Intl. J. River Basin Management Vol. 14, No. 1 (March 2016), pp. 33–45

Social resolution of conflicts over water resources allocation in a river basin using cooperative game theory approaches: a case study

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ABSTRACT
In this paper, cooperative game theory (CGT) approaches are used for water allocation in a river basin considering equity benefit shares among stakeholders. An optimization model is initially developed for allocating water to competing users including agricultural, industrial, and environmental users based on both economic objectives. The model is implemented to determine water shares for different likely coalitions among water users. Then, CGT approaches such as Shapely, Nucleolus, and Nash-Harsanyi are used for reallocating net profits to the users as an attempt to encourage them to participate in equitable cooperation. Finally, the results of different game theoretic approaches are evaluated using the stability index and voting methods such as social choice and fallback bargaining. The proposed methodology is applied to the Zayandehrood River basin located in central part of Iran which struggles with water scarcity. The different CGT approaches applied to two predefined real-life scenarios in the basin under study and their performance were evaluated. The results indicate the proper performance of both Nash-Harsanyi and Shapely methods for pessimist and optimistic scenarios, respectively. It is also found that application of the proposed methodology effectively increases the users' benefits in the study region through optimal water allocation and reallocation of benefits.

Keywords: game theory; cooperative approaches; water allocation; social choice; fallback bargaining; stability index

1 Introduction

The lack of a balance between water resources and water demand along with the multitude of stakeholders and differences in opinion on how best to exploit the available resources commonly lead to conflicts and disputes over the management of watersheds and river basins. A main concern in water resources management is equitable allocation of water. Conflicts on water rights are not solely limited to economic benefits or costs, but they involve social and political issues as well.

Problems commonly arise in the process of decision-making over water allocation in cases where there are more than one decision-maker or stakeholder obviously because diversity in utilities and differences in ideas must then be fully addressed in a process called 'conflict resolution'. Game theory is a universally known theory used to solve conflicts or disputes. It expresses the conflict in the mathematical language. A stable state in this theory means interactions need to be accomplished between certain players or stakeholders in the decision-making process. It must be noted that the stable state does not mean that all the players achieve complete satisfaction.

The four main elements comprising the game theory include players, strategies, payoffs, and information or knowledge of the players. Players are the stakeholders who claim to achieve their objectives (utility). The payoffs are the results of the games that ensue from the strategies adopted by the players and their knowledge of the game or competitors. Game theory may take either of two approaches: cooperative or non-cooperative game. The game will be cooperative if the players agree to cooperate on principles and one player or manager to make certain decision about the game. This can be illustrated by dividing a pie among some stakeholders (players) with the manager as the person who will decide on how to share slices among them (Madani and Hipel 2011). In non-cooperative games, there is no agreement among the players, but all solely mind their own benefits. Sharing groundwater or rivers between neighbouring

Received 10 February 2015. Accepted 5 August 2015.

ISSN 1571-5124 print/ISSN 1814-2060 online
http://dx.doi.org/10.1080/15715124.2015.1081209
http://www.tandfonline.com

countries is an example of the non-cooperative game. Non-cooperative approaches often present stable solution to prevent disputes between stakeholders.

Numerous studies have been conducted on conflict resolution in water resources management. Mostert (2003) investigated conflicts in international freshwater management and suggested integrated river basin management across national, international and all of the levels rather than old water managing limited to national view. Bhaduri and Barbier (2011) claimed water allocation between states in inter-basin water transfer can be market or trading based. The results determine that price-based water transfer can lead to an inefficient outcome.

Plenty of studies adopted the game theoretic approaches to address issues of quantity and quality in reservoirs and groundwater resources as well as the disputes over water sharing in river basins (Kerachian and Karamouz 2007, Salazar *et al.* 2007, Ansink and Ruijs 2008, Karamouz *et al.* 2009, Ganji *et al.* 2007, Madani 2010, Ansink and Weikard 2012). Moreover, a variety of methods have been developed in cooperative games for the decision-making process to solve conflicts, especially in water resources management. They include Shapely (Shapely 1953), Nash bargaining solution (Nash 1953), Core (Gillies 1953), as well as such dependent versions as Nash-Harsanyi solution (Harsanyi 1958), Nucleolus (Schmeidler 1969), and separable cost remaining benefits (SCRB, James and Lee 1971).

Young *et al.* (1982) used the Nucleolus, Shapely, and SCRB definitions for cost allocation in water resources. Their results show that none of the methods was capable of providing for all the players' utilities simultaneously. They claimed that SCRB reallocated costs in a non-uniform manner compared to the other methods. Lejano and Davos (1995) used the normalized Nucleolus method to allocate costs of water resources projects and compared it with the Nucleolus and Shapely ones. Wu and Whittington (2006) allocated water resources in the Nile River basin using such cooperative Game theoretic methods as Shapely and Nucleolus. Their results showed that the economic cooperative model was the preferred beneficial one encouraging greater contributions by the riparian states. Wang *et al.* (2003, 2008) used a mathematical programming framework to develop a cooperative water allocation management model for allocating water to users in a river basin. The conflict resolution process was divided into two steps. In the first step, water was allocated based on water rights. In the second step, the costs and benefits were traded and reallocated among the players. The reallocation values were determined based on the Shapely and Nucleolus definitions. Mahjouri and Ardestani (2010) used economic and environmental concepts in developing a methodology for conflict resolution over an inter-basin water transfer project. They also used the SCRB, minimum costs remaining savings, and Shapely to develop the associated cooperative game theoretic model. Abed-Elmdoust and Kerachian (2012) developed a water resources allocation model using a cooperative game with fuzzy payoffs for an inter-basin water transfer project from the Karoon River basin to the Rafsanjan basin in Iran. Madani and Dinar (2011) used cooperative games for sustainable management of common pool resources to determine the benefits to be shared among stakeholders and used the stability index (Loehman *et al.* 1979) and the plurality rule (Gately 1974, Straffin and Heaney 1981) criteria to evaluate the fairness of the methods.

