



# Optimal water resources allocation in transboundary river basins according to hydropolitical consideration

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## Abstract

Water resources allocation policies can create cooperation or tension among different stakeholders in a large basin. Thus, integrated water resources management and optimal water allocation are crucial to mitigating water stress and conflicts, while maintaining the economic benefits of the basin. The objective of this study is to develop a multi-objective optimization model to optimize water resources allocation among the stakeholders (including all water sectors in eight provinces) in the Sefidrud River basin in Iran. The objective functions consist of (1) maximizing the economic profits of all stakeholders over the planning time horizon and (2) minimizing the Gini coefficient (a socioeconomic indicator) to achieve the equity in water resources allocation in the society. According to the optimization results, the provinces of Guilan and Hamadan, respectively, had the highest and lowest amounts of water allocated. The results also showed that serious water conflicts in this transboundary river basin can be prevented by changing the current operation, which is based on the provincial divisions, and altering the existing agricultural and industrial water allocations especially for the three more populated provinces including Zanjan, Guilan, and East Azerbaijan.

**Keywords** Water resources allocation · Transboundary river · Multi-objective optimization · Water conflict

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## 1 Introduction

Available water resources are allocated for different needs such as urban use, agriculture, industry, and environment. Population increase and increased agricultural and environmental water needs cause imbalance between available water resources and water consumption (Bozorg-Haddad et al., 2018b), which further leads to discontent stakeholders and their conflicts. Many factors such as social, political, economic, climatic circumstances also affect the conflicts and the related consequences. Water conflicts can be categorized into international and domestic conflicts. Conflicts can also be categorized based on water quantity or quality (Oftadeh et al., 2016). Until 2012, 148 countries had created 276 transboundary river basins (De Stefano et al., 2012), which include more than 60% of the world's rivers. The conflicts related to such transboundary rivers can even cause war (Mianabadi et al., 2015). So far, more than 400 agreements have been signed for managing transboundary water resources (Madani et al., 2014).

The most important criterion for transboundary water resources allocation is equity (Zaag et al., 2002). For this reason, a system should be established to ensure equity in water resources allocation among stakeholders. In addition, the system should consider social, economic, environmental, and other aspects for water resources allocation.

Many problems occur when available water in a basin is less than water demands (Degefu & He, 2016). One of such problems is water conflict. One of the main reasons of the conflict is the unsuitable model used for water resources allocation (Yu & Lu, 2018). Optimization for water resources allocation can be a solution for transboundary river basins.

Water resources allocation is a complex optimization problem. Evolutionary algorithms have been used to solve such complex problems (Bozorg-Haddad, 2013a, 2013b, 2015, 2016; Fallah-Mehdipour et al., 2013; Solgi et al., 2016; Farhadian et al., 2015). Although these algorithms may not achieve the global optimum, they reach a near-optimum solution (Bozorg-Haddad et al., 2016, 2017). Roozbahani et al (2015) used an optimization model to allocate water resources in the Sefidrud basin. Their multi-objective model maximized the profits for all stakeholders. The profit of a stakeholder was calculated by the allocated water for the urban, agricultural, and industrial demands of the stakeholder. Davijani et al. (2016) used the particle swarm algorithm to optimize water allocation in the Central Desert basin in Iran. Ghasemi et al. (2016) developed a farm-based cropping pattern optimization model and solved by using the piece-wise genetic algorithm (PWGA). Their results showed that using the proposed model increased the agricultural benefit in the region and demonstrated that the model had flexibility when farmers changed their decision on water use and cultivation. Yu and Lu (2018) developed a multi-objective water resources allocation model for the Songhua River basin in China to increase the economic benefits from allocating water to domestic, agricultural, and industrial sectors, and establish the equity in water resources allocation in such a transboundary basin. Their proposed model combined projection pursuit model (PPM) and Grey wolf optimization (GWO) algorithm. Mianabadi et al. (2014) applied bankruptcy games to water resources allocation. They developed bankruptcy games and applied to the Tigris and Euphrates basin. Bozorg-Haddad et al. (2018a) used the optimization form of bankruptcy games to determine allocation policies to prevent conflict in the Urmia Lake basin in Iran. Madani et al. (2014) used bankruptcy games to solve conflicts in the Sefidrud basin in Iran. Zeng et al. (2017) developed a model that combined multi-criteria decision making and

bankruptcy games for equitable and reasonable water resources allocation, and the model was applied to the Guanting reservoir basin in China. Zhou et al. (2015) proposed a multi-objective model to optimize water resources allocation in the Dongjiang River basin in China. Their optimal model maximized the economic profit by considering the environmental water demand. Their results showed the proposed model balanced the water demand and supply for sustainable development. Wang et al. (2016) developed a model for optimal water resources allocation in the Haihe River basin in China under climate change conditions to address the water security issue. Iftekhar and Fogarty (2017) developed a nonlinear model for managing groundwater and allocating water resources between fields in Western Australia. Their results indicated that the model had greater and better impacts on bigger fields.

