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Application of a Coordination Model for a Large Number of Stakeholders with a New Game Theory Model

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Abstract

Water allocation is an important issue for systems with multiple stakeholders. Individual and collective decisions are very important for such systems. Thus, a new integrated game model is proposed to create a good balance between cooperative and non-cooperative strategies. A dam-aquifer system was selected for the case study in Iraq. The system referred to should supply different stakeholders with water requirements. Three game models are used: 1) cooperative theory, non-cooperative theory, new integrated game structure. Effective factors in the way of cooperation was considered to demonstrate variations in the allocation of water to the stakeholders. The results of the cooperative or centralized model were considered as the best results. The results indicated that the new game model had good agreement with the centralized model. The outputs indicated that the allocation share of the downstream coalition could increase 4, 5 and 7% for high, medium and low inflow, respectively when the allocation share of the upstream coalition decreased 5%, 6% and 5% for high, medium and low inflow, respectively. The inflow excess volume at 90%, 50%, and 10% are considered as low inflow, medium inflow, and high inflow, respectively. It has been observed that the allocated volume of water to coalition downstream is increased by decreasing the more allocated volume of water to the coalition upstream. In addition, the new model supported the individual profits by applying the rationality decision while the cooperative game did not consider the individual benefits. In addition, the effect of inflows to reservoirs was considered to investigate the issue of water allocation in a critical condition.

Keywords Game theory · Cooperative games · Water allocation · Stakeholders

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1 Introduction

Persistently increasing demand for water is an important issue for agriculture, economic and environmental activities. Water supply is a complex and serious issue due to water scarcity (Mehrparvar et al. 2016; Yahya et al. 2019). Water demand management plays a vital role in the economic and political aspects. Various limitations – economic, environmental, and spatial – restrict the construction of new adequate water structures necessary to meet the water demand (Yuan et al. 2019; Ehteram et al. 2019a, b). Increased operation of the available resources is, therefore, a key strategy to achieve the objectives that depend on the management of confined water storage. However, optimal operation of the available resources is a difficult task as the water supply depends on many factors, such as population growth, agricultural production and climate change (Mooselu et al. 2019; Dippong et al. 2018; Dippong et al. 2019; Ahmed et al. 2019; Yaseen et al. 2019b).

When investigating the water management project, modeling-based sophistications may arise from mathematical techniques or software programs, since most water management problems have complex, nonlinear and non- convex characteristic (Wang et al. 2019). In order to achieve effective water resource management planning, a large number of mathematical tools, software computing models, game theory models, and evolutionary algorithms have been developed in recent years; greatly improving their structure and performance (Ahmadi et al. 2019). The choice of a good method for water resource operation is a complex issue because each method has its advantages and disadvantages. These approaches are tested in order to obtain optimal operation strategies for different water systems (Wu et al. 2019). When demand for irrigation and agriculture continues to rise, water supply is critical for decision-makers (Shahraki et al. 2019; Luchner et al. 2019). The enhanced operation of the available projects is a necessary issue to reach the demand-dependent objectives of agriculture and irrigation projects (Lejano and Li 2019). The tools selected for different case studies will primarily relate to 1) the aim of water projects, 2) the nature of the limitations, and 3) the identification of the decision variable. Traditional methods may be ineffective in achieving competing objectives. For example, if a weight-average approach is used for multi-objective problems, the best solution may not achieve the benefits of most individuals and systems (Ristić and Madani 2019). Traditional methods such as dynamic programming methods or some nonlinear models exist. The performance of the dynamic programming method depends on the discretization of different state variables. Thus, the application of dynamic programming is complex with the allocation of water (Konar et al. 2019; Ehteram et al. 2019c; Yaseen et al. 2019b). In addition to the weak performances of traditional methods to solve multi-objective problems and the lack of fast computation to minimize computational times in the case of complex problems, difficulty in obtaining best results by applying the available methods contributes to the search for the best tools to improve water management (Saadatpour and Khoshkam 2018).

In recent decades, game theory has been investigating resource allocation strategies among various stakeholders. Under game theory computation, the different games are used to manage the project. This approach has been extended to a number of water resources and hydrological problems (Zeng et al. 2019). This approach is particularly important because of its high ability and simple structure to achieve the best results and strategies. In general, the water allocation needed for supply-demand is an important issue in various water resource projects (Jeong et al. 2018). Stakeholders' interactions are based on cooperative, coordinate and non-cooperative behaviors. Each of the stakeholders is a member of the overall system. Therefore, there are individual local benefits and system local benefits.

Homayounfar et al. (2011) tested the implementation of dynamic game models for water allocation. The proposed model was used for a real case study commonly needed on the impact of uncertainty on decision-making policy. Through observing the outputs, it has been shown that the proposed model is completely capable of generating optimal operation strategies for the reservoir.

Poorsepahy-Samian et al. (2012) presented a new game theory model for the allocation of water to agricultural demands. The cooperative game model is designed for the reallocation of fair profits. The results showed the benefits of multiple coalitions to increase the overall profit system to 30%.

In another study, an effective performance-based optimization strategy and game theory model was developed to optimally operate the inter watershed (Nikoo et al. 2012). This integrated model was used to reallocate profits to stakeholders for water supply and demand. The performance of this integrated model was investigated using a large case study. The Results showed a reasonably fair water allocation to various stakeholders. The sustainability index has been used to evaluate the model.

Another strategy was also considered to study the service costs for water allocation (Sechi et al. 2013). Results indicated that the core of the cooperative game (CG) was a useful tool for describing cost rates. Furthermore, it could be applied as a festive water allocation tool to achieve the economic strategy needed by the stakeholders.

In another study, the reinforcement-learning model was used to obtain the best operation strategies in multi-reservoir systems for justice and efficiency criteria (Madani and Hooshyar 2014). This model could have produced good results without applying a weight assessment. The model could estimate the profits of the various collations of a complex multi-reservoir system.

Mianabadi et al. (2014) developed an advanced model of water allocation bankruptcy. The results have shown that the new solution is more effective and useful in the allocation of water on the basis of different conflicts.

A hydrological simulation model, an optimization method, and a CG model were used in a basin (Skardi et al. 2013). This integrated model can generate an optimal set of strategies to eliminate target sediments. The model significantly lowered basin management costs. Mehrparvar et al. (2016) used CG and an optimization model for the water allocation problem. An optimization model was used to extract and calculate e the rule curve and the required volume of water. Finally, the outputs of various game strategies were examined by applying the stability index. The results showed that both NASH and Shapley models raised stakeholder's profits in the case study considered.

By applying the improved CG, the correct allocation of net profits warranted by every stakeholder could have increased profits and, as a result, stakeholders were encouraged to pursue a water allocation project that led to optimal operation (Xiao et al. 2016). The outputs have shown that the water allocation strategy used could make a good contribution to various arid regions.

Sedghamiz et al. (2018) applied a multi-objective genetic algorithm (MGA) and a cooperative game to meet environmental and agricultural demands. The results indicated that the MGA and the CG model had a good agreement. There was a slight difference between MGA and CG. For example, MGA was allocated more agricultural water than the CG model.

Another study developed a hybrid Nash-Leader follower game model for the allocation of water to three provinces in China (Fu et al. 2018). The leader was a basin management agency, followed by three provinces. The results indicated that economic improvement was due to the application of brain weights and disagreement points.

Ahmadi et al. (2012) applied an allocation software, non-cooperative game (NCG) strategy to allocate water to various demands. Results indicated that strategic cooperation could improve the benefit of the water project. MODISM was applied to initially allocate water to stakeholders.

Han et al. (2018) considered the performance of a single agent-based optimization model of a river basin study. The results indicated that the proposed model was superior to the conventional optimal model. Fu et al. (2018) suggested a two-level Nash leader-follower game model for the allocation of water to stakeholders. The results indicated that the bargaining weights would guarantee the demand for water. Zeng et al. (2019) proposed a hybrid game theory and mathematical programming model for resolving water conflicts in the reservoir basin. The results revealed that the new model offered certain impetus for policy change in management. Qin et al. (2019) used asymmetric Nash bargaining to model strategic interactions among involved agents. The outputs indicated the need to synthesize the agent's confliction utility when negotiating water allocation.

