# TRANSBOUNDARY WATER RESOURCES ALLOCATION UNDER VARIOUS PARAMETRIC CONDITIONS: THE CASE OF THE EUPHRATES & TIGRIS RIVER BASIN

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**Abstract**

The literature on transboundary water resources allocation modeling is still short on encompassing and analyzing complex geographic multiparty nature of basins. This study elaborates the Inter Temporal Euphrates and Tigris River Basin Model (ITETRBM), which is a linear programming based transboundary water resources allocation model maximizing net economic benefit from allocation of scarce water resources to energy generation, urban, and agricultural uses. The elaborations can be categorized in two directions: *First*, agricultural and urban demand nodes are spatially identified with their relative elevations and distances to water resources supplies (dams, reservoirs, and lakes). Digital elevation model (DEM) database are intensely processed in geographic information system (GIS) environment. *Second*, the agricultural irrigable lands are restructured into a pixel based decision making units (DMUs) in order to be able to see the spatial extent of optimally irrigated land, and then optimization program is converted from linear programming (LP) to a mixed integer programming (MIP). The model applications are designed to cover a series of sensitivity analyses encompassing the various transboundary management, energy and agricultural use value, and transportation cost scenarios over the optimal uses of the Euphrates and Tigris Basin (ETRB) resources. The model results are visually presented via GIS in order to show the transboundary upstream and downstream spatial impacts of these selected parameters. The findings are i) system parameters significantly alter the spatial extent of water resources allocation in the ETRB, and ii) the magnitudes of the parameters also explains the tradeoffs between agriculture and energy sectors as much as upstream and downstream water uses of countries.

**Keywords:** Transboundary Water Resources, The Euphrates and the Tigris Rivers, Mixed Integer Programming, Basin Management, Agriculture, Irrigation.

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## 1. INTRODUCTION

For the 261 transboundary surface water resources basins in the world (Dinar, 2007), one of the main dilemma is upstream-downstream resources allocation among multiple parties. In the Middle East, the Nile, the Jordan, the Euphrates and the Tigris rivers are the main sources of water in the region and so the reasons for various levels of conflict and cooperation. There are similar cases in various parts of the world such as the Ganges in the South East Asia, the Colorado and the Colombia rivers in America, the Syr Darya in the Central Asia, the Rhine and the Danube rivers in Europe, etc.

Settlements evolutions are quite sensitive to the availability of water resources and any change in the main pattern carries significant risk for the sustainability of cities, and even countries. On the one hand, there are explicit or implicit pressures on upstream countries not to develop their water resource infrastructures, which would decrease water release to downstream countries; and on the other hand, there are also increasing needs for availability of water holding capacities to overcome inter-temporal precipitation fluctuations. The global climatic change pushes basin countries to handle the precipitation pattern fluctuation drawbacks in coalition rather than competition.

In the second half of the 20$^{th}$ Century, on the Ottoman geography, newly emerged states – Turkey, Syria, and Iraq – have shown various aspirations to develop their own natural resources especially on the Euphrates and the Tigris rivers. The downstream countries Syria and Iraq benefited from water resources in the Euphrates and the Tigris Rivers Basins (ETRB) together with Turkey especially after 1970s. During the reservoir filling periods of Keban and Atatürk Dams in Turkey, the downstream countries have shown their dissidence for temporarily decreasing river flows. Quite recently, before 'Arab Spring,' Turkey and Syria have come to a high level of cooperation in a dam construction at the downstream of the Orontes River, which could be a base for further coalition in developing the regional resources.

This study aims at improving the Euphrates and Tigris River Basin Model (ETRBM) in describing and database perspective through a series of sensitivity analyses in order to measure the spatial change impacts in the selected parameters. The model results are presented visually in GIS environment with their limitations.

## 2. LITERATURE

The transboundary water resources allocation literature on modeling can be grouped in two categories: The first category is on *optimization* aiming at efficient allocation of scarce water resources, and the second category is on the *strategic aspects of allocation* via game theory concepts. Flinn & Guise (1970), Vaux & Howitt (1984), Booker & Young (1994) and Mahan et al. (2002) are examples of water resources allocation studies via optimization models. Rogers (1969, 1993), Dinar & Wolf (1994), Kucukmehmetoglu & Guldmann (2004, 2010), Kucukmehmetoglu (2009, 2012), Kucukmehmetoglu et al. (2010), Wu & Whittington (2006), Eleftheriadou & Mylopoulos (2008), and Teasley & McKinney (2011) are examples of both optimization and game theoretic approaches to transboundary water resources allocations.

Since the development of the ETRBM (Kucukmehmetoglu, 2002), there have been a series of sequential studies elaborating this basic model. Successive improvements can be described as: i) application of cooperative game theory (Kucukmehmetoglu & Guldmann, 2004), ii) incorporation of time dimension for an inter-temporal allocation of resources (Kucukmehmetoglu, 2009), iii) application of Pareto Frontier concept to determine tradeoffs among the trilateral parties (Kucukmehmetoglu & Guldmann, 2010) and integration of game theoretic concepts to narrow down the solution sets (Kucukmehmetoglu, 2012), and finally iv) utilization of fuzzy logic concept in allocating benefits of coalition among parties in highly political environments (Kucukmehmetoglu et al., 2010). In this study, elaborations are i) on modeling structure in which linear programming (LP) model is converted into a mixed integer programming (MIP),

and ii) on database structure in which the content is extended by means of GIS technology via satellite images and DEM database at 90 m resolution for the ETRB.

