



# Stability Analysis of Stakeholders' Cooperation in Inter-Basin Water Transfer Projects: a Case Study

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## Abstract

This study investigates the conflict resolution among different stakeholders in a water transfer project. The portion of the Beheshtabad Water Transfer Project in Iran which aims to convey water from the Karun Basin to the Gavkhuni Basin is used as a case study. In this process, the initial water allocation scheme is initially determined through simulation in MODSIM ignoring the water transfer project. Then, the concepts of cooperative and non-cooperative games are used to resolve the conflict among the stakeholders. The profits of water transfer project and the payoffs for each player are calculated using an optimization model that optimizes the allocation of the conveyed water. The results of the conflict resolution model show that bilateral cooperation is the best strategy the players may adopt. In the non-cooperative model, it is found that a water transfer agreement that is incentivized by an average payment of 250.66 million US\$ as compensation from the Gavkhuni basin to the Karun basin puts both basins at equilibrium with a Pareto optimal condition; in this case, none of the players will be willing to abandon the cooperation without regret. In the cooperative approach, cooperation is found to be beneficial to all the players involved.

**Keywords** Water allocation · Optimization · Conflict resolution · Game theory · Incentive payment · MODSIM model

## 1 Introduction

The uneven spatial distribution of water resources in Iran and their drastic contribution to the interests and profits of different (e.g., agriculture, industrial and domestic) sectors call for resource management solutions

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that address in a proper manner the emerging regional water scarcity and improve the overall resource utilization (Karamouz et al. 2009a). One such solution to which a lot of research effort has been devoted and is most often contemplated or even practiced, is the inter-basin transfer of water from basins with rich water resources to degraded or economically underdeveloped ones (Zi-hui 2006; Karamouz et al. 2009b).

A great many inter-basin water transfer projects have been executed in different parts of the world. The experiences gained by such countries as India and Japan (Joshi 2013; Dai et al. 2017) indicate that inter-basin water transfer projects generally involve multiple stakeholders with different and often conflicting interests and preferences. Typically, the stakeholders close to the source basin oppose water transfer projects to preserve the economic and environmental status quo, while those near the receiving basin support the project to secure the water needed for regional development. These conflicts among stakeholders can be caused or intensified by economic, environmental, political, social, and technical issues (Karamouz et al. 2009b).

Conflict resolution models such as the game theory can be used to analyze such differences toward reallocation of profits resulting from optimal resource allocation among the parties involved. The ability of game theory to account for players' strategies and their behaviors in response to a strategy adopted by opponents make it a powerful conflict resolution tool (Madani 2010). Already, this theory has been extensively used in various fields of water resource management such as water allocation among users and its economic consequences (Wang et al. 2008; Sechi et al. 2013; Mehrparvar et al. 2016), groundwater management (Loaiciga 2004; Raquel et al. 2007; Parsapour-Moghaddamai et al. 2015), allocation of cross-border water resources (Kucukmehmetoglu and Guldmén 2004; Mianabadi et al. 2014), and water quality management (Nikoo et al. 2012; Zolfagharipour and Ahmadi 2017).

The utility of conflict resolution models for water transfer projects has been shown by researchers. Mahjouri and Ardestani (2010) used cooperative games for water reallocation in inter-basin water transfer projects based on economic and environmental criteria. Sadehgh et al. (2010) provided a method based on fuzzy coalitional game for optimal allocation of water resources based on economic and fairness criteria. Manshadi et al. (2015) developed a new methodology based on combining virtual water concept and cooperative game theory in water transfer projects to achieve sustainable development. The results of these studies show that the cooperative game theory can improve the benefits of players, that is, increase the economic profits from water use while water quality issues are also duly addressed. Mahjouri and Ardestani (2011) optimized economic water allocation with due regard to physical and environmental constraints using both cooperative and non-cooperative methodologies. Results revealed that cooperation among water users guaranteed maximum profits of water resource utilization.

A quick review of past studies reveals that inter-basin water transfer projects pay limited attention to basin conditions before and after project execution. In this study, this deficiency in the past studies is duly addressed by considering the pre-transfer conditions of both the source and the receiving basins. For this purpose, the initial scheme of water allocation to different consumers is simulated at the planning horizon in the MODSIM model based on existing surface and groundwater resources as well as the water demands by the consumers. Also, post-transfer conditions are examined by linking with pre-transfer simulation results using the game theory model. This theory is specifically used to resolve the conflicts among the different stakeholders over the implementation of a water transfer project. The conflict resolution model includes water reallocation based on optimal water transfer volumes with the objectives of maximizing the economic profits of the stakeholders and taking into account the environmental constraints on water quality.

Most previous studies used the cooperative game theory to analyze water transfer conflicts. In the few cases that used the non-cooperative approach, players' strategies were mostly prioritized based on qualitative and ordinal criteria. The present study, however, is different in that it deals with conflict resolution using both cooperative and non-cooperative approaches. The non-

cooperative model utilizes a system of incentive payment and a strategy quantification scheme to achieve greater profits. In this model, the outcomes of the players' strategies are analyzed in the light of definitions of stability. The efficacy of the proposed model is finally evaluated through the analysis of Beheshtabad Water Transfer Project in Iran used as a case study.

## 2 Methodology

The main steps of the proposed methodology (Fig. 1) are: collection of the required data and information, simulation of initial water allocation scheme, development of an optimization model, and conflict resolution among the stakeholders. The first step involves an investigation of the water reserve and consumption conditions at the source and receiving basins and the collection of the information required for simulation and optimization.

