1 Introduction
Sharing the water of the Euphrates and Tigris (E–T) rivers among Turkey, Syria, and Iraq has been the source of increasing conflicts since the early 1970s. In particular, Turkey’s development of Southeastern Anatolia, with water needed for agriculture and energy production, has been viewed as a threat to Syria and Iraq. To help analyze these conflicts, which are likely to worsen in the future because of high population growth and urban and agricultural development, in this paper we formulate a water-allocation optimization model—the Euphrates and Tigris River Basin Model (ETRBM)—that represents, in network form, the system made of the two rivers and their various consumption, supply, and transshipment nodes, and accounts for evaporation and return flows. The constraints include water-conservation balances and maximum and minimum water consumption. The model is used to assess the economic consequences of various cooperation and noncooperation strategies that may be adopted by the riparian countries. Cooperative game-theory concepts (core and Shapley value) are used to identify stable water allocations, under which all three countries find it beneficial to cooperate. The results suggest that an allocation of the total benefits exists, under various scenarios of future energy prices and agricultural productivities, that makes this global cooperation attractive to all countries. Various research extensions are outlined.

2 Literature review
The first strand of literature includes studies on the E–T basin water resources, hydrology, history, economics, and politics. Resource assessments are available in Falkenmark (1989) and Postel (1996). The history of water conflicts between Turkey, Syria, and Iraq, particularly since the start of the Southeast Anatolia Development Project (GAP) by Turkey in 1976, is presented in Kolars (1994), Waterbury (1994), and

Abstract. This paper presents a linear programming model that allocates the waters of the Euphrates and Tigris rivers to irrigation, urban consumption, and on-stream hydroelectricity production in the three riparian countries (Turkey, Syria, and Iraq), by maximizing the aggregate net benefits from water uses while accounting for water-conveyance costs. The model represents, in network form, the system made of the two rivers and their various consumption, supply, and transshipment nodes, and accounts for evaporation and return flows. The constraints include water-conservation balances and maximum and minimum water consumption. The model is used to assess the economic consequences of various cooperation and noncooperation strategies that may be adopted by the riparian countries. Cooperative game-theory concepts (core and Shapley value) are used to identify stable water allocations, under which all three countries find it beneficial to cooperate. The results suggest that an allocation of the total benefits exists, under various scenarios of future energy prices and agricultural productivities, that makes this global cooperation attractive to all countries. Various research extensions are outlined.

Although the above literature provides much of the empirical background of this research, it is essentially qualitative, and does not offer any quantitative modeling framework. The methodology of this research is inspired by the second strand of literature, focusing on (1) water-allocation models, cast as linear and nonlinear optimization models, and (2) cost–benefit allocation models, using concepts and techniques of cooperative game theory.

Water-allocation models maximize the net benefits derived from various water uses, including irrigation, municipal and industrial consumption, and hydroelectricity production, net of water conveyance and treatment costs. These models generally involve price-sensitive demands and, therefore, their objective functions are cast as total net consumer and producer surpluses. In addition to water quantity allocations, these models provide price equilibrium under different scenarios. Flinn and Guise (1970) develop an interregional price equilibrium model taking the form of a quadratic program, because of linear demand and cost functions. The constraints include both maximum reservoir supply and conveyance capacity limits. The model is applied to a hypothetical river system, and incorporates seasonal variations in demand. Vaux and Howitt (1984) apply a similar model to California, using nonlinear demand functions, and price-sensitive linear supply functions. The results show that market-based water transfers reduce the need for supply-augmenting facilities, and generate welfare gains. Booker and Young (1994) model intrastate and interstate water transfers within the Colorado basin, accounting for both water quantity and quality (salinity) balances. They use an explicit representation of the river twenty-node network, with its tributary inflows, diversion points, reservoirs, and hydropower plants. The model (CRIM—Colorado River Institutional Model) is a nonlinear program that maximizes total net benefits, subject to linear water balance and nonlinear salinity balance constraints. Flows and salinity concentrations are functions of withdrawals, exports, and salt discharges, which are all decision variables. The Colorado is treated as a closed system, with a constant water supply. Model results suggest that efficiency gains are derived primarily from intrastate (not interstate) trade. Becker (1995) formulates a linear program for the optimal allocation of water to Israeli regional crops, where the constraints include maximum reservoir supplies, upper limits on regional agricultural areas and total crop land across all regions, and maximum regional water allocations. The objective function represents the aggregate value added of water over all crops and regions, net of transfer costs. Mahan et al (2002), drawing on Booker and Young (1994), develop a nonlinear net benefit maximization model applied to Southern Alberta. The demand sector includes urban, irrigation, industrial, and hydropower nodes. A novel environmental feature is the explicit account of the conversion of untreated water to treated potable water.

Models combining water-system optimization and game theory concepts have been pioneered by Rogers (1969), who formulates a linear program to derive an optimal multipurpose development for the Ganges–Brahmaputra basin that straddles India and Bangladesh. This model accounts for the complex interactions between hydropower, irrigation, flood control, navigation, and salinity control. The model maximizes the benefits from hydropower production and from irrigation with both diverted river water and pumped groundwater, net of reservoir (storage), tube well field, and embankment
costs, subject to constraints related to flow continuity at each reservoir, storage capacity, flood, salinity, and navigation control, hydropower and groundwater capacities, and budget constraints. The model represents one year’s operation of the system, broken down into twelve seasons. The model is then used to investigate six different cases of cooperation and noncooperation between India and Bangladesh. The results, which include the net benefits for India and Bangladesh for each of the six strategies, are analyzed as cooperative two-party nonzero-sum games. Incorporating Nepal into his analysis, Rogers (1993) outlines the applicability of cooperative game theory and core analysis to the allocation of the Ganges–Brahmaputra water. Individual country and two-country coalitions are considered, but their definitions are not fully clear, and seem to imply unrealistic behavior on the part of the country not a member of the coalition. Rogers shows that the core of nondominated benefits imputations is small, but not empty. Dinar and Wolf (1994a) illustrate the potential of water trading among Middle East areas that are not riparian, including Egypt (EG), the Gaza Strip (GS), the West Bank (WB), and Israel (IL). They develop an optimization model that involves trade in both water (from Egypt to the other parties) and technology for reducing water use in agriculture and system losses (from Israel to the other parties). When the players optimize their resources unilaterally, their benefits from regional trade are set equal to zero. Then two coalitions are considered: (1) EG–GS, and (2) the grand one—EG–GS–WB–IL. The model is a linear program that computes equilibrium prices for both water and technology. Finally, one should mention the extensions of the traditional core constraints proposed by Dufournaud and Harrington (1990), whereby both the spatial and the temporal patterns of costs and benefits from river development are considered, and coalitions are defined across periods.