## 3. MODEL

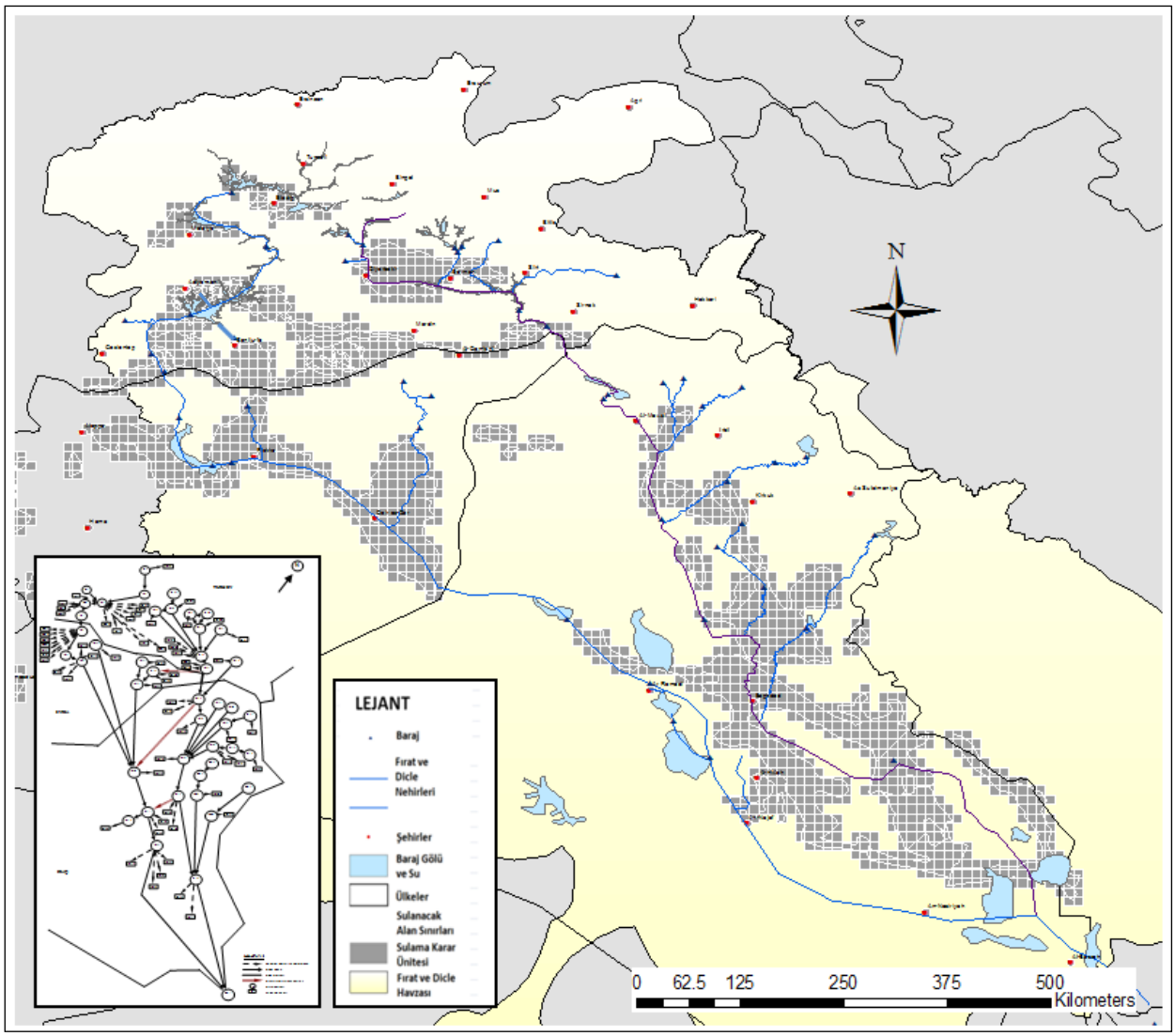
As the longest river in the Middle East, the Euphrates River is heavily fed from the precipitations in Turkey (89%). It then flows into Syria, and subsequently to Iraq. Syria contributes the remaining 11%, whereas Iraq does not have any contribution. Similarly, the Tigris River emerges in Turkey with more than half of its flow (51%). It constitutes a 32 km border line between Turkey and Syria and then enters into Iraq, where it receives significant amount of water (39%) from the eastern part of Iraq. The remaining 10% of the Tigris flow originates from Iran (Kaya, 2009). After confluence of the Euphrates and the Tigris at Shatt Al-Arab, the average annual flow of the unified rivers is around 81.9 $Bm^3$ with significant annual variations (Kolars 1994).

The first version of the ETRBM is developed by Kucukmehmetoglu (2002) in his Ph. D. dissertation and since then it is converted into an inter-temporal model (Kucukmehmetoglu, 2009) enabling wide variety of policy and sensitivity analyses for the structure and nature of the combined basin. In this study, the model details and structure are improved significantly along two directions. Instead of earlier aggregate schematic agricultural demand nodes, first irrigable agricultural lands are spatially identified and integrated into the model with their exact coordinates and elevations on DEM database. All irrigable agricultural lands are subdivided into 10x10 km decision making units (DMUs) according to unique *distance* and *elevation* difference to nearby reservoirs. These distance and elevation information enable the model to differentiate between *gravity* and *pumped* flows. In the model, only gravity flows are considered with the distance to reservoirs, but pumped flows require additional pumping costs, which are important component in any irrigation feasibility study. In other words, while releasing water from dams, model generates energy benefits but while pumping the water to higher lands, model consumes energy for water conveyance. In the same way, all urban centers are also considered as DMUs with their distance and elevation differences to the reservoirs. The 37 agricultural demand nodes identified in Kucukmehmetoglu (2002) are converted into the 1463 DMUs (Figure 1) covering more than 8 million ha irrigable agricultural land in and near the ETRB. The *second* direction is the conversion of the ITETRBM from a linear programming (LP) base into a mixed integer programming (MIP) base. By the help of GIS environment, the MIP results are visually presented and differentiated as irrigated and not irrigated agricultural land DMUs. The new ITETRBM network and mathematical structure are presented in the next section.

### 3.1. Network Structure of the ITETRBM

The updated ITETRBM consists of 46 demand ($i$) and 1499 (maximum 10x10 km size) supply ($j$) nodes, and 3 inter-basin links. The total number of demand nodes, especially agricultural ones, is significantly altered as compared to Kucukmehmetoglu (2002). The total number of agricultural demand nodes is increased from 37 to 1463, and the number of urban demand nodes from 26 to 36 (Figure 1). The inter-basin links are identified with their supply node codes and directions as $j=28 \rightarrow j=14$ and $j=31 \rightarrow j=16$ in Iraq, and $j=21 \rightarrow j=12$ from Turkey to Syria. Among the links, which are from the Tigris to the Euphrates, the one before *Shatt Al-Arab, Thartar Canal*, has already built by Iraq, but the remaining two mentioned by Bilen (1994) still exist only in the literature. Among 1463 agricultural demand nodes, 377, 354, and 732 are assigned to Turkey, Syria, and Iraq, and covers 1.99, 2.03, 4.36 million ha irrigable agricultural land, respectively. For the urban demand nodes, 18, 8, and 10 are the numbers of urban demand nodes in Turkey, Syria, and Iraq, respectively. In the same order, the country allocations of the supply nodes representing water reservoirs are 16, 7, and 23. The supply node $j=45$ represents the *Persian Gulf*. An additional supply node (as compared to the 2002 model) is designed for the lower end of Urfa Tunnel in Turkey, without any reservoir capacity but a power plant to generate energy from a 50 m head loss of water from *Atatürk Dam*. The initial version of ETRBM was based on single period ($t$) optimization,

which was converted into two-period inter-temporal one and called the ITETRBM by Kucukmehmetoglu (2009), however, the current version of the model is based on monthly 12 periods.




The network diagram is from Kucukmehmetoglu (2002: 96).
Figure 1 – Geographic extent and modeling structure of the ITETRBM

### 3.2. Mathematical Structure of the ITETRBM

The mathematical version of the ITETRBM has a similar structure to Kucukmehmetoglu (2002, 2009); however, there are several adjustments to work with the nature of the new database and the aim of the study requiring binary (0 and 1) decision variables. In the mathematical form of the model, the major differences are typed in italic after comparison to the earlier versions.

While maximizing the objective function (Eq. 1) subject to constraints (Eqs. 2-9), the model encounters i) urban and agricultural use values by considering their water conveyance costs, ii) energy generations via release of water from upstream to downstream dams, and iii) water delivery costs for the water conveyed through inter-basin links. The conveyance costs in details are further subdivided into *gravity* and *pumping* cost components, which were not considered in the earlier studies of Kucukmehmetoglu and his coauthors (Kucukmehmetoglu & Guldmann, 2004, 2010; Kucukmehmetoglu, 2002, 2009, 2012; Kucukmehmetoglu

et al., 2010). The constrains of the model (Eqs. 2-9) can be listed as i) continuity equation, ii) minimum-maximum withdrawal constraints, iii) reservoir capacity constraint, iv) withdrawal total equation, and v) binary decision constraints. The details of those equations are further explained in the following section.