In the present study, the cooperative game theoretic approach is used for sharing water resources in a river basin. Domestic, industrial, agricultural, and environmental sectors form the various competing water users in the basin. In this methodology, different coalitions are examined to evaluate the net benefits of cooperative water allocation to users. In order to provide enough incentives for water users to participate in the cooperation, the Shapely, Nucleolus, and Nash-Harsanyi methods are employed for the reallocation of the net benefits of water allocation to the users.

In order to find out the best reallocation approaches, the stability index and the voting methods of social choice and fallback bargaining (Bassett and Persky 1999, Brams and Kilgour 2001, Sheikhmohammady and Madani 2008) are used to assess the results. These evaluation criteria have been recently implemented to solve the decision-making problems of water resources management (Safaei *et al.* 2013) and environmental issues (Madani *et al.* 2014). This novel method in selecting the best game theoretic approach for benefit reallocation is applied to an important basin, that is, the Zayandehrood River basin, in central part of Iran.

2 Methodology

Non-cooperative games are often implemented on cases in which no one has enough power to make a decision that all of the stockholders obey his/her decision, for example, in the case of water allocation in a boundary river between certain countries. In non-cooperative games, solutions are often limited to the stable state of games while equity or efficiency may not occur.

On the other hand, cooperative approaches encourage players to participate by assuring that they will be benefited more or not be lost from cooperation. Totally, the decision will improve the state of system. This paper focuses on water sharing in an inter-basin river while the efficiency of the system is important from the local and national views. Therefore, in this paper, cooperative game theory (CGT) is utilized for water sharing in a river basin.

2.1 *Cooperative game theory*

In most cooperative approaches, the economic performance of consumers or stakeholders is considered as a criterion to allocate resources like water. Fairness assessment is then accomplished by determining the benefits or costs to be paid or gained by consumers. In CGT and the associated coalition, there is no limitation on agreements made among the players or stakeholders regardless of their number. The same value unit is used for all the players to determine and express payoffs ensuing from the cooperative game so that the stable state is conveniently achieved by the easy transfer of costs or benefits among the players; this provision is called 'transferable utility' which serves as a proper incentive for players with identical or close objectives.

In order to decrease the costs or increase the benefits in the allocation of resources, the players enter into coalition schemes. If $U=\{1,2,3,\ldots,J\}$ is the set of stakeholders or players with claims on the resources and j is devoted to a player such that$j \in U$, then, S is a subset of U representing the coalition of players who agree to form a coalition S. If all the players enter into a coalition scheme, then it is called a 'grand coalition' and there will be 2^J-1coalitions for a game with J players. According to Equation (1), an optimization model is developed for each coalition whose objective function $v(s)$ is maximizing the utility functions of the players' participating in the coalition scheme. The player's utility function is the benefits ensuing from consuming water in the river basin. In the following optimization model, two constraints are considered in the model structure. The Inequality Equation (2) shows the management orders that demands must be provided for all the players' except for the ones who form coalition s.

$$v(s)=\max NB(s)=\max\sum_{j\in s} NB(j). \tag{1}$$

Subject to

$$A(p)\geq D(p),\quad p\neq j,\quad \text{for all}\quad p\in U\quad j\in s, \tag{2}$$

where $NB(i)$ represents the benefit from allocating water to player i; $v(s)$ is the benefit devoted to coalition s; and $A(p)$ shows the amount of water allocated to the stakeholders who do not participate in coalition s, which must be at least equal to their demands, $D(p)$. This inequality constraint underlines the fact that the desirably optimal situation for the players participating in coalition s can be made by providing for the demands by other players. Simulation constraint consists of water balancing equations over of the whole upstream–downstream river basin as follows:

$$Q_i(t)=Q_{\text{inflow}}(t),\quad i=1, \tag{3}$$

$$Q_i(t)=A_{ij}(t)+R_{ki}(t)-Q_{i+1}(t),\quad i\in L,\ j,k\in U, \tag{4}$$

$$Q_{outflow}=Q_i(t),\quad i=I, \tag{5}$$

where Q_i, Q_{inflow}, and Q_{outflow} are the inflow rate at node i, internal stream to the river, and outlet from the river, respectively. $L=\{1,2,3,\ldots,I\}$ is the set of allocation nodes and $U=\{1,2,3,\ldots,J\}$ indicates demand nodes while A_{ij} is the water devoted from allocation node I to demand node j. Any return flows from the demand nodes into the river are designated by R_{ki}. Equation (6) expresses the objective function for each coalition as a function of allocated water for a 12-month planning period.

$$NB(j)=f(q_j),\quad q_j=\sum_{t=1}^{12} A_{ij}(t) \tag{6}$$

where, $f(q_j)$ is a net benefit function of demand node j which can be estimated from historical statistics.

Since optimal water allocation in a coalition framework leads to losses/gains of money for the stakeholders as compared to the likely situations in the past, side payments should be simultaneously made. Certain game theoretic approaches including Shapely, Nucleolus, and Nash-Harsanyi are used to determine the payoffs or rewards to each stakeholder.

In the reallocation process, payoffs or rewards received by each stakeholder are determined based on the solution of a game. This payoff or reward vector is expressed by $x=\{x_1,x_2,\ldots,x_J\}$. Nucleolus is one of the cooperative game theoretic approaches which follow from the core definition. Core considers economic incentives encouraging the players to form a cooperative game that satisfies both their individual and group rationalities while also escalating the game to a grand coalition (Young *et al.* 1982, Tisdell and Harrison 1992). The following equations describe the core definition.

$$\sum_{i\in S} x_i\geq v(s),\quad \forall s\subset U, \tag{7}$$

$$\sum_{i\in U} x_i=v(U), \tag{8}$$

where $v(i)$, $v(s)$, and $v(U)$ are individual, partial coalition, and grand coalition benefits, respectively. Equation (7) expresses that no coalition s by acting on its own can achieve an aggregate value higher than the share it receives under the payoff vector and that it must be an incentive for players to cooperate in grand coalitions instead of partial ones. The other constraint should propel the payoff vector to grand coalitions. Equation (8) denotes the sum of payoffs to players, which equals the total payoff gained in a grand coalition.