3 The Euphrates and Tigris River Basin Model (ETRBM)

3.1 The network structure of the ETRBM
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 sixty-three demand (i) and forty-five supply (j) nodes (figure 1, over). 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 the most accessible supply node. Supply node 45 represents the Gulf, which is assigned to Iraq, and represents the end point of all flows downstream. There are three interbasin links, all from the Tigris to the Euphrates, with one already built (j = 31 to j = 16, the Tharthar Canal (see Bilen, 1994)). Although one link connects Turkey to Syria (j = 21 to j = 12), the other two links are located within the borders of Iraq (j = 28 to j = 14, and j = 31 to j = 16). Details on the network structure can be found in Kucukmehmetoglu (2002).

3.2 Mathematical structure of the ETRBM
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 interbasin links. The model accounts for the fundamental trade-off between off-stream water withdrawal for agricultural and urban uses, and on-stream electricity production. We present first the model equations, followed by a discussion of the objective function and constraints. The definitions of all the indices, variables, and parameters are presented in appendix A. The basic model is composed of equations (1)–(4):
Figure 1. The Euphrates and Tigris river basin network.
maximize \[
\text{NEB} = \sum_{i \in A} V_{ag} \sum_j W_{ji} - \sum_{j, i \in A} C_{ag} D_{ji} W_{ji} + \sum_{i \in U} \sum_j V_{ur} W_{ji} - \sum_{j, i \in U} C_{ur} D_{ji} W_{ji} + \sum_{j, i \in U} p^E E_{ji} Q_{ji} - \left[ (Q_{28,14} C_{SS} D_{28,14}) + (Q_{31,16} C_{SS} D_{31,16}) + (Q_{21,12} C_{SS} D_{21,12}) \right],
\]
subject to
\[
\sum_j W_{ji} + \sum_j Q_{ji} + L_j = \sum_j F_{ji} \left( \sum_j W_{ji} \right) + T_j + \sum_j Q_{ji}, \quad \forall j,
\]
\[
\min^a S_i \leq \sum_j W_{ji} \leq \max^a S_i, \quad \forall i \in A,
\]
\[
\min^u S_i \leq \sum_j W_{ji} \leq \max^u S_i, \quad \forall i \in U,
\]
where \( V_{ag} \) is the unit value of water to agriculture, \( W_{ji} \) is the amount of water transferred from node \( j \) to agricultural node \( i \), \( D_{ji} \) is the distance between the nodes, and \( C_{ag} \) is the transportation unit cost per unit distance. Then, \( \sum_j W_{ji} \) is the water consumption at agricultural node \( i \), the total value of the water at node \( i \) is given by \( V_{ag} (\sum_j W_{ji}) \), and the total water transportation cost of getting water to node \( i \) is given by \( \sum_j C_{ag} D_{ji} W_{ji} \). Hence the total net benefits of water usage to agriculture is
\[
\sum_{i \in A} V_{ag} \left( \sum_j W_{ji} \right) - \sum_{j, i \in A} C_{ag} D_{ji} W_{ji}.
\]

Similarly, if \( V_{ur} \) is the unit value of water to urban uses, and \( C_{ur} \) is the transportation unit cost per unit distance, then \( \sum_j W_{ji} \) is the water consumption at urban node \( i \), the total value of the water at node \( i \) is given by \( V_{ur} (\sum_j W_{ji}) \), the total water transportation cost of getting water to node \( i \) is given by \( \sum_j C_{ur} D_{ji} W_{ji} \), and the net benefits of water usage to urban centers is given by
\[
\sum_{i \in U} V_{ur} \left( \sum_j W_{ji} \right) - \sum_{j, i \in U} C_{ur} D_{ji} W_{ji}.
\]

Energy benefits are measured by the market value of the energy generated by the downstream flow of water. Let \( p^E \) be the market price of water-generated energy, \( E_{ji} \) the quantity of energy generated at node \( j \) per unit of water flow, and \( Q_{ji} \) the flow of water into downstream node \( l \) from node \( j \). The total value of energy generated in the basin is
\[
\sum_{j, l} p^E E_{ji} Q_{ji}.
\]

In the cases of interbasin water-transfer links, let \( D_{ji} \) be the distance between supply nodes, and \( C_{SS} \) the transportation unit cost per unit distance. Because there are only three links, they are explicitly represented by their indices. The costs are assumed to be borne by the country receiving the water. Let \( Q_{21,12} \) be the flow from Turkey to Syria, and \( Q_{28,14} \) and \( Q_{31,16} \) the flows within Iraq. The transportation cost for link \( j - l \) is then \( C_{SS} D_{ji} Q_{ji} \). The total interbasin link costs are then given by
\[
(Q_{28,14} C_{SS} D_{28,14}) + (Q_{31,16} C_{SS} D_{31,16}) + (Q_{21,12} C_{SS} D_{21,12}).
\]

Combining the above benefits and costs yields the objective function (1).
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 \( i \), \( \sum_i F_{ij}(\sum_i W_{ij}) \), and water from upstream nodes \( l \) to \( j \), \( \sum_l Q_{lj} \). The total input at node \( j \) is given by

\[
\sum_i F_{ij}(\sum_j W_{ji}) + T_j + \sum_l Q_{lj}.
\]  

(9)

On the other hand, water leaving node \( j \) is allocated to reservoir evaporation \( L_j \), water withdrawal for agricultural and urban uses \( \sum_j W_{ji} \), and water release to downstream nodes \( \sum_j Q_{jl} \). Then the total amount of water leaving node \( j \) is given by

\[
\sum_j W_{ji} + \sum_j Q_{jl} + L_j.
\]  

(10)

Combining equations (9) and (10) leads to the water-balance constraint (2) at node \( j \).