Although single-objective models have been widely used for water resources optimization (Bozorg-Haddad, et al., 2009), including cultivation (Bozorg-Haddad, et al., 2009), reservoir operation (Akbari-Alashti et al., 2014; Asgari et al. 2016), water distribution networks (Fallah-Mehdipour et al., 2011; Sabbaghpour et al., 2012; Soltanjalili et al., 2011), and water project management (Orouji et al., 2014), multi-objective optimization approaches have received relatively less attention and had fewer applications in the related fields (Shokri et al., 2013). Moreover, Solgi et al. (2015) developed an optimization model using the honeybee mating optimization (HBMO) algorithm to find the optimal scheduling of intermittent supply, which reached the maximum number of network nodes with the desired pressure under various conditions of water shortage with consideration of the principles of equanimity and justice in a water distribution network. Bozorg Haddad et al. (2016) linked the HBMO algorithm to a hydraulic simulator and the performance of the linked model was tested with several water shortage scenarios in two different water distribution networks. Solgi et al. (2020) proposed a multi-objective optimization model to address the negative consequences of intermittent water shortages by maximizing the quantitative and qualitative reliability and fairness in water supply and minimizing the frequency of water supply interruption. In this study, a multi-objective model is proposed for optimal water resources allocation. The non-dominated sorting genetic algorithm is used for optimization. The objective functions include maximizing the profit from water resources allocation and the equity of water resources allocation. The Gini coefficient is used for the second objective function. Since the Sefidrud River basin is a transboundary basin, attention to the hydropolitical condition is very important.

## 2 Methodology

Managing the allocation of water resources is one of the recommended strategies to prevent further water loss and further prevent tensions and conflicts. Water allocation is an important part of water resources management at a basin level, which has a significant impact on water supply and demand. Thus, it is of importance to allocate water to stakeholders and satisfy their water demands. For the first time in the selected basin, the Gini coefficient was used to measure the satisfaction of stakeholders in the allocation of water resources, with consideration of the social and political issues of the basin. In particular, the level of the stakeholder satisfaction and justice were considered in the allocation of water resources, in addition to the profits from economic activities. That is, for the first time, the hydropolitical conditions were taken into account in the allocation of water resources of the basin.

## 2.1 Objective functions and constraints

The ultimate goal of the optimization problem is to achieve an optimal condition expressed by the objective function(s). The objective function is a direct or indirect mathematical function of all decision variables. In this research, a multi-objective model is proposed to maximize the profit of the stakeholders and establish equity in water resources allocation in the Sefidrud basin.

The goal of equity is full and equal participation: to meet the needs of all groups in a society that is mutually formed. Equity includes the vision of a society, in which the distribution of resources is correct and all members are mentally and physically safe. Also, equity is the solution to arbitrary equity so that the Gini coefficient is minimized (Helpman and Cooter, 1974). According to the definition, justice in water allocation means the equitable allocation of water resources based on the needs, available resources, and other factors. Sustainability advocates the environmentally sustainable use of land and water resources, implying that today's use of water resources should not expand to such an extent that water resources may not be available in the future (Wang et al., 2003).

It is necessary for sustainability to supply essential water demands and protect the environment. Also, the water right issue related to the Caspian Sea is important according to the transboundary nature. Providing essential water demands for the communities along with maximizing the profit of each stakeholder and establishing equity in water allocation can prevent social conflict. In addition, ensuring the minimum environmental requirement and preventing aquifer depletion can ensure the health of the ecosystem and sustainability. In this study, all domestic water demands and the environmental requirements were first assigned. The remaining available water was allocated between agriculture and industry according to the objective functions and constraints. Figure 1 shows the flowchart of water allocation in this research.

The first objective function in this research is to maximize the profit for all stakeholders of water resources allocation. The mathematical equation of this objective can be expressed as:

Maximize:

$$F_1 = \sum_{t=1}^i \sum_{p=1}^m \sum_{c=1}^{np} q_{p,c}^t \times AEB_{p,c} \quad (1)$$

$$t = 1, \dots, i; p = 1, \dots, m; c = 1, \dots, np$$

where  $i$  is the total number of time steps,  $m$  is the total number of stakeholders (provinces),  $n_p$  is the total number of water users (e.g., agriculture and industry) for stakeholder  $p$ ,  $q_{p,c}^t$  is the amount of water received by stakeholder  $p$  for consumption  $c$  at time step  $t$ , and  $AEB_{p,c}$  is the average economic profit of consumption  $c$  for stakeholder  $p$  (Rial (Iran's currency)/m<sup>3</sup>).