***Maximize:***

Objective Function:

$$\begin{aligned} NEB = \sum_t \{ & \sum_{i \in ag} V_{ag} \cdot \sum_j W_{jit} && \text{(agricultural benefit)} \\ & - \sum_{j,\, i \in ag} C_{ag} \cdot D_{ji} \cdot W_{jit} && \textit{(agricultural distance cost)} \\ & - \sum_{j,\, i \in ag} P_e \cdot ENP \cdot H_{ji} \cdot W_{jit} && \textit{(agricultural pumping cost)} \\ & + \sum_{i \in ur} V_{ur} \cdot \sum_j W_{jit} && \text{(urban benefit)} \\ & - \sum_{j,\, i \in ur} C_{ur} \cdot D_{ji} \cdot W_{jit} && \textit{(urban distance cost)} \\ & - \sum_{j,\, i \in ur} P_e \cdot ENP \cdot H_{ji} \cdot W_{jit} && \textit{(urban pumping cost)} \\ & + \sum_{j,l} P_e \cdot END \cdot DH_j \cdot Q_{jlt} && \text{(energy generation from the reservoirs)} \\ & - [(Q_{28,14,t} \cdot C_{ss} \cdot L_{28,14}) + (Q_{31,16,t} \cdot C_{ss} \cdot L_{31,16}) + (Q_{21,12,t} \cdot C_{ss} \cdot L_{21,12})]\} && \text{(link transport cost)} \end{aligned} \quad (1)$$

**Subject to:**

Constraints:

Continuity equation

$$\sum_i W_{jit} + \sum_l Q_{jlt} + EL_{jt} + RS_{jt} = \sum_i RF_{ij} \cdot (\sum_j W_{jit}) + T_{jt} + \sum_l Q_{ljt} + RS_{jt-1} \quad \forall\ j \,\&\, t \quad (2)$$

Minimum maximum withdrawal constraint

$$Min_{agt} \cdot S_i \le \sum_j W_{jit} \le Max_{agt} \cdot S_i \quad \forall\ i \in ag,\ \forall\ t \quad (3)$$

$$Min_{urt} \cdot S_i \le \sum_j W_{jit} \le Max_{urt} \cdot S_i \quad \forall\ i \in ur,\ \forall\ t \quad (4)$$

Reservoir capacity Constraint

$$RS_{jt} \le RC_j \quad \forall\ j \,\&\, t \quad (5)$$

Withdrawal total equation

$$WT_{it} = \sum_j W_{jit} \quad \forall\ i \,\&\, t \quad (6)$$

Binary decision constraint

$$\sum_z WT_{iz} \le BINWT_{it} \cdot M \quad \forall\ i \,\&\, t \quad (7)$$

$$WT_{agt} = BINWT_{agt} \cdot Max_{agt} \cdot S_i \quad \forall\ i \in ag,\ \forall\ t \quad (8)$$

$$WT_{urt} = BINWT_{urt} \cdot Max_{urt} \cdot S_i \quad \forall\ i \in ur,\ \forall\ t \quad (9)$$

***Indices***

| | |
|---|---|
| *i*: | demand nodes (1 to 1499) |
| *j* & *l*: | supply nodes (1 to 46) |
| *t* & *z*: | periods (1 to 12) |
| *ag:* | set of agricultural demand nodes |
| *ur:* | set of urban demand nodes |

***Variables***

| | | |
|---|---|---|
| *NEB:* | total benefit net of transportation costs | ($) |
| $NEB_T$: | country *NEB* for upstream Turkey | ($) |
| $NEB_{SI/T}$: | country *NEB* for downstream Syria-Iraq coalition after Turkey | ($) |
| $Q_{jlt}$: | inter-nodal flow (node *j* to node *l* at time *t*) | ($Mm^3$) |
| $W_{jit}$ | water transferred from supply node *j* to demand node *i* at time *t* | ($Mm^3$) |
| $WT_{it}$: | total water delivery to node *i* at time *t* | ($Mm^3$) |
| $RS_{jt-1}$: | water stored at time *t-1* transferred to the time *t* in the reservoir *j* | ($Mm^3$) |
| $RS_{jt}$ | water stored in reservoir *j* at time *t* | ($Mm^3$) |
| $BINWT_{it}$: | binary (1: yes, 0: no) variable for water provision to nod *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 $Mm^3$) |
| $C_{ss}$: | inter-basin water transport unit cost | ($ per $Mm^3$-km) |
| $D_{ji}$: | distance from supply node *j* to demand node *i* | (km) |
| $L_{jl}$: | length of a link from supply node *j* to supply node *l* | (km) |
| $P_e$: | energy price for electricity | ($ per MWh) |
| *ENP:* | energy needed to pump water for 1 m head gain | (MWh per $Mm^3$) |
| *END:* | electric generation from 1 m head loss | (MWh per $Mm^3$) |
| $H_{ji}$: | elevation difference between supply node *j* and demand node *i* | (m) |
| $DH_j$: | dam height for the supply node *j* | (m) |
| $RC_j$: | active reservoir capacity at node j | ($Mm^3$) |
| $Max_{ag}$: | maximum agricultural consumption rate | ($Mm^3$ per ha) |
| $Max_{ur}$: | maximum urban consumption rate | ($Mm^3$ per person) |
| $Min_{ag}$: | minimum agricultural consumption rate | ($Mm^3$ per ha) |
| $Min_{ur}$: | minimum urban consumption rate | ($Mm^3$ per person) |
| $EL_{jt}$: | reservoir evaporation loss at supply node *j* at time *t* | ($Mm^3$) |
| $RF_{ijt}$: | return flow rate from demand node *i* to supply node *j* at time *t* | |
| $S_i$: | size of demand node *i* (hectare for agricultural nodes, inhabitants for urban nodes) | |
| $T_{jt}$: | tributary inflow at node *j* at time *t* | ($Mm^3$) |

**Objective Function:** $W_{jit}$ is the quantity of water delivered from node *j* to node *i* in period *t*, $\sum_j W_{jit}$ sums up the quantity of water for withdrawal (agricultural and urban) activities at node *i* in period *t* from all supply node *j*. $V_{ag[ur]}$ is the unit value of water for agriculture [urban] uses, and the total value of the water at *i*-th node and time *t* is $V_{ag[ur]}\sum_j W_{jit}$, and the total value of water for all agricultural [urban] nodes is $\sum_{i\in ag[ur]} V_{ag[ur]}\cdot\sum_j W_{jit}$. $D_{ji}$ and $C_{ag[ur]}$ are the distances between the nodes and the transportation cost per unit distance, respectively; thus, the total *horizontal* component of water transportation cost to node *i* is $\sum_{j,i\in ag[ur]} C_{ag[ur]}\cdot D_{ji}\cdot W_{jit}$. Besides, parameters $P_e$, *ENP*, and $H_{ji}$ are the unit price of energy per MWh, energy needed to pump water for 1 meter head gain, and elevation difference needs to be passed by pump (Figure 3), respectively; then, the *vertical* cost component of water transportation is $\sum_{j,i\in ag[ur]} P_e\cdot ENP\cdot H_{ji}\cdot W_{jit}$. And then total transport cost to the agriculture [urban] demand nodes is $(\sum_{j,i\in ag[ur]} C_{ag[ur]}\cdot D_{ji}\cdot W_{jit}) + (\sum_{j,i\in ag[ur]} P_e\cdot ENP\cdot H_{ji}\cdot W_{jit})$ containing both *vertical* and *horizontal* components. Consequently, the net economic benefit from agricultural and urban uses is equal to the sum of Eq. 10 and Eq. 11.

$$\sum_{i\in ag} V_{ag}\cdot\sum_j W_{jit} - [(\sum_{j,i\in ag} C_{ag}\cdot D_{ji}\cdot W_{jit}) + (\sum_{j,i\in ag} P_e\cdot ENP\cdot H_{ji}\cdot W_{jit})] \quad (10)$$

$$\sum_{i\in ur} V_{ur}\cdot\sum_j W_{jit} - [(\sum_{j,i\in ur} C_{ur}\cdot D_{ji}\cdot W_{jit}) + (\sum_{j,i\in ur} P_e\cdot ENP\cdot H_{ji}\cdot W_{jit})] \quad (11)$$

