An agent-based model for water allocation optimization and comparison with the game theory approach

Mahsa Noori, Alireza Emadi and Ramin Fazloula

ABSTRACT

Despite the advancement of technical tools for the analysis of complex systems, the most important issue in solving water resource problems focuses on the interaction of human and natural systems. Agent-Based Model (ABM) has been used as an effective tool for the development of integrated human and environmental models. One of the main challenges of this method is identifying and describing the main agents. In this study, three main approaches including Genetic Algorithm (GA), cooperative game theory and ABM have been used to optimize water allocation in Tajan catchment. The proposed ABM is a new equation for calculating stakeholder utility and simulating their interactions that can create a hydrological-environmental-human relationship for demand management and optimal water allocation. The results showed that the total benefit of cooperative game theory and ABM relative to GA has been increased 24% and 21% respectively. Although the total benefit in game theory is greater than the ABM, but the ABM considering the agents feedback propose a more comprehensive approach to optimal water allocation.

Key words | agent-based models, cooperative game theory, optimal water allocation, Tajan basin, water resources management

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HIGHLIGHTS

- Combining of GA optimization model with ABM.
- The total benefit of game theory and ABM is significantly more than the GA.
- Proposing an Agent-Based Equation to solve water conflicts and finding solutions based on social and hydrological interactions.
- Comparing the results of game theory and the proposed ABM and GA in water allocation to stakeholders.

INTRODUCTION

The variability of rainfall regimes and river flow in different years, as well as the complexity in predicting the water resources of the catchment in the future, make it necessary to adopt an appropriate strategy to optimally manage the operation of the dam reservoir with scientific methods. Therefore, it is required to formulate water allocation policies with sufficient comprehensiveness and according to criteria such as justice, efficiency, and sustainability. Among the proposed solutions, game theory is one of the

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methods used by some researchers to improve water resource management. Game theory is an essential tool for studying the mathematics of competition and cooperation, which shows how strategic reactions between players correspond to their benefits. Game theory is divided into two general branches: Cooperative and Non-Cooperative games. There are several solutions to cooperative games such as the Core, the Nucleolus, the Shapley Value, and the Kernel, among which Shapley Value is a strong tool as it considers the marginal contribution of each player to the coalitions (Sadegh *et al.* 2010). Von Neumann & Morgenstern (1944) introduced the basic concept of cooperative games and their features. Aadland & Kolpin (2004) studied water allocation decision-making as a cooperative game in the Cut River Basin in South Africa, based on benefit-sharing laws and the principles of game theory. Wang *et al.* (2008) proposed a method for allocating water using cooperative games. The initial water allocation to the players was based on physical and logical constraints. Then, they used the game theory to reallocate water to achieve the optimal conditions. Niksokhan *et al.* (2009) studied the commercial discharge permit using game theory and used the Shapley and Nucleolus methods to redistribute treatment costs. Sadegh *et al.* (2010) modeled the problem of water transfer between basins using fuzzy and non-fuzzy cooperative games theory. Mehrparvar *et al.* (2015) resolved the conflicts of water resource allocation using game theory. They evaluated the results of different games theory methods with stability definitions. Huang *et al.* (2018) investigated the fuzzy cooperative game model in allocating pollution load. They used the fuzzy Shapley value method to allocate benefits from coalition formation. Han *et al.* (2018) optimized the allocation of water resources based on multi-agent game theory and proposed an optimization model for the relationship between agents in the studied river basin. To simulate social processes, agents are considered as individuals or groups of people and their relationships represent the processes of social interaction. In the water resources management, considering independent decision-makers and diverse goals, identifying and accurately describing the factors is complex and behavioral factors must be taken into consideration. Therefore, there has been increasing attention to the Agent-Based Models (ABM). Agent-Based Modeling is an approach for modeling those systems that consist of independent agents that can interact together. Agent-Based Modeling makes it possible to consider two general social and ecological sectors, as well as their interactions with each other. The social part of this approach includes all users, or in other words, those players who are affected by the system and interact with it. The ecological part of the Agent-Based Modeling includes all the sub-models that form water resources and water resource-related systems. The biggest strength of this modeling approach is to regard the social part of the model, aligning the ecological part, as well as considering their interactions. Applications of Agent-Based Modeling in water sciences were first studied on the management of renewable resources by Bousquet *et al.* (1993). In their research, a multi-agent simulator was developed to better understand the interaction between operators and natural resources. Yang *et al.* (2009) presented a decentralized optimization method known as constraint-based reasoning, which allows individual agents to optimize their behaviors over various alternatives. Akhbari & Grigg (2013) provided a framework for managing stakeholders' conflicts in the San Waking catchment. This framework was presented to evaluate effective ways to encourage stakeholders to cooperate more to reduce agricultural water consumption and, consequently, reduce water pollution and increase river water flow. Baldassarre *et al.* (2015) developed a new approach whereby the mutual interactions and continuous feedbacks between floods and societies are explicitly accounted. They showed how the interactions between human and physical systems can be investigated, and demonstrated that changes in flooding and changes in societies are deeply intertwined. Ding *et al.* (2016) proposed the ABM for the allocation of water resources in the Nile Basin. They used a parallel evolutionary search algorithm to introduce the mechanism of income value redistribution among competing factors based on their share. Bakarji *et al.* (2017) modeled the socio-hydrological model for water resources management. They proposed an ABM as a framework for investigating those social behaviors that are related to groundwater pollution. Hyun *et al.* (2019) used an Agent-Based Modeling method to analyze the role of risk perception in water resources management decisions. Lin *et al.* (2019) proposed the ABM for water resources management in the Bakken area. Pouladi *et al.* (2019) proposed a novel socio-hydrological modeling framework for assessing the performance of complex water resources systems. Ponnambalam & Mousavi (2020) proposed basic definitions and challenges/opportunities from different perspectives to study and control water cycle impacts on society and vice versa. Anebagilu *et al.* (2021) developed a behavior model based on a modified Theory of Planned Behavior. They showed that the constructs added to TPB had a significant effect on modeling the intention and behavior of farmers.

According to the literature review, game theory is one of the most widely used methods to study the interaction between stakeholders and how they make decisions in common water resources, which determines the overall benefit of a system. On the other hand, ABMs have been noticed by researchers by considering the social behaviors of stakeholders in a common environment. However, so far the results of these two methods have not been compared based on a real study. Also, in the water resources management, few studies about the ABMs have been presented with real world applications. The main purpose of this study is the optimal water allocation by increasing the overall benefit of the system by application of cooperative game theory and ABM.

In this research, an ABM is presented to describe the main agents in the water decision-making process sending water to agriculture, municipal, industry, and environment sectors with the objective of determining the optimal water allocation based on social and hydrological interactions. The state sector was also considered as a regulatory and determining agent. The proposed equation was used to establish a hydrological-environmental-human relationship as a decision-making tool in water resource conflicts. This scientific solution was presented by simulating the behavior of agents about the amount of water allocation. The level of satisfaction of agricultural agents was used to reallocate water and calculate their utility and total benefit to evaluate the results. The equation presented in this research can be used in other basins in accordance with the management and environmental conditions of each region. Finally, the results of the application of game theory and the proposed ABM in water allocation to stakeholders are discussed.

MATERIALS AND METHODS

In this research, to optimize the water allocation from the Shahid Rajaei Dam reservoir, two methods of cooperative game theory using the Shapley method and Agent-Based Modeling have been used and the results of each of these methods have been studied as well. The proposed models include reservoir simulation using standard operating policy, optimization of water allocation using the Genetic Algorithm (GA), cooperative game theory, and behavioral simulation of agents using the ABM. The flowchart of the research method is shown in Figure 1.

CASE STUDY

The case study in this research is Shahid Rajaei Dam, 45 km southwest of Sari, located in the Tajan basin. The main use of this dam is to supply agricultural water to the surrounding lands and to provide municipal water. Figure 2 shows the Tajan basin. Figure 3 shows the annual time series of the volume of water entering the Shahid Rajaei Dam reservoir.

To allocate water to various needs, including municipal, environmental, agricultural, and industrial, it is necessary to identify all water consumers downstream and the needs of each of them. It is essential to supply the municipal and industrial water demands of all months of the year. Agricultural agents include rice, citrus, oilseeds, maize, fodder corn, olives, stone fruit, and wheat. Figure 4 shows the water demand of agricultural agents. In this study, the water demand was calculated using Cropwat software.