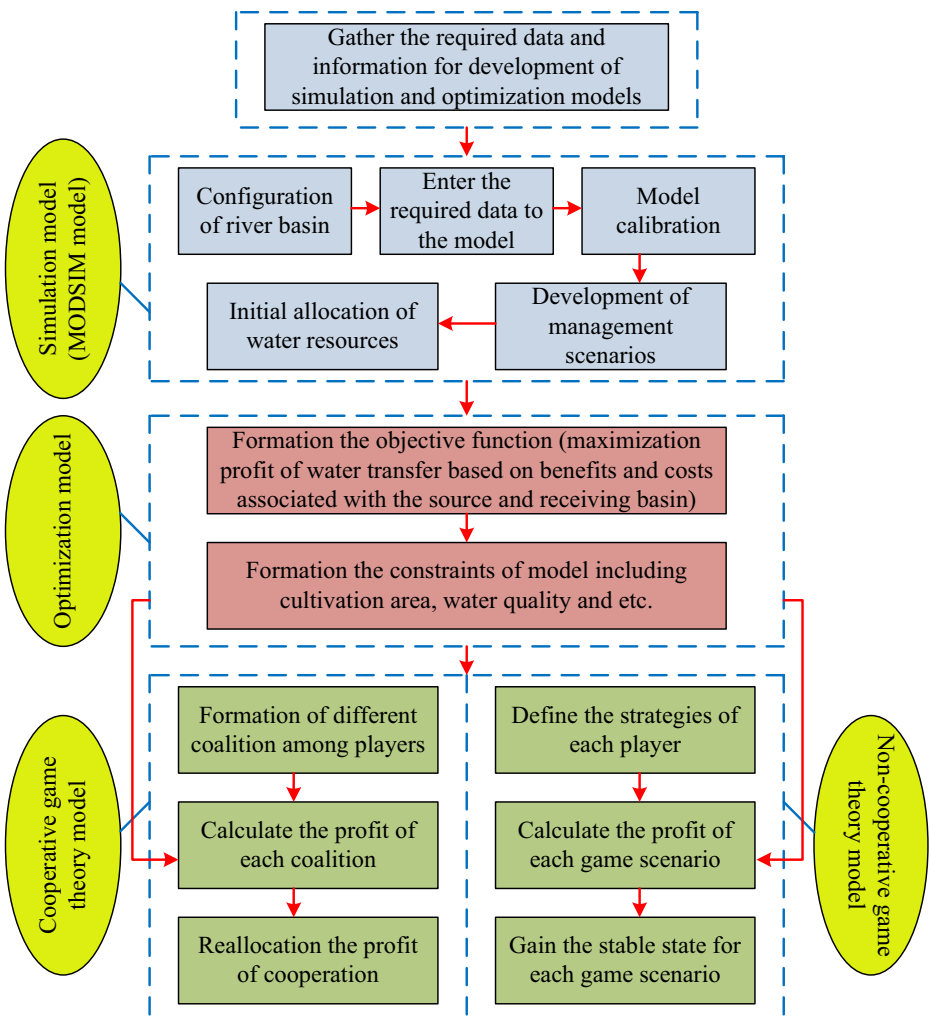


Fig. 1 Structure of optimal water transfer model considering opposite utility of stakeholders

To resolve conflicts over water allocation plans, an initial scheme of allocating surface and ground water resources among the different (e.g., agricultural, industrial, and domestic) sectors is needed that is obtained through simulation in the MODSIM model (Labadie 1995). In MODSIM, water allocation mechanisms of the river basin are simulated by sequential solution of the network flow optimization problem for each time period. Further information about MODSIM and its applications may be found in Fredericks et al. (1998). In the present paper, the initial water allocation is based on the basins' historical records, ignoring the water transfer project. The steps of MODSIM model setup are shown in Fig. 1.

The next step is the development of an optimization model to determine the optimal volume of water transferred through maximization the profits of water allocation to different consumers under environmental constraints. Descriptions and assumptions of the optimization model are presented in the Appendix Section. The game theoretic model is then used to resolve the conflicts regarding the water transfer project. In this process, the players are characterized before solutions are examined through cooperative and non-cooperative approaches.

One of the most important conditions of cooperative games is that the payoff allocated to a player after this cooperation should be greater than the payoff from the initial allocation without cooperation. This condition can be satisfied by the use of such payoff reallocation methods as the Shapley Value (Shapley 1953). Further information may be found in Mahjouri and Ardestani (2010). Also, The impacts of a player's departure from the cooperative coalition on his own and others' profit shares can be determined by the Gately Index (Gately 1974), which is the ratio of the loss inflicted on other players to the loss incurred by the player himself.

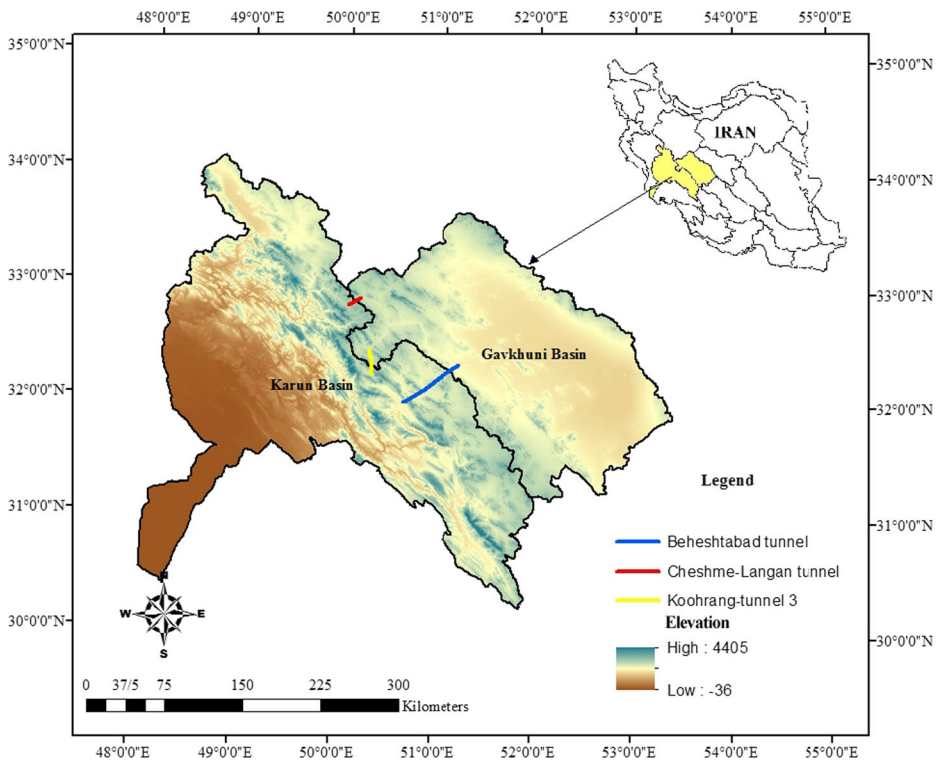
In the non-cooperative approach, analysis will be performed quantitatively in the form of a matrix game. The optimization model is used to quantify the players' strategies within the framework of incentive payment. Finally, the outcomes of the strategies are analyzed with the help of stability definitions. In the context of a game theory, stability or equilibrium refers to the final state of the play – i.e., when no player is willing to alter the set of decisions already made (Madani and Hipel 2011). In this study, four indices are employed to examine the equilibrium of the non-cooperative game. Further information on these stability indices can be found in Madani and Hipel (2011).

### 3 Case Study

The Beheshtabad Water Transfer Project is used as the case study. The project is expected to transfer 580 MCM of water annually from the Karun basin into the central Iranian plateau. One of the most important goals of this project is to meet the domestic demand by the major cities located in central plateau, which suffer from insufficient regional fresh water resources. In this study, we will focus on that part of the project that aims to transfer an annual amount of 250 MCM of water to the Gavkhuni basin (part of Iran's Central Plateau). Figure 2 shows the planned route of water transfer between the Karun and Gavkhuni basins. A major part of the data was obtained from the Iranian Ministry of Energy (2012).

### 4 Results

The proposed model was applied to four management scenarios. In view of the scarcity of water resources in the region, none of these scenarios considers agricultural growth or development. The four scenarios are: 1) Water resources, demands, and consumption in both basins are



**Fig. 2** GIS view of Karun and Gavkhuni basins and Beheshtabad water transfer project

assumed to be the same as they were in 2006. 2) Water resources are assumed to be the same as in the previous scenario, except that consumption is assumed to grow at the typical growth rates of domestic and industrial sectors. Demands and consumption are based on the 2021 Development Plan in Iran. 3) This scenario is similar to the previous one, but it takes account of the ongoing projects that will transfer water from Koohrang-tunnel 3 and Cheshme-Langan to the Gavkhuni basin, amounting to 231 MCM and 176 MCM per year, respectively. 4) This is similar to the previous scenario, except that improved irrigation efficiency (through the development of pressurized irrigation systems) is also considered in the demand management.

An initial scheme for allocating the surface and ground water resources to the different sectors in the region was obtained through simulation in MODSIM. In this initial allocation model, the water transfer project was ignored. Prioritization of sectors in the scheme was based on traditional policies practiced in the region, in which water would be allocated to users based on their historical water rights. This led to the order: domestic>industry>agriculture>environment. The water demands at present and at the end of the planning horizon by the different sectors in both the Karun and Gavkhuni basins were imported into MODSIM as monthly, seasonal, and annual data. The amounts of water to be transferred were also imported into the software as monthly data. In the course of modeling the return flow from each sector, the specifications of the dams and reservoirs were also defined. The data provided to the software covered a period of 41 years. This data was made available by the Iranian Ministry of Energy (2012). Please refer to the Appendix Section to see the MODSIM model calibration charts (Figs. 3 and 4) and simulation results (Table 4) for water allocation to different sectors.