Another study strengthened the leader-follower model and multi-objective algorithm to obtain the best operation policy (Khorshidi et al. 2019). The outputs obtained from the previously mentioned models showed that water allocation was carried out by lowering the risk level. In addition, outputs have shown that the agricultural part is extremely sensitive to periods of drought.

However, the literature review shows that different game models have a high-water allocation capability. These models are used for various water projects while focusing on the application of CG and NCG models (Luchner et al. 2019). It is evident from the literature that previous studies did not consider the balance between cooperation and noncooperation models defining all details. Although multi-objective algorithms can be used for the water allocation problem, random parameters should be precisely defined. In addition, the mentioned algorithms generate a Pareto front with a number of solutions. Multi-criteria decisions should be used to select the best solutions. The computational process is therefore complex for the algorithms mentioned above. From a management point of view, cooperative behavior is the top-down decision-making model. This strategy is centralized management, with all stakeholders designing the central mined to cooperate fully and then implement strategies to maximize efficiency for all stakeholders (Huang et al. 2018). If the benefits of all stakeholders are considered for operation, there will be a desirable system-wide advantage. Cooperative interaction is not common, because water conflicts cause the strategy of non-cooperation to be used in the real world. The non-cooperation strategy consists of individual rationality (Cheng et al., 2019). Individual rationality is the most important factor for the non-cooperation strategy. As a result, different stakeholders do not submit any feedback on applied strategies (Wang et al. 2019). This issue means that the stakeholders cannot increase the desired benefits for the entire system. However, non-cooperation and cooperation models focus on local benefits and global benefits, resulting in imbalances that cannot simultaneously satisfy stakeholders and the overall benefits of the system (Xu et al. 2018). Various studies show that cooperation performance increases the benefits system significantly. It should be noticed that there is an improvement in the exchange of information among various stakeholders.

The current study develops a coordination model for water allocation. This model is capable of fulfilling the profit of both the individual and the system simultaneously. The objectives of the present study are

1) To allocate water to multiple stakeholders based on the CG (cooperative game), NCG (non-cooperative game), and integrated game (IG) models

2) To study the effect of aquifer and dam on the operation policy of the CG, NCG and IG models
3) To investigate the effect of different factors on the performance CG, NCG, and IG models

Two models – CG and NCG – were used to allocate water to stakeholders in southern Iran (Mahjouri and Ardestani 2011). The outputs of these two models were studied on the basis of total profit acquired, and the effect of the cooperation in applying an allocated resource was explained. The investigation of the outputs illustrated the role of cooperation in obtaining maximum profit from the usage of water resources.

The present study shows how well the structure of equilibrium coordination improves the efficiency of water allocation. Thus, the current study defines a new structure for simultaneously completion and cooperation between various stakeholders.

2 Case Study

The Karaj Dam is situated in the central area of Iran. This dam is located 63 km from Tehran City and 23 km from Karaj City. Geographically, it is placed at 35°57 23″ N and 51°05 26″E. Figure 1 shows the location of the dam. Figures 2 and 3 show the average monthly temperature and rainfall for the basin studied during the period 1990–2005. January is the coldest month and July is the hottest month (Fig. 2). The most uncertain temperature is visible in April, as the difference between the maximum and minimum temperatures is considerable. The maximum and minimum rainfall occurs during the months of January and July (Fig. 3). The most uncertain rainfall is visible in the month of January.

Although Iran has one-third of the world's average annual precipitation, it is an arid country. Tehran is the capital of Iran. Tehran has a large population, industrial parts, and agricultural parts. The Karaj Dam should supply Tehran with the water it needs. In fact, the demand for Tehran is $340*10^6$ m^3. Thus, capital is the first priority for water supply. The next priorities are agricultural and municipal demands in the city of Karaj. In addition, the aquifer (Karaj Aquifer) is present in this region. There is no infrastructure to meet the demands of Tehran from this aquifer. The agricultural sector requires $427*10^6$ m^3 whereas the annual average of the dam is $415*10^6$ m^3. The Karaj dam, therefore, cannot supply all the required demands. Karaj Aquifer is used for the city of Karaj. The previously mentioned aquifer supplies the demands of the municipal and agricultural Karaj. Municipal and agricultural sectors return 40 and 50% of the flow to the aquifer. Figure 4 shows the average monthly demand. For example, the highest demand in Tehran is recorded for the month of September. Most agricultural demand has been recorded for the month of January. In addition, the Karaj dam should supply the required volume of water for the power plant. The required volume of water is used to produce 150,000 MW of annual power. Other details can be found in Fig. 4.

3 Methodology

Various game theory models exist. The cooperation models have a central decision-making box. This box uses the produced benefit by the collectivity rationality of individuals. The final decisions of the decision-making box are based on targeting the maximum profit for the whole system. It should be noted, however, that the concentration on local or global decisions only

Fig. 1 Karaj Dam

causes dissatisfaction on the part of individuals. If the local profit of members in the cooperation models is compensated, a good balance is established between the local and global profits. One suggestion is to allocate the resources to stakeholders and then compensate for the shortages of more demand-driven members. Hence, a central decision-making box and cooperation game are defined in order to investigate the effect of cooperation on the benefit of the system as a whole. Then, the model is changed to non-cooperation to investigate the profits of the members. A compensation model can be specified to link the cooperation and noncooperation models to each other. In the noncooperation model, it should be remembered that some individuals need more profit; so that these individuals can be considered as the leader to receive the resources as a first priority and the other members obey them. In the next section, a cooperation game is explained first and then the model is changed to a noncooperation game. The compensation model is then explained to link two models to each other.

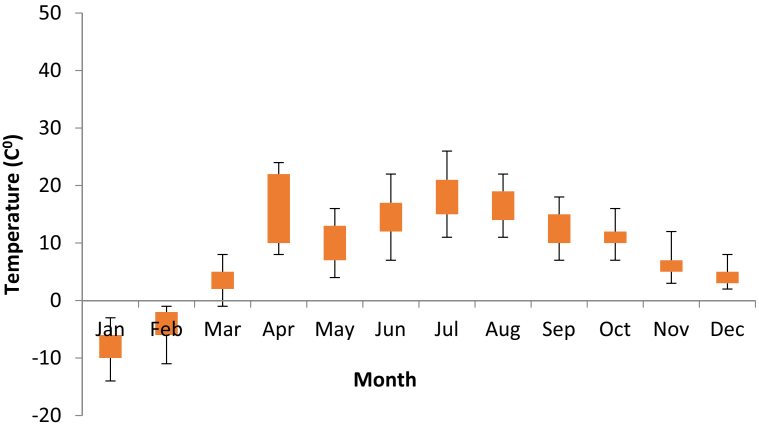


Fig. 2 Monthly temperature (1990–2005)

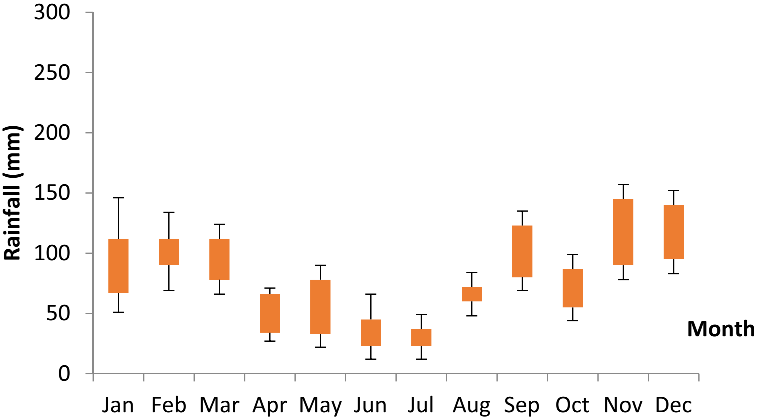


Fig. 3 Monthly rainfall (1990–2005)