$P_e$ is the unit market price of energy; *END* is the amount of generated energy from 1 meter head loss; $DH_j$ is the dam height at node *j*; and $Q_{jlt}$ is the water release from node *j* to node *l* at time *t* in order to generate energy. Then $\sum_{j,l} P_e\cdot END\cdot DH_j\cdot Q_{jlt}$ is the total economic value of energy benefits from all water releases to downstream nodes.

$$\sum_{j,l} P_e \cdot END \cdot DH_j \cdot Q_{jlt} \quad (12)$$

Three of the $Q_{jlt}$, which are ($Q_{21,12,t}$, $Q_{28,14,t}$, $Q_{31,16,t}$) the water conveyed from the Euphrates to the Tigris through inter-basin links, result in conveyance costs. Let $C_{ss}$ is per km distance unit delivery cost; $L_{j,l}$ is the link lengths from supply node *j* to *l*; and then Eq. 13 explicitly sums up the total inter basin water conveyance costs.

$$[(Q_{28,14,t}\cdot C_{ss}\cdot L_{28,14}) + (Q_{31,16,t}\cdot C_{ss}\cdot L_{31,16}) + (Q_{21,12,t}\cdot C_{ss}\cdot L_{21,12})] \quad (13)$$

Finally, Eqs. (10)-(13) constitute the objective function (Eq. 1).

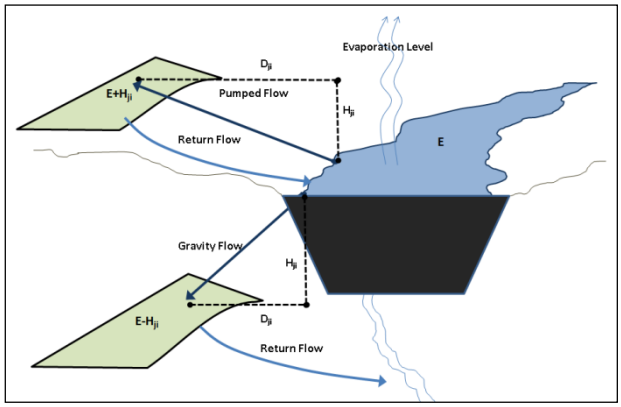
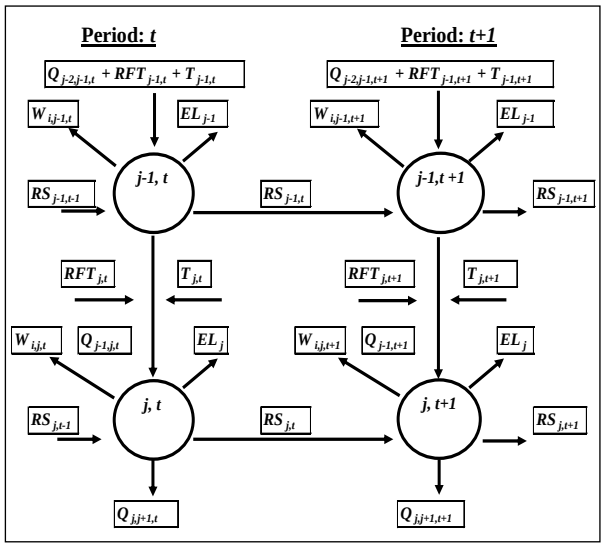



Figure 2. Position of DMUs with respect to a reservoir




Kucukmehmetoglu (2009) p.3077.

Figure 3. Flow relations in the ITETRBM

**Constraints:** The maximization process takes place under 5 different forms of constraints. *Continuity constraint* (Eq. 2) is designed to satisfy network balance for each supply node *j* at time *t* in the basin. The right hand side of equation is for incoming water to the supply node *j* at time *t*, which are tributary inflows ($T_{jt}$), return flows from the withdrawals ($\sum_i RF_{ij} \cdot [\sum_j W_{jit}]$), which is the multiplication of withdrawals ($\sum_j W_{jit}$) with the return flow rates ($RF_{ij}$), incoming water from earlier releases from upstream reservoirs ($\sum_l Q_{ljt}$), and available water in the reservoirs stored in the earlier period *t-1* ($RS_{jt-1}$); on the other hand, the left hand side of the equation is designated for the water leaving the node *j* at time *t*, which are total water withdrawals for the demand nodes ($\sum_i W_{jit}$), water release to downstream nodes ($\sum_l Q_{jlt}$), evaporations losses from the reservoirs ($EL_{jt}$), and stored water for the next period ($RS_{jt}$). Both sides of the equations are required to be equal for each node *j* at time *t*. Figure 3 shows this relation in graph form.

*Minimum and maximum withdrawal constraints* (Eqs. 3-4) are designed to control water withdrawals to demand nodes in coverage size for agricultural node and in number of inhabitants for urban population size, $S_i$. The minimum withdrawals ($Min_{ag[ur]t}$) enable to consider policy decision to provide least amount of water no matter what the conditions are, and the maximum withdrawals ($Max_{ag[ur]t}$) are designed to prevent excessive irrational water withdrawals. Minimum requirements are kept zero in this study.

*Reservoir capacity constraint* (Eq. 5) is designed to store water in node *j* at time *t* ($RS_{jt}$). In this equation stored water can never be more than reservoir capacity at node j ($RC_j$).

*Withdrawal total equation* (6) sums up water withdrawal to the demand node *i* at time *t*. This total is used in the *binary decision constraints*, which force the optimization model to provide sufficient amount of water to node *i* in every period *t* if selected ($BINWT_{it}$=1), otherwise ($BINWT_{it}$=0) no water provision takes place to node *i*. In Eq. (7), if water withdrawal for node *i* is positive, then $BINWT_{it}$ becomes 1 throughout the 12 periods. *M* is a very large number that satisfies the inequality constraint, if a withdrawal takes place once in a year $BINWT_{it}$ is equal to 1 for 12 periods; otherwise, M is multiplied by zero ($BINWT_{it}$ = 0) to force withdrawals to zero throughout the year. Eqs. (8)-(9) make the withdrawal reach maximum for each agriculture [urban] demand node *i* only if the $BINWT_{it}$ is equal to 1, otherwise withdrawal becomes zero.

### 3.2. Database Development

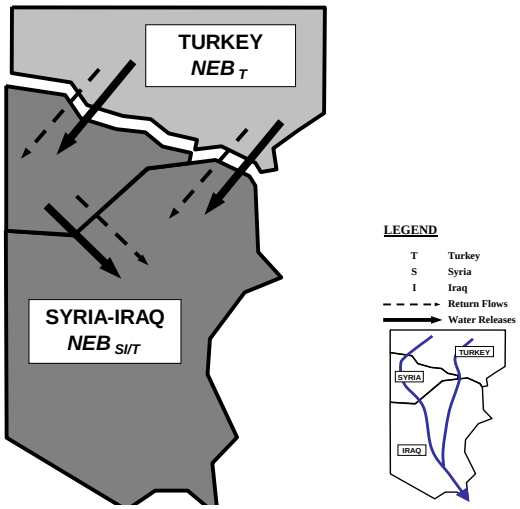
The database can be classified in two groups: The first group is the database developed in the earlier studies, which are provided in Appendix A; the second group is the necessary database updates for the elaboration of this study. There are two main sources of information; one for the determination of irrigable agricultural lands in the basin, and the second for the relative position (altitude and distance) of those irrigable lands with respect to supply nodes and reservoirs. Irrigable agricultural lands are derived from Kolars (1991) and Kliot (1994). The DEM database at 90 m resolution is obtained from https://srtm.csi.cgiar.org. The exact dam locations are identified from the Google Earth (2011).