Various methods are used for solving the core model for the reallocation of costs or benefits to the players participating in a grand coalition. As already mentioned, the Nucleolus, Nash-Harsanyi, and Shapely Value (not following the core definition) methods are used in this paper. Methods are described with more details in the appendix.

2.2 *Evaluation criteria*

According to deference stakeholders' ideas and utilities, there is no warranty that the described methods can provide the stakeholders' claims completely. To choose the best stable method for water allocation, methods such as social choice, fallback bargaining, and stability index are used, a description of each of which follows.

2.2.1 *Social choice*

Decision-making in the social choice method depends on stakeholders' votes or opinions. Conflict resolution is concluded by a voting process and the best alternative will be presented by the majority of the stakeholders' votes. Condorcet and Borda Scoring are rules as subsets of the social choice method that are employed in this study. The earliest definition of Condorcet method is devised by Condorcet in 1785 and De Borda (1781) discusses a simple summing of expressed voter preferences to present a social ranking called as Borda Scoring (Bassett and Persky 1999).

Based on Condorcet choice, alternatives are compared with each other competitively. Each alternative will compete with the others and the result of each competition is victory for the one alternative that gains the maximum number of votes. Finally, the alternative winning more victories will be the winner of the Condorcet choice.

In Borda Scoring, stakeholders score the alternatives and the one which gets the highest total score will be the proper option. Each alternative will gain a score equal to $m - i$ from each stakeholder, where m is the number of alternatives and i presents the priority of each alternative determined by stakeholders.

2.2.2 *Fallback bargaining*

This method follows the reversible or iterative process for negotiations and bargaining to find the optimum alternative (Brams and Kilgour 2001). Stakeholders vote to their first priority in the first step or iteration. In the next step, the second-priority alternatives are chosen by stakeholders. The process is continued until the minimum utility or satisfaction is expressed by the stakeholders. The minimum utility depends on the decision-maker or the problem at hand and its value may be determined from the majority of the votes collected by the alternatives. For example, the alternative obtaining $[n] \times 0.5 + 1$votes sooner than others (where n is the number of stakeholders) will be considered as the optimum solution to the problem.

2.2.3 *Stability index*

In this evaluation method, unlike the other methods described, the alternatives of resource allocation are compared in terms of their degree of stakeholders' satisfaction or the associated inequities. Loehman *et al.* (1979) developed the stability index equation to evaluate the stakeholders' powers in the cooperative approach as follows:

$$\beta_i = \frac{x_i - v_i}{\sum_{j \in N} (x_j - v_j)}, \quad i \in N, \sum_{i \in N} \beta_i = 1, \tag{9}$$

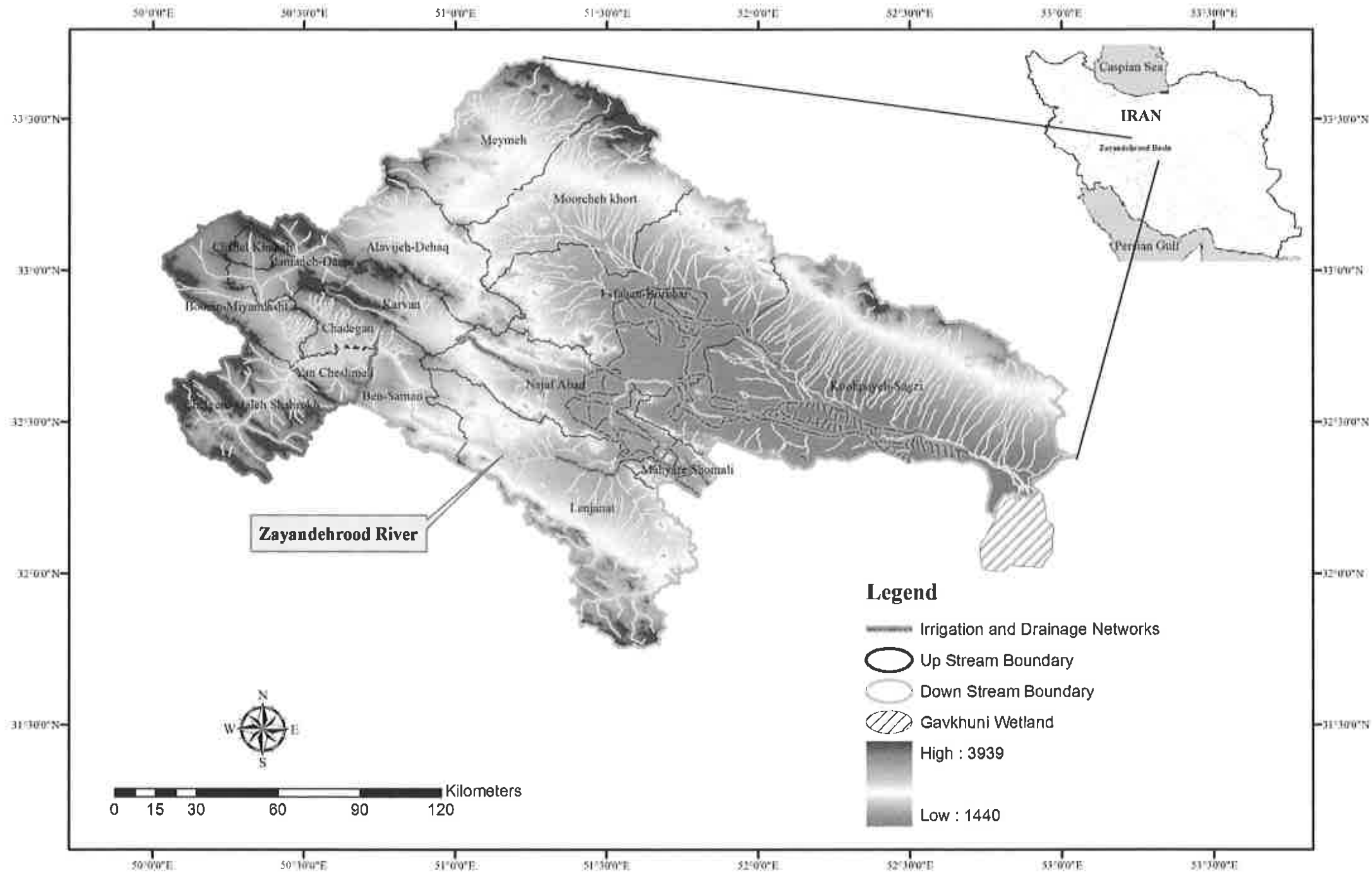


Figure 1 Location of the Zayandehrood River basin.