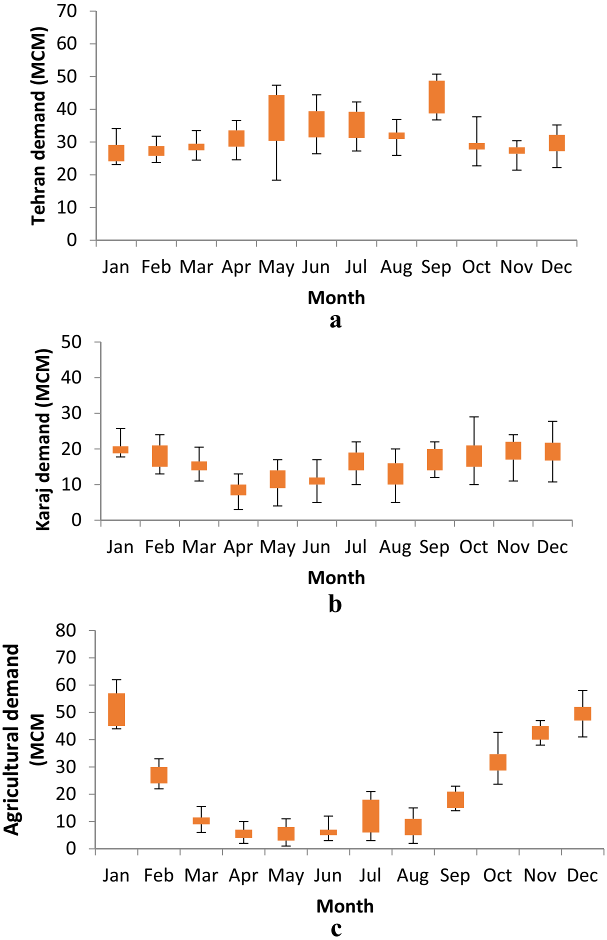


Fig. 4 **a** Demand volume for **a** Municipal demand in Tehran, municipal demand in Karaj, **c** Agricultural demand (MCM)

3.1 Allocation Model

Karaj dam and aquifer will supply water to four stakeholders: 1) Power demand (PD) 2) Municipal water demand of Tehran (Tehran demand; TD), 3) Municipal water demand of Karaj (Karaj demand; KD) and 4) Agricultural water demand of Karaj (Agricultural demand; AD). The upstream requirements (Tehran demand and power demand) are the upstream coalition. First, the Karaj dam should supply the required volume of water for power plants. It should then supply the water needed to meet Tehran's demand. If there is any excess volume of water after fulfilling Tehran's requirement, it will be transported to the Karaj dam. Then the Karaj dam and the aquifer were to supply the municipal demand of Karaj. If the municipal demand for Karaj is fully met, the remaining volume of water is allocated to the agricultural demand of Karaj (Fig. 5).

The municipal demand and the agricultural demand of Karaj is the downstream coalitions. Due to the importance of Tehran's demand and power generation, the upstream coalition should minimize water shortages first. The downstream allocation of water is a mandatory process as the downstream coalition minimizes its own water shortages after allocating water to the upstream coalition.

In this article, a combination of the game-theoretical structure has been improved to model the coalition patterns between the upstream and downstream collation strategies. In fact, four models are used to allocate water to four stakeholders (KAD, TMD, KAD, and PD): centralized model, NCGM, coordination model and compensation model. The reservoir constraints are represented by the following equations:

There are some constraints:

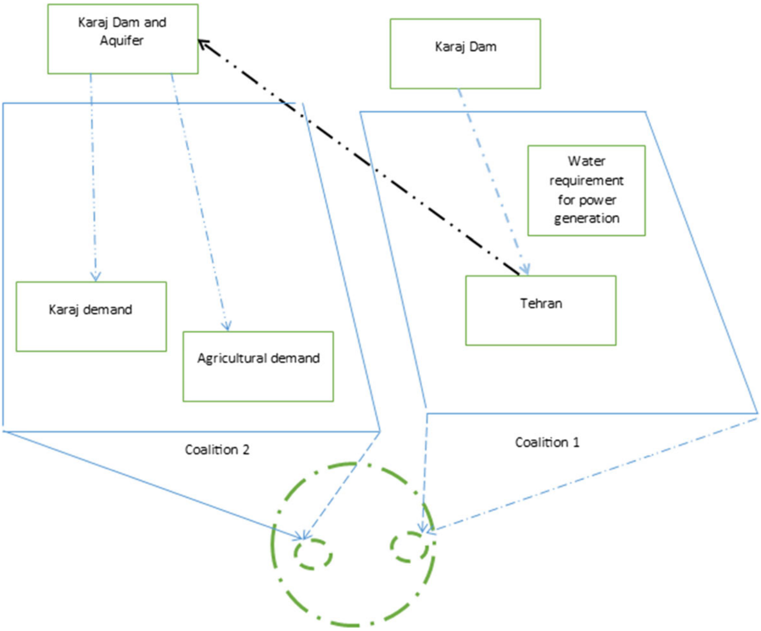


Fig. 5 Allocation way to stakeholders

1- Continuity equation:

$$S_{t+1} = S_t + I_t - R_t - SP_t - Loss_t \tag{1}$$

where S_t: reservoir storage at time t, S_{t+1}: reservoir storage at time t + 1, I_t: inflow at time t, SP_t: spillway at time t, and $Loss_t$: evaporation losses which are computed by Eq. 2.

$$\begin{aligned} &Loss_t = f_1\left(Ev_t, \overline{A}_t\right) \\ &\overline{A} = \frac{(A_t + A_{t+1})}{(2)} \\ &A_t = f_2(S_t) \\ &S_{\min} \le S_t \le S_{\max} \end{aligned} \tag{2}$$

where f_1: function for computing loss by regarding evaporation volume, Ev: evaporation depth, $\overline{A}$: mean water level, A_t: water level at the beginning of the time interval, $S_{\min}$: minimum reservoir storage, and $S_{\max}$: maximum reservoir storage.

The aquifer is the other important factor in the system. A lumped parameter model is used to model the aquifer system. This approach is useful because fewer input data are used for a lumped model. Eq. 4 computes the variation in the volume of the aquifer:

$$\Delta V_t = Ip_t - out_t + \alpha \times River_t + Rai_t - RG_t + \sum_{i=1}^{I} \omega\left(RG_{i,t} + RS_{i,t}\right) \tag{3}$$

where ΔV_t: volume variation, Ip_t: total input, out_t: total output, α: infiltration value from river to aquifer, RG_t: discharge volume, ω: percentage of return flow from ith sector to the aquifer, $RG_{i,t}$: the allocated water from aquifer to the ith sector, $RS_{i,t}$: the allocated water from dam to the ith sector andRai: rainfall at period t. One month is considered for returning flow and in fact, the field study shows the mentioned lag time. Aquifer's head variation is computed from the following equations:

$$\begin{aligned} &\Delta H_t = \frac{\Delta V_t}{A.S_t} \\ &H_{t+1} = H_t + \Delta H_t \\ &H_2 - H_1 \le \gamma \end{aligned} \tag{4}$$

where ΔH_t: head variation at the period, A: aquifer area, S_s: aquifer storage, H_{t+1}: aquifer head at the start of period t, H_t: gerund water level at time t, and γ: permissible drop threshold.

3.2 Centralized Model (Model I)

The centralized structure proposes that all stakeholders (KMD, KAD, TMD, PD) with various aims in a multiple stakeholders' model have a block box (central mind) to act based on group rationality and to develop strategies to reduce overall system shortages.

$$\max F = \sum_{i=1}^{m} \sum_{t=1}^{T} -1 * (D(i.t) - R(i,t)) \tag{5}$$

where F: total water shortage of the multiple stakeholders' model.

