 5 for all 18 scenarios.

The 18 scenarios PFSs are plotted on Figure 4, illustrating not only the variations in the sizes of the PFSs but also the shifts resulting from changing parametric assumptions. The top left quadrant presents a three-dimensional plotting of the 18 different PFSs. The right top quadrant presents an aerial view of the Turkish and Syrian net economic benefits points on the

PFSs. The bottom right quadrant presents vertical cuts of the PFSs, showing changes in Iraqi net economic benefits as functions of changes in Turkish economic benefits. Finally, the bottom left quadrant presents similar cuts showing the relationships between Syrian and Iraqi net economic benefits.

Table 5 shows that scenario AI1 has the most extensive PFS. This scenario assumes that Turkish agricultural land is more productive than that of the downstream countries, energy generation is ignored, and the annual flow is at its minimum. This combination generates the most extensive tradeoff among the three riparian countries. The size of the PFS declines with the inclusion of energy production, increasing annual flows, and increasing agricultural productivity in Iraq. However, the last column (maximum annual flow and P_e=\$25/MWh) points to an increase in the PFS, suggesting that, after satisfaction of consumptive uses, energy generation is the basis of country benefit tradeoffs.

Figure 4: Pareto Frontier Surfaces (PFS) Under 18 Scenarios

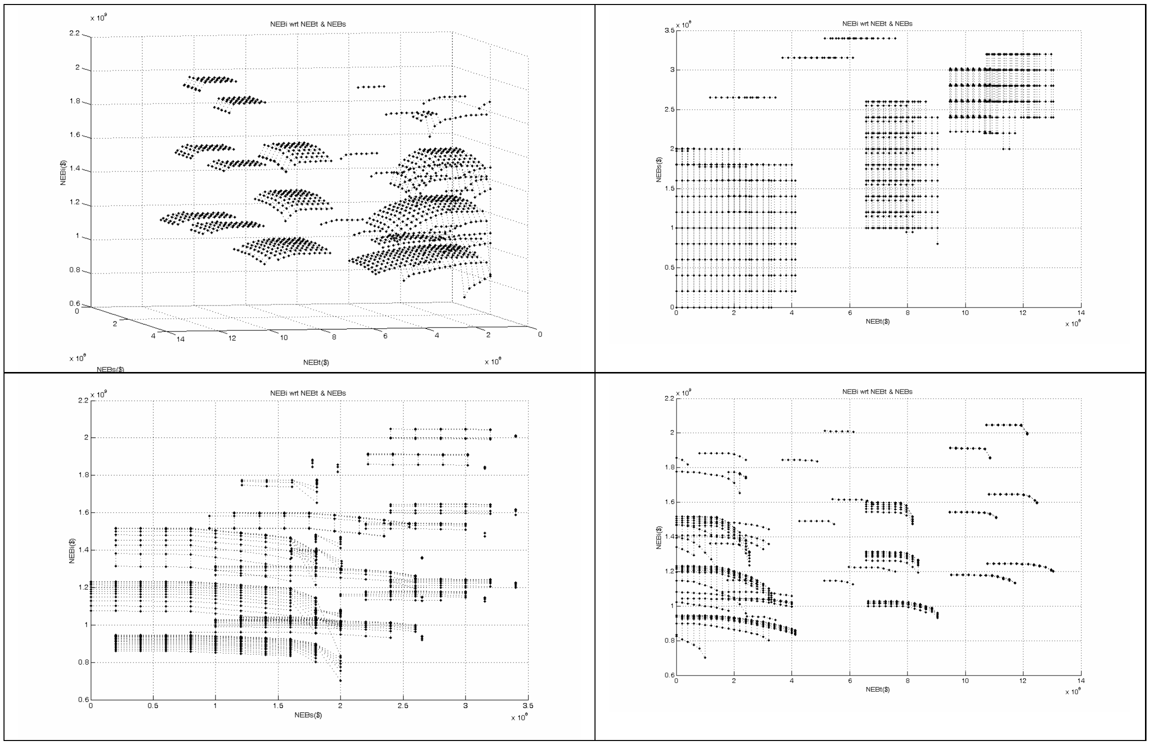
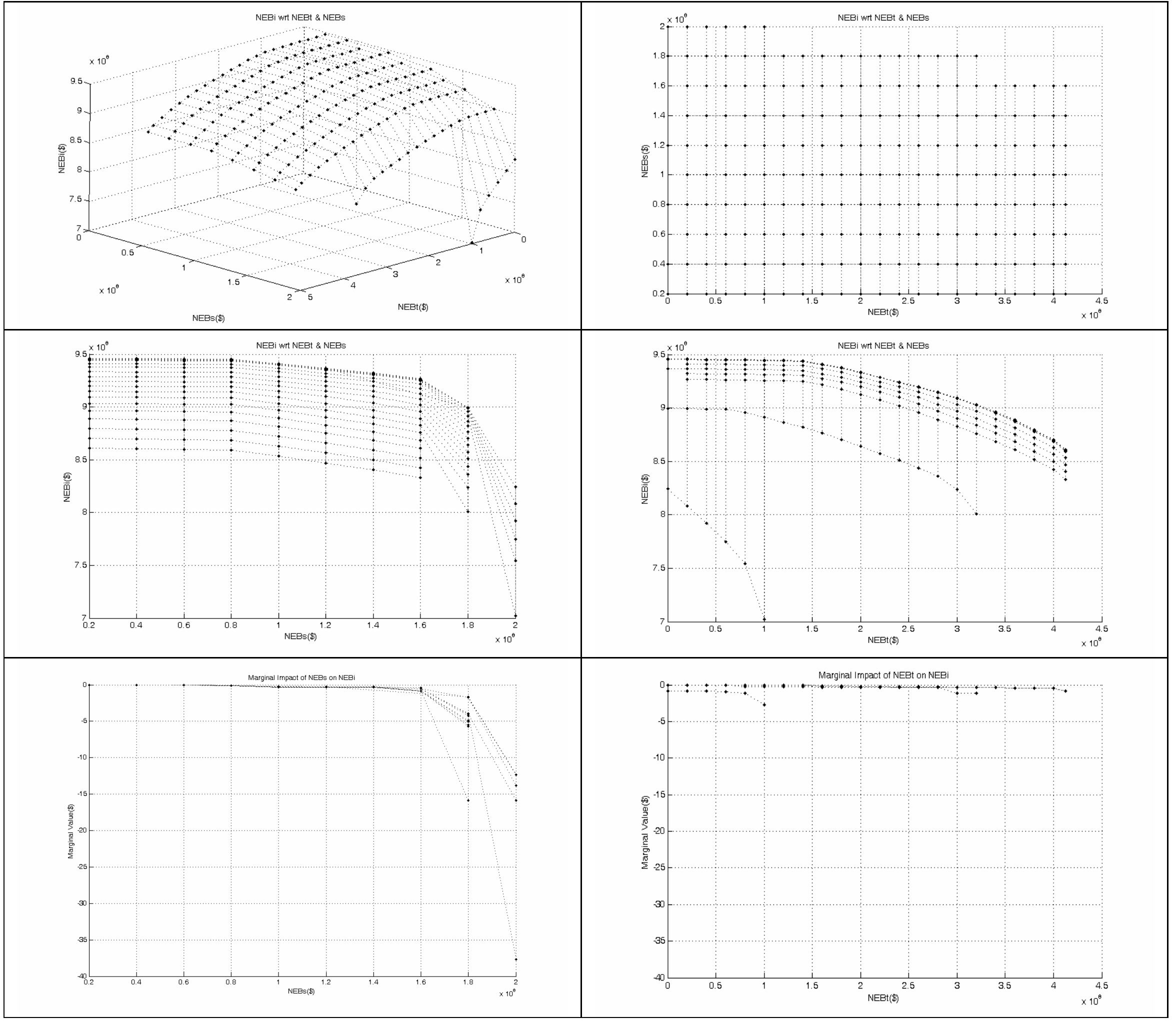


Table 5: Numbers of Valid Solutions on the PFS

	Minimum Flow		Average Flow		Maximum Flow	
	EPR=\$0	**EPR=\$25**	**EPR=\$0**	**EPR=\$25**	**EPR=\$0**	**EPR=\$25**
A	195	122	66	61	25	66
B	175	96	30	46	19	52
C	119	87	24	47	12	45

Figure 5 presents, in the case of scenario AI1, three-dimensional, aerial, and vertical views of the PFS, as well as the marginals of constraints (17) and (18). Scenario AI1 has the most extensive PFS among the 18 scenarios.