Establishing equity in water resources allocation is an essential condition for stakeholders' satisfaction. If any stakeholders are not satisfied, a conflict can be created. Creating equity is always one of the important concerns for the managers. In this study, the Gini coefficient (Gini, 1921) determined by the Lorenz curve (Fig. 2) is used to calculate equity in water resources allocation (Dai et al., 2018). The Gini coefficient was originally proposed to calculate the inequity for income distributions of a society.

The Gini coefficient criteria, according to the principle of the organization related to the United Nations, are shown in Table 1 (Liu et al., 2015). A lower Gini coefficient

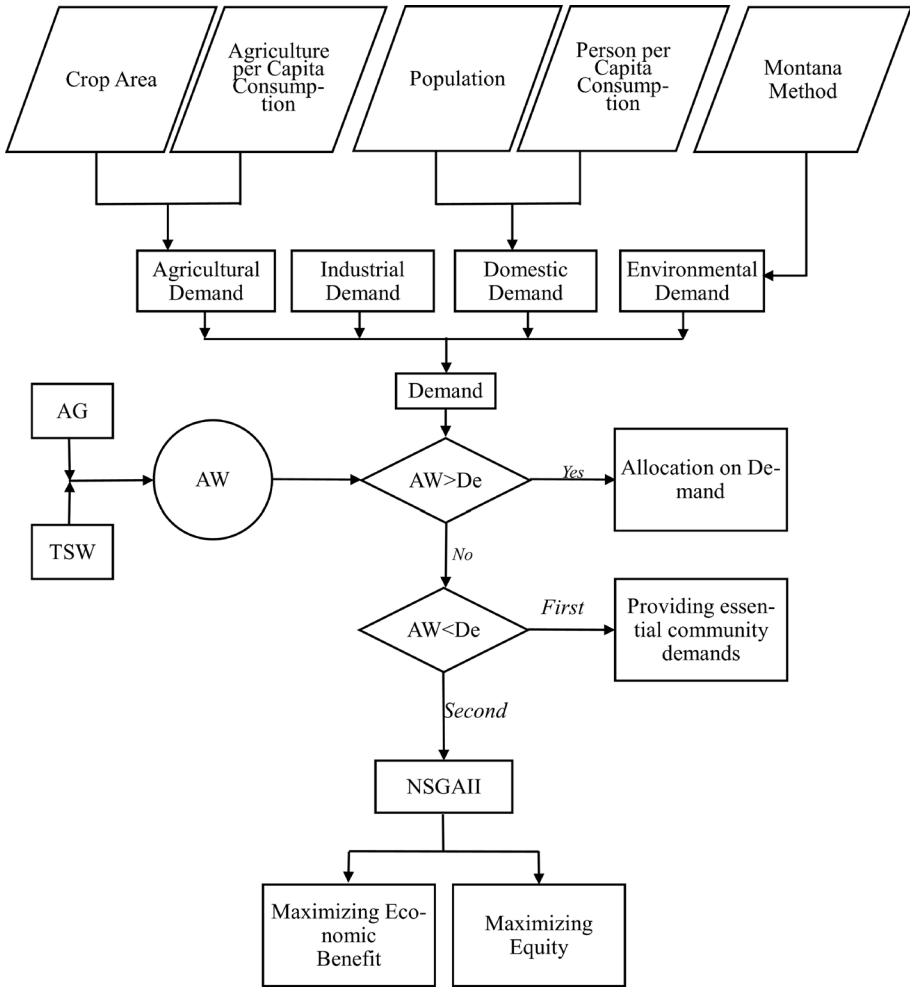


Fig. 1 Flowchart of modeling steps

indicates higher equity in the society. The second objective function obtained from the Gini coefficient can be expressed as:

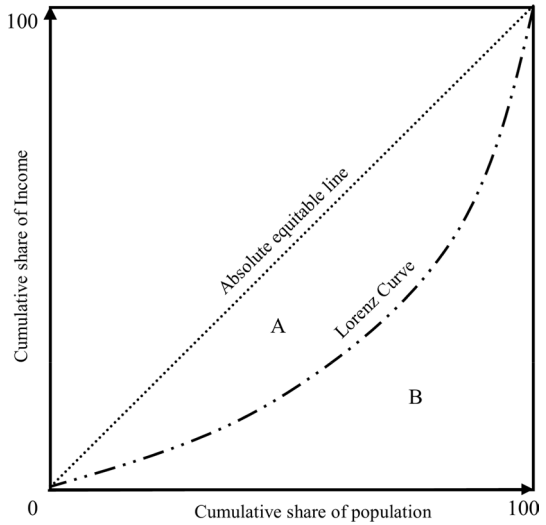
Minimize:

$$F_2 = \frac{1}{2m \sum_{p=1}^m Q_p / EB_p} \times \sum_{p=1}^m \sum_{k=1}^o \left| \frac{Q_p}{EB_p} - \frac{Q_k}{EB_k} \right| \tag{2}$$

where  $Q_p$  is the total amount of water received by stakeholder  $p$  and  $EB_p$  is the economic profit from water consumption for stakeholder  $p$  [million Rial (Rial is the currency of Iran.)].