Several comments about the ETRBM are in order. First, in terms of modeling river basin system structure and flow conservation, the ETRBM is similar to the CRIM by Booker and Young (1994), but it does not account for salinity, low biochemical oxygen demand levels, and the existence of groundwater resources, for which no geographically specific information could be found. In terms of its linear objective function, the ETRBM is very similar to Becker’s (1995) model. Second, although notation implying geographically invariant agricultural and urban water unit values, energy price, and water transportation unit costs are used to clarify the presentation, they can easily be adjusted to reflect geographical differences in terrain, economic development, alternative energy sources (for example, oil in Iraq), technology, and sociocultural factors. Third, upper limits to water use are set for cities (per capita) and agriculture (per hectare) to reflect technological limits, but also to prevent unrealistic solutions, where large amounts of water would be allocated to the users with the largest net unit economic benefit (for example, cities and agricultural districts closest to the rivers). Such constraints might not have been necessary with nonlinear gross benefit functions with decreasing marginal benefits, but at the cost of dealing with a more difficult-to-solve nonlinear model. In any case, the data to build realistic nonlinear benefit and cost functions are not available. The data used to calibrate the ETRBM are presented in appendix B.

4 Benchmark model application

We assume that all three countries have the same agricultural efficiency \( V^{ag} = \text{US} \$25,000/\text{Mm}^3 \) and energy price \( P^e = \text{US} \$25/\text{Mwh} \), with average annual tributary flows. Table 1 presents the optimal values of the net overall system benefits, the gross benefits from water use and energy generation, the total water transportation costs for urban and agricultural uses, the costs of interbasin transfers, the water released to the Gulf, the total water withdrawal, the total return flow, and the total urban and agricultural water withdrawals. Also included are the total tributary flow and reserve evaporation, and the minimum and maximum total water withdrawals for urban and agricultural uses. We observe that (1) the total net benefits for the three countries are close to $3 billion, with energy benefits close to 40% of the total, (2) return flows make up 41% of the water input from tributaries, and are available for reuse, (3) the total water withdrawal represents 107% of the total tributary inflow, whereas water released
to the Gulf makes up 12.3% of this inflow, and (4) total water withdrawals for agriculture and urban use represent about 50% of the maximum withdrawals.

Table 2 presents the allocation of benefits and costs to each country, including total economic benefits and transportation costs, net economic benefits, ratios of economic benefits to transportation costs ($B/C$), and percentages of economic benefits and transportation costs by category. Turkey derives most of her benefits (78%) from energy generation, and Iraq from irrigation (70%). The overall system optimization involves first the utilization of the energy generation potential at the upstream nodes, and then the utilization of the agricultural potential at the downstream nodes. The opportunity cost of withdrawing water at the upstream nodes is higher than that of withdrawing water at the downstream nodes, as water withdrawn can no longer be used for electricity generation, whereas water not withdrawn can be used several times for this purpose, until it reaches the flat agricultural lands and the Gulf. In Syria, the benefits

<table>
<thead>
<tr>
<th>Table 1. Summary of the benchmark solution.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Solution variable</strong></td>
</tr>
<tr>
<td>Net system benefits ($)</td>
</tr>
<tr>
<td>Water use benefits ($)</td>
</tr>
<tr>
<td>Energy generation benefits ($)</td>
</tr>
<tr>
<td>Transportation costs for urban uses ($)</td>
</tr>
<tr>
<td>Transportation costs for agricultural uses ($)</td>
</tr>
<tr>
<td>Interbasin transfer costs ($)</td>
</tr>
<tr>
<td>Water release to the Gulf (Mm$^3$)</td>
</tr>
<tr>
<td>Total water withdrawal (Mm$^3$)</td>
</tr>
<tr>
<td>Total return flow (Mm$^3$)</td>
</tr>
<tr>
<td>Total agricultural water withdrawal (Mm$^3$)</td>
</tr>
<tr>
<td>Total urban water withdrawal (Mm$^3$)</td>
</tr>
<tr>
<td><strong>Major parameters</strong></td>
</tr>
<tr>
<td>Total tributary inflow (Mm$^3$)</td>
</tr>
<tr>
<td>Total reserve evaporation (Mm$^3$)</td>
</tr>
<tr>
<td>Minimum total withdrawal for agriculture (Mm$^3$)</td>
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<tr>
<td>Maximum total withdrawal for agriculture (Mm$^3$)</td>
</tr>
<tr>
<td>Minimum total withdrawal for urban use (Mm$^3$)</td>
</tr>
<tr>
<td>Maximum total withdrawal for urban use (Mm$^3$)</td>
</tr>
<tr>
<td><strong>Table 2. Benefits and costs allocation.</strong></td>
</tr>
<tr>
<td>Total</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td><strong>Summary</strong></td>
</tr>
<tr>
<td>Economic benefits ($)</td>
</tr>
<tr>
<td>Transportation costs ($)</td>
</tr>
<tr>
<td>Net economic benefits ($)</td>
</tr>
<tr>
<td>Economic benefits/transportation costs ($B/C$)</td>
</tr>
<tr>
<td><strong>Percentage distribution (%)</strong></td>
</tr>
<tr>
<td>Economic benefits total withdrawal</td>
</tr>
<tr>
<td>energy</td>
</tr>
<tr>
<td>urban withdrawal</td>
</tr>
<tr>
<td>agricultural withdrawal</td>
</tr>
<tr>
<td>Transportation costs urban withdrawal</td>
</tr>
<tr>
<td>agricultural withdrawal</td>
</tr>
<tr>
<td>transshipment</td>
</tr>
</tbody>
</table>
are derived, in a balanced fashion, from water withdrawals (67% in total—31% for urban uses and 35% for irrigation) and energy generation (33%). The $B/C$ ratios show that Turkey has the lowest transport cost related to water withdrawal, and Iraq the highest. Urban transportation costs make up the following shares of total transportation costs: 77% in Turkey, 43% in Syria, and 8% in Iraq.