The objective function can maximize negative water shortages or minimize water shortages. The negative form is used in this analysis because the Nash bargaining theory will be defined on the basis of maximizing the objective function. Therefore, it is recommended that all objective functions have the same format to simplify the computing process. The previous constraints (Eqs. 1–4) and the following equations are considered:

$$\begin{aligned} &SQ = \sum_{i=1}^{m} \sum_{t=1}^{T} R_{i,t} \\ &SQ \leq S_{av} \\ &O_{i,t} \leq R_{i,t} \end{aligned} \tag{6}$$

where $SQ_{i,\,t}$: total allocated water volume to stakeholders, S_{av}: total available water volume, $O_{i,\,t}$: output from each stakeholder, T: total operational period, and m: number of stakeholders. Thus, the model (I) is first applied to allocate water to 4 stakeholders.

3.3 NCG Model (Model II)

In the scope of the NCG model, the scenarios considered by stakeholders target the most profits for their own purpose, without taking into account the demands of other stakeholders. For this case study, the upstream coalition is the first priority for water supply (Launcher et al. 2019). The AKD and MKD make decisions on the allocation of water based on the strategies applied by the upstream coalition because the upstream and downstream stakeholders do not communicate with each other. As a result, the allocation of water is shifted from Tehran to the municipal and agricultural sectors of Karaj.

$$\max F = \sum_{t=1}^{T} -1 * (D(i.t) - R(i,t)) \tag{7}$$

In addition, the previous constraints (Eqs. 1–4, 6) are considered for this section.

3.4 Stackelberg Theory (ST) (Model IIIa)

Stackelberg's conception is used as the theory of NCG. This theory uses the succession of decisions to allocate resources to multiple stakeholders. There is a decision-making process for the allocation of resources to multiple stakeholders. A dominant stakeholder or coalition (leader) first implements its own strategy, and then the obedient stakeholder (follower) or coalition makes its own decision. In this study, there are two coalitions:

1- Tehran demand + water requirement for power generation (dominant coalition)
2- Karaj demand + agricultural demand (obey coalition).

The follower is informed of the leader's decisions before starting the game. In addition, the leader simultaneously aware of the followers' information about himself. When the leader and follower exchange information, the coalition process between leaders and followers is carried out:

$$G = [Z_u, Z_D; u_U, u_D] u_U \in Z_U, u_D \in Z_D \tag{8}$$

$$z_U = \left[S_{1,1}...S_{1,T}, S_{2,1}....S_{2,T}, S_{n_1,1}....S_{n_1,T}\right] \tag{9}$$

$$z_D = \left[S_{n_1+1,1}...S_{n_1+1,1,T}, S_{n_1+1,1,1}....S_{n_1+1,1,T}, S_{n_1+1,1,1}....S_{n_1+1,1,T}\right] \tag{10}$$

$$\max_{z_d \in Z_d} u_D(z_u, z_d) = \max F_D(z_u, z_d) \tag{11}$$

$$z_D^* = S_D(z_U) \tag{12}$$

$$\max_{z_u \in Z_u}\left(z_U, z_D^*\right) = \max_{z_U \in Z_u}(z_U, S_D(z_U)) \tag{13}$$

$$z_u^* = S_U\left(z^*{}_D\right) \tag{14}$$

where Z$_u$, Z$_d$: scenario spaces for upstream and downstream cooperation, z_u and z_d: the decision scenarios depending to Z$_u$ and Z$_d$, F$_u$ and F$_d$: water supply function of upstream and downstream cooperation; n$_1$: number of stakeholders of the upstream cooperation, z_D^*: the best reaction of the downstream cooperation to the decision z$_u$ determined for the upstream cooperation, z_u^*: the best response of the upstream cooperation to the decision determined for the upstream cooperation to the decision z$_d$ determined for the upstream cooperation. Thus,z_D^*, z_u^* shows the Nash equilibrium for the total system.

Equation 14 shows Z$_u$ and Z$_d$ for the upstream and downstream cooperation:

$$F_u = \sum_{i=1}^{n_1}\sum_{t=1}^{T}(D_t - R_t) \tag{15}$$

$$F_d = \sum_{i=n_1+1}^{M}\sum_{t=1}^{T}(D_t - R_t) \tag{16}$$

The effect of the upstream decision on the downstream decision is defined by the coefficient, λ:

$$\lambda = \ln\frac{F_D(z_U, z_D)}{F_{D,non}} \tag{17}$$

Where $Z_{D,\ non}$: the rational water supply of cooperation downstream acquired thorough NCG model

Each of the strategies of the downstream coalition can be responded by the upstream coalition:

$$\max z_u\left(z_u, z_D^*\right) = \max\lambda(Z_D(z_U, z_D))Z_U(z_u) \tag{18}$$

The requirement of the downstream coalition should be considered when the upstream coalition decisions attempt to increase its own profit.

$$u_U(z_U, z_D) = \begin{bmatrix} \leq 0 \leftarrow Z_D(z_U, z_D) \leq Z_{D,non} \\ > 0 \leftarrow Z_D(z_U, z_D) > Z_{D,non} \end{bmatrix} \tag{19}$$

In addition, the previous constraints (Eqs. 1–4, 6) are considered for this section.

3.5 Profits Compensation Model (Model IIIb)

Improving downstream coalitions will reduce the percentage of upstream coalition water allocation. Therefore, the upstream coalition prefers to increase the NCG model's allocation share. The profit compensation model leads to a balance between the NCG model and the CG model. A Nash theory can fairly allocate resources to multiple stakeholders.

$$\Omega = \max \prod_{i=1}^{n} \left(F_i^* - F_i\right) \tag{20}$$

$$\begin{array}{l} subject \\ \sum_{i=1}^{n} F_i^* = S \\ F_i^* \geq F_i \end{array} \tag{21}$$

where Ω: the solution of Nash theory, F_i^*: the water shortage of stakeholder i based on the water allocation by the Nash Theory, F_i: the water shortage of stakeholder i based on the water allocation through non-cooperation, and S: total water shortage of the system.

3.6 Successive Linear Programming Method (SLPM)

The non-linear optimization problem is well modeled by the SLPM model. The SPLM model simplifies large, non-linear and complex problems. The sequence of linear programs is applied to solve the nonlinear problem (Ahmadi et al. 2019). There are many strategies for upstream and downstream coalitions because a large number of stakeholders should be supplied at different time intervals. The strategy of the upstream coalition is known as strategy space 1.

Therefore, the application of a method that selects some strategies amongst other strategies is necessary for a complex allocation problem. Strategies are decisions on the allocation of water to stakeholders at different time intervals. The SLPM has a cycle of iteration. Each iteration process computes the objective function value for each strategy. Two successive strategies are selected for strategy space 1 if the difference in objective function values is more than a threshold:

$$\begin{array}{l} z_{U,k}{}^* = \arg(\max) Z_u\left(z_{U,k,j}\right), j = 1, \ldots, n; k \geq 2 \\ Z_U\left(z_{U,k}^*\right) - Z_U\left(z_{U,k-1}^*\right) \geq u_{\min} \\ z_{U,k}^* \in stratgey \end{array} \tag{22}$$

where $z_{U,\ k,\ j}$: release decisions in iteration k, n: the total number of release decisions and $u_{\min}$:minimum difference of two successive objective functions for two strategies. The strategy of the downstream coalition is known as strategy space 2. The optimal strategy space 2 under the upstream coalition decisions is computed on the basis of eq. 18. In addition, the models are evaluated based on the following indexes:

$$SI_t^i = \sum_{i=1}^{M} \sum_{t=1}^{T} \left(\mathrm{Re}l_t^i * \mathrm{Re}s_t^i * \left(1 - Vul_i^t\right)\left(1 - \max Def^i\right)\right)^{\frac{1}{4}} \tag{23}$$

$$\begin{aligned} RMSE &= \sqrt{\sum_{t=1}^{T} \frac{\left(D_t - R_t\right)^2}{T}} \\ MAE &= \frac{\sum_{t=1}^{T} \left|D_t - R_t\right|}{T} \\ NSE &= 1 - \frac{\sum_{t=1}^{T} \left(D_t - R_t\right)^2}{\sum_{t=1}^{T} \left(D_t - \overline{D}\right)^2} \end{aligned} \tag{24}$$

where SI_t^i: sustainability index, Rel: reliability index, Res: resiliency index, Vul: vulnerability index, $\overline{D}$: Average demand, and maxDef^i: maximum deficiency