In order to pursue these database updates, an intense work in GIS environment is required. In this process, for practicality and presentation purposes, the irrigable agricultural lands in the basin are converted into 10x10 km parcels (see Figures 1 and 5). This is the maximum DMU size, which can be smaller at the end of irrigation zones and in narrow strip areas. The relative position of each pixel to the reservoirs is chosen to be shortest distance from the highest elevation point of the selected pixel to the nearest reservoir. The elevation difference of both ends is computed to be the head gain or head loss needed ($H_{ji}$) in the water delivery. For the head losses, the elevation difference is considered zero because of the gravity flow, but head gain requires pumping, which takes 1.7 times of energy generation as compared to the same head loss (Oğuz, 2011). Hirshleifer at al. (1969) in their water conveyance cost figures illustrate that gravity flow is almost half of the pumping cost. Therefore, as compared to the earlier studies with the ITETRBM, the distance costs are halved and pumping cost are added into the model.

## 4. MODEL APPLICATIONS

The model application section consists of two subsections: In the first one, there are initial results of the ITETRBM applications, which are considered as a reference for the further analyses; and in the second section, there is a series of sensitivity analyses encountering changes in *energy prices* ($P_e$), *value of water in agricultural uses* ($V_{ag}$), *distance component of transport cost* ($C_{ag}$), and *alternative management scenarios* (integrated vs. disintegrated). The scenario results are comparatively evaluated in the coming section with regard to the benchmark model results.

### 4.1. Benchmark Model Application




The benchmark model is based on two-stage sequential optimization runs, and it divides the ETRB into two parts as upstream (Turkey) and downstream (Syria-Iraq). Initially, there is an optimization, in which Turkey maximizes the available resources in the country. Then water releases and return flows are obtained by the downstream Syria-Iraq coalition for the consecutive optimization operation (Figure 4).

Figure 4. Sequential optimization framework.
(Derived from Kucukmehmetoglu et al., 2010).

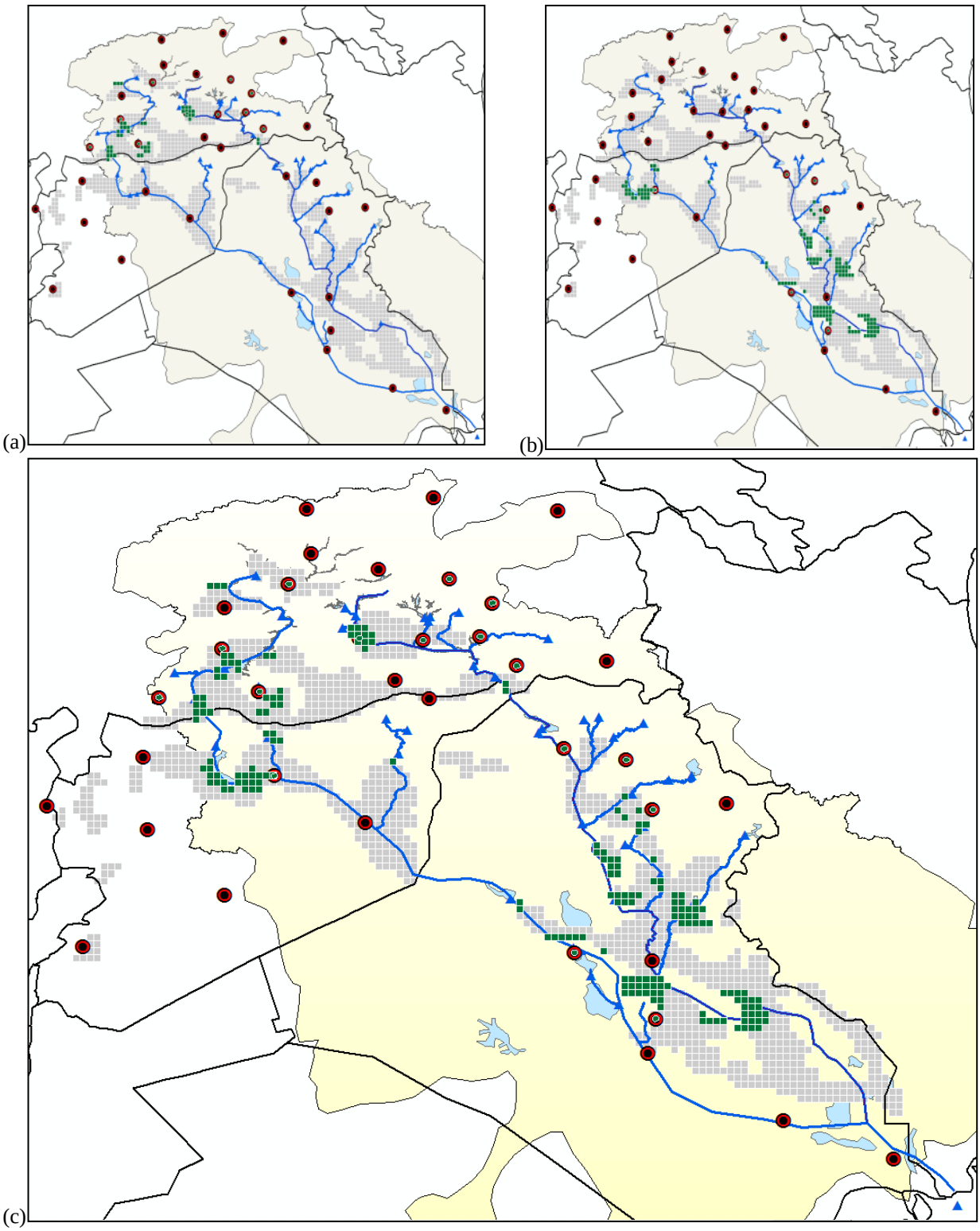



Figure 5. Sequential disintegrated optimization results: a) Turkey; b) Syria-Iraq's after Turkey; and c) Combined (a) and (b).

Figure 5 presents the details of sequential optimization process. In Figures 5(a)-(c) green colors present the irrigated DMUs. In the same way, the urban demand nodes withdrawing water from supply nodes are also presented by green centered red dots. Figure 5a shows only Turkey's maximization, then Figure 5b presents the maximization of Syria-Iraq coalition after obtaining return flows and water releases from Turkey, and finally, Figure 5c combines the two previous figures to show basin-wide outcome of the benchmark ITETRBM application.

When considering the ETRB as a unified entity, irrigated districts can only be seen at the downstream countries (Figure 6). This identifies Turkey for energy generation, but downstream countries Syria and Iraq as agricultural water consumers. Although the solution generates higher basin-wide net economic benefit ($2600x$10^6$) as compared to disintegrated basin scenarios ($2574 x$10^6$), this contrasting result is politically unacceptable by the upstream country Turkey.