The constraints of this optimization problem include:

**Fig. 2** Schematic of the Lorenz curve (Dai et al., 2018)



**Table 1** Gini coefficient and assessment criteria

Gini coefficient	0.0–0.2	0.2–0.3	0.3–0.4	0.4–0.5	0.5–1.0
Assessment	Absolutely equity	Relatively equity	Acceptable	Relatively inequity	Absolutely inequity

$$\sum_{p=1}^m Q_p \leq AW \tag{3}$$

$$AW = TSW + AG - ED - DD \tag{4}$$

$$\sum_{c=1}^n q_c^p \leq Q_p + AG \tag{5}$$

$$WA_c^{p,t} \leq De_c^{p,t} \quad \forall p, c, t \tag{6}$$

$$WA_c^{p,t} \geq 0 \quad \forall p, c, t \tag{7}$$

where  $AW$  is the available water,  $TSW$  is the total surface water,  $AG$  is the available groundwater,  $ED$  is the environment demand,  $DD$  is the domestic demand,  $WA_c^{p,t}$  is the amount of allocated water to stakeholder  $p$  for consumption  $c$  at time  $t$ , and  $De_c^{p,t}$  is the water demand of stakeholder  $p$  for consumption  $c$  at time  $t$ .

## 2.2 Multi-objective optimization and non-dominated sorting genetic algorithm

The NSGA-II algorithm (Aboutalebi et al., 2015; Deb et al., 2002) has been widely used for solving multi-optimization problems (Fallah-Mehdipour et al., 2018). This algorithm was based on non-dominated sorting and elitist selection. In the NSGAI, the initial population is generated randomly and the corresponding objective functions are calculated and evaluated. After crossover and mutation, the children population is produced and the objective functions are reevaluated. By combining the initial and children populations, new population is created, ranked and classified into fronts. The crowding distance is then calculated for each front and the associated members. If the stop criterion is satisfied, the process is stopped. Otherwise, the algorithm will be back to evaluating the objective function values for the selected parent population and such a process continues.

## 2.3 Computing water demands

### 2.3.1 Domestic demand

Growing population has increased the domestic (urban) water demand. Based on per capita consumption of water and the population of each province in the basin (Table 2), the amount of domestic water demand for each province (i.e., stakeholder) was calculated. It should be noted that the services for water demand are considered.

### 2.3.2 Agricultural demand

The agricultural sector is the largest water user in the basin. For this reason, determining the exact amount of water for this demand will help resolve this optimization problem. According to the crop patterns of each province and the water consumption per unit area in each province, the agricultural water demand was calculated based on the Mahab Ghodss Company report (MGC, 2011).

### 2.3.3 Industry demand

The MGC (2011) report was used to calculate the industrial demand in each province in this basin.

### 2.3.4 Environment demand

There are many methods for determining the environment demand. One of the most important and practical methods is the modified Montana method (Tennant, 1976), in which the

**Table 2** Population and crop areas of the eight provinces

Province	Guilan	East Azerbaijan	Ardebil	Zanjan	Kurdistan	Hamadan	Ghazvin	Tehran
Population	453,096	307,999	121,754	723,885	366,316	42,521	50,040	25,799
Crop area (Hectare $\times$ 1000)	83,230	46,040	14,093	95,402	60,055	5590	24,028	6685

minimum amount of river environment demand is calculated as a percentage of the average annual discharge of the river. In this research, the modified Montana method is used for estimating the environment demand of rivers. Specifically, the monthly average discharge is calculated and the environmental water demand is then estimated based on a coefficient of 0.3 for the spring and summer months and a coefficient of 0.1 for the fall and winter months. This method does not consider the annual, seasonal, and daily changes in river discharge. Note that the environmental demand is calculated only for the Sefidrud River that flows into the Caspian Sea.

## 2.4 Case study

The Sefidrud basin, located at the intersection of Alborz and Zagros mountains in Iran (Fig. 3), has an area of 59.44 km<sup>2</sup>. The basin ranges from 46°37' to 51°13' E and from 35°00' to 38°00' N (MGC, 2011). This basin covers the country divisions of eight provinces including Kurdistan, Hamadan, Ghazvin, Zanjan, East Azerbaijan, Ardebil, Alborz, and Guilan. The Sefidrud River finally flows into the Caspian Sea. According to Fig. 3, the Sefidrud River and the Shahrood River flow from south to north and from east to west, respectively.