4 Results and Discussion

4.1 Strategies of Multiple Stakeholders

The technique referred to in section 3.3.6 was used to identify strategies for strategy space 1 (upstream coalition) and strategy space 2 (downstream coalition). Figure 2 shows the best strategy space 1 (SS1) for the period 1990–2005. The optimal strategy space 2 (SS2) is achieved on the basis of the SS1 decisions. For example, if the fifth strategy has been selected for SS2, the fourth strategy is the optimal response of SS1. If the second strategy has been selected for SS1, the second strategy is the optimal response of SS2. Figure 6b has overlapping points for presenting the Nash equilibrium strategy (NES). The optimum point was the least water shortage among other overlapping points. The sum of strategies of coalition 1 and 2 that are overlapping with each other is used to determine the total shortage for each (??) (NSEi, i: number of the equilibrium points).

4.2 The Evaluation of Game Theory Models

The RMSE, NSE and MAE indexes were calculated for the monthly allocation of water to different stakeholders (Fig. 7). The Model (I) outputs could meet Tehran demand (TD) better than Model (II) and Model (IIIa) with an RMSE value of 1.5 to 2.5 MCM and an MAE of 0.8 to 1.8 MCM. The results investigated showed that TD of Model (II) had the weakest performance among other models with an RMSE of 2.6 to 3.6 MCM and an NSE of 0.55 to 0.80, respectively. It was found that the allocated water of Model I supplies the PD demands better than Model II and Model IIIa with an RMSE of 1.6 to 2.6 MCM and an NSE of 0.76 to 0.90. However, the overall results showed that the model (I) had better results than the other models. AD had more shortages than other demands. For example, Model (I) had the best

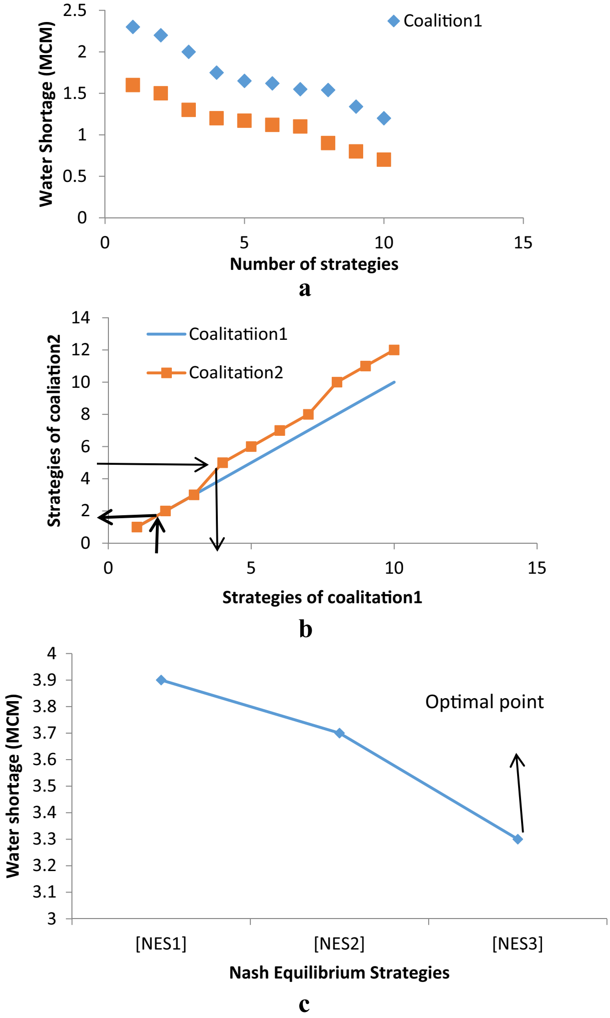


Fig. 6 **a** strategies of two collations and **b** the best response of coalition's **c** total water shortage based on NSE

performance for AD with an RMSE of 5.5 to 7.2 MCM, but PD, TD, and PD could be supplied with a smaller RMSE and MAE compared to AD.

In order to evaluate the coordination performance, the individual water allocation implanted in Model II was considered to be the baseline. Figure 8 indicates the deviation of the allocation of water for stakeholders in Model IIIa. It was found that the amount of water allocated to the upstream stakeholders is less than that allocated by Model II, while the amount of water allocated to downstream stakeholders (Coalition 2) by Model IIIa is considerably higher than that implemented by Model II. Thus, the objectives were compared in order to show a way of compromise between the two collations: the objective was enhanced when the other objective was found to be worse off. Agricultural demand was more than Karaj's demand. In order to increase the allocation of water to agricultural demand, one strategy should be chosen to increase water allocation to the agricultural demand, which could lead to a reduction in

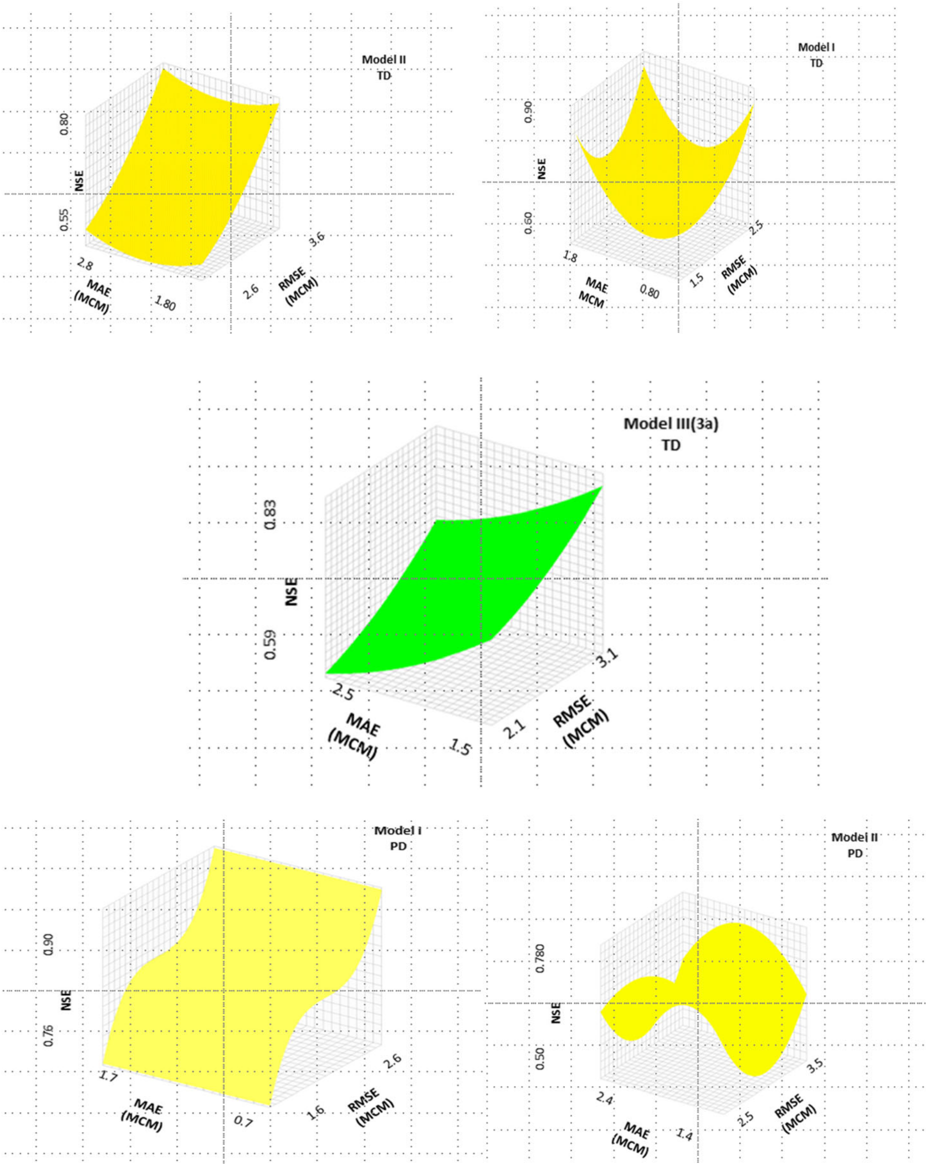


Fig. 7 Total monthly deficiencies of all stakeholders

demand for Karaj. Thus, the volume of water allocated to agricultural demand is larger than that allocated to other stakeholders.