Table 1 shows the crop cultivation area in the case study and Table 2 shows the amount of water demand that must be supplied from the Shahid Rajaei Dam reservoir.

RESERVOIR SIMULATION BASED ON STANDARD OPERATING POLICY (SOP)

Standard operating policy is one of the operating methods of the reservoir. In this method, the amount of released water is assumed to be equal to the water demand. When the reservoir is unable to fully supply the requirements, it supplies a percentage of it (Tan *et al.* 2017). In this method, it is tried to

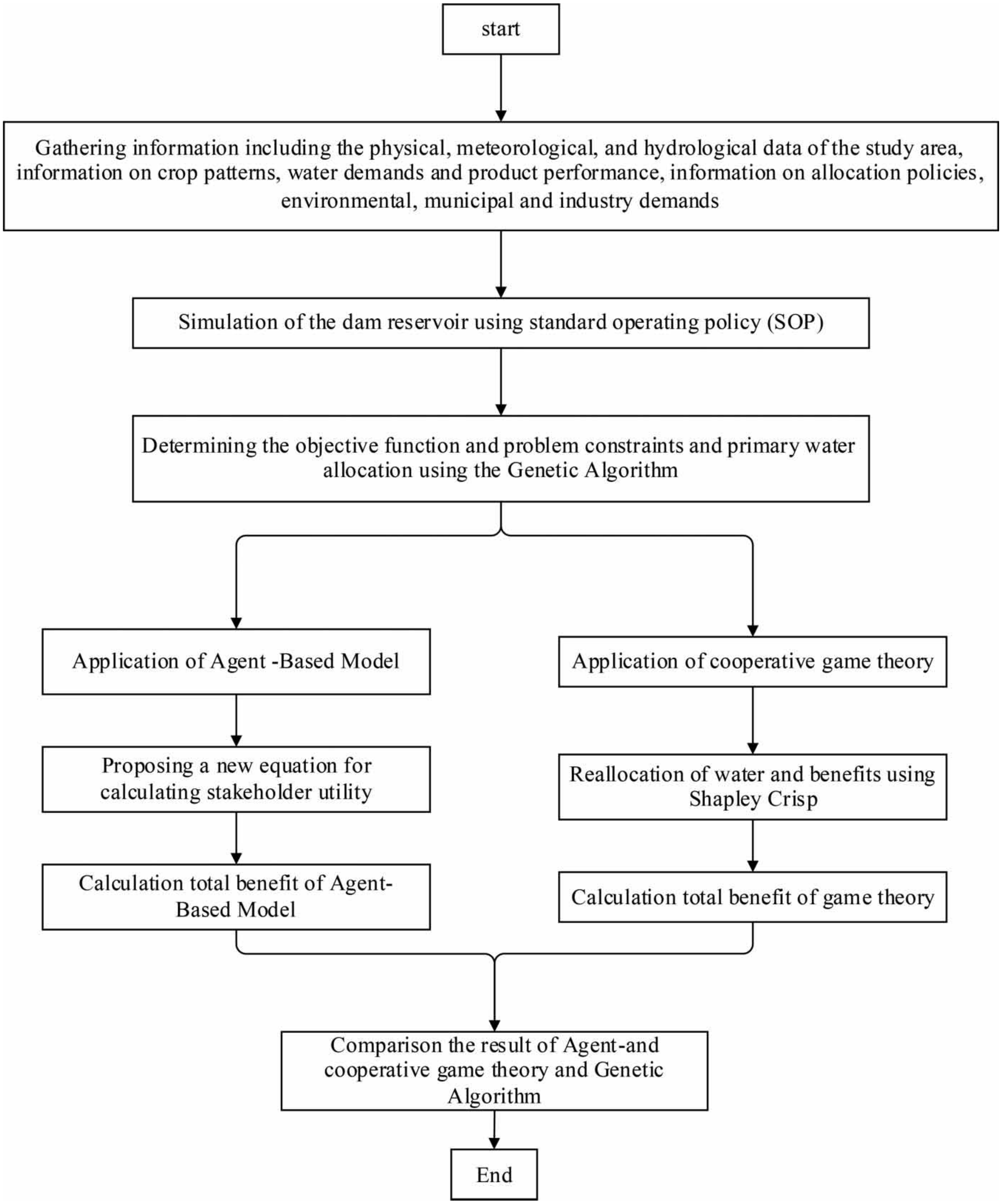


Figure 1 | Flowchart of the proposed methodology.

supply the total downstream water demand in each period. In this study, the reservoir simulation program was developed based on the standard operating policy (SOP). The information about the dam reservoir, including the monthly discharge values to the reservoir in chronological order, a monthly distribution of evaporation and precipitation

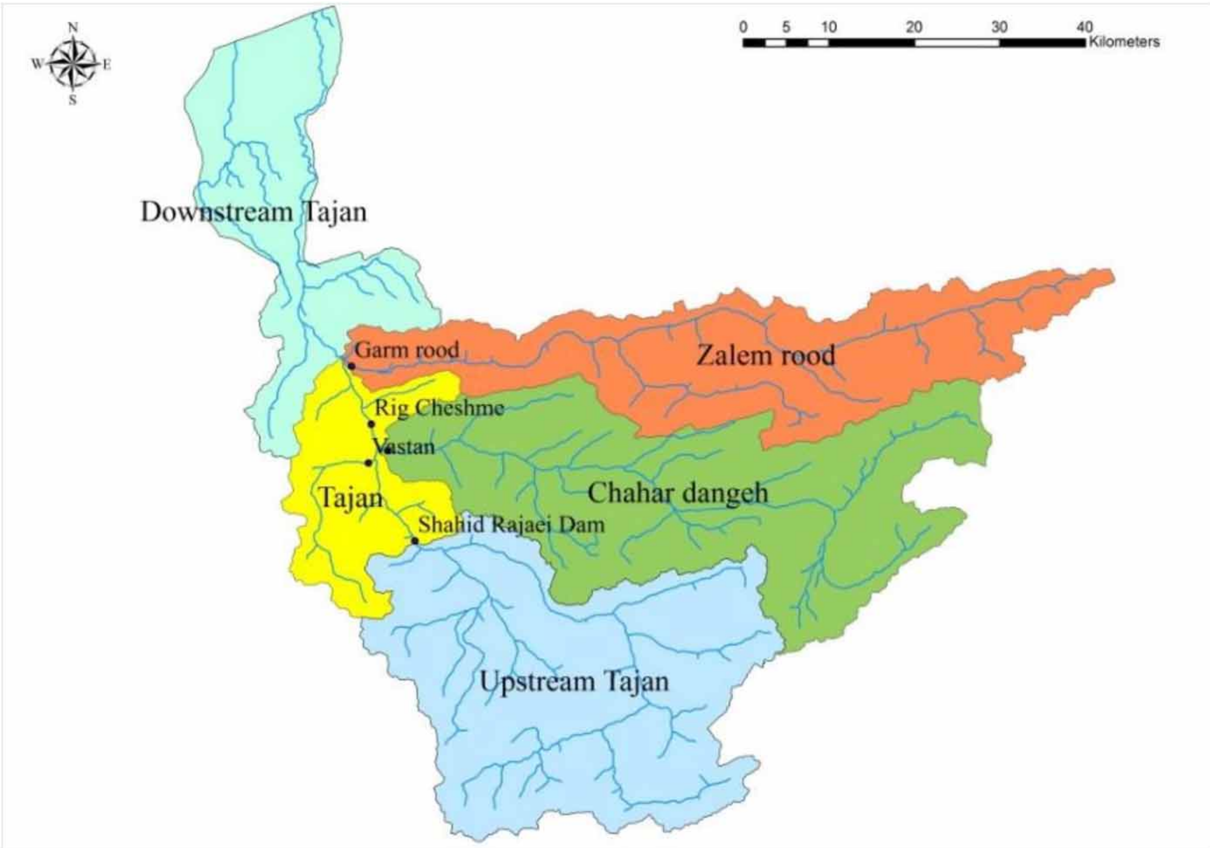


Figure 2 | Tajan basin.