Figure 5: PFS and Marginal Values for Scenario AI1



The PFS may be represented, mathematically, by the relationship

$$NEB_i = F(CNEB_t^*, CNEB_s^*)\,. \tag{19}$$

The marginal values are the derivatives:

$$MNEB_{it} = \partial F / \partial CNEB_t^* \tag{20}$$

$$MNEB_{is} = \partial F / \partial CNEB_s^* \tag{21}$$

The bottom quadrants of Figure 5 present the values of $MNEB_{it}$ and $MNEB_{is}$ at each valid point on the PFS. The marginal benefits are, of course, obtained as the dual solutions for constraints (17) and (18). Graphically, the marginal benefits measure the slopes of the PFS.

Table 6 presents country *minimum* and *maximum* net benefits, and the corresponding *ranges,* as obtained by application of the *constraint method.* The ranges are decreasing with increasing water availability in the basin (I→II→III). This decline is most prominent for NEB_i, and implies that the more water is available, the lesser the tradeoffs between Iraq and the other countries. When energy is included, the ranges increase because energy generates economic value, but not necessarily in competition with consumptive uses in downstream countries. The larger ranges for Turkey imply that the upstream country faces more extensive tradeoffs with the other countries.

Table 6: Net Benefits ($\$10^6$)

		Minimum Flow						**Average Flow**						**Maximum Flow**					
		EPR=\$0			**EPR=\$25**			**EPR=\$0**			**EPR=\$25**			**EPR=\$0**			**EPR=\$25**		
		Range	**Min**	**Max**	**Range**	**Min**	**Max**	**Range**	**Min**	**Max**	**Range**	**Min**	**Max**	**Range**	**Min**	**Max**	**Range**	**Min**	**Max**
A	$\mathbf{NEB_t}$	412	-	412	660	243	903	400	-	400	660	511	1,171	400	-	400	706	597	1,303
	$\mathbf{NEB_s}$	180	20	200	185	80	265	80	120	200	115	200	315	20	180	200	100	240	340
	$\mathbf{NEB_i}$	244	702	946	109	920	1,029	70	973	1,043	54	1,127	1,182	39	1,044	1,083	47	1,199	1,247
B	$\mathbf{NEB_t}$	329	-	329	660	177	837	320	-	320	680	426	1,106	320	-	320	707	541	1,248
	$\mathbf{NEB_s}$	200	-	200	165	100	265	40	161	201	95	220	315	20	180	200	100	240	340
	$\mathbf{NEB_i}$	397	835	1,232	186	1,129	1,315	116	1,294	1,410	72	1,473	1,545	73	1,410	1,484	59	1,589	1,648
C	$\mathbf{NEB_t}$	253	-	253	701	117	817	240	-	240	718	367	1,085	240	-	240	701	513	1,214
	$\mathbf{NEB_s}$	160	20	180	170	95	265	60	121	181	94	222	315	20	178	198	100	240	340
	$\mathbf{NEB_i}$	303	1,216	1,519	244	1,357	1,601	124	1,652	1,776	80	1,835	1,915	66	1,819	1,885	56	1,993	2,049

Every point on the PFS is associated to marginal Iraqi net economic benefits resulting from changes in both Turkish and Syrian net economic benefits. Table 7 presents the extreme values of the marginal benefits of Iraq with respect to the minimum benefits of Turkey and Syria. On the PFS, all marginal values are negative. They measure the decrease in Iraq's net benefits resulting from a \$1 increase in $CNEB_t^*$ and $CNEB_s^*$. The greater the absolute value of

Table 7: Ranges of Marginal Values (\$)

		Minimum Flow						**Average Flow**						**Maximum Flow**					
		EPR=\$0			**EPR=\$25**			**EPR=\$0**			**EPR=\$25**			**EPR=\$0**			**EPR=\$25**		
		Range	**Min**	**Max**	**Range**	**Min**	**Max**	**Range**	**Min**	**Max**	**Range**	**Min**	**Max**	**Range**	**Min**	**Max**	**Range**	**Min**	**Max**
A	$\mathbf{MNEB_{it}}$	2.67	-2.68	-0.01	4.83	-4.84	-0.01	0.46	-0.47	-0.01	1.65	-1.66	-0.01	0.87	-0.88	-0.01	1.65	-1.66	-0.01
	$\mathbf{MNEB_{is}}$	37.66	-37.67	-0.01	400.48	-400.49	-0.01	6.54	-6.55	-0.01	372.20	-372.21	-0.01	10.42	-10.51	-0.09	651.28	-651.32	-0.04
B	$\mathbf{MNEB_{it}}$	8.30	-8.31	-0.01	1.82	-1.84	-0.02	1.40	-1.41	-0.01	1.17	-1.19	-0.02	1.47	-1.48	-0.01	6.83	-6.84	-0.01
	$\mathbf{MNEB_{is}}$	68.31	-68.33	-0.02	1113.65	-1113.67	-0.02	19.40	-19.41	-0.01	922.27	-922.28	-0.01	19.18	-19.36	-0.18	859.96	-859.97	-0.01
C	$\mathbf{MNEB_{it}}$	8.90	-8.91	-0.01	5.63	-5.66	-0.03	4.05	-4.07	-0.02	4.58	-4.61	-0.03	1.52	-1.54	-0.02	4.60	-4.61	-0.01
	$\mathbf{MNEB_{is}}$	47.77	-47.79	-0.02	1701.61	-1701.63	-0.02	54.55	-54.56	-0.01	1365.28	-1365.29	-0.01	20.37	-20.65	-0.28	1229.34	-1229.35	-0.01