#### 4.1 Cooperative Approach

The stakeholders in the basins (players) are Gavkhuni's agriculture (A), Gavkhuni's industry (B), and Karun's agriculture (C) sectors. The profits from cooperation under different coalitions, the results of profit redistribution, and the players' side payment to each other under each scenario are reported in Table 1. The grand coalition is formed by the presence and cooperation of all the players. According to this Table, the players in the grand coalition will gain greater profits than those working individually outside the coalition. As can be seen, B and C gain more profits than A does, which is because of B and C's presence in the coalition and the value of the water allocation function. C affects the formation of coalition because of its effect on the transfer of water to the Gavkhuni basin. In fact, initiation of the game itself depends on C's participation in the coalition. As a result, A and B make the same profits from their coalition as they would from the initial allocation. It is also seen that the water allocation function for the industrial sector has a high value, which leads to the greater profit for this sector under all the scenarios. In Scenario 3, for example, the development of the industrial sector after water transfer into the Gavkhuni basin leads to the sharpest growth in B's profits.

Cooperation among the players might be associated with gains by or even losses to the players in the coalition. It is, therefore, necessary to use the profit redistribution method in order to share out in a fair manner the overall profit gained from the cooperation among all the players (i.e., in proportion to each player's contribution to the increase in total profit); in this way, each player's profit increases compared to that at the initial point. In this method, losses to players are compensated for by those who received increased shares of the total profit (side payments). According to Table 1, all the players gain more profits after profit redistribution than they would under the initial allocation scheme. This occurs when A and B allocate amounts to C in the different scenario. With these side payments, each player gains more from the coalition than from the noncooperation situation, which motivates all to stay in the coalition.

Fig. 5 shows the percentage of each player's impact on the increased profit from water transfer under different coalitions for each scenario. Generally, the Gavkhuni's industry (player B) is the most effective sector in increasing profits under the different coalitions. It is also seen

**Table 1** Results of different coalition and profit reallocation (million US Dollars)

Scenario	Players	Initial allocation	AC coalition	BC coalition	AB coalition	Grand coalition	Reallocation	Side payments
1	A	237.73	245.86	237.73	237.73	241.77	239.04	-2.74
	B	1040	1040	1540	1040	1540	1288.29	-251.83
	C	358.75	354.56	356.66	358.75	354.56	609	254.57
	Total	1636.48	1640.42	2134.39	1636.48	2136.33	2136.33	0
2	A	228.43	237.49	228.43	228.43	233.99	229.72	-4.29
	B	1353.67	1353.67	1856	1353.67	1856	1603.78	-252.53
	C	354.59	346.21	348.31	354.59	346.21	602.7	256.82
	Total	1936.69	1937.37	2432.74	1936.69	2436.2	2,4236.2	0
3	A	236.1	244.78	236.1	236.1	240.97	237.03	-3.89
	B	1502.08	1502.08	2000	1502.08	2000	1748.89	-251.5
	C	354.77	346.37	348.47	354.77	346.37	601.42	255.39
	Total	2092.95	2093.23	2584.57	2092.95	2587.34	2587.34	0
4	A	246.6	254.7	246.6	246.6	250.71	247.57	-3.14
	B	1457.53	1457.53	1976.17	1457.53	1976.17	1714.47	-261.7
	C	368.73	361.03	362.45	368.73	361.03	625.87	264.84
	Total	2072.86	2073.26	2585.22	2072.86	2587.91	2587.91	0

in the diagram that the industrial sector has a greater effect under Scenario 2 than under Scenario 1; this is because industrial development occurs under Scenario 2. Moreover, this sector receives its maximum allowable water due to the high value of its profit function.

Table 2 shows the losses incurred by the players when a coalition member leaves the coalition under different scenarios. According to this Table, the Karun's agriculture sector experiences a greater loss from its own departure from the coalition than from the other players' departure. Departure of the Gavkhuni's industry has the second strongest negative effect on this sector and on the other players. It is, however, seen that the departure of Gavkhuni's agriculture from the coalition will inflict a far lower loss than that of any other player. Given the strong effects of the departure by the Karun's agriculture and the Gavkhuni's industry from the coalition, it may, therefore, be concluded that they play critical roles in the formation of a grand coalition.

As mentioned, the Gately Index expresses the impact of a player's departure from the cooperative coalition on its own and others' profits as well as their inclination to leave the coalition. The Gately index of each player was calculated (see Appendix Section) and presented in Fig. 6. According to this Figure, the Gately indices of the Karun agriculture and Gavkhuni industry (players effective in the formation of the coalition) are close to one under all the scenarios examined; the Gavkhuni agriculture, however, is more inclined to leave the coalition due to its higher Gately index.

## 4.2 Non-cooperation Approach

The players participating in the game are Karun and Gavkhuni. Karun can adopt either of two strategies: noncooperation or cooperation. This is while Gavkhuni can choose from among six strategies: cooperation of agricultural sector with Karun through side payment, cooperation of industrial sector with Karun through side payment, cooperation of agricultural and industrial sectors with Karun through side payment, noncooperation of agricultural sector with Karun, noncooperation of industrial sector with Karun, and noncooperation of agricultural and industrial sectors with Karun.

Adoption of each strategy entails its own consequences for a player. Table 3 summarizes the outcomes of these strategies under different scenarios. The numbers on the left and right hand sides in each cell represent the strategies belonging to Gavkhuni and Karun, respectively. The results obtained under Scenario 1 are presented in Fig. 7. Clearly, when Karun selects the noncooperation strategy, its profit is independent of the strategy adopted by Gavkhuni (since Karun does not cooperate regardless of Gavkhuni's strategy). In this state, the profits of both

**Table 2** The loss of leaving coalition under different scenarios (million US\$)

	Amount of loss to the player himself			Amount of damage to other players		
	Gavkhuni's agriculture	Gavkhuni's industrial	Karun's agriculture	Gavkhuni's agriculture	Gavkhuni's industrial	Karun's agriculture
Scenario 1	1.300	248.067	250.033	0.393	247.750	249.383
Scenario 2	1.233	247.767	248.167	2.433	248.700	249.000
Scenario 3	0.967	246.867	246.347	2.033	247.020	247.833
Scenario 4	0.957	256.800	256.933	1.933	257.367	257.933

players are the same as those gained individually under the initial allocation scheme and the game ends with the move of Gavkhuni.

According to Table 3, execution of the water transfer project increases the profit made by Gavkhuni but decreases that by Karun. As a result, Karun opposes the project. In this state, the Nash equilibrium is the cancellation of water transfer project, which is not Pareto optimal. But with the incentive payment by Gavkhuni to Karun, the game's stability shifts from the previous Nash equilibrium (noncooperation) toward the Pareto optimal solution (cooperation with regard to water transfer). This leads to the convergence of the Nash equilibrium and the Pareto optimal point. In this state, the players' arrival at the Nash equilibrium does not induce regret, since this point is Pareto optimal as well. As shown in the Table, the incentive payments that led to this state in scenarios 1 to 4 are equal to 250.38, 248.47, 246.67, and 257.13 (million US\$), respectively.