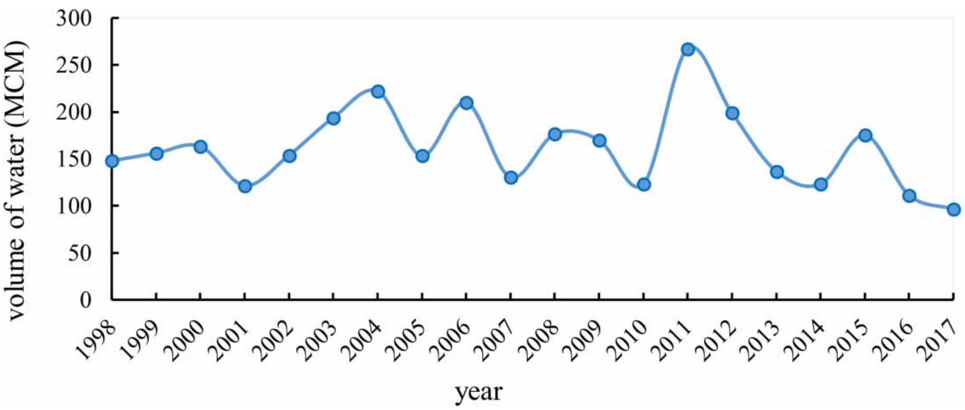


Figure 3 | Annual time series of volume of water entering the dam reservoir (million cubic meters).

altitude, number of operation months, minimum and maximum of reservoir volume, a monthly distribution of demands, and maximum volume demands are entered in this method. By establishing the relationship between the surface and volume of the reservoir in each period from the area–volume–elevation curve of the reservoir, the volume of evaporation and precipitation in each period is obtained. Then, assuming the initial volume of the reservoir

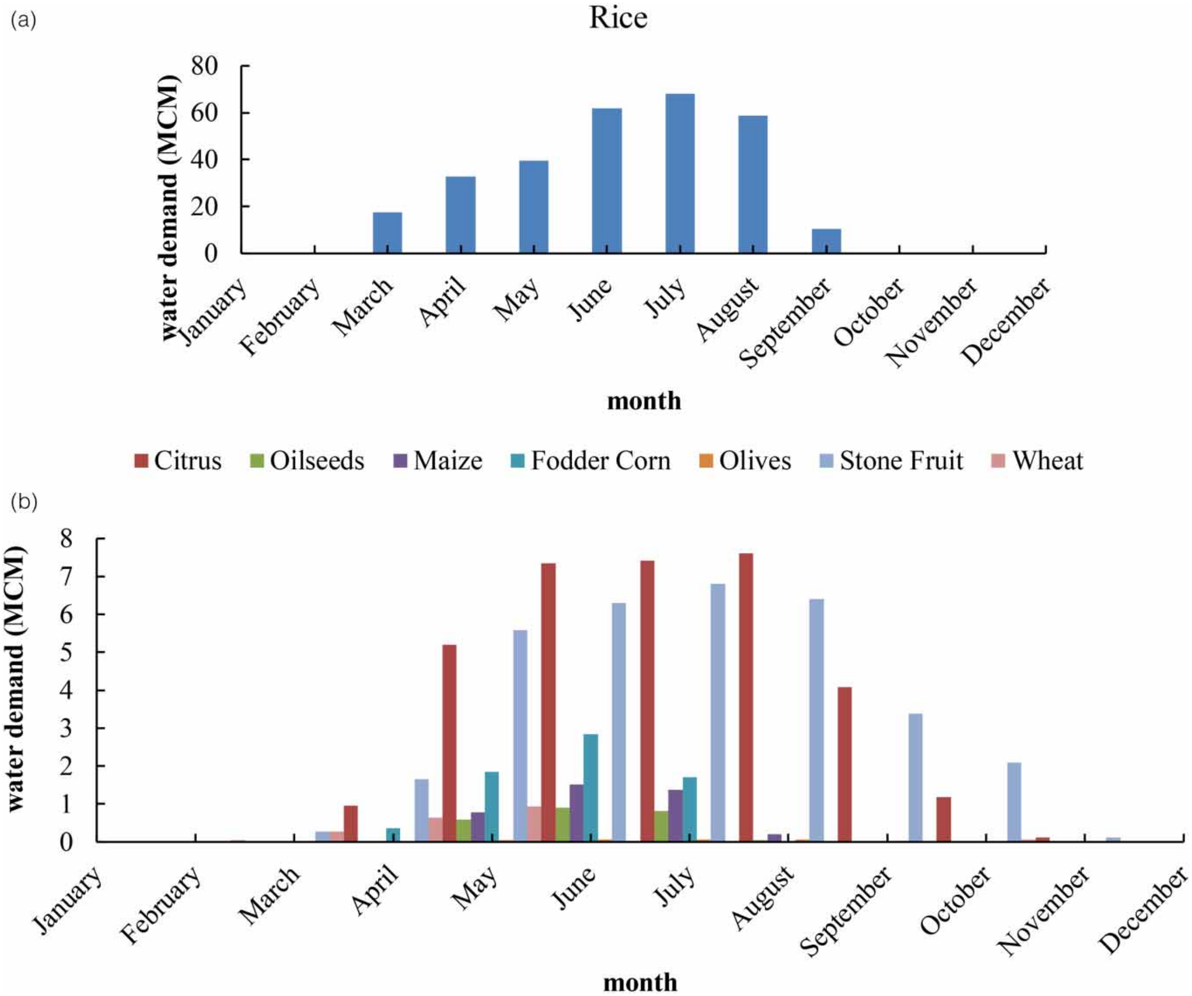


Figure 4 | (a) Water demand of agricultural agents (million cubic meters). (b) Water demand of agricultural agents (million cubic meters).

Table 1 | Crop cultivation area in the case study

Product type	Area under cultivation (Hectares)
Rice	20,944
Citrus	5,394
Oilseeds	418
Maize	700
Fodder corn	1,378
Olives	45
Stone fruit	2,271
Wheat	635

and observing the constraints and limitations, the storage volume of the reservoir, the volume of the overflow, and the quantity of water that can be released in each period are calculated. Finally, this simulation model is used to calculate the target function specified to operate the reservoir in combination with the GA optimization model. The continuity equation which is one of the most basic modeling relationships of reservoir operation is presented in Equation (1). Relationships 2–5 show the constraints and limitations of the problem.

$$S_{t+1} = S_t + Q_t + P_t - Ev_t - Re_t - Sp_t \quad (1)$$

$$S_{min} \leq S_1 \leq S_{max} \quad (2)$$

$$Sp_t = 0\,,\ \ Re_t = De_t \quad (3)$$

Table 2 | The most important downstream demands of Shahid Rajaei Dam (million cubic meters)

Water demand	Municipal water sector	Environmental sector	Industry sector
January	0.50	1.4	0.34
February	1.10	1.4	0.34
March	2.90	1.7	0.85
April	2.30	1.9	1.10
May	3.50	1.9	1.36
June	3.50	1.8	1.45
July	4.70	1.8	1.87
August	4.10	1.8	1.63
September	3.50	1.8	1.36
October	2.30	1.5	0.85
November	1.10	1.5	0.51
December	0.50	1.4	0.34

$$\text{if} \quad S_{t+1} > S_{max} \quad \begin{cases} Sp_t = S_{t+1} - S_{max} \\ S_{t+1} = S_{max} \end{cases} \tag{4}$$

$$\begin{aligned} &\text{if} \quad S_{t+1} < S_{min} \quad Def_t = S_{min} - S_{t+1} \\ &\text{if} \quad Def_t < De_t \quad \rightarrow \begin{cases} Re_t = De_t - Def_t \\ S_{t+1} = S_{min} \end{cases} \\ &\text{if} \quad Def_t > De_t \quad \rightarrow \begin{cases} Re_t = Q_t \\ S_{t+1} = S_{min} \end{cases} \end{aligned} \tag{5}$$

where, S_t is reservoir volume at the beginning of the t period, S_{t+1} is reservoir volume at the end of the t period, Q_t is the volume of inlet flow to the reservoir during the t period, Sp_t is the volume of the overflow from the reservoir during the t period, EV_t is the volume of evaporation from the reservoir surface per month t, P_t is the rainfall volume on the reservoir surface per month t, Re_t is the volume of released water from the reservoir in the steps t, S_1 is the initial volume, S_{min} is the minimum volume of reservoir is equal to the dead volume of the dam, S_{max} is the maximum volume of reservoir is equal to the normal volume of the dam, De_t is the volume of water demand in the step t and Def_t is the amount of deficiency in the step t.