the marginal benefits, the larger the impact. Scenario CI2 is characterized by the largest impact on NEB_i : $MNEB_{is}$= \$1702 as a result of a \$1 increase in $CNEB_s$ (Syria). Turkey's impact on Iraq is much smaller ($MNEB_{it}$=\$8.92).

Tables 8 and 9 present minima, maxima, and ranges of water allocations associated to the PFS under the 18 scenarios. Table 8 shows that the ranges for urban uses are relatively small as compared to those for agricultural uses, because of limited size and high economic return. Increases in annual flows lead to increases in agricultural consumptions. Table 9 presents similar data total water withdrawal by country. When energy generation is ignored (P_e=\$0/MWh), increasing water availability decreases the ranges of water consumptions for both Turkey and Iraq. When energy generation is included (P_e=\$25/MWh), increasing water supply does not lead to significant changes in the water consumption ranges of both Turkey and Syria. However, Iraq's water consumption range is significantly reduced, implying that the amount of water withdrawn satisfies almost all feasible consumptive uses in Iraq.

Table 8: Ranges of Water Withdrawals by Use (10^3 Mm^3)

		Minimum Flow						**Average Flow**						**Maximum Flow**					
		EPR=\$0			**EPR=\$25**			**EPR=\$0**			**EPR=\$25**			**EPR=\$0**			**EPR=\$25**		
		Range	**Min**	**Max**	**Range**	**Min**	**Max**	**Range**	**Min**	**Max**	**Range**	**Min**	**Max**	**Range**	**Min**	**Max**	**Range**	**Min**	**Max**
A	$\mathbf{WT_U}$	1.91	6.83	8.75	3.24	5.50	8.75	1.01	7.74	8.75	0.94	7.81	8.75	0.89	7.85	8.75	1.10	7.65	8.75
	$\mathbf{WT_A}$	2.71	56.74	59.45	2.97	55.44	58.41	4.62	84.90	89.51	13.51	71.65	85.16	4.61	96.83	101.45	14.07	80.67	94.73
B	$\mathbf{WT_U}$	2.06	6.69	8.75	2.00	4.32	6.32	0.89	7.85	8.75	1.10	5.22	6.32	0.93	7.82	8.75	2.30	5.12	7.42
	$\mathbf{WT_A}$	2.81	56.74	59.56	1.89	56.82	58.72	4.63	84.88	89.51	13.20	74.54	87.75	4.63	96.88	101.51	15.82	81.04	96.86
C	$\mathbf{WT_U}$	1.91	4.40	6.32	1.89	4.42	6.32	0.66	8.09	8.75	1.21	5.10	6.32	0.90	7.85	8.75	2.19	5.22	7.42
	$\mathbf{WT_A}$	2.41	57.40	59.80	1.99	57.00	59.00	3.79	84.89	88.68	13.53	73.78	87.30	3.56	96.75	100.31	15.08	81.04	96.12

Table 9: Ranges of Water Withdrawals by Country (10^3 Mm^3)