Table 1 Benefit functions of different groups of water users

Stakeholder	Benefit Function (2.5×10^{10}US$)
Group A (Agriculture-upstream)	$-0.02q^2 + 16.8q + 44.8$
Group B (Agriculture-middle)	$0.015q^2 + 21.9q - 29.1$
Group C (Agriculture-middle)	$0.41q^2 + 15.7q + 584.1$
Group D (Agriculture-downstream)	$-0.0067q^2 + 18.6q - 11.2$
Group E (Industry-middle)	$-3.83q^2 + 1410q - 82254$
Group F (Environmental-downstream)	$639.6q - 7497$

$$S_\beta = \frac{\sigma_\beta}{\bar{\beta}}, \qquad (10)$$

where β_i is the power index, x_i is the value devoted to stakeholder i, v_i is the stakeholder's utility, and σ_β and $\bar{\beta}$ indicate the average and standard deviations of the power indices. The alternative with the lower Stability Index (S_β) shows lower inequity among the stakeholders and will thus be the more stable and proper option.

3 Study area

The Zayandehrood River basin is the main sub-basin of the Gavkhooni basin located in central Iran. The area is approximately semi-arid and the weather conditions change along the west to east direction with the annual precipitation varying from 1400 mm in the west to 100 mm in the east.

There are plenty of industrial, agricultural, domestic, and environmental water users downstream the watershed who withdraw water from both surface and groundwater resources. Figure 1 shows the location of the river basin and its irrigation and drainage networks. The Zayandehrood reservoir is recharged by precipitation in the west through three tunnels. Recently, there has been a significant decrease in the inflow into the Gavkhooni wetland at the end of the river due to the drought conditions and the lack of a proper demand management in the basin. Over extraction from groundwater resources in this region has led to the water table drawdown, which has consequently led to increased salinity of the water in the basin.

The DOEI (Department of Environment of Iran) which is in charge of water delivery to the Gavkhooni wetland has developed the net benefit function of the environment sector based on how much financial losses will be occurred if water demand of the Gavkhooni wetland is not entirely supplied. Some criteria such as immigration of birds, tourist industry and social issues are considered for benefit function development (Tavakkoli Nabavi 2010).

Table 1 shows the benefit functions developed by polynomial regression based on history data, in which q indicates the amount of water consumption in the benefit functions. Clearly, there are six groups of stakeholders or players that include four from the agricultural, one from the industrial, and one from the environmental sector. Figure 2 shows the water users in the Zayandehrood River basin. Isfahan Regional Water Authority (IRWA) as a governmental organization is in charge of water resources allocation in the river basin.

Two scenarios are considered for evaluating the different effects of the applied strategies on supplying water demands and demand management. The strategies include irrigation efficiency improvement, agricultural development, water-use pattern improvement, and inter-basin water transfer projects all embedded in the two scenarios.

Two scenarios are defined as pessimistic (scenario I) and optimistic (scenario II). Pessimistic scenario includes the conditions with no water resources development projects and no improvement of demand management such as no inter-basin water transfer project in the future and no improvement of agricultural and industrial water efficiencies along with the agricultural area development which leads to water scarcity. But based on the optimistic scenario, the water resources development projects and demand management strategies are considered. These are summarized in Table 2.

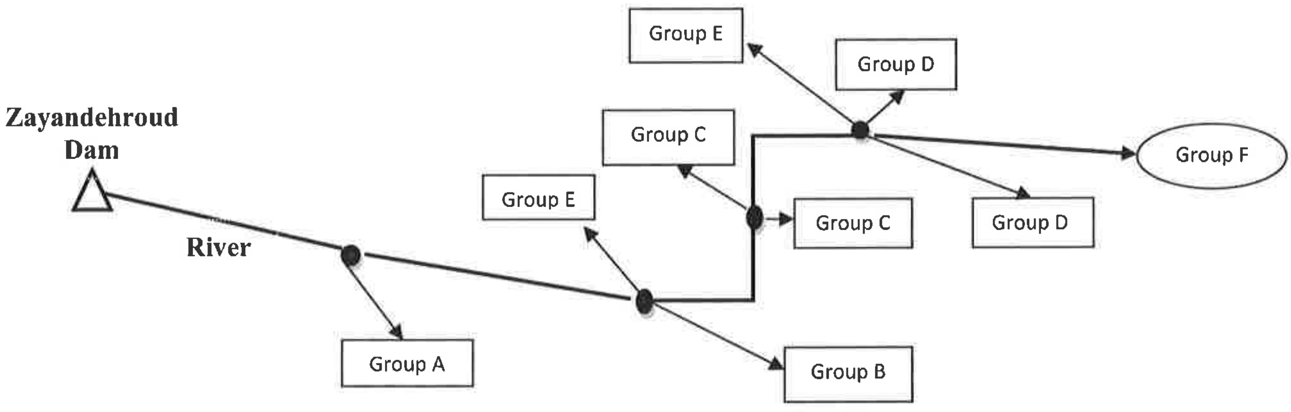


Figure 2 Distribution of the water users in the river basin.