PRIMARY WATER ALLOCATION USING THE GENETIC ALGORITHM OPTIMIZATION MODEL

In the first step, available water is allocated to the players based on equity criteria. The purpose of the initial allocation is to supply the water demands regardless of the economic aspects. In other words, in this step, water allocated to the players is proportional to their water demands. If the volume of water available in the dam reservoir does not fully supply the stakeholder's water demands, using the constraints of equity, the percentage supplying their demands will be the same. Model decision variables are the monthly amounts of water allocated to the players over the 17 years. In this study, three main players in the agricultural sector are considered in the first scenario. In this model, first, the municipal, industrial and environmental requirements are supplied, then the agricultural demands are supplied according to the values of each demand. In this step, the GA optimization model is used and the time step for performing optimization calculations is monthly. The objective functions and constraints are shown in Equations (6)–(9).

$$\text{Min } Z = \sum_{S=1}^{3} \sum_{y=1}^{17} \sum_{m=1}^{12} (d_{s,m,y} - r_{s,m,y})^2 \tag{6}$$

$$r_{s,m,y} \leq d_{s,m,y} \tag{7}$$

$$\frac{\sum_{m=1}^{12} r_{1,m}}{\sum_{m=1}^{12} d_{1,m}} = \frac{\sum_{m=1}^{12} r_{2,m}}{\sum_{m=1}^{12} d_{2,m}} = \frac{\sum_{m=1}^{12} r_{3,m}}{\sum_{m=1}^{12} d_{3,m}} \tag{8}$$

$$\sum_{s=1}^{3} r_{s,m,y} = R_{m,y} \tag{9}$$

where, s is the index of competing user (player), $r_{s,m,y}$ is the allocated water to the player s in the month of m of the year y (million m^3), and $d_{s,m,y}$ is the water demand of the player s in the month of m of the year y (million m^3). $R_{m,y}$ is the water released from the dam reservoir in the month of m of the year y (million m^3).

In the second scenario for Agent-Based Modelling, 10 agents including eight agricultural agents, one environmental agent, and one state agent are considered. In this scenario, based on equity criteria and by using the GA optimization model, the amount of available water is allocated to the agents. Model decision variables are the monthly amounts of water allocated to agents over 12 months. In this scenario, eight main agents in the agricultural sector, including rice, citrus, oilseeds, maize, fodder corn, olives, stone fruit, and wheat, have been considered during a growing season. In this model, the priority is to supply the municipal and industrial demands, and then the demands of agricultural agents are supplied. In this step, the GA optimization model is used and the time step for performing the optimization calculations is monthly. The objective functions and constraints are shown in Equations (10)–(13).

$$\text{Min } Z = \sum_{S=1}^{8}\sum_{m=1}^{12}(d_{s,m} - r_{s,m})^2 \tag{10}$$

$$r_{s,m} \le d_{s,m} \tag{11}$$

$$\frac{\sum_{m=1}^{12} r_{1,m}}{\sum_{m=1}^{12} d_{1,m}} = \frac{\sum_{m=1}^{12} r_{2,m}}{\sum_{m=1}^{12} d_{2,m}} = \frac{\sum_{m=1}^{12} r_{3,m}}{\sum_{m=1}^{12} d_{3,m}} = \frac{\sum_{m=1}^{12} r_{4,m}}{\sum_{m=1}^{12} d_{4,m}} = \frac{\sum_{m=1}^{12} r_{5,m}}{\sum_{m=1}^{12} d_{5,m}} = \frac{\sum_{m=1}^{12} r_{6,m}}{\sum_{m=1}^{12} d_{6,m}} = \frac{\sum_{m=1}^{12} r_{7,m}}{\sum_{m=1}^{12} d_{7,m}} = \frac{\sum_{m=1}^{12} r_{8,m}}{\sum_{m=1}^{12} d_{8,m}} \quad m = 1, 2, \ldots, 12 \tag{12}$$

$$\sum_{s=1}^{8} r_{s,m} = R_m \tag{13}$$

where, s is the agricultural agents, d is the water demand of each agricultural agent per month m, r is the amount of released water for each agent of the dam per month m that is allocated to agricultural agents, R_m is the total water that can be released from the dam reservoir per month m. Equation (11) shows that the amount of allocated water to each agent per month should not exceed the demands of that agent per month. Equation (12) shows the constraint of equity between all agents. Equation (13) is also a physical constraint related to the volume of water that can be released from the dam reservoir.

REALLOCATION OF WATER AND BENEFITS USING COOPERATIVE GAME THEORY

In cooperative games, the goal in the system is to reach an agreement on a conflict issue. The purpose of the model is to obtain the highest possible benefit through the water allocation process, considering different possible coalitions between the players. In this model, the main objective is to maximize the benefits of the system based on a national perspective and distribute the produced benefits between the players equitably so that they have the economic incentives to participate in the coalitions. The basic assumption in cooperative game theory is that the grand coalition, that is the group consisting of all players, will form. One of the main research questions in cooperative game theory is how to allocate the payoff of the grand coalition to the players in some fair way. In this study, Shapley Crisp's cooperative game is used to maximize total benefits. In this method, players participate in the various possible coalitions, until finally, the most optimal situation for water sharing and the benefit received from each of them is obtained. In the Shapley Crisp method, players participate in the coalition with all the water allocated to them (Sadegh *et al.* 2010). The flowchart of calculating the characteristic functions for the Crisp Shapley method to reallocate water to the players who participated in each coalition is shown in Figure 5.

Where, S: Crisp coalition, $x(s)$: Summation of all amounts of water brought to Crisp coalition. $w(i)$: Initial water allocation to player (i), $D(i)$: Demand of player i to use water. $r(i)$: Benefit coefficient of player i per each m^3 of water assuming that $r(2) > r(3) > r(1)$. $n(s)$: characteristic function of Crisp coalition S.

In the next step, each player is assigned a unique benefit called the Shapley value which is proportional to its average marginal contribution to each coalition and it is a power index of the player in each coalition. Shapley Value is represented as (Young *et al.* 1982):

$$x_i = \sum_{i \in S \subseteq N} \frac{(|S|-1)!(n-|S|)!}{n!}[v(S) - v(S - \{i\})] \tag{14}$$

where, X_i is Shapley Value, n is the number of players, $|S|$ is the number of member of coalition S, $v(S - \{i\})$ is the worth

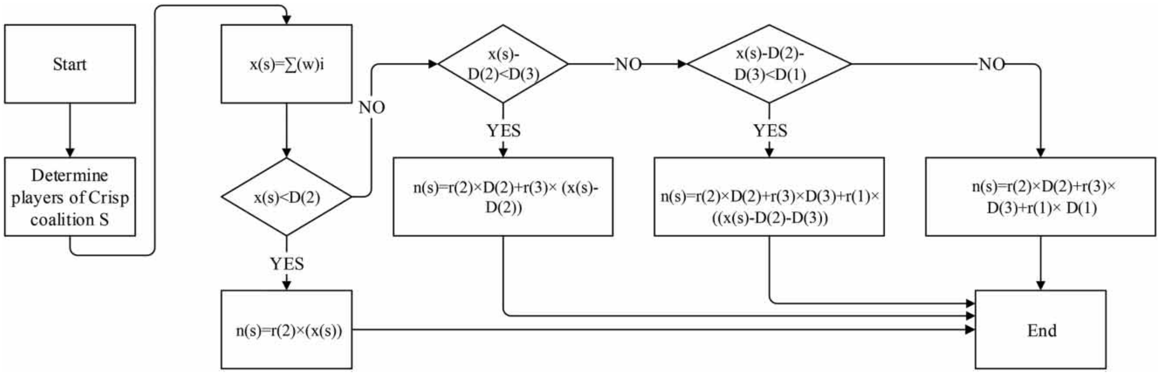


Figure 5 | Flowchart of calculating the characteristic function for Crisp Shapley method.

of coalition *S* without participation of the player *i*. At this stage, secondary reallocation of water quantity and benefit is done to regard equity. For this purpose, the amount of payments that must be exchanged between participants in each coalition is determined each month. For example, if a participant was given a share in a coalition and if that amount was less than the share assigned to the player in the initial allocation, other participants in the coalition must pay the player an equivalent share of his lost water.

AGENT-BASED MODELS

The main idea of this modeling approach is to bring the model as close as possible to the real situation of the problem and, as a result, to achieve more realistic results in the model. Therefore, the use of the modeling approach in the field of modeling in complex systems and especially water resources systems has increased significantly in recent years (Berglund 2015).

