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CONFLICT RESOLUTION OF WATER RESOURCES ALLOCATIONS USING GAME THEORETIC APPROACH: THE CASE OF ORUMIEH RIVER BASIN IN IRAN

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ABSTRACT

The unavoidable consequences of increased demand for, and decreased supply of, various natural resources, especially water, have caused increased conflict over their allocation. Water allocations merely based on a water rights approach usually do not make efficient use of water for the whole river basin. Thus, there is a need for a comprehensive and stable allocation scheme that can satisfy all the involved interest groups. In this study, cooperative game theoretic approach was suggested to solve the water allocation problems. In this regard, the Core, the Shapely Value and the Gately propensity to disrupt concepts were applied to evaluate the possible cases of cooperation among riparian parties. Moreover, not only have efficient and equitable allocations been done among different users, but also the stability of the allocations was investigated. In particular, through the case study of the Orumieh River Basin in Iran with scarce water resources and multiple users, effectiveness and potential advantages of this approach have been shown. The results of this research showed that cooperative game theory can be applied to assess the cases of cooperation in the Orumieh River Basin in conjunction with a comprehensive water planning model.

Keywords: Conflict Resolution, Cooperative Game Theory, Water Planning Model, Water Allocation

INTRODUCTION

Water resources allocation is one of the complex topics in integrated water resources management, which could vary over time due to changes in several involved parameters. In recent years, population growth and economic development have resulted in more demands on limited water resources and also caused serious challenges in allocation plans. Furthermore, transboundary river basins, or basins shared by two or more water consumers, increase complexity in managing water resources. So far, more than 200 river basins have been found around the world as being shared by two or more users.

Conflict arises in transboundary river basins when asymmetries exist with respect to information, power, or location. Asymmetric information arises when riparian parties have different access to the data related to a basin. Asymmetric power can be stemmed from either wealth or military power. Usually, power asymmetry allows some riparian parties to develop more water projects, such as reservoirs or irrigation systems, than the others. Location asymmetry refers to upstream-downstream geographic location of riparian users in a basin. All of these asymmetries allow some users to have strategic power in water negotiations within a basin (Just and Netanyahu, 1998). Among many approaches presented by the researchers to overcome conflicts between riparian parties and improve the management of water resources, cooperative game theory has been used successfully. Cooperative game theory can be regarded as a tool for determining if cooperation can exist in a basin between riparian parties. It also provides methods to calculate fair and equitable allocations of cooperative gains to stakeholders if cooperation is possible. To determine the benefits of cooperation among riparian parties in a river basin, water planning models can be very helpful. Often, these models are manipulated in such ways that satisfy the requirements of the game theory calculations.

Sharing the water of the Orumieh River Basin among Kordestan, West Azarbayejan, and East Azarbayejan provinces has been the source of increasing conflict since the past decade. In recent years, considerable decrease in precipitation, successive droughts especially during 1992-2002 and the considerable development of agricultural projects have led to decreasing amount of streamflows entering the Lake Orumieh. Therefore, these natural and human made factors not only have been

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serious threat to economical, social and environmental aspects of both basin and the Lake, but also have caused great concerns for scientific, local, national and even international communities.

In this study, a linear optimization model was developed to calculate the total net benefit of the Orumieh River Basin. Then, depending on a desired coalition of water users, some constraints were added to the model for evaluating the benefit of that coalition. And finally, by combining the Orumieh River Basin Model (ORBM) with cooperative game theory concepts, different cases of cooperation among stakeholders have been investigated. The results of this study can provide river basin riparian parties a sound tool for making more reliable and stable decisions.

LITERATURE REVIEW

Game theory is the mathematical study of conflict and cooperation. The players in a game strategically make decisions where a decision of each player affects the costs or benefits allocated to the others (J.Neumann and O.Morgenstern, 1944). Generally, games are divided into two main groups: non-cooperative and cooperative. In non-cooperative games, each player is not aware of the others' decisions but in cooperative games, all possible strategies that could exist are determined and the players can be informed of the consequences of each decision prior to play by making communication with each other.