Table 3 presents the optimum water withdrawals by country, basin, and use. Iraq’s withdrawals represent 88.3% of all withdrawals, Syria’s 7.3%, and Turkey’s 4.4%. The highest usage-specific withdrawal (73,073 Mm$^3$) is for agriculture in Iraq (83.5%). Turkey, with agricultural land nearly two thirds that of Iraq, withdraws only 2589 Mm$^3$. Total urban withdrawals (6317 Mm$^3$) are less than 10% of agriculture withdrawal (81,218 Mm$^3$). The Tigris contributes 67% of all withdrawals, and most of them take place in Iraq (64.6%) and for irrigation (61.2%). Most of the withdrawals from the Euphrates also take place in Iraq, and primarily for irrigation.

Table 3. Water withdrawals allocation.

<table>
<thead>
<tr>
<th>Basin and use</th>
<th>Total</th>
<th>Turkey</th>
<th>Syria</th>
<th>Iraq</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mm$^3$</td>
<td>%</td>
<td>Mm$^3$</td>
<td>%</td>
</tr>
<tr>
<td><strong>Basin and use</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Euphrates urban</td>
<td>2282</td>
<td>2.6</td>
<td>209</td>
<td>0.2</td>
</tr>
<tr>
<td>Tigris urban</td>
<td>4035</td>
<td>4.6</td>
<td>1026</td>
<td>1.2</td>
</tr>
<tr>
<td>Euphrates agricultural</td>
<td>26606</td>
<td>30.4</td>
<td>1548</td>
<td>1.8</td>
</tr>
<tr>
<td>Tigris agricultural</td>
<td>54612</td>
<td>62.4</td>
<td>1041</td>
<td>1.2</td>
</tr>
<tr>
<td><strong>Basin</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Euphrates</td>
<td>28,888</td>
<td>33.0</td>
<td>1757</td>
<td>2.0</td>
</tr>
<tr>
<td>Tigris</td>
<td>58,647</td>
<td>67.0</td>
<td>2067</td>
<td>2.4</td>
</tr>
<tr>
<td><strong>Use</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urban</td>
<td>6,317</td>
<td>7.2</td>
<td>1,235</td>
<td>1.4</td>
</tr>
<tr>
<td>Agricultural</td>
<td>81,218</td>
<td>92.8</td>
<td>2,589</td>
<td>3.0</td>
</tr>
<tr>
<td><strong>All basins and uses</strong></td>
<td>87,534</td>
<td>100.0</td>
<td>3,824</td>
<td>4.4</td>
</tr>
</tbody>
</table>

5 Cooperation and conflict: game-theoretic analyses
The implementation of the system-optimal resource allocation determined by the ETRBM requires that the three riparian countries agree to participate in this scheme. Their willingness to do so depends upon how the aggregate net benefits are shared, and whether individual countries are better off going their own way, or in smaller coalitions. The purpose of this section is to analyze these cooperation and conflict issues, using tools of cooperative game theory.

5.1 Individual and coalition strategies
Figure 2 illustrates country interactions under all possible configurations. Figure 2(a) illustrates the case of independent action by each country. Because of its upstream location, Turkey is the first to utilize optimally the resources within its border (step 1). Next, in step 2 Syria, taking the return flows and water released from Turkey as determined exogenously, utilizes optimally this input and the resources within its border. Finally, in step 3 Iraq utilizes optimally its internal resources and the water inputs from Turkey and Syria (releases and return flows). The step sequence reflects the dominance of upstream over downstream countries. In figure 2(b), the various two-country coalitions are presented. Diagram 1 displays the Turkey–Syria coalition, with Iraq acting independently. In step 1 Turkey and Syria utilize the resources available
within their territories jointly and optimally. In step 2 Iraq optimizes the use of its
own resources, together with the exogenous input from Turkey and Syria. Diagram 2
presents the Syria–Iraq coalition, with Turkey acting independently. In step 1 Turkey
optimally utilizes the available resources within its territory, and releases unused water
to the Syria–Iraq coalition, which takes this input as exogenous, and optimally utilizes
all its available resources. Diagram 3 explains the interactions between the Turkey–
Iraq coalition, and Syria acting independently. Because both the coalition and Syria
are affected by each other’s decisions and output, a stable solution is represented by a
Nash equilibrium, which is reached when the sequential optimizations stop because
there is no longer any change in their solutions. Figure 2(c) illustrates the grand
coalition, which is equivalent to the benchmark model.

The ETRBM is appropriately adjusted to reflect the optimization decisions of
individual countries and coalitions of countries. The notations for the optimal individ-
ual and coalition benefits derived from these decisions are presented in appendix A.

5.2 Core, Shapley value, and subsidy determination
Consider the total net benefit of the grand coalition, \( \text{NEB}_{\text{TSI}} \). This is clearly the
maximum aggregate benefit achievable by the three countries. The problem is to
allocate this aggregate benefit among the three countries in a way that will persuade
them to accept this allocation. Let \( X_T \), \( X_S \), and \( X_I \) be the benefits allocated to Turkey,
Syria, and Iraq, respectively. This allocation should then verify that

\[ X_T + X_S + X_I = \text{NEB}_{TSI}. \] (11)

To be sustainable, it should also verify both individual and coalition rationality constraints, so that no country acting alone or within a coalition, has an incentive to reject the allocation. The three coalition constraints are straightforwardly represented by equations (13)–(15), where \( \text{NEB}_{TS} \), \( \text{NEB}_{TI} \), and \( \text{NEB}_{SI} \) are the benefits achieved by the coalitions TS, TI, and SI, respectively. The case of the individual rationality constraints is more complicated. Indeed, a given country may act individually under two situations: (a) the other two countries also act individually, and (b) they act as a coalition. The benefits to the country in these two cases need not be the same. We assume that any country aims, conservatively, at guaranteeing itself the minimum of these two benefits, hence constraints (16)–(18).