DEVELOPMENT OF AGENT-BASED MODELS

In this study, to optimize the water allocation from the Shahid Rajaei Dam reservoir by developing the ABMs, according to the requirements of the basin, the agricultural sector includes rice, citrus, oilseeds, maize, fodder corn, olives, stone fruit and wheat, and the environment and state sectors will be considered as agents. After satisfying the water demands of the municipal and industrial sectors, as well as determining the value of water rights of eight agricultural agents, the percentage of their utility and the percentage of the environmental sector utility should be calculated. The Montana-Tenant method has been used to calculate the environmental utilities. The Montana-Tenant method is based on the allocation of a certain percentage of the river's water flow during water shortage and flooding periods. The percentage of water supply means establishing a constant ratio of natural river flow as environmental flow. In this method, six main levels for determining environmental flow and one level for flood conditions have been identified (Davis & Hirji 2003).

In the main method, specific months of the year are dedicated to the period of water shortage and flooding. However, due to the dissimilarity between climatic conditions and water resources in Iran with the country of origin of this method, these periods are different in Iran. For this reason, to reach greater adaptability in the modified method, the months of AD have been removed and replaced by the period of water shortage and flooding. Table 3 shows the modified Montana-Tenant method for determining environmental flow based on the percentage of annual river flow average (CIWP 2014).

In this study, according to the environmental conditions of the downstream river of the dam and Montana -Tenant methods, ecosystem conditions were considered good. Thus, the percent of the annual river flow average for spring and summer seasons were identified 40% and for autumn and winter seasons were identified 20%. Furthermore, the annual river flow average according to the 17-year statistics data in the study area is 168 million cubic

Table 3 | Montana-Tenant modified method for determining the environmental flows based on the percentage of annual river flow average (CIWP 2014)

	The percentage of annual river flow average (%)	
Target	**Spring – Summer**	**Autumn – Winter**
River flow	60–100	60–100
Ecosystem conditions	Percentage of flow required to maintain ecosystem conditions	Survival of river conditions
Excellent	60	40
Very good	50	30
Good	40	20
Medium	30	10
Weak	10	10
Very destructive	0–10	<10

Table 4 | Benefit per each cubic meter of water allocated and the percentage of water demand supplying without significant reduction in product performance

Product type	Benefit per cubic meter of water allocated (Rials)	The percentage of water supplying without significant reduction in product performance (%)
Rice	10,030	95
Citrus	35,430	70
Oil Seeds	6,040	80
Maize	3,030	80
Fodder corn	6,850	70
Olives	10,980	75
Stone fruit	58,110	70
Wheat	15,000	75

meters. To calculate the utility of agricultural agents, Equation (15) is presented in this research.

$$U_i = \frac{Al_i}{D_i} + \left(1 - \frac{Q_{river}}{\propto(\bar{Q}_{river})}\right) + \beta\left(1 - \frac{Al_i}{D_i}\right) \quad i = 1, 2, \ldots, 8 \tag{15}$$

$$\text{if } Q_{river} > \propto(\bar{Q}_{river}) \rightarrow \frac{Q_{river}}{\propto(\bar{Q}_{river})} = 1$$

where, i is the number of agricultural agents, Al_i is the amount of water allocated to each agricultural agent during the cultivation period, D_i is the water demands of each agricultural agent during the cultivation period, Q_{river} is the average of downstream river flow, $\propto$ is Tenant's coefficient, $\bar{Q}_{river}$ is the annual average of downstream river flow, β is the percentage that the state intends to pay in exchange for water shortages to agricultural agents.

The first part of Equation (15) relates to the agricultural agents and depends on the percentage of water supply. The second part is the pressure level of the environmental agent, which will increase the utility of agricultural agents and consequently will reduce their demands if the demand is not supplied or the environment is vulnerable. The third part is related to the state, which can be determined by allocating subsidies in exchange for not supplying the water demands of agricultural agents. After calculating the utility of agricultural agents, the amount of benefit per cubic meter of water allocated to them is calculated using Table 4 to analyze the applied changes.

The information of Tables 4–7 and Figures 3–6 have been received from the agricultural organization of Mazandaran Province.

After determining the agent's utilities, the water demand of each agent is modified using the Equation (16) and then the GA will be given to the optimization model to reallocate

Table 5 | The benefit of players per each cubic meter of water

Player	Player 1(Rice)	Player 2 (Citrus)	Player 3 (Other crops)
Benefit (Rial)	10,030	35,430	28,650

Table 6 | The benefits of water allocation to the participants in the coalitions (Billion Rials)

		Type of coalition			
Benefit	**Initial allocation**	**Coalition 1, 2**	**Coalition 1, 3**	**Coalition 2, 3**	**Grand coalition**
Player1 (Rice)	54,558	52,510	53,198	54,558	51,150
Player2 (Citrus)	22,116	30,138	22,116	30,138	30,138
Player 3 (Other crops)	9,869	9,869	13,351	4,625	13,351
Coalition	–	82,648	66,549	34,763	94,639
Total	86,543	82,648	66,549	34,763	94,639

Table 7 | Players' payments and receipts based on Shapley Crisp game (Billion Rials)

Equivalent Water Revenues		Player 1 (Rice)	Player 2 (Citrus)	Player 3 (Other crops)
Grand Coalition	Optimization model	51,150	30,138	13,351
	Shapely value	57,680	25,566	11,393
	Payable or receivable share	6,530	−4,572	−1,958
Coalition 1, 2	Share of the coalition	52,510	30,138	9,869
	Payable or receivable share	2,048	−2,048	0
Coalition 1, 3	Share of the coalition	53,198	22,116	13,351
	Payable or receivable share	1,360	0	−1,360
Coalition 2, 3	Share of the coalition	54,558	30,138	4,625
	Payable or receivable share	0	−5,245	5,245

according to the feedback of the agents.

$$\mathrm{D_{new_i}} = \mathrm{Al_i} + (1 - \mathrm{U_i}) \times (\mathrm{D_{i-}Al_i}) \tag{16}$$

where, $D_{\mathrm{new_i}}$ is the new water demand of each agricultural agents and U_i is the utility of each agricultural agent.

At this stage, the constraint of equity is removed from the GA and replaced by another constraint, so that in conditions of water shortage, the amount of water allocation to each agricultural agent does not exceed the percentage of water supplying without significant reduction in product performance. The new constraint is represented as:

$$\frac{\sum_{\mathrm{m=1}}^{12} \mathrm{r_{i,m}}}{\sum_{\mathrm{m=1}}^{12} \mathrm{d_{i,m}}} \leq \alpha \quad i = 1, .., 8 \tag{17}$$

where, i is the number of agents, α is the percentage of water supplying without significant reduction in the product performance according to Table 4.

These steps will be repeated until the amount of water released from the dam is equal to the demand of agricultural agents, as well as the utility of the environmental sector to be satisfied without destroying it. This condition is considered as a criterion to stop the calculations.

CALCULATE TOTAL BENEFIT

In general, in the proposed model, 10 agents are considered, including eight agricultural agents, one environmental agent, and one state agent. Using the agents' benefit (Table 4) and the values allocated from the implementation of the GA model, the benefit values for each of the agricultural agents were calculated. The total benefit of agricultural agents is defined as the total benefit. Table 5 shows the benefit of three players based on the amount of water received and the product performance, which are used for Shapley Crisp method.

RESULTS AND DISCUSSION

In the first step, the amount of water released from the Shahid Rajaei dam reservoir was determined monthly using the standard operating policy. Supplying municipal, industrial and environmental demands were also considered as a constraint on the SOP model. The other constraints used in the SOP model include the amount of inflow to the dam reservoir measured by the hydrometric station, as well as the physical limitations of the problem, including the maximum and the minimum flow. The results of this step are used as part of the inputs for the second step. Figure 6 shows the monthly amount of water released from the dam reservoir for one year. In the second step, using the GA optimization model, the initial water allocation to the downstream agricultural demands was determined.