One of the first applications of game theory in water resources management was presented by Rogers (1969). It revealed that treaty negotiation between India and the province of East Pakistan for their shared water resources of the Ganges and Brahmaputra rivers can be analyzed effectively by applying game theory. Since that application, cooperative game theory has been applied to various water management topics such as cost allocation for water development projects, water quality, aquifer and transboundary water resources management.

Suzuki and Nakayama (1976) calculated the allocated costs and benefits of a reservoir construction project to agricultural and municipal users. Five years later, Straffin and Heaney (1981) used this idea and allocated the costs equitably between hydropower, flood management and navigation projects of the Tennessee Valley. Becker and Easter (1997 and 1999) applied cooperative game theory for allocating water from the Great Lakes. By forming different partial coalitions, they concluded that the non-cooperative coalitions could be induced to cooperate ones and the grand coalition was shown to be the best solution for all players. Loaiciaga (2004) evaluated the cooperation role in extracting shared groundwater resources in the United States by using various mathematical and game theoretical methods. He showed that in some cases, reaching a stable cooperation is not possible unless a persuasive force exists because the general tendency of riparian parties is to extract groundwater resources more than what they are allowed. Dinar et al. (2006) applied a cooperative game based on the negotiation, the Shapely and the Nucleolus approaches in a water allocation problem for the Kat Basin in South Africa. They concluded both negotiation and cooperative game theory methods allocate the same amount of benefit to the players under different cooperation cases.

Most of the transboundary river basin cooperative games have used optimization models to calculate the characteristic functions of their games. Nonlinear Programming was applied in the Nile game (Wu, 2000; Wu and Whittington, 2006), which maximized the net economic benefit to each player and considered physical basin constraints. In the case of the Euphrates and Tigris (Kucukmehmetoglu, 2002; Kucukmehmetoglu and Guldmann, 2004; Kucukmehmetoglu, 2009), Linear Programming models were utilized and the objective was to maximize the net benefit to each player in terms of monetary value derived from hydropower production, irrigation and urban uses. In addition to these researches, Zara et al. (2006) provided a thorough review of cooperative game theory applications to natural and environmental problems other than water resources. Moreover, Madani (2010) investigated the capabilities of the application of game theory in various water resources management and conflict resolution issues using a series of non-cooperative games.

METHODOLOGY

The Physical Structure of the ORBM

The ORBM mainly consists of three provinces of West Azarbayejan (WA), East Azarbayejan (EA), Kordestan (K) and the Lake Orumieh, which are shown in Figure 1. The Lake is fed by 19 main branches which collect the excess water from all over the basin. Since the whole network of the basin is too extensive to show, a typical branch incorporating demand sites, river and supply reservoir in the east part of the Lake is illustrated in Figure 2. As it is seen, the whole system includes 117 subbasins which all serve as agricultural demand nodes (i), and 6 reservoirs that are responsible for supplying demand nodes together with the subbasins' incremental flows. These supply nodes provide water for agricultural, urban and industrial uses, and the demand of each node is assumed to be supplied by the most nearest and accessible supply node. Moreover, there are two interbasin links, none of them stemming from West Azarbayejan. Actually, one of them connects Kordestan to West Azarbayejan and the other one connects East Azarbayejan to West Azarbayejan.