Table 2 Defined scenarios and their specifications

	Irrigation efficiency		Agricultural development		Inter-basin water transfer		Industrial efficiencies	
Scenario	Past	Modified	No	Yes	No	Yes	Common	Desirable
I	x			x	x		x	
II		x	x			x		x

4 Results

4.1 *Optimization model results*

A nonlinear optimization model has been developed for each possible coalition to calculate the benefit payoffs. The optimization process has been performed using a sequential quadratic programming method by *Fmincon* as a nonlinear matrix laboratory optimization function.

Water allocation has been executed by stakeholders participating in a grand coalition. Figure 3 shows the results of the grand coalition model over a period of 10 years as its planning horizon for two defined scenarios. As already described in the previous section, scenario II (optimistic scenario), as compared to scenario I (pessimistic scenario) which employs certain methods to decrease water consumption and increase water availability leading to a total increase in stakeholders' benefits by 12%. As can be seen in Figure 3, in the year 8 of the drought conditions, the payoff was the lowest during the planning horizon.

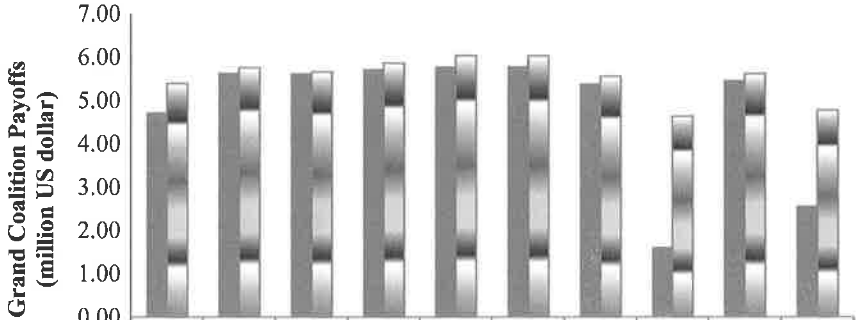
Figure 4 shows the time series of monthly water demands and water allocation to water users including upstream agricultural (groups A and B), downstream agricultural (groups C and D), industrial (group E), and the environmental (group F) sectors in the grand coalition for a period of 120 months. It is clear that the allocated water is less than the demands; however, the results are different for the Gavkhooni wetland (group F) because it operates like a sink as an end node in the river basin, thus receiving more water when the other stakeholders do not need water.

For the six groups of stakeholders, there are 2^6-1 coalitions. Table 3 presents the results for possible coalitions, by which is meant if coalition *S* can be made, there will be a feasible solution for the optimization model devoted to coalition *S*. For example, coalition 'ABC' has no feasible solution because it needs to supply completely the players that do not participate in the coalition including groups D, E, and F. But the water resources of the river basin cannot meet the water demands by groups D, E, and F which have high water demands.

The results of individual and group rationality including partial and grand coalitions during the planning horizon are presented in Table 3.There is no feasible solution for coalitions without number. It means that it is impossible to provide stakeholders' water demand that enter into the coalitions. For example, coalition ABC has no solution under scenario I and cooperation of stakeholders A, B, and C will not be adequate under scenario I.

Since water demands by groups C and D are higher than those of others (Table 3), the coalition in the absence of these groups has no feasible solution. As shown in Table 3, 16 coalitions under scenario I and 31 coalitions under scenario II have feasible solution, indicating the better performance of scenario II compared to the historical policy (i.e. scenario I). Also, the grand coalition under both scenarios has the highest net benefit compared to all other coalitions.

In order to calculate the payoffs or rewards received by each stakeholder, the approaches based on the CGT were implemented. Three methods including Shapely, Nucleolus, and Nash-Harsanyi were also used and payoffs were reallocated. The results for the two scenarios are presented in Figures 5 and 6.



	1	2	3	4	5	6	7	8	9	10
■ Scenario I	4.73	5.65	5.63	5.73	5.79	5.80	5.40	1.62	5.47	2.57
⊟ Scenario II	5.40	5.76	5.67	5.86	6.04	6.03	5.56	4.64	5.62	4.78

Figure 3 Grand coalition payoffs in 10 years for defined scenarios.