In contrast, when Karun chooses the cooperation strategy, the profits of both players will differ from their individual profits in the state of noncooperation. In this state, the game can be continued in the dynamic mode and the stable state can be determined based on different equilibrium definitions. For this particular game, all the four equilibrium definitions (Nash, GMR, SMR, and SEQ) yield the same results for both players in all scenarios. For each equilibrium index, there is one unilateral equilibrium under all the scenarios for Karun in the following strategies: (cooperation of Gavkhuni agricultural sector, Karun cooperation) and (cooperation of Gavkhuni industrial sector, Karun cooperation); a bilateral equilibrium for both players in the strategies: (cooperation of Gavkhuni agricultural and industrial sectors, Karun cooperation); but no equilibrium under any of the scenarios for the strategies: (cooperation of Gavkhuni agricultural sector, Karun

**Table 3** Results of each strategy (million US Dollars)

Gavkhuni's strategies		Karun's strategies	
		Noncooperation	Cooperation
Scenario 1	Cooperation of agricultural sector	1277.73, 358.75	1279.7, 360.73
	Cooperation of industrial sector	1277.73, 358.75	1526.47, 607.83
	Cooperation of agricultural and industrial sectors	1277.73, 358.75	1527.11, 609.14
	Noncooperation of agricultural sector	1277.73, 358.75	1285.2, 354.56
	Noncooperation of industrial sector	1277.73, 358.75	1776.99, 356.66
Scenario 2	Noncooperation of agricultural and industrial sectors	1277.73, 358.75	1777.69, 354.56
	Cooperation of agricultural sector	1582.11, 354.57	1584.79, 354.96
	Cooperation of industrial sector	1582.11, 354.57	1831.3, 601.43
	Cooperation of agricultural and industrial sectors	1582.11, 354.57	1833.5, 602.7
	Noncooperation of agricultural sector	1582.11, 354.57	1593.5, 346.2
Scenario 3	Noncooperation of industrial sector	1582.11, 354.57	2084.47, 348.3
	Noncooperation of agricultural and industrial sectors	1582.11, 354.57	2090.03, 346.2
	Cooperation of agricultural sector	1738.2, 354.77	1738.35, 354.9
	Cooperation of industrial sector	1738.2, 354.77	1983.9, 600.47
	Cooperation of agricultural and industrial sectors	1738.2, 354.77	1986, 601.45
Scenario 4	Noncooperation of agricultural sector	1738.2, 354.77	1746.87, 346.37
	Noncooperation of industrial sector	1738.2, 354.77	2236.23, 348.48
	Noncooperation of agricultural and industrial sectors	1738.2, 354.77	2241.1, 346.37
	Cooperation of agricultural sector	1704.13, 368.73	1704.3, 368.92
	Cooperation of industrial sector	1704.13, 368.73	1959.97, 624.9
Scenario 4	Cooperation of agricultural and industrial sectors	1704.13, 368.73	1962.04, 625.87
	Noncooperation of agricultural sector	1704.13, 368.73	1712.22, 361.03
	Noncooperation of industrial sector	1704.13, 368.73	2222.8, 362.45
	Noncooperation of agricultural and industrial sectors	1704.13, 368.73	2226.9, 361.03



noncooperation), (cooperation of Gavkhuni industrial sector, Karun noncooperation), and (cooperation of Gavkhuni agricultural and industrial sectors, Karun noncooperation).

For example, let us consider the strategy state (cooperation of Gavkhuni industrial sector, Karun cooperation) for scenario 1 (Table 3). In this state, Karun does not want to change its strategy from cooperation to noncooperation since doing so decreases its profit from 607.83 to 358.75 (million US\$). But Gavkhuni is inclined to change its strategy from cooperation of industrial sector to cooperation of agricultural and industrial sectors to increase its profit from 1526.47 to 1527.11 (million US\$). Thus, this strategy ensures a unilateral Nash equilibrium for Karun.

Gavkhuni increases its profit from 1526.27 to 1527.11 (million US\$) by changing its strategy from cooperation of industrial sector to cooperation of agricultural and industrial sectors. As a result of this shift in strategy, Karun's profit will also increase from 607.83 to 609.14 (million US\$). In this case, Karun is not opposed to this shift of Gavkhuni's strategy because it increases its profit and there is no reason for restricting it. In the conflict resolution game, the concept of stability and achievement of a possible solution involves the immutability of the game status and the unwillingness of a player to change its strategy. In this game, as Gavkhuni tends to change its strategy and Karun does not oppose it either (due to its increased profit), this strategy is not a stable state for Gavkhuni; hence, the unilateral GMR equilibrium for Karun.

It should also be noted that in response to the increment in Gavkhuni's profit due to the change in its strategy from cooperation of industrial sector to cooperation of agricultural and industrial sectors, Karun can penalize Gavkhuni by changing its strategy from cooperation to noncooperation. In this case, Gavkhuni will not be able to increase its profit by changing strategy. In fact, in the non-cooperation of Karun with any of the Gavkhuni's strategies, the profit of both players will remain constant at the level of the initial allocation (individual performance of each player). Therefore, the SMR equilibrium control loop ends. Accordingly, in this strategy state, there is a unilateral SMR equilibrium for Karun.

Finally, with the increase in Gavkhuni's profit following its change of strategy from cooperation of industrial sector to cooperation of agricultural and industrial sectors, Karun cannot increase its own profit by reducing Gavkhuni's. Therefore, the SEQ equilibrium control loop ends, resulting in a unilateral SEQ equilibrium for Karun.

Let us now consider the strategy state (cooperation of Gavkhuni agricultural and industrial sectors, Karun cooperation) for Scenario 1 (Table 3). In this state, Karun does not want to change its strategy from cooperation to noncooperation, since this alteration decreases its profit from 609.14 to 358.75 (million US\$). Neither does Gavkhuni want to change its strategy in this case from cooperation of agricultural and industrial sectors to cooperation of one of agricultural or industrial sectors, since such a move will decrease its profits from 1527.11 to 1279.7 or 1526.47 (million US\$), respectively. Therefore, in this strategy state, there is a bilateral Nash equilibrium for both players. The use of other equilibrium indices also results in the same bilateral equilibrium.

## 5 Summary and Conclusion

This paper employed the cooperative and non-cooperative games to analyze the profits of players involved in Beheshtabad Water Transfer Project in Iran. Unlike in previous studies, the non-cooperative concepts in the form of matrix game were used in the present study to analyze the cooperation and noncooperation between the source and receiving basins. To perform the conflict resolution procedure, an initial water allocation based on present demands in the absence of the water transfer project was first obtained by simulation in MODSIM. In the next

step, an optimization model was developed for maximizing the profits in accordance with the economic and environmental conditions in the two basins. This model was found capable of determining the outcomes of different strategies in the game theory model.

The results of cooperative and non-cooperative approaches revealed that cooperation of the players led to an equilibrium and Pareto-optimal solution. In the cooperative approach, the players were found to benefit more from the coalition than from their individual work. Also, the highest profit was achieved upon the formation of a grand coalition. Analysis of the outcomes of players' withdrawal from the grand coalition showed that departure of Gavkhuni's industrial sector and Karun's agricultural sector would have the greatest effect on the coalition. The coalition was found to be strongly affected by the industrial sector, because of the high value of its allocation function, and Karun's agricultural sector, because of its key role in water transfer to the Gavkhuni basin. However, Gavkhuni's agricultural sector was found to have a larger Gately index, indicating its higher inclination to leave the coalition.