Figure 9 indicates the percentage variation of the individual water allocations set out in Model IIIa compared to Model II. Three scenarios were considered for the Karaj dam inflow. A flow duration curve was obtained for the monthly inflow to the dam. The 90%, 50%, and 10% excess inflows were considered to be low inflow, medium inflow, and high inflow, respectively. It was noted that the allocated volume of water to the coalition downstream is increased by decreasing the more allocated volume of water to the coalition upstream. It has

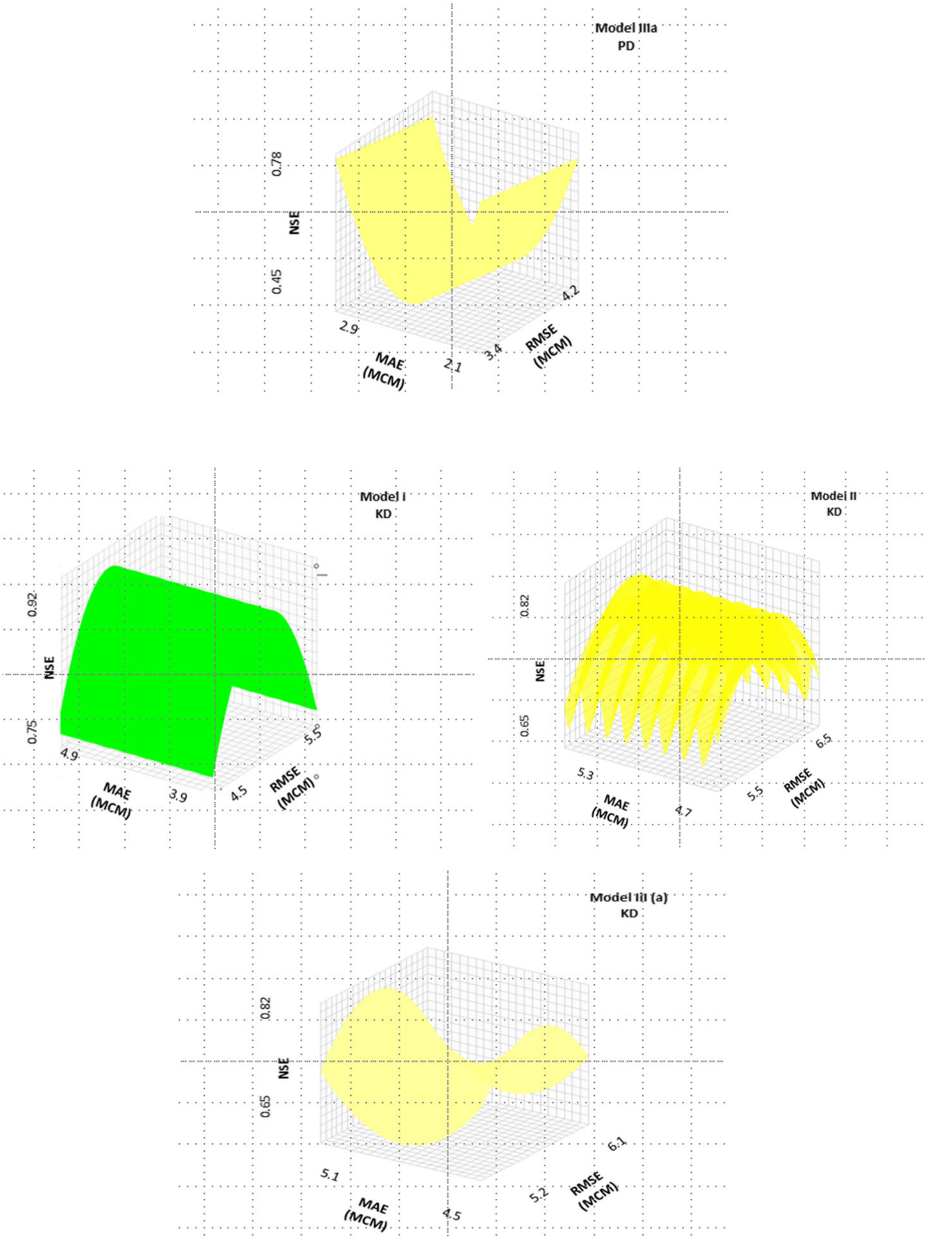


Fig. 7 (continued)

been observed that ascending water allocation of downstream stakeholders, carried out by the allocated water decrement of upstream stakeholders, has been limited as accessible water has decreased. As a result, water deficiency had a decreasing effect on the allocation of water by the downstream coalition's thorough contribution. Figure 9 showed that the allocation share of the downstream coalition could increase by 4%, 5%, and 7% for high, medium, and low

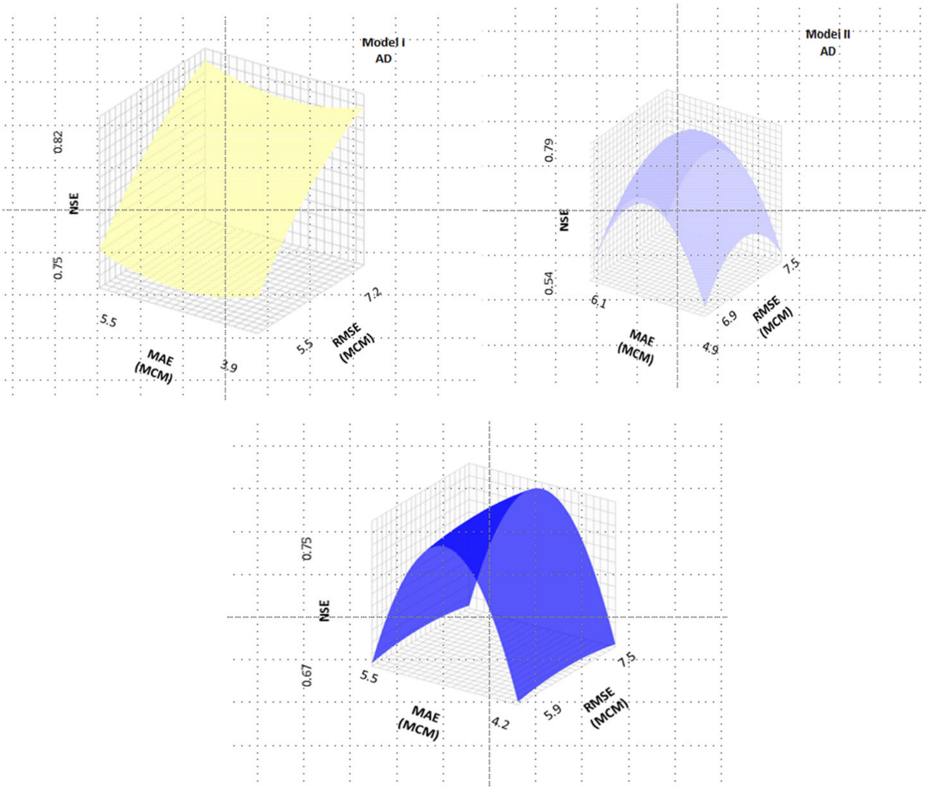


Fig. 7 (continued)

inflows, respectively, when the allocation shares of the upstream coalition decreased by 5%, 6%, and 5% for high, medium, and low inflows, respectively.