The eight stakeholders (i.e., provinces) have different political powers, different levels of utilization, varying degrees of dependence on the river water in the basin, and dissimilar geographic locations, which tend to lead to conflicts. Therefore, there is a need for a comprehensive water resources allocation model and conflict resolution among the stakeholders for this important area of the country.

This basin consists of two main rivers: Ghezlouzan and Shahrood, which are connected to the Sefidrud dam in the City of Manjil. The Ghezlouzan River is 660 km long and has an annual average discharge of 150 m<sup>3</sup>/s. It is originated from Kurdistan and passes Zanjan,

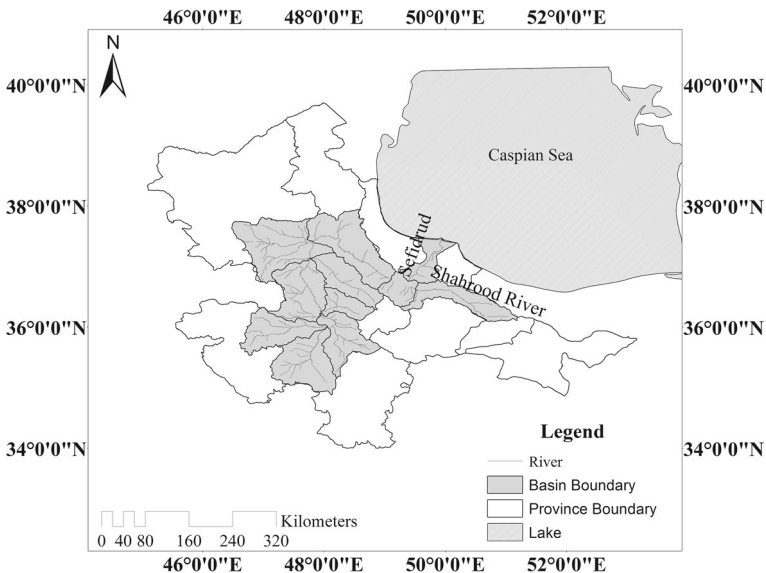


Fig. 3 Study area and the Sefidrud River basin



East Azerbaijan, and Ardebil Provinces. The Shahrood River is 80 km long and has an annual average discharge of 33 m<sup>3</sup>/s. It is originated from Taleghan and passes Ghazvin Province. The rainfall in this basin varies from 245 mm in Zanzan Province to 1250 mm in Guilan Province. Until now, 82 dams have been constructed in the Sefidrud basin. In this basin, there are about 30,000 wells, 30,000 springs, and about 950 aqueducts (MGC, 2011).

## 2.5 Causes of water conflicts in the Sefidrud basin

In recent years, many water conflicts occurred in this basin. The large number of stakeholders and the construction of many dams are the main cause of these conflicts. The eight provinces and the Caspian Sea are the stakeholders in this basin. The hydropolitical importance of the Caspian Sea also makes the water allocation more complicated. The eight provinces in the basin try to access more water resources. The Sefidrud River flows into the Caspian Sea. Due to the transboundary nature, the Caspian Sea water right is very important. Population growth and the limited water resources have caused water conflicts in this basin. Thus, optimal water resources allocation based on equity is essential.

So many dams in the Sefidrud basin have reduced water quantity and altered the water quality in the downstream areas. A long-term plan has been proposed by MGC (2011), in which 166 dams will be operated in this basin up to 2041. This factor can cause more water conflicts among stakeholders. Figure 4 shows the number of dams in the eight provinces in this basin by 2041.

## 2.6 Rainfall and runoff trends

The precipitation and runoff data at some stations in the basin indicate that runoff has a negative trend with an increase in rainfall. This can be attributed to more water use and land use change. The trends of rainfall and runoff are shown in Figs. 5 and 6.