The results of the non-cooperative model showed that when Karun and Gavkhuni tried to cooperate without any incentive or compensation, the Nash equilibrium resulted in noncooperation, which is not Pareto optimal. Thus, to achieve a desirable solution, there should be an incentive payment from Gavkhuni to Karun. With such an incentive, the strategies shift from the noncooperation to the most beneficial cooperation. In this state, when Gavkhuni attempts to disrupt the equilibrium by refusing to make the incentive payment, Karun can penalize Gavkhuni by opposing the water transfer. Thus, the best solution is the Pareto optimal one, where none of the players wishes to alter the situation. It is in this situation that the cooperation between the players is at an equilibrium and is Pareto optimal as well. Further study is required to address the uncertainties in the parameters of the model described.

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## Compliance with Ethical Standards

**Conflict of Interest** The authors declare that they have no conflict of interest.

## Appendix

### Model assumptions

Considering the extensive size of the study area, the modeling is performed based on the following assumptions:

- The simulation model includes only the dams and water bodies larger than 5 MCM while identical reservoir water levels are considered for the start and end of the simulation period.
- The simulation models for both basins are executed with the water demand of all the fields considered. In the optimization model, four regions in the receiving basin (Najafabad, Kuhpayeh-Sagzi, Esfahan-Borkhar, and Lenjanat) are considered because of their importance and location alongside the river.

- The water allocated to agricultural, domestic, and industrial sectors is not consumed in full; so, the return flows are incorporated into the optimization and simulation models.
- The game theory approach to conflict resolution of shared resources is based on financial payments in exchange for a reduction or non-utilization of the common source. However, given the importance attached to the full supply of the domestic and environmental demands, it is not possible to consider the stakeholders' utilities of these sectors through game theory models. These sectors are, therefore, excluded from the game, but not from the optimization model.
- Basins are assumed to have the same agricultural productivity equal to 0.35.

### Optimization model structure

#### Objective function

The objective function maximizes the difference between the benefits and the costs. In this model, the costs and benefits of the water transfer project are considered to consist of the following components:

Equation 1 expresses the benefits in US Dollars to be gained from allocation of water to the agricultural sector at the receiving basin ( $B_1$ ).

$$B_1 = \sum_{n=1}^N \sum_{s=1}^S \sum_{m=1}^M \left( cpd_{n,s,m} * \frac{X_{n,s,m}}{D_{n,s,m}} * P_s \right) \tag{1}$$

In this Equation,  $X$ ,  $cpd$ ,  $D$ , and  $P$ , respectively, denote the volume of water allocated ( $m^3$ ), yield (ton/ha), water demand ( $m^3/ha$ ), and net benefit of crops (US\$/ton). The parameters  $m$ ,  $n$ , and  $s$  are the counters of the month, field, and product.

The benefits gained from allocation of water to domestic (drinking) and industrial uses are a function of the volumes of water allocated to these demands. In this study, the equations required for estimating the benefits of water allocation to the industrial sector ( $B_2$ ) and domestic use ( $B_3$ ) in  $10^5$  US Dollars at the receiving basin are derived by fitting the benefits of the industrial and domestic uses of water for the volumes of water consumed. In these equations,  $X_{ind,m}$  and  $X_{Dom,m}$  denote the volume of water allocated to industrial and domestic uses, respectively, in million cubic meters (MCM) at month  $m$ .

$$B_2 = 16.308 * X_{ind,m}^3 - 8799.6 * X_{ind,m}^2 + 2 * 10^6 * X_{ind,m} - 10^8 \tag{2}$$

$$B_3 = -325.53 * X_{Dom,m} + 109425 \tag{3}$$

The water transfer project will reduce the rate of withdrawal from groundwater resources at the receiving basin. The benefit to be gained from the reduced pumping costs ( $B_4$ ) in US Dollars depends on the amount of water conveyed. In this equation (Karamouz et al. 2009a),  $\zeta$ ,  $W$ ,  $h_2$ ,  $h_s$ , and  $p$  represent pumping efficiency, volume of water conveyed (MCM), groundwater level relative to the surface (m), hours of pumping per month, and power price in US Dollars per kiloWatt-hour (kWh), respectively.

$$B_4 = \frac{1}{3.67 * 10^{-4} * \zeta} \sum_{m=1}^M (W * h_2 * h_s * p) \tag{4}$$

The benefit of water allocation to environmental purposes at the receiving basin is a function of volume of water diverted toward the wetland to maintain the ecosystem. In this study, the benefit of water allocation to environmental purposes is obtained from Eq. 5, where,  $X_{ins}$  is the amount of water allocated to environmental use (MCM) and  $B_5$  is the benefit of water allocation to the wetland ( $10^5$  US Dollars).

$$B_5 = 639.6 * X_{ins} - 7497 \quad (5)$$

The transfer of water from the source basin limits the water rights and future agricultural development in its vicinity. Eq. 6 gives the loss borne by the agricultural sector ( $C_1$ ) in US Dollars as a result of this limitation. In this equation, the new allocation is initially determined based on the volume of water conveyed and then compared with the original allocation to determine the extent of loss. In this eq.  $X''_{n, m, s}$  denotes the volume of water allocated ( $m^3$ ) to the crop  $s$  in field  $n$  at month  $m$  after the implementation of the water transfer project. Other variables and parameters are as previously defined.

$$C_1 = \sum_{n=1}^N \sum_{s=1}^S \sum_{m=1}^M \left( cpd'_{n,s,m} * \frac{X'_{n,s,m}}{D'_{n,s,m}} * P'_s \right) - \sum_{n=1}^N \sum_{s=1}^S \sum_{m=1}^M \left( cpd_{n,s,m} * \frac{X'_{n,s,m}}{D'_{n,s,m}} * P'_s \right) \quad (6)$$

Water transfer projects have other negative consequences for the source basin, such as elevated dredging costs, reduced hydroelectric power generation, and reduced water quality, which are incorporated into the objective function as costs. With the reduction of annual river flow due to the water transfer project, a dredging budget needs to be set aside to maintain the river bed or keep the river ready for water transportation. The additional dredging cost due to the project is a function of both the river flow and the water transfer flow. In this paper, the equation required for estimating the dredging costs is obtained by fitting the cost of dredging operations for the river flows at the source basin. In this equation,  $C_2$  and  $Q_I$  denote the dredging costs ( $10^{11}$  US Dollars) and the river flow ( $m^3/s$ ), respectively.

$$C_2 = -0.5406 * Q_I + 552.31 \quad (7)$$

>The financial loss at the source basin due to reduced hydroelectric power generation is a function of the size of power generation loss (which depends on water transfer flow) multiplied by the price of electricity. The equation of financial loss due to reduced hydroelectric power generation is obtained by fitting the annual power generation values for the transfer flows at the source basin. In this equation,  $C_3$ ,  $Q_2$ , and  $p'$  denote financial loss (million US Dollars), water transfer flow ( $m^3/s$ ), and power price in US Dollars per kilowatt-hour (kWh), respectively.

$$C_3 = (-10.653 * Q_2 + 3814.9) * p' \quad (8)$$

Water transfer may also alter the water quality along the source basin and cause significant declines in quality indicators. Therefore, a price should be assigned to the preservation of environmental quality through water treatment. This cost can be defined as the product of deviation of qualitative variables from their standard values by the unit price of treatment. River quality is mostly a function of its biochemical oxygen demand ( $BOD$ ) and electrical conductivity ( $EC$ ); these variables can be, therefore, used as water quality indicators. Water quality preservation costs due to water transfer from the source basin are expressed by the following equation (Mojahedi 2006).