Equality (11) and inequalities (13)–(18) may or may not have a solution. In order to find out, the standard approach is to transform this linear system into a linear program (LP), by optimizing any linear function of the variables \( X_T, X_S, X_I \). If the LP has no solution, the system of inequalities/equality has no solution, and the core is empty. A variation on this approach is to modify equation (11) by introducing a new variable, \( Z \), leading to equation (19), and to use \( Z \) as the LP objective function. The LP is represented by equations (12)–(19):

\[
\begin{align*}
\text{maximize} & \quad F = Z, \\
\text{subject to} & \quad X_T + X_S \geq \text{NEB}_{TS}, \\
& \quad X_T + X_I \geq \text{NEB}_{TI}, \\
& \quad X_S + X_I \geq \text{NEB}_{SI}, \\
& \quad X_T \geq \min\{\text{NEB}_T, \text{NEBS}_{TS}\} = \text{NEB}_{T}^{\text{MIN}}, \\
& \quad X_S \geq \min\{\text{NEBS}, \text{NEBS}_{TI}\} = \text{NEB}_{S}^{\text{MIN}}, \\
& \quad X_I \geq \min\{\text{NEBI}, \text{NEBS}_{TS}\} = \text{NEB}_{I}^{\text{MIN}}, \\
& \quad X_T + X_S + X_I + Z = \text{NEB}_{TSI}.
\end{align*}
\] (19)

If the optimal \( Z^* \) is strictly equal to zero, the core exists but is reduced to only one acceptable allocation. If \( Z^* \) is positive, the core is nonempty and made of an infinite number of feasible allocations. The allocation obtained with \( Z^* \) is sustainable and allows a supragovernmental authority to extract the maximum benefits from the three countries for future use. In this case, \( Z^* \) can be viewed as the maximum tax. If \( Z^* \) is negative, the core is empty. However, if a benefit subsidy in the amount (absolute value) of \( Z^* \) were added to \( \text{NEB}_{TSI} \), a sustainable allocation would be obtained.

Although the core may not always exist, a unique imputation is always obtained via the Shapley method, which is based on the power of each player, as measured by the weighted additional benefits resulting from the addition of this player to all the possible coalitions not including that player (Shapley, 1953). This imputation may be out of the core. Let \( B(S) \) be the benefit derived by coalition \( S \) not including player \( i \), and \( B(S \cup i) \) the benefit of the expanded coalition \( S \cup i \). The incremental benefit for player \( i \) of joining coalition \( S \) is then given by \( B(S \cup i) - B(S) \). This incremental benefit must be weighted by the joint probability \( P(i, S) \) of the coalition \( S \) being chosen, and
player $i$ joining coalition $S$. The Shapley value, $V_i$, for player $i$ is then
\begin{equation}
V_i = \sum_{\forall S} P(i, S) \left[ B(S \cup i) - B(S) \right].
\end{equation}

Given $n$ players, and $s$ players in coalition $S$, the probability is computed as follows:
\begin{equation}
P(i, S) = \frac{s!(n-s-1)!}{n!}.
\end{equation}

To illustrate the application of the Shapley method, consider the case of Iraq as the player joining other coalitions. The first case is that of Iraq joining the ‘empty’ coalition, with the incremental benefit, $I_i$:
\begin{equation}
I_{i/\emptyset} = \text{NEB}_{\text{min}}^i.
\end{equation}

Next, Iraq can join either Turkey or Syria, with the incremental benefits:
\begin{align*}
I_{i/T} &= \text{NEB}_T - \text{NEB}_{\text{min}}^T, \\
I_{i/S} &= \text{NEB}_S - \text{NEB}_{\text{min}}^S.
\end{align*}

Finally, Iraq can join the Turkey–Syria coalition, with the incremental benefits:
\begin{equation}
I_{i/TS} = \text{NEB}_{TS} - \text{NEB}_{\text{TS}}.
\end{equation}

### 5.3 Benefits under different cooperation scenarios

Sensitivity analyses of the benchmark model, reported in Kucukmehmetoglu (2002), show that the most critical parameters are the price of energy (electricity), and the value of water for agriculture. Nine scenarios involving various combinations of values for these parameters have been used as exogenous inputs to the modeling approach presented in the previous sections. These scenarios are presented in table 4. The energy price varies from $0/M\text{Wh}$, implying no demand for hydroelectricity, to a high of $100/M\text{Wh}$. The water value for agriculture is expressed in terms of productivity weights. Case B, where the weights are all equal to 1.0, corresponds to the benchmark value of £25 000/Mm$^3$. Case A corresponds to a 20% increase in this value for Turkey and Iraq, respectively. Case C corresponds to the reverse situation. In all cases, Syria’s water value remains at its benchmark level. These parameter combinations allow an assessment of the trade-offs between the two major sources of benefit for the three countries, energy and agriculture, and how these trade-offs enhance or inhibit cooperative agreements.

The benefits for each country under each parameter–cooperation scenario have been computed according to the procedure outlined in section 5.1, and are available from the authors. As expected, benefits increase with (a) increasing energy prices ($P_e = $0 $\rightarrow$ $25 \rightarrow$ $100$), and (b) a shift of agricultural productivity from Turkey (case A) to Iraq (case C). For instance, the maximum benefit of $1590117000$ under scenario A1 increases to $6875319000$ under scenario C3. Under the grand coalition,
Turkey is by far the major beneficiary of an increase in the energy price, with its benefits increasing 9 to 18 times. This is not surprising in view of the hydropower infrastructure developed under the GAP. In contrast, the benefits to Syria and Iraq increase four-fold and less than two-fold, respectively, under the same price shift. Under the agricultural productivity shift from Turkey (A) to Iraq (C), Iraq’s benefits increase between 30% and 50%, the lesser increase corresponding to the higher energy price, simply because more water is left in-stream to produce hydroelectricity.