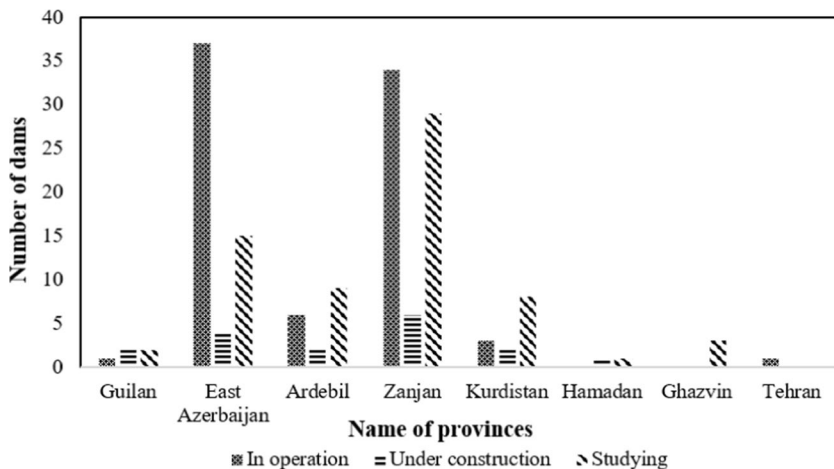
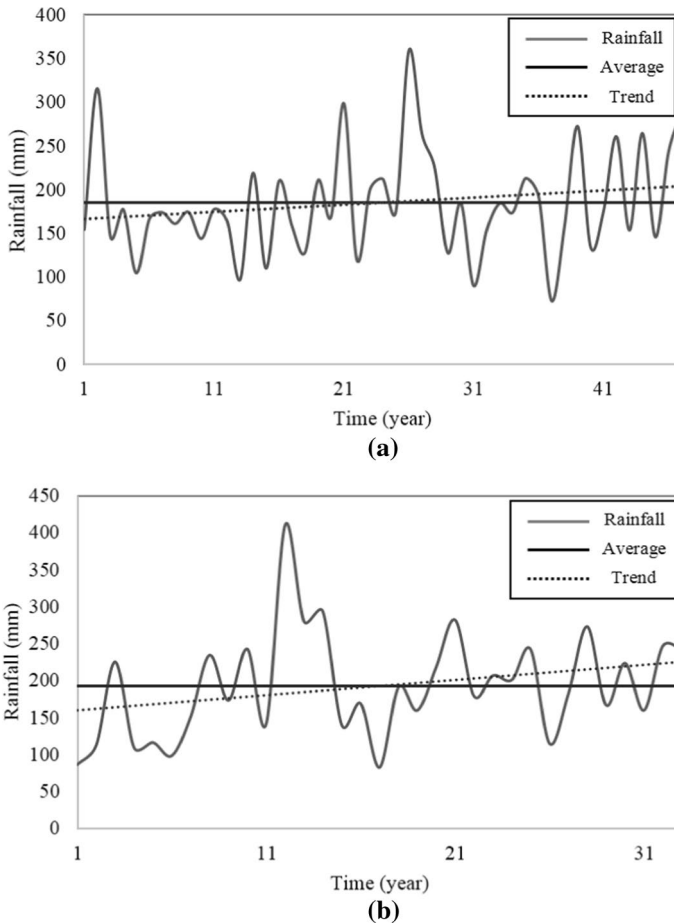


Fig. 4 Number of dams in the eight provinces in Iran

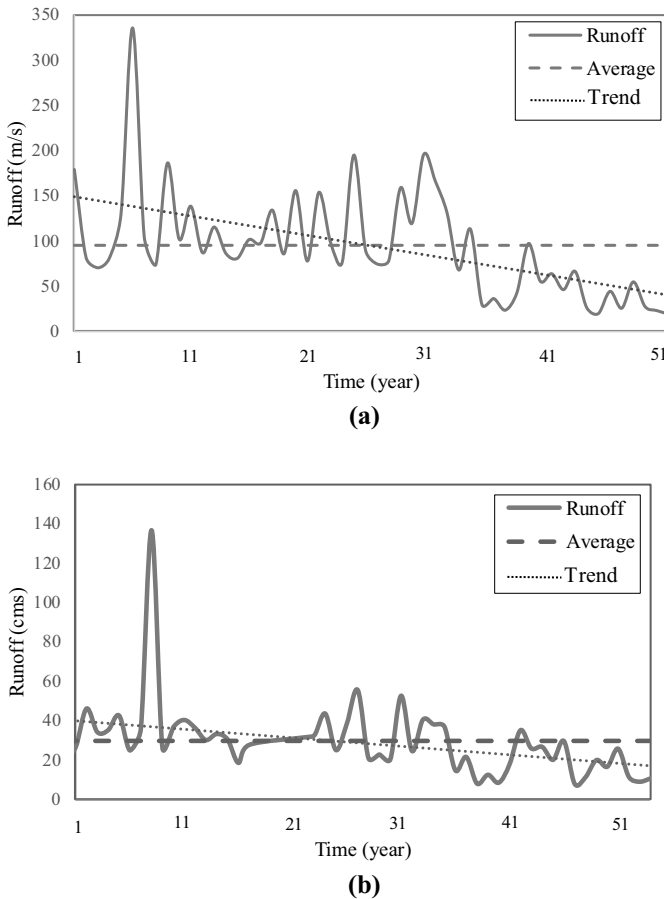


**Fig. 5** Rainfall, and its average and trend at **a** Givan station and **b** Loshan station

As aforementioned, the environmental demand in this study was estimated by using the modified Montana method for dams and shown in Fig. 7. In addition, the environment demand for the Caspian Sea was also calculated, indicating that the water entering the Sea through the Sefidrud River (Fig. 8) was more than the demand for the Caspian Sea ecosystem (Fig. 9).