Figure 1. Orumieh River Basin

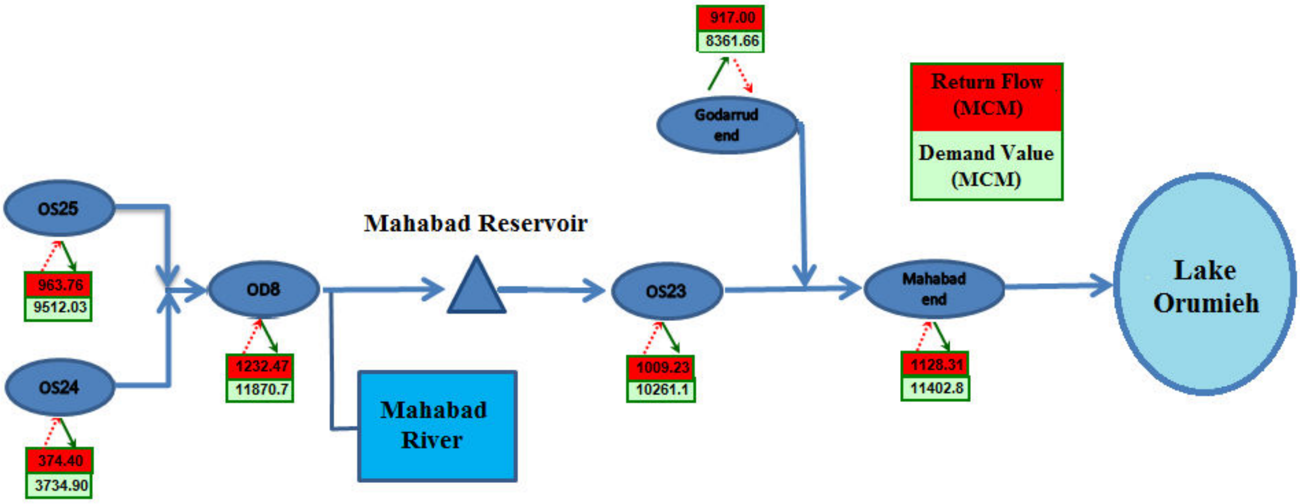

Figure 2. A Typical Branch of Orumieh River Basin Network

Mathematical Structure of the ORBM

The ORBM is a linear optimization model designed to maximize the total net benefits of the three riparian users–West Azarbayejan, East Azarbayejan and Kordestan–subject to water resources availability, continuity, demand and environmental constraints. In this study, due to the fact the agriculture sector has the most usage of water and the other sectors have less contribution to increase objective function relative to the agriculture sector, the benefits of using water in agricultural demand nodes were only considered. Thus, the net benefits are the gross benefits derived from agricultural use of water in the basin at various demand nodes, minus the production costs. Moreover, in order to improve the final results of the model, all demands nodes throughout the basin have been modeled separately rather than integrating the ones in each province and considering them as a lump unit. The objective function and constraints of the basic model are as follows:

Maximize

$$TNB = \sum_{p=1}^{216} \sum_{i=1}^{117} Ag_{p,i} \times (Benefit_{p,i} - Cost_{p,i})$$

Subject to

$$WA_i = \sum_j Inflow_{ji} + IncFlow_i + \sum_j Rl_{ji} + \sum_j (Ag_{ji} \times ARC_{ji}) + Rres$$

$$0 \le Ag_i \le AgDem_i$$

$$Ag_i + EnvDem_i \le WA_i \qquad \forall\ i,j$$

where, $Ag_{p,i}$ is the amount of water allocated to each demand node, $Benefit_{p,i}$ is the total benefit derived from the agriculture sector, $cost_{p,i}$ is the total cost of production, WA_i is water availability at each demand node i, $Inflow_{ji}$ is the amount of water entering node i from upstream rivers, $IncFlow_i$ is the incremental flow, Rl_{ji} is the released water from upstream node j to downstream node i, *ARC* is the return flow coefficient of upstream agricultural nodes, *Rres* is the amount of water releasing from a reservoir, *AgDem* is the maximum agricultural water demand, *EnvDem* is the downstream environmental demand of each agricultural demand node or reservoir and finally, *p* is the number of monthly periods.