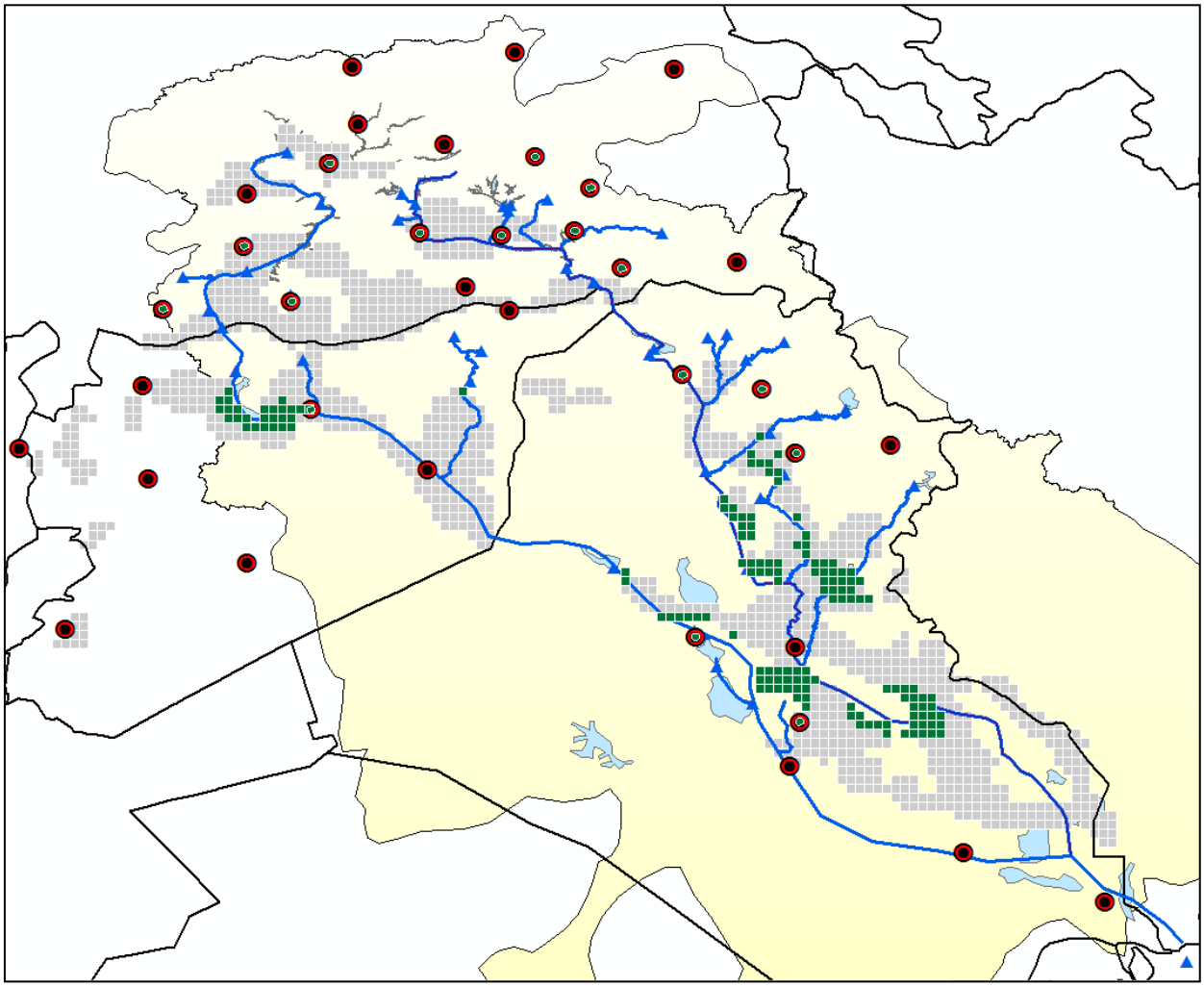


Figure 6. Basin-wide integrated optimization results

The total economic benefit from the basin is $1269 million for upstream Turkey, $1305 million for downstream Syria-Iraq coalition, which add up to $2574 million (Table 1). It is clear that benefits derived from the system are nearly equal among the upstream and downstream parties. In detail, total benefit is higher in the downstream countries; however, the transport costs are higher, too. This is an outcome of the higher water withdrawals in the downstream countries. This is easily seen in Table 2 with 4-fold higher irrigated land area, and 4-fold agricultural water withdrawals in the downstream countries, Syria-Iraq, as compared to upstream Turkey. Table 3 presents the sources of economic benefits by countries. It is clearly seen that upstream Turkey, instead of irrigating extensive agricultural land, uses higher hydro-power energy generation potential. On the other hand, downstream countries Syria-Iraq prefer to use water for irrigation, especially when not much energy generation potential is left in the downstream before the Gulf.

Table 1. Economic figures of the base model ($\$10^6$)

| Country | Total Economic Benefit | Total Transport Cost | Net Economic Benefit |
|---|---|---|---|
| **Turkey** | 1,531 | 261 | 1,269 |
| **Syria-Iraq** | 1,826 | 521 | 1,305 |
| **Total** | 3,356 | 782 | 2,574 |

Table 2. Irrigation area and water withdrawals

| Country | Irrigated Land ($10^3$ ha) | Agricultural Withdrawal ($Mm^3$) | Water Withdrawal ($Mm^3$) |
|---|---|---|---|
| **Turkey** | 223,405 | 4,469 | 7,051 |
| **Syria-Iraq** | 871,118 | 17,426 | 22,335 |
| **Total** | 1,094,523 | 21,895 | 29,386 |

Table 3. Benefit components of the total economic benefits

| Country | Energy Benefits | Withdrawal Benefits | Urban Withdrawal | Agricultural Withdrawal |
|---|---|---|---|---|
| **Turkey** | 1,032 | 499 | 387 | 112 |
| **Syria-Iraq** | 654 | 1,172 | 736 | 436 |
| **Total** | 1,685 | 1,671 | 1,124 | 547 |

## 4.2. Sensitivity Analyses

As reference to the benchmark model, four different sensitivity analyses are pursued in order to see the economic and spatial impacts of selected parameters. These sensitivity analyses are based on i) variation in energy price ($P_e$: \$5-\$25 MWh), ii) variation in agricultural water use values ($V_{ag}$: \$25000-\$75000 per $Mm^3$); iii) variation in transport cost values ($C_{ag}$: \$85, \$425, and \$766 per $Mm^3$/km); and iv) management scenarios (integrated vs. disintegrated). Management scenarios are applied to (i), (ii), and (iii) coded sensitivity analyses. All benchmark values in Tables 4-6 are highlighted with grey background color.

**Energy Price Impacts:** Energy price (EPR) scenarios are a set of separate optimization runs with $P_e$= \$25, \$15, and \$5 per-MWh. Table 4 combines these scenario results in terms of economic benefit, irrigated land, and water withdrawals. Decreasing energy prices naturally result in decline of total benefits; however, this makes water withdrawals relatively more productive as compared to energy generation. In the basin, because Turkey has a water contributing upstream position, she takes advantage of this, so that her irrigated land and water withdrawal increases (223,405→1,430,890 ha). This results indicate declines in irrigated land in the downstream Syria-Iraq coalition (871,118→0 ha). Consideration of the same scenarios in the integrated management framework, while the energy price decreases, Turkey's water withdrawals and irrigated land coverage increase, but, they are not as much as in the disintegrated management scenarios. On the other hand, Syria-Iraq total irrigated agricultural land and total withdrawal, first slightly increases, but then decreases due to significantly increasing upstream withdrawals.