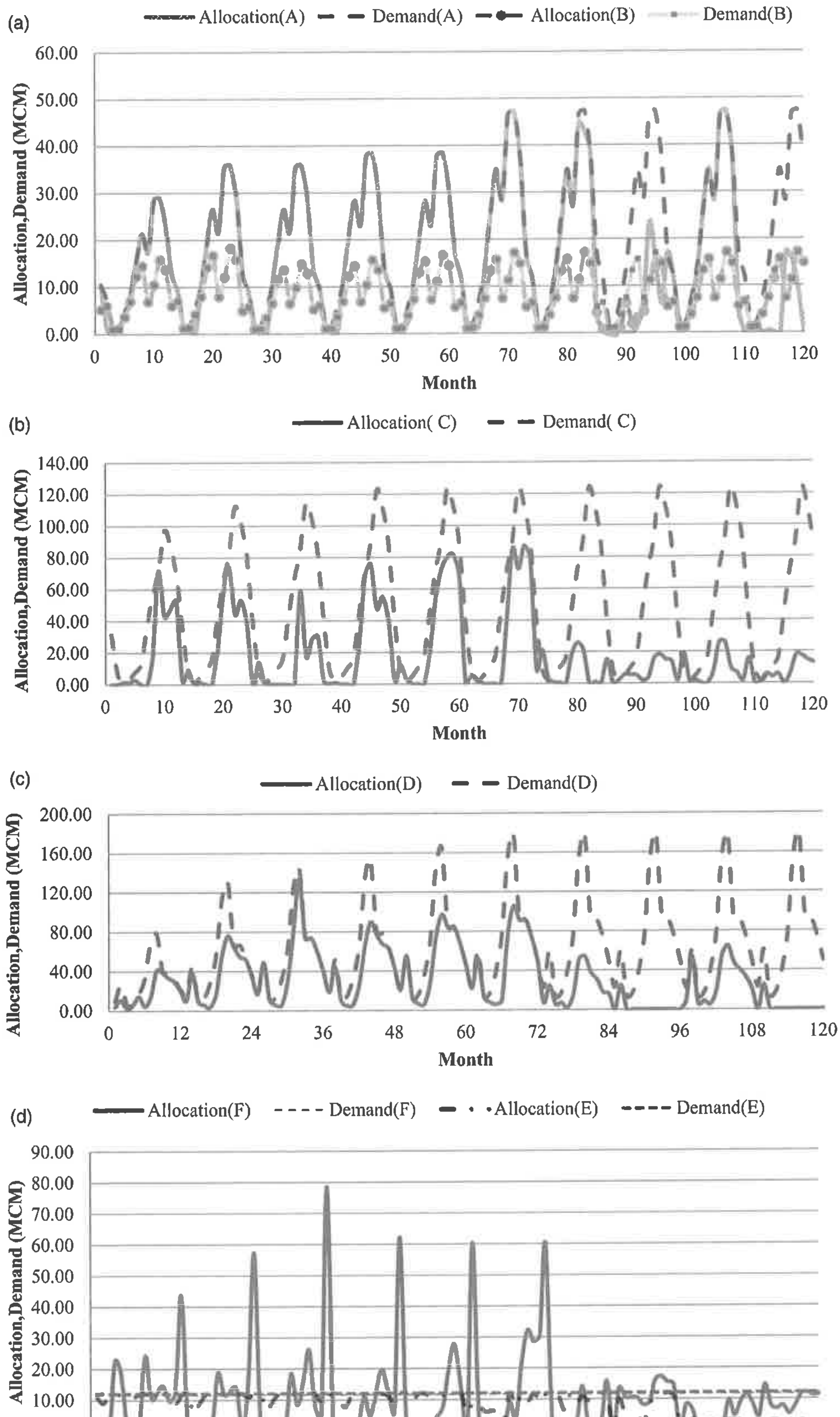


Figure 4 Time series of water allocation in the grand coalition under Scenario II to the, (a) upstream agricultural, (b) mid-stream agricultural, (c) downstream agricultural, and (d) industrial and environmental sectors.

Table 3 Coalition payoffs for defined scenarios (10^6 USD)

coalition	Scenario I	Scenario II	coalition	Scenario I	Scenario II	coalition	Scenario I	Scenario II
A	–	–	ACE	–	12.51	BDEF	–	–
AB	–	–	ACEF	–	36.63	BDF	–	–
ABC	–	2.24	ACF	–	21.28	BE	–	–
ABCD	4.49	5.54	AD	–	–	BEF	–	–
ABCDE	19.51	22.11	ADE	–	–	BF	–	–
ABCDF	34.71	38.71	ADEF	–	–	C	–	0.62
ABCE	–	14.80	ADF	–	–	CD	1.45	3.02
ABCEF	–	42.16	AE	–	–	CDE	9.51	17.43
ABCF	–	24.36	AEF	–	–	CDEF	33.41	44.89
ABD	–	–	AF	–	–	CDF	20.69	29.49
ABDE	–	–	B	–	–	CE	–	10.60
ABDEF	–	–	BC	–	1.27	CEF	–	30.39
ABDF	–	–	BCD	2.93	3.78	CF	–	14.41
ABE	–	–	BCDE	14.79	18.82	D	–	–
ABEF	–	–	BCDEF	41.16	45.94	DE	–	–
ABF	–	–	BCDF	27.62	31.29	DEF	–	–
AC	–	1.66	BCE	–	11.97	DF	–	–
ACD	2.95	4.54	BCEF	–	–	E	–	–
ACDE	16.33	21.22	BCF	–	21.08	EF	–	–
ACDEF	42.96	54.18	BD	–	–	F	–	–
ACDF	29.41	35.79	BDE	–	–	Grand	48.40	55.35

– no feasible solution.

Based on the benefit functions of the groups involved, water allocations to groups F and E were found to be more beneficial. These two groups were less willing to cooperate or reallocate costs and benefits. As shown in Figures 5 and 6, they would not receive more benefits due to reallocation than the grand coalition payoff. In contrast to groups E and F, the others were willing to cooperate under both scenarios I and II.

Groups C and D needed more water than the other players did. They, therefore, participated in most of the possible partial coalitions for obvious reasons as seen in Table 3. In other words, when groups C and D are not participating in any coalition scheme, their water demands must be met as completely as possible even in case of water shortage or droughts in the basin. Therefore, the partial coalitions have no solution without the participation of C and/or D. Thus, groups C and D should naturally prefer Shapely methods to reallocate payoffs.

Compared to the Shapely method, the Nucleolus and Nash-Harsanyi methods that use the core definition, however, provide more benefits to such groups as A, E, and F due to their lower claims on water.

Another point on the reallocation results that is worth mentioning here is the high benefit value devoted to group C by the Shapely method under scenario II (Figure 6). As already seen in Figure 3, this player received less water than other players did, especially over the last 40 months of the planning horizon. This deficit in the water supplied to C had to be compensated for by other players and, thus, Shapely released 23.63 million dollars to group C to hold on fairness.

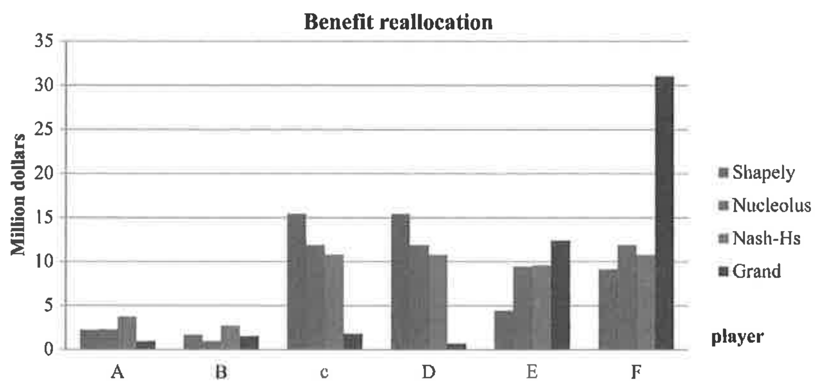


Figure 5 Allocation of benefits to stakeholders using the game theory methods in scenario I.