It should be noted that at all demand nodes which were supplied only by the incremental flows, the allocation priority was on the agriculture sector and the additional water, if exists, would be allocated to the downstream environmental demand of each node. In wet periods, the fraction of downstream environmental demand to average annual discharge of each node was considered equal to 0.1, while this fraction was taken as 0.3 in dry periods. But at the other demand nodes that were also supplied by reservoirs, the objective was to cover both agriculture and environmental demands as much as possible. In addition, the operating rule of the reservoirs followed standard operating policy (SOP), which can be shown as follows:

$$Rl_t = \begin{cases} 0 & if \quad Storage_t - EnvDem_t - AgDem_t - Loss_t \prec= 0 \\ Storage_t - Loss_t - V_{\min} & if \quad 0 \prec Storage_t - EnvDem_t - AgDem_t - Loss_t \prec= V_{\min} \\ EnvDem_t + AgDem_t & if \quad V_{\min} \prec Storage_t - EnvDem_t - AgDem_t - Loss_t \prec= V_{\max} \\ Storage_t - Loss_t - V_{\max} & if \quad Storage_t - EnvDem_t - AgDem_t - Loss_t \succ V_{\max} \end{cases}$$

$$Storage_{t+1} = Inflow_{t+1} + Storage_t - Rl_t - Loss_t$$

where *Storage* is the reservoir storage, *Loss* is the amount of reservoir evaporation, V_{min} is the minimum amount of water that should be kept in the reservoir and V_{max} is the reservoir maximum capacity.

Cooperative Game Theory Application

The application of optimization models like ORBM, which use traditional optimization methods in allocating limited resources, assumes that all the riparian parties agree to cooperate with each other and participate in the given scheme. But, there may be the possibility for the parties to find better forms of cooperation, either individual or smaller coalitions, to increase their total net benefits. This is the situation where conflict may arise among the parties and as a result, presenting an efficient and sustainable method of allocation seems urgent. Thus, the purpose of this section is to analyze different cases of cooperation between riparian parties using game theory concepts as a powerful tool in resolving the desired conflict.

All possible interactions between three provinces are listed in Table 1. A coalition is defined as any subset of players (riparian provinces) that can cooperate and make an agreement. Each player in the game has the choice of three feasible actions: to act unilaterally, to make partial coalition(s) with one or more other players, or to join the grand coalition which includes all players. As can be seen form Table 1, the first three rows illustrate the case of individual action by each province or the coalitions with only one player, such as {West Azarbayejan}, {East Azarbayejan} and {Kordestan}. Various partial–two province–coalitions are presented in the second three rows, which include {West Azarbayejan-East Azarbayejan}, {West Azarbayejan-Kordestan} and {East Azarbayejan-Kordestan}. Finally, the case of full cooperation among all existing provinces which is known as grand coalition–{West Azarbayejan-East Azarbayejan-Kordestan}–can be found in the last row.

Table 1. Different Interactions of Players

Types of Cooperation	Coalition Reference
{Kordestan}	Individual Coalition
{West Azarbayejan}	Individual Coalition
{East Azarbayejan}	Individual Coalition
{Kordestan, West Azarbayejan}	Partial Coalition
{Kordestan, East Azarbayejan}	Partial Coalition
{West Azarbayejan, East Azarbayejan}	Partial Coalition
{Kordestan, West Azarbayejan, East Azarbayejan}	Grand Coalition

Typically, to represent the benefits of cooperation to each coalition, the characteristic function (ν) is used. Characteristic function values for a water resources cooperative game are often calculated using a water resources model. In this study, in order to calculate the net benefit of each coalition, the ORBM was appropriately adjusted to evaluate the characteristic function values of different coalitions of provinces by adding required constraints.