		Minimum Flow						**Average Flow**						**Maximum Flow**					
		EPR=\$0			**EPR=\$25**			**EPR=\$0**			**EPR=\$25**			**EPR=\$0**			**EPR=\$25**		
		Range	**Min**	**Max**	**Range**	**Min**	**Max**	**Range**	**Min**	**Max**	**Range**	**Min**	**Max**	**Range**	**Min**	**Max**	**Range**	**Min**	**Max**
A	$\mathbf{WT_t}$	22.12	-	22.12	13.22	0.08	13.30	15.90	5.75	21.65	13.48	0.30	13.77	10.08	11.38	21.46	13.97	0.27	14.24
	$\mathbf{WT_s}$	8.10	0.14	8.24	8.73	0.01	8.74	5.44	2.80	8.23	8.56	0.61	9.17	1.00	7.39	8.39	8.52	0.86	9.38
	$\mathbf{WT_i}$	26.22	37.62	63.84	19.21	43.31	62.52	11.78	68.38	80.16	5.57	72.09	77.66	6.54	80.34	86.88	7.41	79.45	86.86
B	$\mathbf{WT_t}$	22.69	-	22.69	11.21	0.04	11.24	14.66	5.83	20.48	11.12	0.25	11.37	10.09	11.35	21.44	11.84	0.30	12.14
	$\mathbf{WT_s}$	8.24	-	8.24	8.72	0.02	8.74	3.09	5.19	8.28	8.50	0.67	9.17	1.24	7.39	8.63	8.70	0.68	9.38
	$\mathbf{WT_i}$	26.75	37.12	63.87	16.88	44.68	61.55	10.64	69.50	80.13	4.88	73.33	78.21	6.70	80.19	86.89	5.11	81.47	86.58
C	$\mathbf{WT_t}$	16.08	-	16.08	9.60	0.03	9.63	11.66	6.02	17.68	9.77	0.27	10.03	6.82	10.91	17.73	9.38	0.24	9.62
	$\mathbf{WT_s}$	7.24	0.14	7.39	8.72	0.01	8.74	4.60	2.85	7.44	8.55	0.62	9.17	1.32	7.24	8.56	8.74	0.64	9.38
	$\mathbf{WT_i}$	19.04	43.03	62.07	15.10	46.52	61.63	7.78	72.30	80.09	4.01	74.20	78.20	4.11	82.77	86.89	4.56	82.07	86.63

5. CONCLUSION

The countries of the Euphrates and Tigris basin have implicit and explicit powers derived from their geographical positions, socio-economic characteristics, military power, internal affairs, and international affiliations. These powers may be implicitly (or explicitly) considered in the process of negotiations for water resources allocation. In a multi-objective programming setting, these weights provide net economic benefit points on the associated Pareto Frontier Surface (PFS), where none of the countries can be made better-off without making the others worse-off. The PFS is generated with the constraint method, using the best available data.

Obtaining the PFS enables the negotiating parties to understand: 1) at the macro scale, how much tradeoff takes place among the countries, and their marginal impacts on each others; 2) at the micro scale, the detailed solutions for all the optimization variables of the ETRBM (e.g., how much water needs to be withdrawn, how much water needs to be released etc.). Once a PFS is obtained, any allocation or reallocation decision or agreement can be easily located on the associated PFS and can be easily evaluated. With regard to the scenarios analyzed with the constraint method, it has been observed that: (1) including energy production reduces the size of the PFS; (2) the more water in the basin, the smaller the trade-off surface, i.e., the smaller the extent of the PFS.

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APPENDIX

Indices

i:	demand nodes (1 to 63)
j & l:	supply nodes (1 to 45)
agr:	set of agricultural demand nodes
urb:	set of urban demand nodes

Variables

NEB:	total benefit net of transportation costs	(\$)
NEB_t:	net economic benefit of Turkey	(\$)
NEB_s:	net economic benefit of Syria	(\$)
NEB_i:	net economic benefit of Iraq	(\$)
Q_{jl}:	inter-nodal flow (node j to node l)	(Mm^3)
$Q_{21,12}$:	total water transfer from Turkey to Syria through link 21 to 12	(Mm^3)
$Q_{28,14}$:	total water transfer from Turkey to Iraq through link 28 to 14	(Mm^3)
$Q_{31,16}$:	total water transfer from Turkey to Iraq through link 31 to 16	(Mm^3)
W_{ji}:	water transferred from supply node j to demand node i	(Mm^3)

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_{ii}:	distance from supply node j to demand node i	(km)
D_{jl}:	distance from supply node j to supply node l	(km)
P_e:	energy price for electricity	(\$ per MWh)
E_j:	electric generation rate for node j dam	(MWh per Mm^3)
Min_{ag} :	minimum agricultural consumption rate	(Mm^3 per ha)
Max_{ag} :	maximum agricultural consumption rate	(Mm^3 per ha)
Min_{ur} :	minimum urban consumption rate	(Mm^3 per inhabitant)
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)