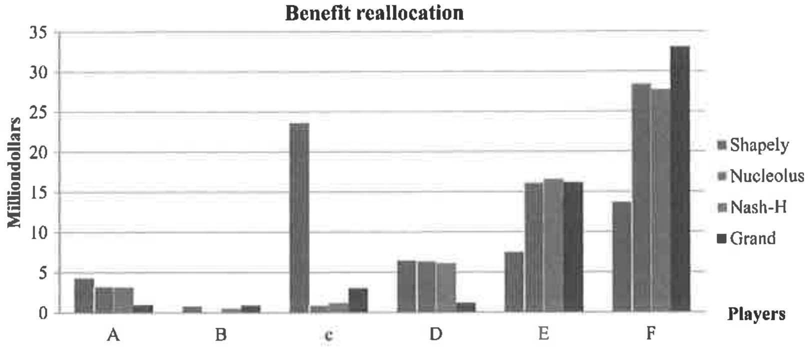


Figure 6 Allocation of benefit to stakeholders using the game theory methods in scenario II.

To determine the stakeholders' shares of costs and benefits, side payments are determined via a variety of methods. These are calculated by subtracting the benefit or cost value obtained in a grand coalition from the reallocated value in the game theory definition. If the given result is positive, the player will receive benefits; otherwise, s/he shall pay the cost due. Table 4 presents the side payments and benefits allocated to each group before and after applying the Game theoretic approaches during the planning horizon. For instance, group A received benefits worth US$ 0.94 in scenario I when water resources were being allocated within the grand coalition scheme. After reallocation of benefits within the Shapely, group A had benefits worth US$ 2.23, or received US$ 1.29.

Due to the shortage of water in the river basin, it is impossible to consider extra benefits or water supplied to players or stakeholders. So, not all players are satisfied at the same time by the formation of a grand coalition and reallocation methods, They can, however, be assured that the situation in the basin will be better than initial allocation scheme was operated on the basis of water rights according to which Industry (Group E), Agriculture (Groups A, B, C, and D), and the Environment (Group F) would be put first, second, and third, respectively, on the priority list. Table 5 is a comparison of the total benefits associated with the initial allocation, Grand coalition, and reallocation for the basin. The comparisons are based on calculation of the ratios of the values obtained from each method to that under the initial conditions.

The results in Table 5 demonstrate that conditions tend to become better than it would be under the initial allocation scheme (i.e. under scenario I) if the players participate in the grand coalition and when the reallocation Game theoretic methods are employed. The initial allocation scheme would only devote US$ 22.61 worth of benefits to all the players while this value has been increased to US$ 43.47 under the grand coalition and to US$ 48.4 as a result of implementing the Shapely method, indicating ratios of 1.92 and 2.14, respectively.

4.2 *Evaluation of the game theoretic approaches*

The three methods of social choice, fallback bargaining, and stability index were utilized to evaluate the fairness of different

Table 4 Side payments and benefit payoffs of game theory methods (10^6 USD)

Scenario I	player	A	B	C	D	E	F
Grand	Benefit payoff	0.94	1.51	1.82	0.68	12.42	31.02
Shapely	Benefit payoff	2.23	1.70	15.43	15.43	4.45	9.16
	Side payment	1.29	0.19	13.61	14.74	−7.97	−21.86
Nucleolus	Benefit payoff	2.28	0.95	11.90	11.90	9.47	11.89
	Side payment	1.34	−0.56	10.08	11.21	−2.95	−19.13
Nash-H	Benefit payoff	3.74	2.72	10.78	10.78	9.60	10.78
	Side payment	2.81	1.20	8.96	10.09	−2.82	−20.24
Scenario II	**Player**	**A**	**B**	**C**	**D**	**E**	**F**
Grand	Benefit payoff	0.98	0.90	3.03	1.19	16.17	33.07
Shapely	Benefit payoff	4.30	0.81	23.63	6.47	7.50	13.69
	Side payment	3.32	−0.09	20.60	5.28	−8.66	−19.38
Nucleolus	Benefit payoff	3.27	0.15	0.95	6.43	16.14	28.41
	Side payment	2.30	−0.75	−2.09	5.23	−0.02	−4.66
Nash-H	Benefit payoff	3.18	0.52	1.21	6.13	16.60	27.71
	Side payment	2.20	−0.38	−1.83	4.94	0.44	−5.36

Table 5 Comparison between initial, grand coalition and game theory methods

	Initial	Grand	Shapely	Nucleolus	Nash-HS
Scenario I					
Total benefit(USD)	22.61	43.47	48.4	48.4	48.4
Ratio	1	1.92	2.14	2.14	2.14
Scenario II					
Total benefit(USD)	28.55	52.98	56.41	55.35	55.35
Ratio	1	1.86	1.98	1.94	1.94

Game theoretic approaches. In the first step, stakeholders or players were asked to prioritize methods based on the results presented in Table 4, the results of which are presented in Table 6.

Table 7 shows the results of the social choice and fallback bargaining procedures. Condorcet choice compares the methods competitively. For example, the competition between Shapely and Nucleolus shows that Shapely won 4 votes out of 6 (6 is the number of stakeholders) while Nucleolus won only two. So, Shapely won 4–2 in this competition against Nucleolus. As shown, the Shapely method wins the game with 2 victories under scenario II, but Nash-Hs wins with one victory under scenario I.

Borda Scoring evaluates the methods based on the total scores given by stakeholders according to benefits gained (Table 7). Clearly, Shapely with a score of 8 is regarded as the proper option for water allocation under scenario II and Nash-Hs with a score of 7 is the right option under scenario I.

Fallback bargaining sets 6 votes as the minimum condition for the option to be regarded as the one agreed upon. However, as shown in Table 7, all the methods received a total vote of 6 in the last selection step (Choice 3). Thus, the minimum agreement was decreased to 5 and 4 votes for scenarios I and II, respectively. Accordingly, the fallback bargaining selected the Nash-Hs and Shapely as proper alternatives for water allocation under scenarios I and II, respectively. In scenario I which reflects the historical policy, Nash-Hs is regarded as the proper choice, but the proper option for scenario II is Shapely.