After calculating the characteristic function values of a cooperative game, various allocation methods can be utilized to distribute the total benefits of a coalition to its players. A commonly used method for determining the range of the possible allocations that all players might agree to is the Core. The Core is a set of allocations that are not dominated by any other allocations; in other words, these are allocations that all players in a coalition are willing to accept (Gillies, 1953). Besides, these allocations must satisfy two essential criteria, which provide sufficient incentive for the players to commit to the agreements. If X_i denotes the allocation to each player i, the Core of the water allocation game is defined by a set a constraints as:

$$X_K \geq \nu(K)$$
$$X_{WA} \geq \nu(WA)$$
$$X_{EA} \geq \nu(EA)$$
$$X_K + X_{EA} \geq \nu(K,EA)$$
$$X_K + X_{WA} \geq \nu(K,WA)$$
$$X_{EA} + X_{WA} \geq \nu(EA,WA)$$
$$X_{EA} + X_{WA} + X_K = \nu(K,EA,WA)$$

The first criterion is individual rationality, which means that no player will accept an allocation smaller than what they can receive without cooperation. On the other hand, the second one that is known as group rationality states that the benefits allocated to any subgroup of riparian provinces should be at least the same as what that partial coalition could achieve on its own.

Taking into account these concepts, the Shapley method is used to divide the total benefits of a coalition to its player. In general, this method of allocation is mainly based on the marginal contribution of each player to enhance coalition benefit and as a result, it can be used to distribute the gains of a coalition to its player in a fair and equitable manner as:

$$\varphi_i = \frac{1}{n!}\sum_{i \in C}((p-1)!\times(n-p)!\times[\nu(C)-\nu(C-i)])$$

where φ_i is the Shapely value for player i, n is the total number of players, C is the coalition which contains i, p is the number of players in coalition C, $\nu(C)$ is the characteristic function value for coalition C and $\nu(C - i)$ is the characteristic function value for coalition C without i.

At last, the probability that a player will quit the grand coalition because of dissatisfaction with its allocation may be accessed through stability indices. One of helpful indices to measure this dissatisfaction is the Gately propensity to disrupt index (Gately, 1974), which can be calculates as:

$$d_i = \frac{\sum_{i \neq k} \varphi_k - \nu(N-i)}{\varphi_i - \nu(i)}$$

where d_i is the propensity to disrupt of player i and $\nu(N-i)$ is the characteristic function value of the grand coalition without player i. In the next section, more details will be given about the results of the procedure stated above.

RESULTS AND DISCUSSION

The characteristic function values of the coalitions under the water allocation game for the 18-year period ranging from 1988 to 2006 are displayed in Table 2. These characteristic values will be used in examining the existence of the Core. As Table 2 shows, the full cooperation among the players has the most benefit for the system and this is mainly because of utilization of various available water resources by all players. For instance, due to the special geographic location of the provinces relative to each other, operation of Zarinehrud reservoir, which is located in the north of Kordestan and south of West Azarbayejan, depends on existence a kind of cooperation between these two provinces. In other words, the most amount of water entering to West Azarbayejan should be passed through Zarinehrud reservoir. As a consequence, a connection, say cooperation, between them results in supplying more agricultural demand nodes and also environmental demand of the Lake Orumieh.

Table 2. Characteristic Function Values of Different Coalitions

Coalition	Characteristic Function Value (Million Rials)
{Kordestan}	1198
{West Azarbayejan}	193669
{East Azarbayejan}	143851
{Kordestan, West Azarbayejan}	194876
{Kordestan, East Azarbayejan}	189628
{West Azarbayejan, East Azarbayejan}	378215
{Kordestan, West Azarbayejan, East Azarbayejan}	379438

To see the possible allocations each player agrees to accept, it is useful to plot the Core in barycentric coordinates. The Core is limited by the minimum allocation that each player will agree to accept and the maximum value that the other players in the coalition agree to give that player under the grand coalition. Thus, the Core can be drawn on a simplex as shown in Figure 3.