$$C_4 = \sum_{m=1}^M \{ [RegBOD_m(Q_{headwater,m} - Q_{trans,m}, DO_{headwater,m}) - RegBOD_m(Q_{headwater,m}, DO_{headwater,m})] * P_{BOD} + [RegEC_m(Q_{headwater,m} - Q_{trans,m}, EC_{headwater,m}) - RegEC_m(Q_{headwater,m}, EC_{headwater,m})] * P_{Cond} \} \tag{9}$$

In this equation,  $C_4$ ,  $Q_{headwater,m}$ ,  $Q_{trans,m}$ ,  $DO_{headwater,m}$ ,  $RegBOD_m$ ,  $P_{BOD}$ ,  $RegEC_m$ , and  $P_{EC}$  are water treatment cost (US Dollars), headwater flow at month  $m$  (m<sup>3</sup>/s), transfer flow at month  $m$  (m<sup>3</sup>/s), headwater  $DO$  concentration at month  $m$  (mg/lit),  $BOD$  regression equation at month  $m$ , treatment cost for one milligram of  $BOD$  concentration (US Dollars),  $EC$  regression equation at month  $m$ , and treatment cost for one milligram  $EC$  concentration (US Dollars), respectively.

In Eqs. 10 and 11, the changes in river quality are expressed in terms of water quality indicators. The values for the coefficients in these equations for different months are derived from Mojahedi (2006).

$$RegBOD(Q, BOD) = C_t * DO + D_t * Q + Const_1 \tag{10}$$

$$RegCond(Q, EC) = E_t * EC + F_t * Q + Const_2 \tag{11}$$

Finally, the equation of the objective function will take the following form:

$$maximize \ Z = \left( \sum_{i=1}^I Benefit_i - \sum_{j=1}^J Cost_j \right) \tag{12}$$

**Constraints**

Equation 13 controls the minimum and maximum cultivation areas and prevents the allocation of all the available water to only one crop. As such, the priority of this constraint is to ensure that water is at least allocated to all the crops. Equation 14 expresses the effect of irrigation efficiency on the amount of water allocated to agricultural crops. Based on the cultivation area for a 10-year period,  $\mu_1$  and  $\mu_2$  are considered to be 0.8 and 1.2, respectively. In these equations,  $a_s$ ,  $A_n$ , and  $X_{n,s,m}$  represent percentage of historical cultivation area of crop  $s$ , cultivation area in field  $n$  (ha), and the amount of water allocated to crop  $s$  in field  $n$  at month  $m$  (m<sup>3</sup>) for the source basin as well as the pre- and post-water transfer conditions at the receiving basin (that is, the variables  $X$ ,  $X'$  and  $X''$ ), respectively. Also,  $\varphi$  is agricultural productivity.

$$\sum_{n=1}^N \sum_{s=1}^S \sum_{m=1}^M (\mu_1 * a_s * A_n * D_{n,s,m}) \leq \sum_{n=1}^N \sum_{s=1}^S \sum_{m=1}^M X_{n,s,m} \leq \sum_{n=1}^N \sum_{s=1}^S \sum_{m=1}^M (\mu_2 * a_s * A_n * D_{n,s,m}) \tag{13}$$

$$\sum_{n=1}^N \sum_{s=1}^S \sum_{m=1}^M X_{n,s,m} = \sum_{n=1}^N \sum_{s=1}^S \sum_{m=1}^M x_{n,s,m} * \varphi \tag{14}$$

The following equation is the mathematical expression of the water input of agricultural sector and includes water returned from the domestic and industrial sectors as well as that from each farm field. It may be noted that the environmental demand (equal to 140 MCM) is also considered. In this equation,  $R$ ,  $X_{agr,i,ins}$ ,  $\gamma_1$ ,  $\alpha_1$ ,  $V_{ind}$ , and  $V_{dom}$  denote river flow before reaching the first farm field (m<sup>3</sup>/s), initial water allocation (the water available) to field  $i$  (m<sup>3</sup>), minimum environmental demand for water (m<sup>3</sup>), coefficients of return flow from domestic and industrial uses, and the volume of conveyed water that is allocated to industrial and domestic uses (m<sup>3</sup>), respectively.

$$R = (X_{agr,i} + V + (\gamma_1 - 1) * V_{dom} + (\alpha_1 - 1) * V_{ind-ins}) \quad (15)$$

Equation 16 indicates the constraint on the water allocated to the first field, which must be less than or equal to the total amount of water allocated to the agricultural sector ( $R$ ). Equation 17 limits the water allocated to other fields based on the amount of water returned from the preceding fields. In this equation,  $k$  and  $\delta$  represent the field counter and the coefficient of return flows from the other fields.

$$\sum_{s=1}^S \sum_{m=1}^M (x_{1,s,m}) \leq R \quad (16)$$

$$\sum_{k=2}^K \sum_{s=1}^S \sum_{m=1}^M (x_{k,s,m}) \leq R - (1 - \delta) * \sum_{k=1}^{K-1} \sum_{s=1}^S \sum_{m=1}^M (x_{k,s,m}) \quad (17)$$

According to Eq. 18, the total amount of water allocated to the agricultural sector ( $R$ ) equals the total water allocated to all fields (continuity equation). For the agricultural sector of the source basin, the continuity equations for pre- and post-water transfer conditions are expressed by Eqs. 19 and 20, in which  $V$  and  $C$  are the volumes of available and conveyed water ( $m^3$ ), respectively.

$$\sum_{n=1}^N \sum_{s=1}^S \sum_{m=1}^M (x_{n,s,m}) = R \quad (18)$$

$$\sum_{n=1}^N \sum_{s=1}^S \sum_{m=1}^M (X'_{n,s,m}) = V \quad (19)$$

$$\sum_{n=1}^N \sum_{s=1}^S \sum_{m=1}^M (X''_{n,s,m}) = V - C \quad (20)$$

The following equations must be incorporated to maintain the water qualitative standards at the source basin.  $BOD_{std}$  and  $EC_{std}$  denote standard  $BOD$  and  $EC$  concentrations (mg/lit), with maximum allowable values of 10 (mg/lit) and 1200 (mho/cm), respectively (Krenkel and Novotny, 1980).

$$RegBOD_m(Q_{headwater,m} - Q_{trans,m}, BOD_{headwater,m}) > BOD_{std} \quad (21)$$

$$RegEC_m(Q_{headwater,m} - Q_{trans,m}, EC_{headwater,m}) > EC_{std} \quad (22)$$

## Simulation model results

The following Figures show the results of model calibration for the changes in aquifer volumes in the two plains of the receiving basin. Clearly, the regression errors ( $R^2$  error) in the two Figures are 0.98 and 0.81, respectively, confirming the accuracy of the modeling process. Also, Table 4 reports the MODSIM results for water allocation to different sectors.