Table 7 Social choice and fallback bargaining results

Condorcet choice

	Shapely		Nucleolus		Nash-Hs		Wins	
Scenario	I	II	I	II	I	II	I	II
Shapely	–	–	3-3	4-2	2-4	4-2	0	2
Nucleolus	3-3	2-4	–	–	3-3	3-3	0	0
Nash-Hs	4-2	2-4	3-3	3-3	–	–	1	0

Borda Scoring

	Shapely		Nucleolus		Nash-Hs	
Scenario	I	II	I	II	I	II
Group A	0	2	1	1	2	0
Group B	1	2	0	0	2	1
Group C	2	2	1	0	0	1
Group D	2	2	1	1	0	0
Group E	0	0	1	1	2	2
Group F	0	0	2	2	1	1
Sum	5	8	6	5	7	5

Fallback bargaining

	Choice 1		Choice 2		Choice 3	
Scenario	I	II	I	II	I	II
Shapely	3	4	3	4	6	6
Nucleolus	1	1	4	4	6	6
Nash-Hs	2	1	5	4	6	6

Stability index is another evaluation criterion used for determining the more stable alternative or method with minimum inequity level. In contrast to social methods, this criterion finds the most stable method that may not satisfy all stakeholders, but it assures that the approach will not be failed. The stability indices for different methods under the two scenarios are presented in Table 8. The results show that the Shapely method had a lower stability index under scenario II, indicating a

Table 6 Stakeholders' priorities for choosing game theory method

Group F	Group E	Group D	Group C	Group B	Group A	Priority
			Scenario II			
Group F	Group E	Group D	Group C	Group B	Group A	Priority
Nucleolus	Nash-Hs	Shapely	Shapely	Shapely	Shapely	1
Nash-Hs	Nucleolus	Nucleolus	Nash-Hs	Nash-Hs	Nucleolus	2
Shapely	Shapely	Nash-Hs	Nucleolus	Nucleolus	Nash-Hs	3
			Scenario I			
Group F	Group E	Group D	Group C	Group B	Group A	Priority
Nucleolus	Nash-Hs	Shapely	Shapely	Nash-Hs	Nash-Hs	1
Nash-Hs	Nucleolus	Nucleolus	Nucleolus	Shapely	Nucleolus	2
Shapely	Shapely	Nash-Hs	Nash-Hs	Nucleolus	Shapely	3

Table 8 Stability index result for Scenarios A and B

	Shapely		Nucleolus		Nash-Hs	
Scenario	I	II	I	II	I	II
Stability Index	0.78	0.87	0.63	1.22	0.47	1.19

lower inequity level among the stakeholders. This is different for scenario I. As already explained, there is no chance of forming many partial coalitions in this scenario; therefore, Shapely method is unable to set fairness among the players and Nash-Hs method with a stability index of 0.47 is the optimum choice in scenario I.

Although the efficient water allocation is derived by game theory approaches, the equity is the other main concern of the paper evaluated by the stability index. The results demonstrate that the water allocation policies will be applicable if the players find the solution with the equitable shares. The stability index shows that all stakeholders may not be satisfied, but it assures that the water allocation approach will not fail and its implementation will be guaranteed. The lower stability index shows lower inequity among the stakeholders which leads to encourage stakeholders for participation and improve the efficiency of the system.

5 Conclusion

In this study, water allocation based on sharing benefits was implemented for the Zayandehrood River basin located in the central part of Iran. Optimization models are developed using the cooperative Game theoretic approaches to schedule a model for conflict resolution in the region without any priority among the stakeholders. A total number of 63 optimization models were developed for different coalitions among water users with the objective functions of maximizing the benefit or utility function of stakeholders who participate in the coalitions. Not all the possible coalitions could be formed due to the water shortage in the basin. The numbers of feasible coalitions are 16 and 31 for scenarios I (pessimistic scenario) and II (optimistic scenario), respectively, which show the effects of management policies on water supply and water demand management in the study area during the planning horizon.

The results proved that the best results are achieved when the players constitute a grand coalition. Therefore, water allocation must be implemented based on a grand coalition which requires the cooperation and participation by all the stakeholders and that no one can make claims on complete supply for their water demands. The fact that more benefits may be gained with the grand coalition rather than with other possible ones provides sufficient incentives for all the water users to cooperate and participate in the grand coalition. Certain Game theoretic approaches including the Shapely, Nucleolus, and Nash-Harsanyi methods were then used to determine payoffs assigned to each player in the reallocation process. Side payments to each stakeholder are obtained by reallocation of benefits. The social choice, fallback bargaining, and stability index criteria were implemented to evaluate the fairness and stability of the methods. The Shapely value which considers the results of grand and partial coalitions to reallocate the benefits showed a better performance in water allocation under scenario II. For scenario I, however, in which partial coalitions cannot be made, the Nash-Harsanyi method which follows the core definition was found to be the proper choice.

The results also demonstrate that this novel methodology can be easily applied to real-world problems to achieve equitable resolutions. The results can be utilized as a basis for supporting decision-makers of a river basin to resolve social conflicts.

Acknowledgment

This study was sponsored by research committee of Isfahan Regional Water Authority, Research Grant No. IRWA91.144.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Appendix

A.1 Nucleolus method

The nucleolus minimizes the maximum excess of any coalition s. Equation (9) shows the gap between utility payoff and allocation vector x. in order to minimize the excess value, ε, under the constraints of the core definition (Schmeidler 1969). The following optimization model is used to determine the payoff or reward vector:

$$\min \varepsilon \tag{A1}$$

$$v(s) - \sum_{i \in S} x_i \leq \varepsilon, \tag{A2}$$

$$\sum_{i \in U} x_i = v(U). \tag{A3}$$

A.2 Nash-Harsanyi method

Harsanyi (1958, 1963) combines the Nash bargaining solution with the core definition for the cooperative game by developing an optimization