4.3 Profits Compensation Evaluation

The previous section showed that the water allocated to the downstream coalition was slightly increased to significantly improve the water allocation of the downstream coalition. As a result, the overall water shortage of the system was reduced by Model III compared to that of Model II. Nash-Harsani Bragging Theory (NHBT) was used to compensate for the water shortage of upstream collation. The sustainability index was based on the NHBT and the revised allocation of water to stakeholders in the three inflow scenarios as illustrated in Table 1. It should be considered that the total amount of water allocated to all stakeholders was constant before and after the compensation Model IIIb. At this level, the TD sustainability index computed by Model II and Model IIIa was lower than that computed by Model I. Similarly, such a process could be observed for AD, KD, and PD. The Model IIIb did not increase the AD sustainability index compared to the Model IIIa. In fact, the water allocation of AD was sacrificed through the cooperation process. For example, the KD adds 1%, 1%, and 1% to the PD, AD, and TD, respectively, for the high inflow scenario. As a result, the amount of water allocated to the PD, AD, and TD by the compensation Model IIIb was more than that obtained by the NCG and CG models.

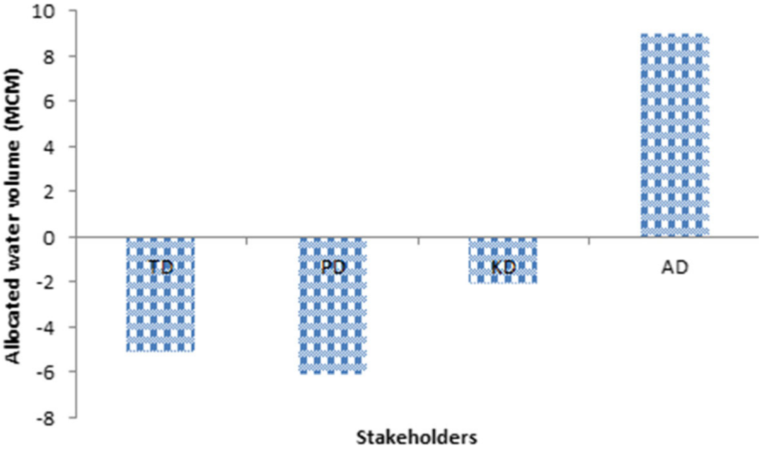


Fig. 8 Water allocation to stakeholders based on Model (IIIa) compared to model II

4.4 Factors Varying the Performance of Cooperation

The combined game model was used in different patterns of cooperation to investigate the factors that varied the performance of the cooperation. The first pattern was that the decisions applied by the TD were attempted to minimize its own water shortage. The coordination model between the PD and the downstream coalition was used on the basis of the decisions taken by TD. For the second pattern, the decisions applied by the PD were aimed at minimizing their own water shortage. On the basis of the decisions taken by the PD, the coordination model between AD and Coalition 2 was used. The results showed that the sustainability percentages of the PD computed by Model II and Model IIIa were lower than those of the Model IIIb. Table 2 also showed the sustainability index of PD and AD with the downstream coalition. As shown in Table 2, the allocated water volumes for the AD and PD were sacrificed to enhance the allocated water for coalition 2. In addition, the sustainability percentage of downstream coalition calculated in Pattern II was more than that calculated in Pattern I.

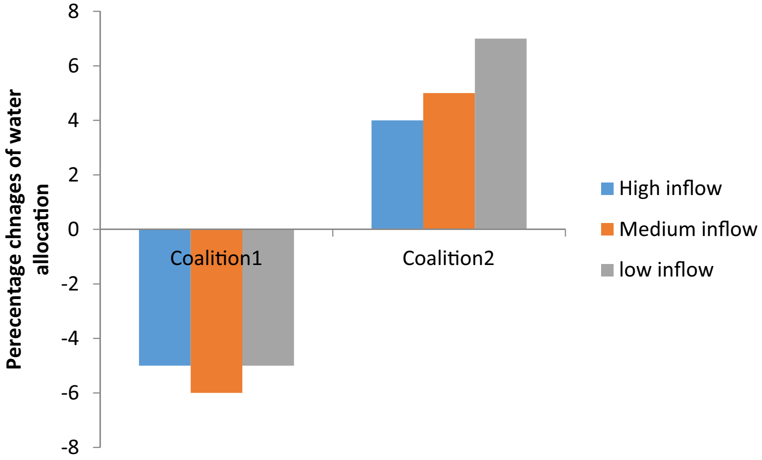


Fig. 9 Percentage change of the water allocation of two collations obtained by Model III (a) compared to the Model II

Table 1 Sustainability index for stakeholders

Models	ModelI	Model(II)	Model (III) (a)	ModelI	Model(II)	Model (III) (a)	ModelI	Model II	Model III (a)
Stakehodler	High inflow			Medium Inflow			Low Inflow		
TD	87%	82	85%	85%	80%	82%	81%	78%	80%
PD	91%	76%	77%	82%	78%	75%	81%	70%	68%
KD	90%	78%	82%	83%	78%	82%	82%	80%	81%
AD	89%	83%	89%	84%	81%	82%	82%	80%	81%
	Model (III) (b)			Model (III) (b)			Model (III) (b)		
TD	87% (85 + 2)			83%(82 + 1)			81% (80 + 1)		
PD	75% (77–2)			76%(75 + 1)			70% (68 + 2)		
KD	80%(82–2)			79% + (82–3)			77% (81–4)		
AD	91% (89 + 2)			83%(82 + 1)			82%(81 + 1)		

Model IIIa, Model IIIb, Pattern I and Pattern II (Table 2). In fact, there were 180 months (1990–2005) and the circle consisted of 180 equal sectors. The months went from January 1990 to January 2005 (Fig. 10). The water level was determined for each month and the months were divided on the perimeter of the circle. The aquifer level for Pattern II was lower than the other models, as coalition 2 included three high-demand stakeholders. Model I was the highest water level for the aquifer. The availability of water in the dam had a considerable impact on the water level. For example, when the dam had low inflows, all game models had lower water levels compared to high and medium inflows.

However, when the number of stakeholders and demands are high, it will be difficult for decision-makers to apply the hybrid game model. In addition, a more accurate technique can be used to solve the nonlinear problem instead of the Successive Linear Programming Method. Optimization algorithms may be useful tools instead of applying the SLPM model. However, it should be considered that there are different uncertainties about the models used, such as uncertainty in the inflow to the reservoir, which can be regarded in the next research.