THE RESULTS OF THE COOPERATIVE GAMES THEORY

In this method, the agricultural demands in the downstream of the dam reservoir were divided into three categories of rice, citrus, and other products according to the variety of

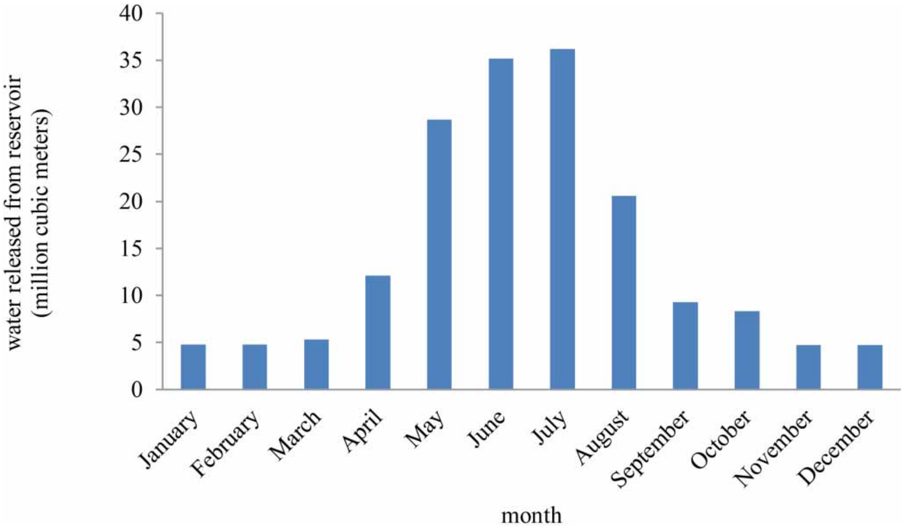


Figure 6 | The amount of released water from the reservoir per month (million cubic meters).

cultivation and the area under cultivation. Other products include stone fruit, wheat, maize, fodder corn, oilseeds, and olives. The Cropwat model was used to determine the water demand of these products. The optimization model was implemented for a 17-year statistical period according to the available data. Since the benefits of each product are calculated annually, the monthly allocation obtained from the GA model must be converted into an annual allocation to be usable in the Shapley Crisp model. Figure 7 shows the annual initial water allocation to the three categories of rice, citrus, and other products. The results of this step are used as input for the third step.

At this stage, using the players' benefit (Table 5), and the water allocated by the GA model, the initial benefit values for each stakeholder were calculated.

In the third step, using Shapley Crisp's method, the amount of water allocation to each player and the corresponding economic benefits for the grand coalition as well as for the bilateral coalitions of the players were obtained. In this way, first, the coalition was formed, and the players participated in the coalition with all the water allocated to them. Then, according to the benefit of each player in the coalition, first, the water was allocated to the player who has the highest benefit and in the same way to the player who has the lowest benefit in the coalition. After that, according to the values of the benefit (Table 5), the amount of benefit of each player in the coalition was calculated and finally, the benefit of each coalition was determined. Table 6 shows the benefits of the water allocated to each player by participating in various coalitions.

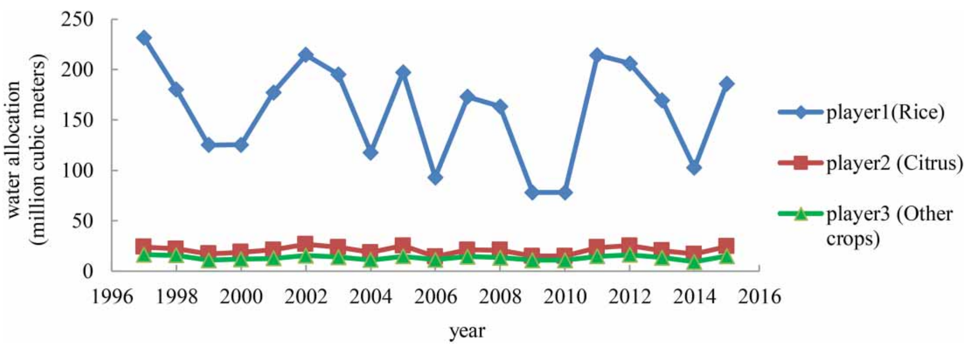


Figure 7 | Annual allocation of water to agricultural demands.

The results show that the grand coalition has more benefits in comparison with both the bilateral coalitions and the benefit of the initial allocation. At this point, the Shapley value equation is used to reallocate benefits to the players. After allocating water to three participants based on different coalitions, at this stage, to observe equity, payments must be made between the players. Each player who has received more water than his share will have to pay money to those players who have been received less than their fair water share. Table 7 shows the amounts of shares, payments, and financial receipts of players based on the Shapley method. The proposed method was used for a statistical period of 17 years to allocate water between stakeholders, which its results are shown in Figure 8. As can be seen, during the statistical period, the formation of the grand coalition has increased the total benefit of the system, without the need for any additional costs and only by changing the management of the operation.

THE RESULTS OF AGENT-BASED MODELING

First, in the Agent-Based Modeling, the amount of water released from the Shahid Rajaei dam reservoir was determined using the standard operating policy. Then, using the GA optimization model, the amount of initial water allocation to the agricultural agents in the downstream was determined by observing equity. In this method, the agents' demands in the downstream of the dam were divided into eight categories according to the variety of cultivation and cultivation area: rice, citrus, oilseeds, maize, fodder corn, olive, stone fruit, and wheat. Table 8 shows the initial monthly water allocation to eight agricultural agents using the GA. According to the volume of water released in spring and summer for 153.6 million cubic meters and in autumn and winter for 42.3 million cubic meters, the utility of the environmental sector was calculated 100% using Montana-Tenant method and its demand is fully supplied. In other words, aquatic species in the downstream river will not be threatened. As a result, the environment sector will not use its pressure level described in Equation (15) to reduce the agricultural agents' demand for this year. The state's subsidy rate (β) to agricultural agents is considered to be equal to 20% of the amount of water shortage allocated (Equation 15). This will increase the utility of agricultural agents and, consequently, will be effective in determining their new water requirements. The utility of agricultural agents and the state's subsidy rate and new demand for each agent are shown in Table 9.

As can be seen in Table 9, according to the initial demands of agricultural agents and the amount of allocated water, the utility of agents is between 53% and 56%. Due to the shortage of water and the amount of specified water (45% of the initial demands of agricultural agents), the product performance is very poor. As a result, the new demand for agricultural agents must be calculated using Equation

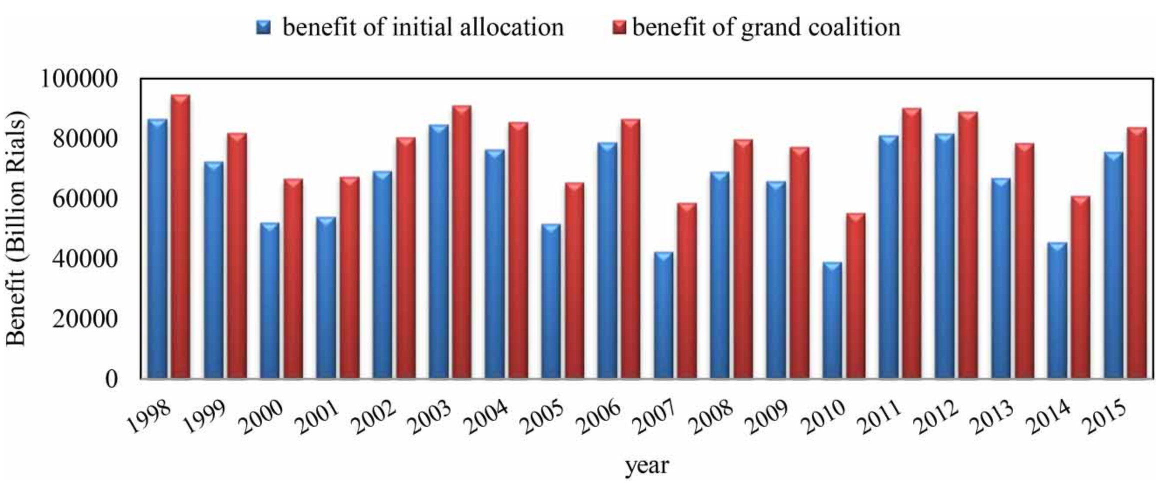


Figure 8 | Comparison of benefits from primary and reallocation of water.