### 3 Results and discussion

One of the goals of this study was to establish justice (using the Gini index) and maximize economic benefits. Using NSGA-II in the study area, justice was achieved in allocating water resources to an acceptable level. The use of optimization modeling effectively reduced the current water stress. In addition, the model also optimized the economic profit. Therefore, by allocating water resources in the study basin using NSGA-II, the objectives of this study were successfully achieved, which improved the existing conditions.

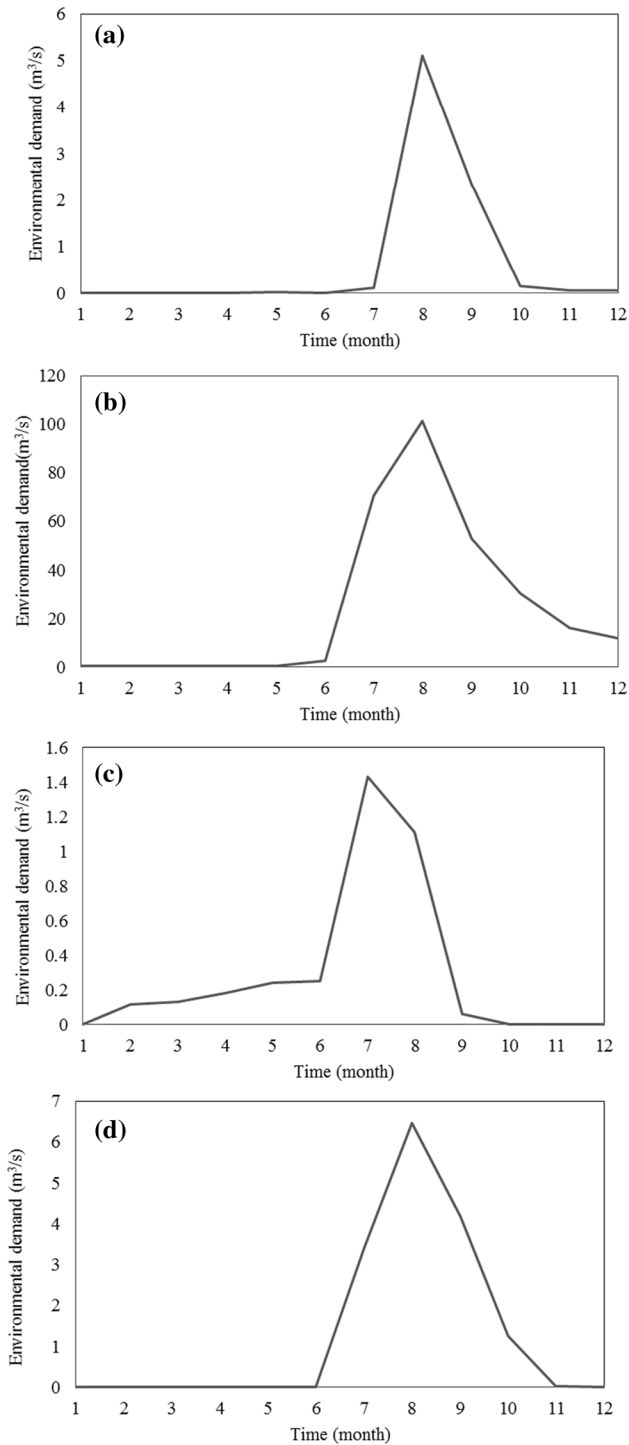


**Fig. 6** Runoff, and its average and trend at **a** Givan station and **b** Loshan station

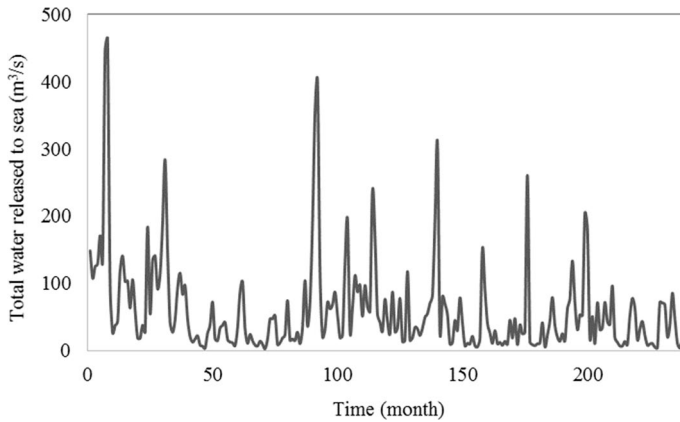
### 3.1 NSGA-II model result

In this study, the essential water demands such as domestic and environmental demands have the first priority. The reason for this prioritization is to satisfy the stability criteria of the region, as one of the most important hydrological parts. To have favorable conditions in terms of sustainability in the basin, a higher priority was given to the environmental need than the needs of agriculture and industry.