5 Conclusion

This article suggested a combined game model for the allocation of water resources to some stakeholders. For the use of the combined model, two sub-models were used. The Stackelberg theory has been used to simulate coordination between the upstream coalition and the downstream

Table 2 The sustainability index water allocation based on different coalitions

Inflow		High inflow			Medium inflow		
Pattern	Stakeholder	Model II	ModelIII(a)	Model (IIIb)	Model II	ModelIII(a)	Model (IIIb)
Pattern I	TD	82%	80%	81%	80%	82%	83%
	Coalition2:	82%	85%	83%	81%	84%	85%
Pattern II	PD	84%	87%	89%	82%	86%	86%
	Coalition2:	83%	86%	85%	82%	87%	86%
Inflow			Low Inflow				
Pattern		Stakeholder	ModelII		ModelIII(a)		Model (IIIb)
Pattern I		TD	78%		76%		77%
		Coalition2: PD AD KD	80%		82%		84%

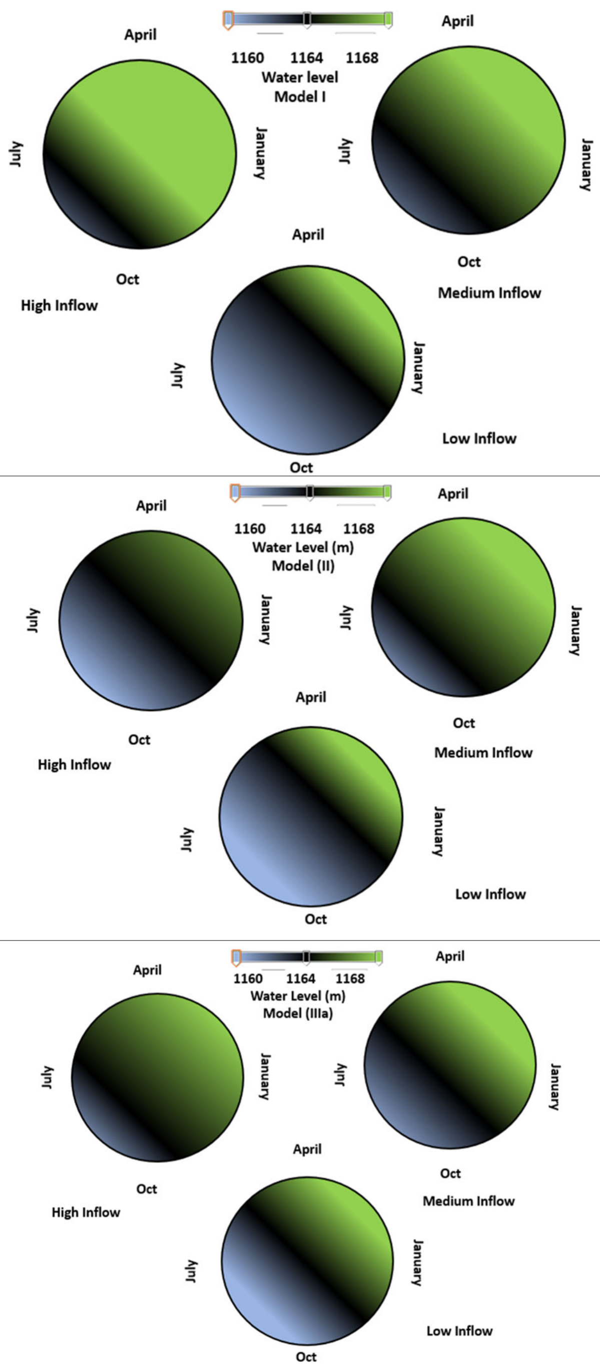
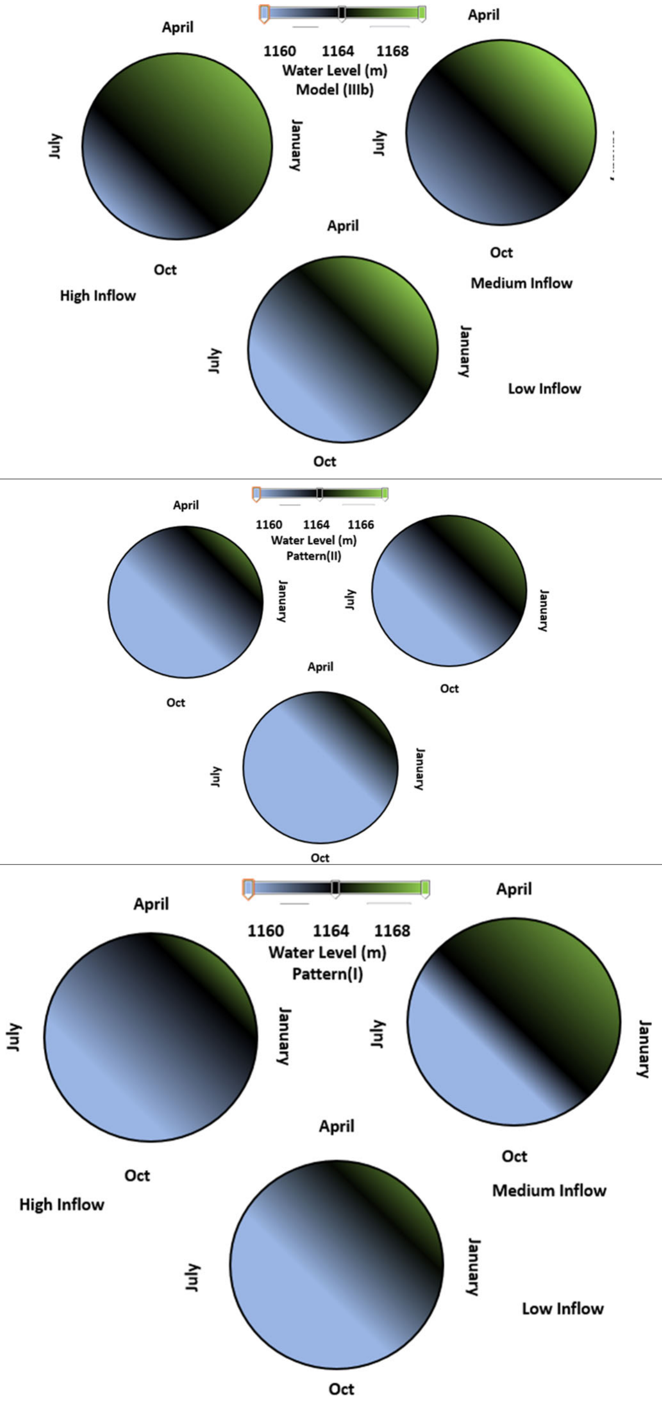


Fig. 10 Water level of aquifer (Left figures: High inflow, right figures: Medium Inflow, central figures: Low inflow)



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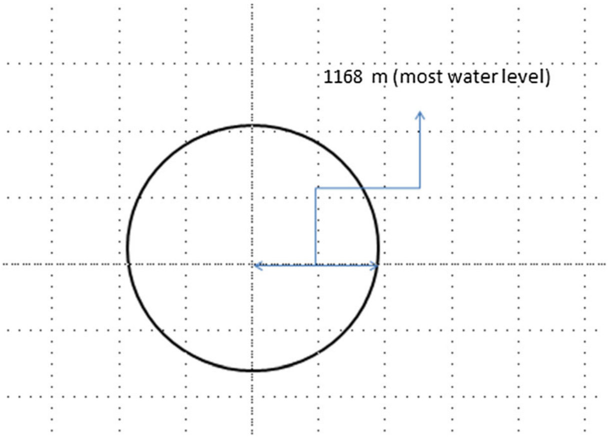

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coalition. The above model showed coordination strategies for the allocation problem with multiple stakeholders. The second model was the profit compensation model, which rationally allocated resources to multiple stakeholders. A dam-aquifer system with some stakeholders was considered to be the case study. The win-win strategy for the stakeholders was considered then the combined game model was used. The results indicated that the combined model decreased water shortage compared to the NCG model. Water availability has been effective in the performance of the new integrated game model. For example, the water allocation of the upstream coalition was sacrificed to increase the volume of water allocation to the downstream coalition. The current article showed that the model of compensation led to a good balance between CG and NCG models. It was found that the amount of allocated water to upstream stakeholders is less than that allocated by Model II, while the amount of allocated water to the downstream stakeholders (Coalition 2) implanted by the Model IIIa is considerably higher than that implemented by Model (II). The amount of water allocated to the PD, AD, and TD by the compensation Model IIIb was greater than that obtained by the NCG and CG models.

Although the combined game model did not minimize water shortages, the model provided a good balance for the coordination of multiple stakeholders. It should be noticed that the selection of the upstream coalition was important to reduce the overall water shortage. Future research can apply the new model to the problem of water allocation under climate change conditions. This issue will be a comprehensive assessment of the new model.

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Compliance with Ethical Standards

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

Ethical Approval This article does not contain any studies with human participants or animals performed by any of the authors.

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