Table 8 | Initial monthly water allocation to agricultural demands (million cubic meters)

	Rice	Citrus	Oilseeds	Maize	Fodder corn	Olives	Stone fruit	Wheat
January	0	0	0.34	0	0	0	0	0.004
February	0	0	0.26	0	0	0	0	0.024
March	2.931	0	0.002	0	0	0	0.125	0.121
April	18.567	0.473	0	0.010	0.124	0.006	1.120	0.286
May	29.212	2.029	0.252	0.535	0.949	0.025	3.032	0.425
June	16.373	4.487	0.352	0.633	1.516	0.027	1.632	0.016
July	26.020	2.962	0.359	0.420	0.489	0.032	4.000	0
August	31.569	3.487	0.051	0.174	0	0.030	1.638	0
September	6.996	1.397	0	0	0	0.011	2.002	0
October	0	0.563	0.003	0	0	0.005	1.239	0.028
November	0	0.049	0	0	0	0	0.072	0
December	0	0	0	0	0	0	0	0

Table 9 | The utility of agricultural agents and the state's subsidy and new demand for each agent

Production	Water allocation (MCM)	Water demand (MCM)	Agricultural agent utility based on the water allocation (%)	Percentage of water shortage for the agent (%)	The state subsidies (%)	Total agricultural agent utility (%)	Modified water demand (MCM)
Rice	131.67	289.21	45	49	10	56	201.08
Citrus	15.45	33.93	45	24	7	53	24.23
Oilseeds	1.08	2.38	45	35	9	54	1.67
Maize	1.77	3.88	45	34	8	54	2.74
Fodder corn	3.08	6.67	45	24	7	53	4.83
Olives	0.14	0.3	45	30	8	53	0.213
Stone fruit	14.86	32.64	45	24	7	53	23.30
Wheat	0.9	2.01	45	30	8	53	1.42

(16) to increase the agents' utility. The utility of agents increases in such a way that due to water shortages, agricultural agents reduce their demand by reducing the area under cultivation so that their water share increase compared to the new cultivation area, and as a result, their product performance reaches an acceptable value. The new water demand of agricultural agents is calculated in Table 9 to re-enter the GA model as input and determine the new agents' demands. At this stage, in the GA, the constraint of equity is removed from the model, and instead a new constraint is placed that the amount of water share of each agent does not exceed the percentage of water supply without significant reduction in performance (Equation 17). Then, the utility of the agricultural agents and the state's subsidy have calculated, and have shown in Table 10.

As can be seen in Table 10, the removal of the equity constraint, as well as the application of the new constraint, has improved the allocation and thus increased the utility of agricultural agents. As a result, the utility of agricultural agents compared to the previous step, which was between 53% and 56%, has changed to 66% to 93%. In other words, the utility of agricultural agents has increased from

Table 10 | The new utility of agricultural agents and the state's subsidy and new demand for each agent

production	Water allocation (MCM)	Water demand (MCM)	Agricultural agent utility based on the water allocation (%)	Percentage of water shortage for the agent (%)	The state subsidies (%)	Total agricultural agent utility (%)	Modified water demand (MCM)
Rice	185.92	201.08	92	2	1	93	186.98
Citrus	16.47	24.23	68	2	1	69	18.91
Oilseeds	1.26	1.68	75	5	1	76	1.36
Maize	2.05	2.74	75	5	1	76	2.21
Fodder corn	3.14	4.83	65	5	1	66	3.7
Olives	0.16	0.21	75	0	0	75	0.17
Stone fruit	15.04	23.30	64	5	1	66	17.84
Wheat	1.07	1.42	75	0	0	75	1.16

19% to 47%. Also, the percentage of water shortage allocated to the agents compared to the allowable amount of shortage (percentage of water supply without significant reduction in performance) is between 2% and 5.5%. The amount of state's subsidy has also decreased significantly compared to the previous step, so that it was between 7.4% and 10% in the previous step, and at this step, the highest calculated amount was 2%. At this phase, due to the stop condition, the calculation steps will be completed and the total benefit will be discussed. Figure 9 shows a comparison of the utility of agricultural agents in two cases of primary water allocation with the equity constrain and secondary water allocation to increase the total benefit.

Using the benefit of the agents (Table 4) and the values allocated from the implementation of the GA model, the benefit values for each of the agricultural agents were calculated. The total benefit from the water allocation to the agents can be compared to the previous step. The utility function and the total benefit can be considered as tools for evaluating the efficiency of the proposed model. The

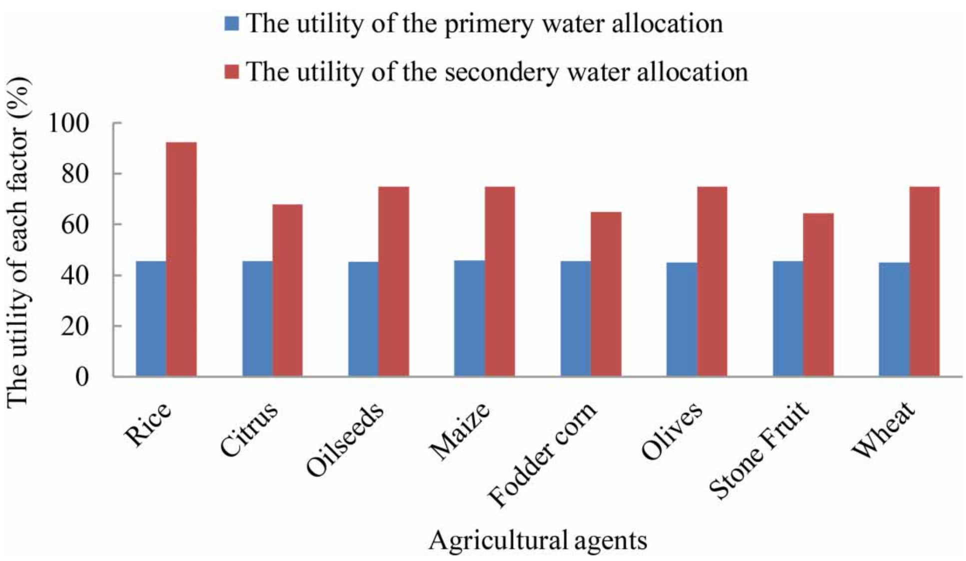


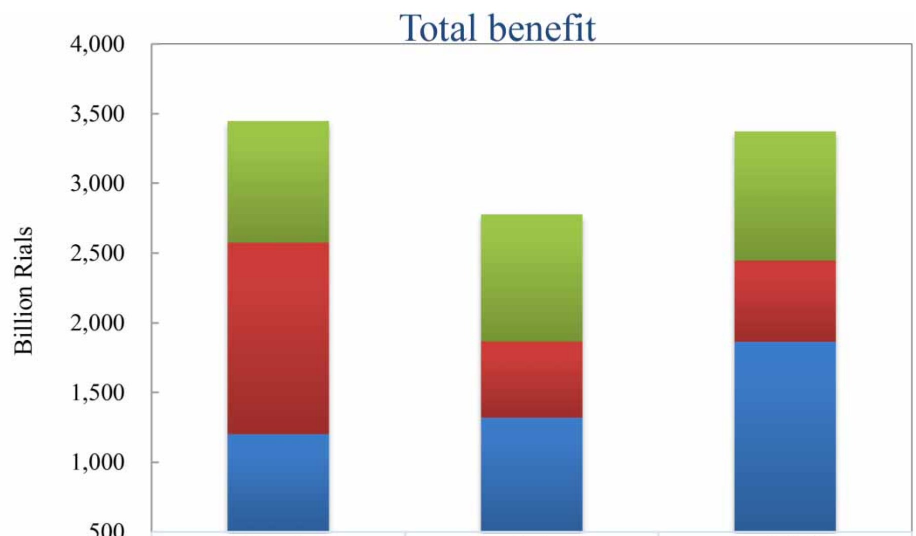
Figure 9 | Comparison of agricultural agent utilities in primary and secondary water allocation.

total benefit of agricultural agents for Tables 9 and 10 are calculated, which are equal to 2780 billion Rials and 3375 billion Rials, respectively. However, not only the total benefit has increased by 21.4%, but also the utility of agricultural agents has increased. Moreover, the amount of subsidy that the state must pay to the agricultural agents has also decreased significantly.

COMPARISON OF THE RESULTS OF SHAPLEY COOPERATIVE GAME THEORY WITH AGENT-BASED MODELLING

In this step, we compare the results of the cooperative games theory and Agent-Based Modeling in the optimization of water allocation. As can be seen in Table 6, the total benefit in the grand coalition is higher than the other coalitions. The total benefit obtained in one year in the Shapley method was equal to 3,449 billion Rials and in the ABM in the last computational step, it was equal to 3,375 billion Rials. Figure 10 shows a comparison of total benefit in the optimal water allocation of the dam reservoir using Shapley's methods, GA, and Agent-Based Modeling.