Table 4. Energy value impact

| Price of Energy (per-MWh) | Country | Economic Benefit ($10^6$) | | Irrigated Land (ha) | | Agricultural Withdrawal ($10^6 m^3$) | |
|---|---|---|---|---|---|---|---|
| | | Disintegrated | Integrated | Disintegrated | Integrated | Disintegrated | Integrated |
| EPR = $25 | Turkey | 1,269 | 1,251 | 223,405 | - | 4,469 | - |
| | Syria-Iraq | 1,305 | 1,349 | 871,118 | 955,383 | 17,426 | 19,111 |
| | Total | 2,574 | 2,600 | 1,094,523 | 955,383 | 21,895 | 19,111 |
| EPR = $15 | Turkey | 912 | 829 | 782,501 | 6,936 | 15,653 | 139 |
| | Syria-Iraq | 741 | 1,105 | 101,691 | 977,043 | 2,034 | 19,545 |
| | Total | 1,653 | 1,933 | 884,192 | 983,979 | 17,687 | 19,684 |
| EPR = $5 | Turkey | 666 | 496 | 1,430,890 | 248,202 | 28,624 | 4,965 |
| | Syria-Iraq | 433 | 794 | - | 784,212 | - | 15,687 |
| | Total | 1,100 | 1,290 | 1,430,890 | 1,032,414 | 28,624 | 20,652 |

**Agricultural Water Use Value Impact:** The scenarios for the value of water in agriculture ($V_{ag}$) are chosen to be $25000, $50000, and $75000 per-$Mm^3$. Table 5 presents the results in terms of economic benefit, irrigated land, and water withdrawals. An increase in the value of water in the agricultural use, results in basin-wide increase in the net economic benefits ($2,574→5,812 million), but this increase is much prominent for Turkey in the disintegrated basin management as compared to the integrated basin management. The integrated management favors the downstream countries such that their water withdrawals and irrigated agricultural land increase significantly (19,111→71,136 $Mm^3$).

Table 5. Agricultural water use value impact

| Value of Water in Agriculture (per-$Mm^3$) | Country | Economic Benefit ($10^6$) | | Irrigated Land (ha) | | Agricultural Withdrawal ($10^6 m^3$) | |
|---|---|---|---|---|---|---|---|
| | | Disintegrated | Integrated | Disintegrated | Integrated | Disintegrated | Integrated |
| VALAG = $25000 | Turkey | 1,269 | 1,251 | 223,405 | - | 4,469 | - |
| | Syria-Iraq | 1,305 | 1,349 | 871,118 | 955,383 | 17,426 | 19,111 |
| | Total | 2,574 | 2,600 | 1,094,523 | 955,383 | 21,895 | 19,111 |
| VALAG = $50000 | Turkey | 1,684 | 1,304 | 1,296,063 | 69,734 | 25,926 | 1,395 |
| | Syria-Iraq | 2,085 | 2,457 | 1,704,813 | 1,974,835 | 34,103 | 39,505 |
| | Total | 3,769 | 3,761 | 3,000,876 | 2,044,569 | 60,030 | 40,900 |
| VALAG = $75000 | Turkey | 2,401 | 2,039 | 1,489,564 | 844,853 | 29,797 | 16,900 |
| | Syria-Iraq | 3,410 | 4,774 | 2,266,506 | 3,556,102 | 45,339 | 71,136 |
| | Total | 5,812 | 6,812 | 3,756,070 | 4,400,955 | 75,136 | 88,037 |

**Transportation Cost (Distance Component) Impact:** The transport costs are selected as $85, $450, and $766 per-km distance for per $Mm^3$ of water. In the disintegrated water management scenario, the decrease in the distance cost increases the water withdrawals for upstream country Turkey, while decreasing withdrawals in the downstream county Syria-Iraq (Table 6). The increasing cost makes completely opposite impact to the basin parties. Again, an integrated basin management forces Turkey to generate energy and to reduce water withdrawal for agriculture.

Table 6. Transportation cost (distance component) impact

| Transport Cost (per-$Mm^3$/km) | Country | Economic Benefit ($10^6$) | | Irrigated Land (ha) | | Agricultural Withdrawal ($10^6 m^3$) | |
|---|---|---|---|---|---|---|---|
| | | Disintegrated | Integrated | Disintegrated | Integrated | Disintegrated | Integrated |
| $85 | Turkey | 1,572 | 1,439 | 956,567 | 71 | 19,135 | 1 |
| | Syria-Iraq | 1,793 | 2,251 | 102,828 | 860,843 | 2,057 | 17,220 |
| | Total | 3,365 | 3,690 | 1,059,395 | 860,914 | 21,192 | 17,222 |
| $425 | Turkey | 1,269 | 1,251 | 223,405 | - | 4,469 | - |
| | Syria-Iraq | 1,305 | 1,349 | 871,118 | 955,383 | 17,426 | 19,111 |
| | Total | 2,574 | 2,600 | 1,094,523 | 955,383 | 21,895 | 19,111 |
| $766 | Turkey | 1,160 | 1,153 | 90,670 | 6,936 | 1,814 | 139 |
| | Syria-Iraq | 1,025 | 1,080 | 908,234 | 1,040,824 | 18,168 | 20,821 |
| | Total | 2,184 | 2,233 | 998,904 | 1,047,760 | 19,982 | 20,959 |

**Management Impact:** Management scenarios illustrate that in all cases integrated basin management generates higher benefits; however, all the integrated basin management scenarios bring quite contrasting results considering the upstream and downstream parties. These scenarios put Turkey into energy generation position whereas the downstream countries draw water for agricultural uses.

## 5. CONCLUSION

DEM and GIS based databases are the main contribution of this study in optimally allocating transboundary water resources. The improved database requires that the ITETRBM contains binary variables and renders the model into mixed integer programming form. The model can be a prototype for various river basins in the world.

The model application section consists of, i) benchmark model application and ii) a series of sensitivity analyses via changes in the selected parameters. It is found that disintegrated systems enable upstream countries utilize more water in agriculture as compared to integrated basin management. In the case of providing higher basin-wide net economic benefits, the integrated basin management makes Turkey as energy generation country with water utilization for urban uses only, whereas the same management makes Syria-Iraq as heavy water consumption party. Briefly, the results show that i) system parameters significantly alter the spatial extent of water resources allocation in the basin, and ii) the magnitudes of the parameters also explain the tradeoffs between agriculture and energy sectors as much as upstream and downstream countries.

A shortcoming of this model is that the optimization results do not cover any local multiplier effects of water uses. This area remains as a political dilemma in any form of water allocations. In order to solve this issue, basin-wide multi-party water-saving technology policies are of vital importance. The current database is still rough, and further policy studies require higher resolution databases and further in-depth analyses. Scale economies need to be included into the model for better infrastructural development policies. Finally, effects of global climatic change can be easily incorporated into the model, since the technical aspects of the current model are capable of analyzing multi-year variations in the river flows.

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## APPENDIX A: DATA AND ASSUMPTIONS

As detailed for the ETRBM in Kucukmehmetoglu (2002) and Kucukmehmetoglu & Guldmann (2004, 2010), and for the ITETRBM in Kucukmehmetoglu (2009) and Kucukmehmetoglu et al. (2010), the demand-supply data, various system parameters, and assumptions are as follows:

- In the ITETRBM the planned dams are considered as complete and all irrigable lands are developed by the year 2040. Current population is projected to the year 2040, assuming that the current growth rates remain constant. For the seasonal ITETRBM, monthly periods are considered in this study. Due to the lack of adequate data on the Euphrates and the Tigris basins, some parameters are adopted from earlier studies conducted in the Middle East countries and the U.S.A. The *supply* figures are from Kolars (1986, 1992, 1994), Kolars and Mitchell (1991), Kliot (1994), and Bağış (1989); the demands are drawn from Bağış (1989), Kolars and Mitchell (1991), Kolars (1994, 1992, 1986), Kliot (1994), FAO (1993), Altinbilek (1997), and www.library.uu.nl/wesp/populstat/Asia/; agricultural and urban water usages are adjusted from Howitt et al. (1982), and Dinar and Wolf (1994); the water transfer cost and energy levels are taken from Hirshleifer et al. (1969), Gibbons (1986); and Bilen (1994). *Reservoir capacity* figures are given by Altinbilek (1997, 2004) and UNEP (2001), *tributary flows by* Kliot (1994); *seasonal evaporation rates* from a study on the Nile River by Hurst (1952); monthly *urban and agricultural demands* are from İlhan and Utku (1998) and İstanbul Su ve Kanalizasyon İdaresi (İSKİ) (2004). The base model does not consider geographic variations in urban and agricultural consumptions, energy prices, and transportation cost parameters. These variables vary with time, technology, alternative energy resources' availability, economic and socio-cultural development level characteristics.