5.4 Core analyses and Shapley allocations

This section presents the results obtained by (1) solving the linear program, and (2) applying the Shapley formula. A core exists in all nine cases: five have a single-allocation core, and four (B1, C1, A2, B2) have a multiple-allocation one. The Shapley allocation is never in the core.

Table 5 presents the optimal values of $Z$ (always $\geq 0$). Positive $Z$ values represent the maximum extractable taxes, which vary between 0.00% and 1.75% of the grand coalition benefits. The largest core corresponds to scenario C1, with a zero energy price and the highest agricultural productivity in Iraq. The other multiple-allocation cores are much smaller, pointing to less room for negotiation within the core.

Table 5. Optimal Z-values and grand coalition benefits.

<table>
<thead>
<tr>
<th>Agricultural productivity scenario</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy price 1</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tax/subsidy Z ($ thousand)</td>
<td>0.00</td>
<td>1.865</td>
<td>37.612</td>
</tr>
<tr>
<td>$Z/B$ (%)</td>
<td>0.00</td>
<td>0.10</td>
<td>1.75</td>
</tr>
<tr>
<td>Grand coalition benefit ($ thousand)</td>
<td>1,590,117</td>
<td>1,842,881</td>
<td>2,149,350</td>
</tr>
<tr>
<td><strong>Energy price 2</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tax/subsidy Z ($ thousand)</td>
<td>2.013</td>
<td>3.717</td>
<td>0</td>
</tr>
<tr>
<td>$Z/B$ (%)</td>
<td>0.08</td>
<td>0.13</td>
<td>0.00</td>
</tr>
<tr>
<td>Grand coalition benefit ($ thousand)</td>
<td>2,600,295</td>
<td>2,918,320</td>
<td>3,275,643</td>
</tr>
<tr>
<td><strong>Energy price 3</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tax/subsidy Z ($ thousand)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$Z/B$ (%)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Grand coalition benefit ($ thousand)</td>
<td>6,249,967</td>
<td>6,521,555</td>
<td>6,875,320</td>
</tr>
</tbody>
</table>

The minimum benefits allocation corresponds to what each country would gain at a minimum, were it to act alone, and thus constitutes the benchmark with which the other allocations can be compared. Table 6 presents the incremental benefits derived by each country in accepting the core allocation [as obtained by solving equations (12)–(19)] over the minimum benefits. In absolute terms, Iraq gains the most from complete cooperation, followed by Turkey, whereas Syria achieves the least gains. When these gains are related to the minimum benefits, they display much less variability, and the largest gain is achieved by Turkey under C2 (3.15%), followed by Iraq under A3 (2.60%), and Syria under A2 (2.40%). The gains to Iraq increase with its agricultural productivity at the lowest energy price, but decrease with this productivity at the highest energy price. There are, however, no clear patterns for the gains of Turkey and Syria. In six out of the nine scenarios, Syria achieves no gain at all.

Table 7 presents the benefit differential between the Shapley and the “core-augmented” allocations, which involve adding to the core allocation [equations (12)–(19)] an allocation of the optimal tax $Z^*$, so that the sums of both allocations are equal, and their differentials necessarily sum to zero. To illustrate, consider the case of country k,
and let \( X_k \) and \( V_k \) be the maximum-tax benefit allocation [equations (12)–(19)] and Shapley allocation, respectively. Let \( Z^* \) be the maximum tax. We have, necessarily:

\[
Z^* + \sum_{k} X_k = \sum_{k} V_k .
\] (26)

The core-augmented solution \( Y_k \) is then computed as follows:

\[
Y_k = X_k + \frac{V_k}{\sum_{k} V_k} Z^*. \] (27)

Scenarios C1 and A3 provide the highest gains under Shapley to Turkey and Syria, to the detriment of Iraq. Similar, but smaller gains (losses), take place under scenarios B1, B2, and B3. Under scenario C2, Iraq gains significantly, to the detriment of Turkey. A similar, but smaller, gain is achieved by Iraq under scenario C3. A gain by a country reflects the incremental benefits that its joining other countries helps achieve. Although it is clear that these gains are larger under extreme cases of energy prices and agricultural productivity, the results in table 7 do not point to extensive correlational patterns between gains and parameter scenarios.
6 Conclusions
The major contributions of this paper are, first, the development of the ETRBM as a backbone model and, second, its application, using the best available data, to analyze whether it is possible to find a distribution of the total ETRBM benefits to the three riparian countries—Turkey, Syria, and Iraq—that will provide them with incentives to join the water-allocation plan that provides the maximum aggregate benefits. This assessment requires an in-depth analysis of the decisionmaking processes of the three countries and any of their coalitions. Using concepts and methods of cooperative game theory, various scenarios of energy price and agricultural productivity were considered, and turned out to be characterized by nonempty cores, where cooperation can be rationally induced.

This research could be extended along several lines. First, the current model could be improved with a more disaggregated representation of the agricultural sector, accounting for various possible crops and their specific benefits. Second, the time dimension could be introduced into the model, to account for both seasonal and multiannual flow variations, and for the role of reservoirs in smoothing these variations. Stochastic programming might be used to account for weather and flow randomness. Third, a multiyear framework would provide the opportunity to model water-related investment decisions (for example, interriver canals) over time, accounting for complex technical and political scheduling issues. The cooperative game theory framework could then be extended over time, possibly along the lines suggested by Dufournaud and Harrington (1990). Finally, environmental considerations could be introduced into the model. Salinity, particularly in the basin's lower reaches, could be modeled along the lines proposed by Booker and Young (1994), and wastewater and water treatment could be modeled along the lines proposed by Mahan et al (2002). Also, groundwater resources, their use, and their interactions with surface river waters, could be modeled into the ETRBM. All these extensions are contingent upon the availability of quality data, which remains a serious problem in the Middle East.

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Appendix A

Indices

\(i\) is a demand node (1 to 63),
\(j, l\) are supply nodes (1 to 45),
\(A\) is a set of agricultural demand nodes,
\(U\) is a set of urban demand nodes.