Although the total amount of benefit obtained from the Shapley method was higher, the first condition for achieving this benefit is the formation of a grand coalition. To form a grand coalition, all three players, including rice, citrus, and other crops, must reach an agreement on the distribution of benefit (as shown in Table 6), which is simply not possible. On the other hand, if the Shapley method is used, no information about the region's environment will be provided to the state to distribute water between the stakeholders. Even if the state is informed of the environmental threat to the area according to the allocation of water, tools and facilities will not be available to solve this problem using the Shapley method. Moreover, the state will not be able to obtain information about the satisfaction or dissatisfaction of the stakeholders after allocating water to them, and will not be aware of the feedback of his decisions. Therefore, if the decision feedback is not informed, it might lead to creating chaos by the stakeholders due to their dissatisfaction. On the other hand, if the state decides to pay subsidies to help farmers during the years of water shortage, this will not be possible in the Shapley method. While, in the ABM, the state is aware of the needs of the environment, as well as the consequences that may threaten it. Also, due to



	Shaply	GA	ABM
Other Products	872	911	926
Citrus	1,374	547	583
Rise	1,202	1,320	1,864

Figure 10 | Comparison of total benefit in the optimal water allocation of the dam reservoir using Shapley's methods, Genetics Algorithm and Agent-Based Modeling.

the level of satisfaction or dissatisfaction of stakeholders using the utility function defined in the model (where it is possible to make any changes and localization in this function), the state can be aware of his decisions and any feedback. It is also possible to determine the amount of subsidy in the ABM based on the amount of water shortage for stakeholders per year.

According to what has been said, it can be concluded that to optimally allocate water, the ABMs have more advantages than the Shapley method and the GA model. These advantages will provide many opportunities for the state to make informed and correct decisions so that the possibility of sustainable development for the region can be taken into consideration. Therefore, considering social issues and the ability to create a hydrological–environmental–human relationship to manage demand and to optimize water allocation to the needs, Agent-Based Modeling is a completely practical approach and can be used in real conditions.

CONCLUSIONS

In this study, water allocation from the dam reservoir was optimized using the cooperative game theory and the ABM. The water allocation from the Shahid Rajaei dam reservoir in the Tajan basin was examined based on the equitable distribution of water. The optimization model was developed using Shapley Crisp's cooperative game approach to maximize the overall benefit of the system as well as increase the benefits of the players who participated in the coalition. Also, the financial payments between stakeholders in the coalition was determined based on the Shapley value. The formed coalitions show the effects of management on water supply and demand management policies in the study area. Studies show that the best results are achieved when players form a grand coalition. In other words, by participating in the grand coalition and reallocating water and benefit among the players, the total benefit of the system increases by 10% and the benefits of the players of rice, citrus and other products increase by 6%, 16% and 15%, respectively, compared to those who do not participate in the grand coalition.

The ABM was also developed to optimize the water allocation for agricultural, municipal, industrial, and environmental agents. In the proposed model, the state was considered as a regulating and determining agent. Based on the obtained results, it can be seen that by using the ABM, even in the years of water shortage, in addition to increasing the total benefit, the utility of agricultural agents has also increased and the amount of subsidy that the state should pay to agricultural agents has decreased. Whereas, only by applying a series of computational steps and analyzing the feedback of agents through the utility function, it is possible to optimize water allocation and increase benefit.

Generally, by comparing the results of the cooperative game theory and the ABM, it can be concluded that the proposed ABM has high efficiency in terms of optimization of water allocation from the dam reservoir to the downstream needs. Furthermore, ABM is a new method to simulate stakeholder interactions, which creates a hydrological–environmental–human relationship to manage demand and to optimize the water allocation to the needs. This method also helps to make informed and practical decisions in water resources management. The proposed model in this study can be used in other catchments for optimal water allocation taking into account social and hydrological issues.

CONFLICT OF INTEREST

None.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

Aadland, A. & Kolpin, V. 2004 Erratum to environmental determinants of cost sharing. *Journal of Economic Behavior & Organization* **55** (1), 105–121.

Akhbari, M. & Grigg, N. S. 2013 A framework for an agent-based model to manage water resources conflicts. *Journal of Water Resources Management* **27** (11), 4039–4052.

Anebagilu, P. K., Dietrich, J., Prado-Stuardo, L., Morales, B., Winter, E. & Arumi, J. L. 2021 Application of the theory of planned behavior with agent-based modeling for sustainable management of vegetative filter strips. *Journal of Environmental Management* **284**, 112014.

Bakarji, J., Malley, D. & Vesselinov, V. 2017 Agent-based socio-hydrological hybrid modeling for water resource management. *Journal of Water Resources Management* **31** (11), 3881–3898.

Berglund, E. 2015 Using agent-based modeling for water resources planning and management. *Journal of Water Resources Planning and Management* **141** (11), 04015025.

Bousquet, F., Cambier, C., Mullon, C., Morand, P., Quensiere, J. & Pave, A. 1993 Simulating the interaction between a society and a renewable resource. *Journal of Biological Systems* **1** (02), 199–214.

Conservation of Iranian Wetlands Project (CIWP) and Asarab Consulting Company 2014 *Manual for Determining the Water Requirement of Wetlands*. Talaei Press, Tehran, p. 188 (in Persian).

Davis, R. & Hirji, R. 2003 *Water Resources & Environment, Technical Note c1- c3, Environmental Flows: Case Studies*. World Bank, Washington, DC, USA.

Di Baldassarre, G., Viglione, A., Carr, G., Kuil, L., Yan, K., Brandimarte, L. & Blöschl, G. 2015 Debates– perspectives on socio-hydrology: capturing feedbacks between physical and social processes. *Journal of Water Resources Research* **51** (6), 4770–4781.

Ding, N., Erfani, R., Mokhtar, H. & Erfani, T. 2016 Agent-based modelling for water resource allocation in the trans boundary Nile River. *Journal of Water*. https://doi.org/10.3390/w8040139

Han, Q., Tan, G., Fu, W., Mei, Y. & Yang, Z. H. 2018 Water resource optimal allocation based on multi-agent game theory of HanJiang River Basin. *Journal of Water* **10** (9), 1184.

Huang, X., Chen, X. & Huang, P. 2018 Research on fuzzy cooperative game model of allocation of pollution discharge rights. *Journal of Water* **10** (5), 662.

Hyun, J. Y., Huang, S. Y., Yang, Y., Tidwell, V. & Macknick, J. 2019 Using a coupled agent-based modeling approach to analyze the role of risk perception in water management decisions. *Journal of Hydrology and Earth System Sciences* **23** (5), 2261–2278.

Lin, Z., Lim, S. H., Tong Lin, T. & Borders, M. 2019 Using agent-based modeling for water resources management in the Bakken Region. *Journal of Water Resources Planning Management* **146** (1), 05019020.

Mehrparvar, M., Ahmadi, A. & Safavi, H. R. 2015 Social resolution of conflicts over water resources allocation in a river basin using cooperative game theory approaches: a case study. *International Journal of River Basin Management* **14** (1), 33–45.

Niksokhan, M. H., Kerachian, R. & Karamouz, M. 2009 A game theoretic approach for trading discharge Permitsin Rivers. *Journal of Water Science and Technology* **60** (3), 793–804.

Ponnambalam, K. & Mousavi, S. J. 2020 CHNS modeling for study and management of human–water interactions at multiple scales. *Journal of Water* **12** (6), 1699.

Pouladi, P., Afshar, A., Afshar, M. H., Molajou, A. & Farahmand, H. 2019 Agent-based socio-hydrological modeling for restoration of Urmia Lake: application of theory of planned behavior. *Journal of Hydrology* **576**, 736–748.

Sadegh, M., Mahjouri, N. & Kerachian, R. 2010 Optimal inter-basin water allocation using crisp and fuzzy Shapley games. *Journal of Water Resources Management* **24** (10), 2291–2310.

Tan, Q. F., Wang, X., Wang, H., Wang, C., Lei, X. H., Xiong, Y. S. & Zhang, W. 2017 Derivation of optimal joint operating rules for multi-purpose multi-reservoir water-supply system. *Journal of Hydrology* **551**, 253–264.

Von Neumann, J. & Morgenstern, O. 1944 *Theory of Games and Economic Behavior*. Princeton University Press, Princeton.

Wang, L., Fang, L. & Hipel, K. W. 2008 Basin-wide cooperative water resources allocation. *European Journal of Operational Research* **190** (3), 798–817.

Yang, Y. C. E., Cai, X. & Stipanović, D. M. 2009 A decentralized optimization algorithm for multi agent system based watershed management. *Water Resources Research* **45** (8), W08430.

Young, H., Okada, N. & Hashimoto, T. 1982 Cost allocation in water resources development. *Journal of Water Resources Research* **18** (3), 463–475.

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