**Supply Data**

- Data on the water contributions of each riparian country are available in Kolars (1986, 1992, 1994), Kolars and Mitchell (1991), Kliot (1994), Bagis (1989). From those figures, for each tributary of the Euphrates and the Tigris a tributary flow amount is derived.
- The return flow rate is assumed 35% for agriculture, and 80% for urban use.
- Evaporation rates (per-km$^2$) from the reservoirs are computed for the three riparian countries based on observed annual evaporation figures given the reservoir surface areas for the major reservoirs in the Euphrates basin (Altinbilek, 1997) and then the estimated evaporation rates are applied to the other reservoirs.

**Demand Data**

- Total planned irrigable land areas for each riparian country are available in the literature, with: 1,770,956 ha for Turkey, 1,040,000 ha for Syria, and 5,833,000 ha for Iraq, or a total of 8,643,956 ha for the whole region along the two rivers. Those values are assigned to 21 agricultural districts (nodes) in the Euphrates basin, and 16 in the Tigris basin.
- Irrigable areas are only available at country or regional level for Syria and Iraq. The delineation of irrigation districts was made using existing irrigation maps.
- Due to a lack of spatial information, agricultural productivity ($V_{ag}$) is assumed to be the same throughout the region, and crop diversity and double cropping options are ignored.
- The agricultural districts are located close to the two rivers, with the water conveyance distance varying mostly between 4 and 40 km.
- There are 8 urban demand nodes in Turkey (South Eastern Anatolia Region), 8 in Syria, and 10 in Iraq. These nodes are constituted by cities having 100,000 or more inhabitants. Historical population data for these cities, from 1965 to 1995, have been used to estimate populations in year 2040.

**Agriculture and Urban Water Values**

- Agriculture and urban water values are derived from Dinar and Wolf (1994b) and Howitt, Mann, and Vaux (1982), and the following values are selected: $V_{ur}$ = \$150,000/$Mm^3$, $V_{ag}$ = \$25,000/$Mm^3$.

**Maximum and Minimum Consumption Rates**

- Using the upper-bound estimate of Dinar and Wolf (1994a), $Max_{ag}$ = 0.020 $Mm^3$/ha is selected as the upper bound of water withdrawal and $Max_{ur}$=0.000106 $Mm^3$/capita is selected as the upper water use rate. Because some districts may not be irrigated and some urban areas are not served, minimum withdrawals are chosen to be $Min_{ag}$ = 0.0 $Mm^3$/ha and $Min_{ur}$=0.0 $Mm^3$/capita.

**Water Transportation Costs**

- Each demand node is assigned to the most accessible supply node that distances are strait line distances measured through map analysis. Then transportation costs are derived from Hirshleifer et al. (1969) as $C_{ag}$=\$850/$Mm^3$-km for agricultural uses, $C_{ur}$=\$4,958/$Mm^3$-km for urban uses, and $C_{ss}$ = \$850 per $Mm^3$-km for inter-basin links.

**Electricity Generation**

- The average electric generation rate is known as 0.87 kWh per foot-head and acre-feet of water (Gibbons, 1986). This value have been converted into electricity generation per $Mm^3$ of water released from the head of the dam. The literature provides head heights of dams from the riverbed on the main branch of the Euphrates (Bilen, 1994). The head heights for the other dams are estimated to range between 20-35 m, in view of the change in elevation through Syria and Iraq.

**Additional Data and Assumptions needed for the ITETRBM**

For each reservoir, there are two types of water holding capacities: dead and active reserves. While the dead reserve capacity has no use for energy generation and water distribution, the active one is critical for inter-temporal allocations. Those active reservoir capacities are almost completely available in Turkey and partially in Syria and Iraq (Altınbilek 1997, 2004; UNEP 2001). In Turkey, the total active storage capacity is 63.3 $Mm^3$. The 47.6 $Mm^3$ of this total is in the Euphrates, and the remainder 15.7 $Mm^3$ in the Tigris basin. In the Euphrates basin, in Syria and Iraq, the known total active storage capacities are respectively 9 and 10.4 $Mm^3$. In the Tigris basin of Iraq, the only available active reservoir capacity is Mosul Dam with 8.2 $Mm^3$. The remainders, in Iraq and Syria, are derived by multiplying total storages by the average ratio of active reservoir capacities to total storage in the basin. This ratio is obtained from available reservoir figures in the basin. The computed average ratio is .52, and the calculated ranges of the ratios vary from .40 to .80. In the text, the reservoir capacities refer only the active reserve capacities but not the dead reserves.

- 12 monthly periods ($t=1 \rightarrow 12$) are selected for the application of inter-temporal allocation.

- Kliot (1994: p.106, 107) provides monthly variations of the Euphrates and the Tigris in graph form. These figures are aggregated into the 12 working periods and their ratio is used as multiplier for the tributary flows used in Kucukmehmetoglu (2002). These multipliers are $mT_1$ ... $mT_{12}$, and they can be used to compute periodically defined tributary flows for each supply node as $T_{jt} = T_j \cdot mT_t$.
- The water demand is expected to vary from dry to rainy season. The values of water used in these 12 monthly periods are the same, but quantities demanded are different. Therefore, adjustments of the maximum withdrawal limits for the 12 periods are needed. In the literature, İlhan & Utku (1998) provide monthly variations of water demands in the GAP area of Turkey. The monthly figures are converted into 12 water demand multipliers, by computing the monthly ratios of water demanded in the total annual demand ($mMax_{ag1}$ ... $mMax_{ag12}$), then these ratios are used as multiplier to adjust maximum water withdrawal limits $Mm^3$ per-ha in agriculture ($Max_{agt} = Max_{ag} \cdot mMax_{agt}$). The same procedure is applied for maximum urban water demands $Mm^3$ per-inhabitant by using monthly Istanbul metropolitan area water use figures (İSKİ, 2003) to obtain the periodical water demand ratios ($mMax_{ur1}$ ... $mMax_{ur12}$). Then conversion is done by multiplying the maximum urban water demands $Mm^3$ per-inhabitant by these multipliers ($Max_{urt} = Max_{ur} \cdot mMax_{urt}$).
- The constant evaporation values in Kucukmehmetoglu (2002) need to be apportioned into 12 periods. The necessary multipliers are adapted from the graph provided by Hurst (1952) for the Aswan Dam over the Nile. Monthly evaporation figures are aggregated into 12 periods, and then the ratios of periodical to annual evaporation total are calculated ($mEL_1$ ... $mEL_{12}$). Then the constant evaporation values are apportioned to periods by using these ratios as multipliers ($EL_{jt} = EL_j \cdot mEL_t$).
- Energy values are assumed to be the same throughout the year in calculating the economic benefits from water releases from reservoirs. But this assumption is relaxed in this research for the analyses.