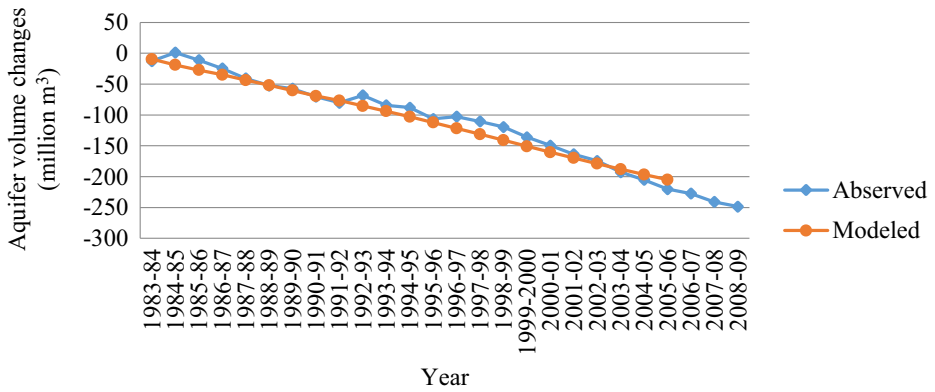


Fig. 3 Groundwater volume changes in the Chelgerd-Ghal'e Shahrokh sub-basin

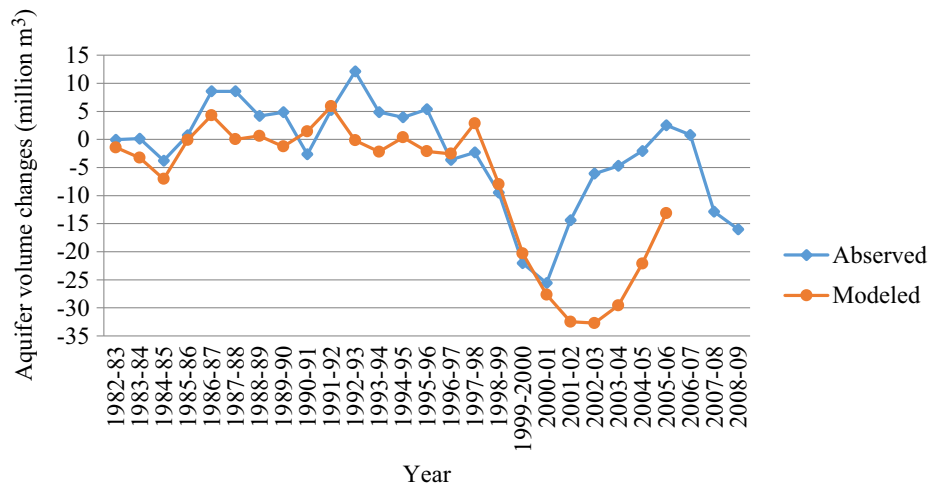


Fig. 4 Groundwater volume changes in the Karvan sub-basin

Table 4 Initial allocation with MODSIM model (MCM)

Consumer	Scenario			
	1	2	3	4
Agriculture of Gavkhuni	3186.6	2963	3096	3005
Industrial of Gavkhuni	130	169.5	187.5	184.5
Agriculture of Karun	10,628	10,577	10,583	10,599

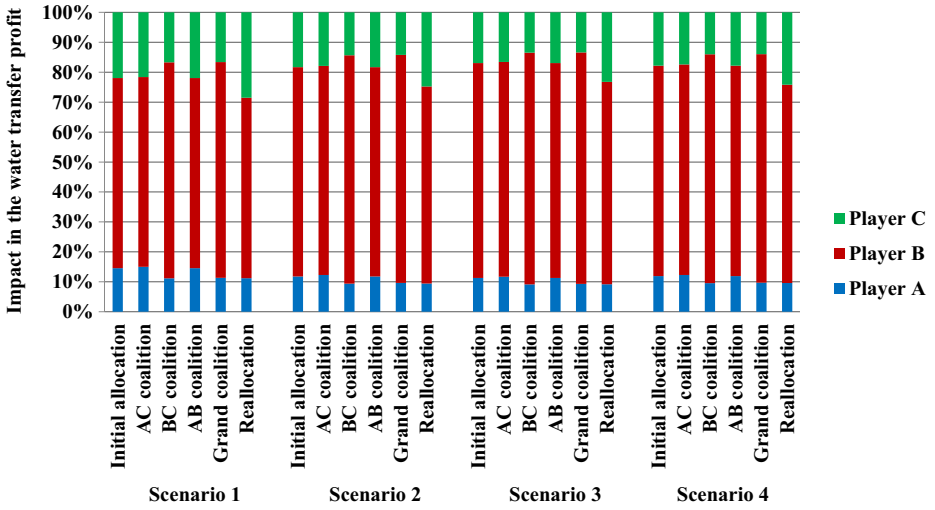


Fig. 5 The effectiveness of players resulting from the different coalitions in each scenario

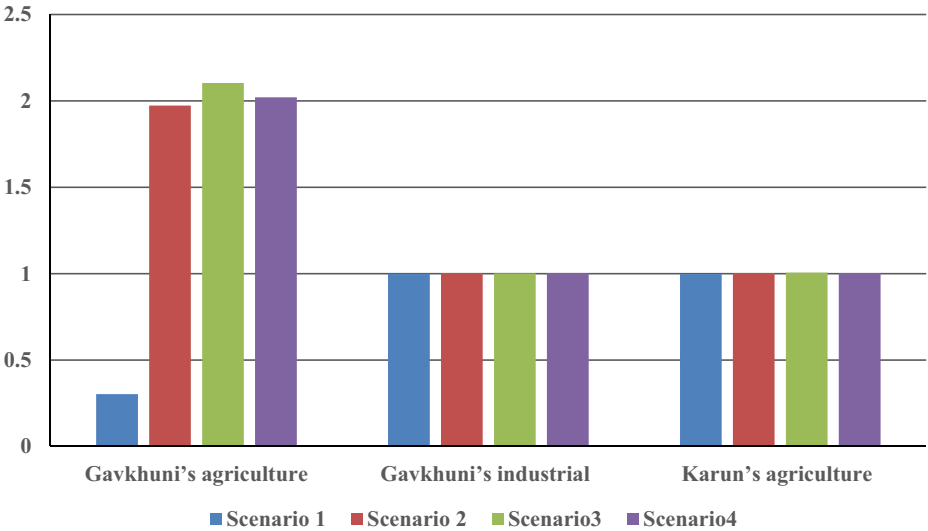
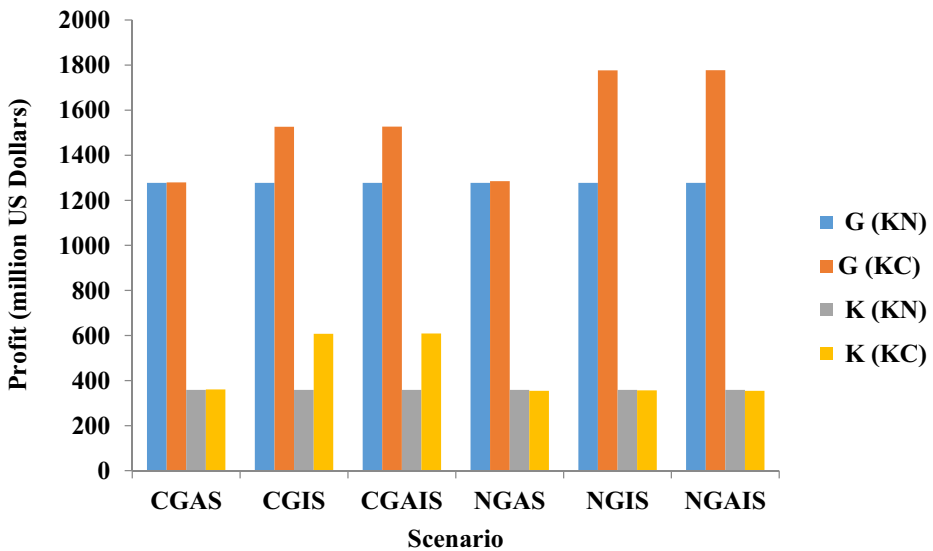