Variables

\(\text{NEB}\) is total benefit net of transportation costs ($),
\(Q_{jl}\) is internodal flow (from node \(j\) to node \(l\)) (Mm³),
\(Q_{21,12}\) is total water transfer within Syria through link 21 to 12 (Mm³),
\(Q_{28,14}\) is total water transfer within Iraq through link 28 to 14 (Mm³),
\(Q_{31,16}\) is total water transfer within Iraq through link 31 to 16 (Mm³),
\(W_{ji}\) is water transferred from supply node \(j\) to demand node \(i\) (Mm³),
\(\text{NEBT}\) is net economic benefit to Turkey, all countries acting independently ($),
\(\text{NEBS}\) is net economic benefit to Syria, all countries acting independently ($),
\(\text{NEBI}\) is net economic benefit to Iraq, all countries acting independently ($),
\(\text{NEBT}\) is net economic benefit to Turkey and Syria acting as a coalition ($),
\(\text{NEBI}\) is net economic benefit to Iraq given the TS coalition action ($),
\(\text{NEBSI}\) is net economic benefit to Syria given the TI coalition action ($),
\(\text{NEBT}\) is net economic benefit to Turkey and Iraq acting as a coalition ($),
\(\text{NEBSI}\) is net economic benefit to Syria and Iraq acting as a coalition ($),
\(\text{NEBTSI}\) is net economic benefit to Turkey, Syria, and Iraq in the grand coalition ($).

Parameters

\(C_{\text{ag}}\) is the agricultural water transport unit cost ($ per Mm³ per km),
\(C_{\text{ur}}\) is the urban water transport unit cost ($ per Mm³ per km),
\(V_{\text{ag}}\) is the agricultural water unit value ($ per Mm³),
\(V_{\text{ur}}\) is the urban water unit value ($ per Mm³),
\(C_{\text{sl}}\) is the internodal water transport unit cost ($ per Mm³ per km),
\(D_{ji}\) is the distance from supply node \(j\) to demand node \(i\) (km),
\(D_{jl}\) is the distance from supply node \(j\) to supply node \(l\) (km),
\(P_{e}\) is the energy price for electricity ($ per MWh),
\(E_{j}\) is the electricity generation rate for a node-\(j\) dam (MWh per Mm³),
\(\text{min}_{\text{ag}}\) is the minimum agricultural consumption rate (Mm³ per ha),
\(\text{max}_{\text{ag}}\) is the maximum agricultural consumption rate (Mm³ per ha),
\(\text{min}_{\text{ur}}\) is the minimum urban consumption rate (Mm³ per inhabitant),
\(\text{max}_{\text{ur}}\) is the maximum urban consumption rate (Mm³ per inhabitant),
\(L_{j}\) is the reservoir-evaporation loss at supply node \(j\) (Mm³),
\(F_{ij}\) is the return flow rate from demand node \(i\) to supply node \(j\),
\(S_{i}\) is the size of demand node \(i\) (hectares for agricultural nodes, inhabitants for urban nodes),
\(T_{j}\) is the tributary inflow at node \(j\) (Mm³).
Appendix B
This appendix provides an overview of data sources, assumptions, and derivations of model parameters. For more details, see Kucukmehmetoglu (2002). Because of a lack of data on the E–T basin, some of the parameters are derived from water-related studies on other Middle Eastern countries and the USA. Also, the ETRBM reflects the planned dam infrastructure, to be completed in 2040. This future supply is matched with corresponding water-demand forecasts, derived from population and agricultural expansion forecasts. Although an earlier terminal date (for example, 2020) might have reduced the uncertainty in long-term demand forecasts, no data were available on the corresponding infrastructure.

B1 Supply data
Data on the water contributions of each riparian country are available in Kolars (1986; 1992; 1994), Kolars and Mitchell (1991), Kliot (1994), and Bagis (1989). However, these data do not include detailed tributary inflows at each confluence. Therefore, total country contributions must be apportioned among all tributaries. Nevertheless, the major tributary inflows for the Greater and Lesser Zab, Diyala, and Adhaim rivers, are available. The remainder is assigned using secondary data, such as energy generation and dam heights.

Return-flow data are available in the literature at the country level. There are also return-flow data for the major tributaries of the Tigris in Iraq (Kolars, 1992; 1994; Kolars and Mitchell, 1991). The other data found in the literature are the expected return flows in conjunction with withdrawals for planned irrigation areas, specifically for the Euphrates in Turkey and Syria. From these figures, the necessary return-flow rates are computed by dividing return flows by the quantity of water withdrawn. Because these rates do not vary much across agricultural districts, they are applied to the other irrigation districts. Return-flow destinations (supply nodes) are inferred from maps and catchment area data for the basin. The overall return-flow rate is 35% for agriculture, and 80% for urban use.

Evaporation losses are functions of the depth and surface area of a reservoir, and ambient temperature. Because data are not available to model precisely the relationship between reservoir depth, surface area, volume, and net flow, evaporation rates (per km$^2$) are computed for the three riparian countries, based on observed annual evaporation quantities and reservoir surface areas for the major reservoirs in the Euphrates basin (Altinbilek, 1997). These rates are applied to the other reservoirs, yielding annual average evaporation rates for each supply node.

B2 Demand data
B2.1 Agricultural areas and urban populations
Productivity of agricultural land and water demand per hectare vary, because of climatic differences along the river basin. Located in the northern part of the system, Turkey has a relatively lower water demand per hectare than Iraq and Syria, because it has more rainfall, less evaporation, and less exposure to salinity and overutilization.