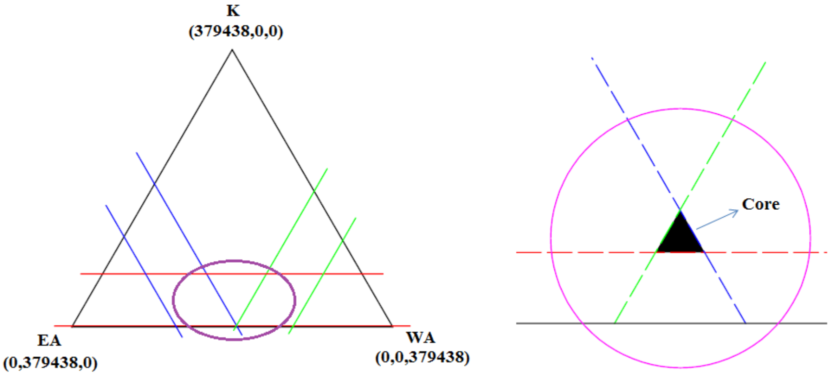

Figure 3. The Core of the Water Allocation Game

The Core of the water allocation game exhibits that the negotiation range for all the players is not wide enough. The reason of this characteristic is we only considered the benefits of the agriculture sector rather than regarding the others such as industrial and urban sectors, too. But it is apparent that the case of cooperation benefits all the players much more than they can gain under non-cooperative actions.

After investigating the existence of the Core, the Shapely value method was used to distribute the gains of a coalition to its players. According to Table 2, the grand coalition has the highest value of characteristic function and obviously, it will be the selected coalition for this game. So, the Shapley values were calculated for this coalition, which are shown in Table 3.

Table 3. Shapely and Non-cooperative Allocations to Players

Players	**Non-cooperative Allocation (Million Rials)**	**Shapely Allocation (Million Rials)**
Kordestan	1198	8637.667
West Azarbayejan	193669	199166.7
East Azarbayejan	143851	171633.7

Owing to Table 3, a comparison can be made between the cases of cooperation and non-cooperation. As can be seen from the results, in the grand coalition, Kordestan has a minimum delivery value of 1198 million Rials but can negotiate for an additional 7440 million from the grand coalition. East Azarbayejan has a minimum delivery value of 143851million Rials, but receives an additional 27813 million from the Core for an allocation of 171634 million. The same results can also be concluded for West Azarbayejan. Therefore, these are the values that each player could expect to benefit as a result of cooperation and receive an increase over its non-cooperative value.

To evaluate the stability of the allocations, the propensity to disrupt index was used to measure a player's willingness to leave the coalition. Actually, this index compares the level of loss a player would experience by leaving the coalition to the loss of the remaining players. The propensity to disrupt for each player under the Shapley allocations is displayed in Table 4.

Table 4. Propensity to Disrupt of the Players

Players	**Propensity to Disrupt**
Kordestan	-0.9
West Azarbayejan	-2.6
East Azarbayejan	0.6

The propensity to disrupt is measured relative to each player in a coalition and should be less than one if a player is satisfied. As it is seen, all the players have the propensity to disrupt under one which verifies the importance of cooperation among them. Moreover, Kordestan and West Azarbayejan have negative propensity to disrupt indicating that they would lose much more than the other player by leaving the coalition.

CONCLUSION

In this study, a combination of water planning model and cooperative game theory was used to investigate the possible cooperation among riparian parties. Also, the Orumieh River Basin was selected as the case study due to increasing conflicts during recent years and cooperative game theory tools were applied to measure the additional benefits deriving from cooperation. The analysis of the Core defined the range of allocations each player will be willing to accept under grand coalition. Besides, the Shapley Value method was used to equitably allocate the potential gains of cooperation of the coalition to the individual players in that coalition. Finally, the propensity to disrupt index was calculated for each player and the analyses showed that all players will be satisfied with the applied method of allocation and as a result, it provides a reasonable starting point of cooperation by the players. This research has shown that cooperative game theory can be applied as a useful tool for evaluating the water management scenarios in the Orumieh River Basin in conjunction with a comprehensive water planning model.

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