Fig. 6 Gately index for each player in different scenarios





**Fig. 7** Results of non-cooperative approach under scenario 1. **Note:** K=Karun, G=Gavkhuni, KN=Karun Noncooperation, KC = Karun Cooperation, CGAS = Cooperation of Gavkhuni's Agricultural Sector, CGIS = Cooperation of Gavkhuni's Industrial Sector, CGAIS = Cooperation of Gavkhuni's Agricultural and Industrial Sector, NGAS = Non-cooperation of Gavkhuni's Agricultural Sector, NGIS = Non-cooperation of Gavkhuni's Industrial Sector, NGAIS = Non-cooperation of Gavkhuni's Agricultural and Industrial Sector

## Gately index

The Gately index is expressed by the following equation, in which  $d_i$ ,  $X_k$ ,  $V(N-i)$ , and  $V(i)$  represent the inclination to non-cooperation for player  $i$ , the allocation due to cooperation, the value of the coalition without player  $i$ , and the value of the coalition for player  $i$ , respectively.

$$d_i = \frac{\sum_{i \neq k} (X_k) - V(N-i)}{X_i - V(i)} \quad (23)$$

## References

- Dai X, Han Y, Zhang X, Chen J, Li D (2017) Development of a water transfer compensation classification: a case study between China, Japan, America and Australia. *Agric Water Manag* 182:151–157. <https://doi.org/10.1016/j.agwat.2016.05.026>
- Fredericks J, Labadie J, Altenhofen J (1998) Decision support system for conjunctive stream-aquifer management. *J Water Resour Plan Manage* 124(2). doi: [https://doi.org/10.1061/\(ASCE\)0733-9496\(1998\)124:2\(69\)](https://doi.org/10.1061/(ASCE)0733-9496(1998)124:2(69))
- Gately D (1974) Sharing the gains from regional cooperation: a game theoretic application to planning investment in electric power. *Int Econ Rev* 15(1):195–208. <https://doi.org/10.2307/2526099>
- Iran Ministry of Energy (2012) Studies for the update of water country Iran master plan, Research Report (in Persian)
- Joshi NM (2013) National River Linking Project of India. *Hydro Nepal: J Water, Energy Environ* 12:13–19. <https://doi.org/10.3126/hn.v12i0.9026>
- Karamouz M, Ahmadi A, Nazif S (2009a) Development of management schemes in irrigation planning: economic and crop pattern consideration. *Sci Iranica, Trans A: Civil Eng* 16(6):457–466
- Karamouz M, Mojahedi SA, Ahmadi A (2009b) Interbasin water transfer: economic water quality-based model. *J Irrig Drain Eng* 136(2):90–98. [https://doi.org/10.1061/\(ASCE\)IR.1943-4774.0000140](https://doi.org/10.1061/(ASCE)IR.1943-4774.0000140)
- Krenkel PA, Novotny V (1980) *Water quality management*. Academic Press, New York, p 10003

- Kucukmehmetoglu M, Guldmen J (2004) International water resources allocation and conflicts: the case of the euphrates and tigris. *Environ Plan A* 36(5):783–801. <https://doi.org/10.1068/a3670>
- Labadie J (1995) MODSIM: river basin network flow model for conjunctive stream-aquifer management. Program User Manual and Documentation, Colorado State University
- Loaiciga HA (2004) Analytic game-theoretic approach to ground-water extraction. *J Hydrol* 297:22–33. <https://doi.org/10.1016/j.jhydrol.2004.04.006>
- Madani K (2010) Game theory and water resources. *J Hydrol* 381(3):225–238. <https://doi.org/10.1016/j.jhydrol.2009.11.045>
- Madani K, Hipel KW (2011) Non-cooperative stability definitions for strategic analysis of generic water resources conflicts. *Water Resour Manag* 25(8):1949–1977. <https://doi.org/10.1007/s11269-011-9783-4>
- Mahjouri N, Ardestani M (2010) A game theoretic approach for interbasin water resources allocation considering the water quality issues. *Environ Monit Assess* 167(1–4):527–544. <https://doi.org/10.1007/s10661-009-1070-y>
- Mahjouri N, Ardestani M (2011) Application of cooperative and non-cooperative games in large-scale water quantity and quality management: a case study. *Environ Monit Assess* 172(1–4):157–169. <https://doi.org/10.1007/s10661-010-1324-8>
- Manshadi HD, Niksokhan MH, Ardestani M (2015) A quantity-quality model for inter-basin water transfer system using game theoretic and virtual water approaches. *Water Resour Manag* 29(13):4573–4588. <https://doi.org/10.1007/s11269-015-1076-x>
- Mehrpourvar M, Ahmadi A, Safavi HR (2016) Social resolution of conflicts over water resources allocation in a river basin using cooperative game theory approaches: a case study. *Int J River Basin Manag* 14(1):33–45. <https://doi.org/10.1080/15715124.2015.1081209>
- Mianabadi H, Mostert E, Zarghami M, van de Giesen N (2014) A new bankruptcy method for conflict resolution in water resources allocation. *J Environ Manag* 144:152–159. <https://doi.org/10.1016/j.jenvman.2014.05.018>
- Mojahedi SA (2006) Development of an algorithm for assessment of water development projects from standpoint of economic and environmental factors. M.Sc. Thesis, University of Tehran, Tehran, Iran (in Persian)
- Nikoo MR, Kerachian R, Niksokhan MH (2012) Equitable waste load allocation in rivers using fuzzy Bi-matrix games. *Water Resour Manag* 26(15):4539–4552. <https://doi.org/10.1007/s11269-012-0165-3>
- Parsapour-Moghaddami P, Abed-Elmdoust A, Kerachian R (2015) A heuristic evolutionary game theoretic methodology for conjunctive use of surface and groundwater resources. *Water Resour Manag* 29(11):3905–3918. <https://doi.org/10.1007/s11269-015-1035-6>
- Raquel S, Ferenc S, Emery C, Abraham R (2007) Application of game theory for a groundwater conflict in Mexico. *J Environ Manag* 84:560–571. <https://doi.org/10.1016/j.jenvman.2006.07.011>
- Sadegh M, Mahjouri N, Kerachian R (2010) Optimal inter-basin water allocation using crisp and fuzzy Shapley games. *Water Resour Manag* 24(10):2291–2310. <https://doi.org/10.1007/s11269-009-9552-9>
- Sechi GM, Zucca R, Zuddas P (2013) Water costs allocation in complex systems using a cooperative game theory approach. *Water Resour Manag* 27(6):1781–1796. <https://doi.org/10.1007/s11269-012-0171-5>
- Shapley LS (1953) A value for n-person games. *Contrib Theory Games*, Princeton: Princeton Univ Press 2(28):307–317
- Wang L, Fang L, Hipel KW (2008) Basin-wide cooperative water resources allocation. *Eur J Oper Res* 190(3):798–817. <https://doi.org/10.1016/j.ejor.2007.06.045>
- Zi-hui LIU (2006) Middle Route Project of South-to-North Water Transferring. World Environmental and Water Resource Congress: Examining the Confluence of Environmental and Water Concerns, 1–6. doi: [https://doi.org/10.1061/40856\(200\)229](https://doi.org/10.1061/40856(200)229)
- Zolfagharipour MA, Ahmadi A (2017) Effluent trading in river systems through stochastic decision-making process: a case study. *Environ Sci Pollut Res* 24(25):20655–20672. <https://doi.org/10.1007/s11356-017-9720-z>