There are twenty-one agricultural districts (nodes) in the Euphrates basin, and sixteen in the Tigris basin. Total planned irrigable land areas for each riparian country are available in the literature (Bagis, 1989; FAO, 1993; Kliot, 1994; Kolars, 1986; 1992; 1994; Kolars and Mitchell, 1991), with 1770 956 ha for Turkey, 1040 000 ha for Syria, and 5833 000 ha for Iraq, or a total of 8643 956 ha for the whole region along the two rivers. These figures are assumed to apply to the year 2040. In the case of Iraq the planned irrigation areas include 4000 000 ha in the Tigris basin, and 1833 000 ha in the Euphrates basin (up from 2.00 and 1.29 million ha in 1990, respectively). In the case of Turkey, data on each irrigation district and their associated supply nodes are available in
Altinbilek (1997), corresponding to the completion of the GAP project. Irrigable areas are available only at country or regional level for Syria and Iraq. The delineation of irrigation districts was made using existing irrigation maps. Because of 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 km and 40 km.

There are eight urban demand nodes in Turkey (South Eastern Anatolia Region), eight in Syria, and ten in Iraq. These nodes are constituted by cities having 100 000 or more inhabitants. Historical population data for these cities, drawn from [http://www.library.uu.nl/wesp/populstat/Asia/](http://www.library.uu.nl/wesp/populstat/Asia/), and ranging, in varying numbers, from 1965 to 1995, have been used to estimate constant-growth models through regression analysis. The models have been used to project city populations to 2040. From 2000 to 2040 the cities selected in Turkey are projected to grow from 2.7 to 23.1 million, the cities in Syria from 5.8 to 28.9 million, and the cities in Iraq from 10.7 to 65.4 million. These projections should be viewed as upper-bound estimates, as it is very unlikely that the recent and current growth rates are sustainable over the very long term. Most of the urban nodes are located close to the rivers, except for a few cases such as Aleppo (312 km) and Latakia (208 km).

**B2.2 Agriculture and urban water values**

Dinar and Wolf (1994b) use a value of \$300 000/Mm\(^3\) for agricultural and urban uses in Israel, where the value of water is market determined, with both the domestic and agricultural sectors expected to purchase water at the same price. In contrast, they value water at \$6000/Mm\(^3\) in Egypt, which is characterized by low-technology economic returns from intensive water-consuming agriculture. Howitt et al (1982) provide water prices data for Southern California, whose climate is comparable to the E–T basin climate, with urban water valued at \$292.638/Mm\(^3\) and agricultural water at \$1611/Mm\(^3\). Using the mid-ranges of the above intervals (\$0 – \$300 000/Mm\(^3\) for urban use, and \$6000 – \$52 000/Mm\(^3\) for agricultural uses), the following values are selected: \(V^{ur} = \$150 000/Mm^3\), \(V^{ag} = \$25 000/Mm^3\). Using an urban value significantly lower than in Israel or Southern California reflects the lesser industrial development of the E–T countries. The agricultural value reflects a compromise between low (Egypt) and high (Southern California) productivities.

**B2.3 Maximum and minimum consumption rates**

Dinar and Wolf (1994b) indicate that the minimum amount of water to sustain agriculture corresponds to sprinkler irrigation systems (0.015 Mm\(^3\)/ha), and the maximum amount to surface irrigation (0.020 Mm\(^3\)/ha). Howe and Easter (1971) indicate that the smallest amount of water providing the minimum incremental benefit for agriculture is 0.00107 Mm\(^3\)/ha, whereas the amount providing the maximum incremental benefit is the maximum water withdrawal of 0.01337 Mm\(^3\)/ha. Using the upper-bound estimate of Dinar and Wolf (1994b), we select max\(^ag\) = 0.020 Mm\(^3\)/ha. We allow for the possibility that some districts may not be irrigated by the E–T, with min\(^ag\) = 0.0 Mm\(^3\)/ha, to avoid having districts irrigated at a net loss in the optimal solution (economic unit benefit smaller than transportation unit cost). It is assumed that such districts would obtain water from non-E–T sources (for example, underground waters).

Dinar and Wolf (1994b) provide water budgets for Egypt, Israel, the West Bank, and the Gaza Strip. The minimum amount of water consumed by the domestic and industrial sectors is 0.0000325 Mm\(^3\)/capita in the Gaza Strip, and the highest amounts pertain to Egypt (0.000126 Mm\(^3\)/capita) and Israel (0.000106 Mm\(^3\)/capita). The value in Israel is selected as the maximum rate max\(^ur\). For reasons similar to the agricultural case, min\(^ur\) = 0.0.
B3 Water-transportation costs
Internodal distances are measured through map analysis as straight-line distances. Each demand node is assigned to the most accessible supply node. In the case of agricultural nodes, the distances represent averages over the district area. Transportation costs are derived from Hirshleifer et al. (1969), who provide conveyance unit costs for systems using pumping or gravity, and for different capacity levels (Mm³ per year). Determining when pumping or gravity are appropriate would have required detailed engineering and geographical (terrain) studies that were beyond the scope of this research. The pumping unit costs were selected, as they provide upper-bound estimates, with the highest capacity (138.15 Mm³ per year) for agriculture, and the second highest (2.763 Mm³ per year) for urban use, with: $C_{ag} = $850/Mm³ per km, and $C_{ur} = $4958/Mm³ per km. The transport unit cost for interbasin links is assumed to be the same as for agricultural projects, with $C_{SS} = $850 per Mm³ per km.

B4 Electricity generation
The electricity-generation capacities of the dams and the expected total annual energy generations are available for every dam in the Turkish sections of the Euphrates and Tigris, but not for Syria (with minor exceptions) and Iraq. The average electric generation rate is 0.87 kWh per foot-head and acre-feet of water (Gibbons, 1986). The annual energy generation capacities of the dams have been converted into electricity generation per Mm³ of water released from the head of the dam. In order to estimate these figures, dam heights are needed. Turkey has the advantage of generation from high-head dams. Syrian and Iraqi dams are of limited size. The literature provides head heights 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 m and 35 m, in view of the change in elevation through Syria and Iraq. For instance, the Euphrates in Iraq has a 200 m elevation change from the Syrian border to the Gulf. The unknown head heights are assigned under the following assumptions: (1) all dams have electric generation capacities, unless otherwise stated in the literature; (2) if a dam is in mountainous terrain, the height is 35 m; (3) if the dam is in flat area, the height is 20 m.