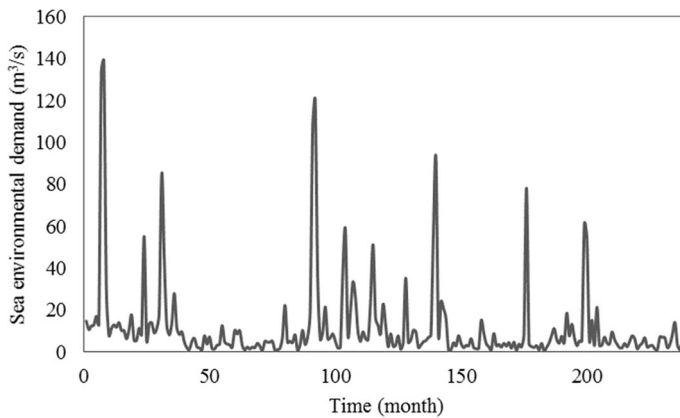
The amount of groundwater used for consumption was subtracted from the available water resources and demands because groundwater was used locally and was not transferable from one province to another. The remaining available water was optimized with the two objective functions: maximizing the economic benefit and the equity of water resources allocation between agriculture and industry. The amount of available surface water for the allocation between stakeholders is  $3201 \times 10^6 \text{ m}^3$ . Figure 10 shows the amount of water received by each province. Guilan having good groundwater resources, sufficient water rights, and the exploitation of Sefidrud dams, received the highest amount of water in the basin. Zanjan Province with a large number of dams in operation (34 dams,



**Fig. 7** Environmental demands for **a** Taleghan dam, **b** Sefidrud dam, **c** Golbolagh dam, and **d** Aydoghmoush dam



**Fig. 8** Temporal distribution of the total water released to the Caspian Sea



**Fig. 9** Temporal distribution of the environmental demands for the Caspian Sea

Fig. 4) and more use of groundwater resources received the most water. East Azerbaijan Province, located in the branches of the Ghezlouzan River, sought operation of more surface water resources, as indicated by the number of dams currently in operation (37 dams, Fig. 4). Due to the dams on the branches of the Ghezlouzan River, Kurdistan also received more water than Ardebil, Hamadan, Qazvin, and Tehran. Hamadan Province had the lowest amount of water in the basin due to the lack of dams its small area in the basin. Because of more political power, Tehran Province with a smaller area received more water than Hamadan and Ardebil.

The Pareto front obtained from the NSGA-II algorithm of the multi-objective optimization model, as the best result from the model runs, is shown in Fig. 11. After the simulation–optimization model was run for 10 times, the Pareto front was determined.

According to Fig. 11, with increasing the profit, equity decreased. To increase the profit in the basin, more water should be allocated to the stakeholders that provide more profit for the area. As a result, the water resources allocation is out of equity, which potentially causes conflicts. According to Table 1, when the value of the Gini coefficient is between

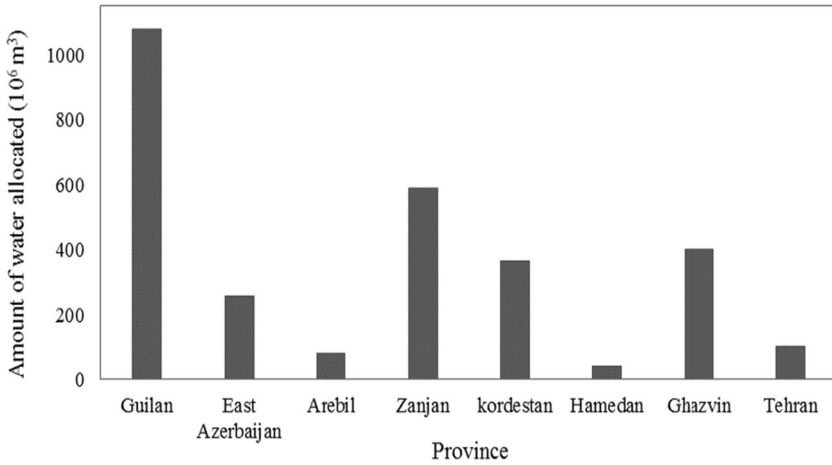


Fig. 10 Amounts of water allocated to the eight provinces

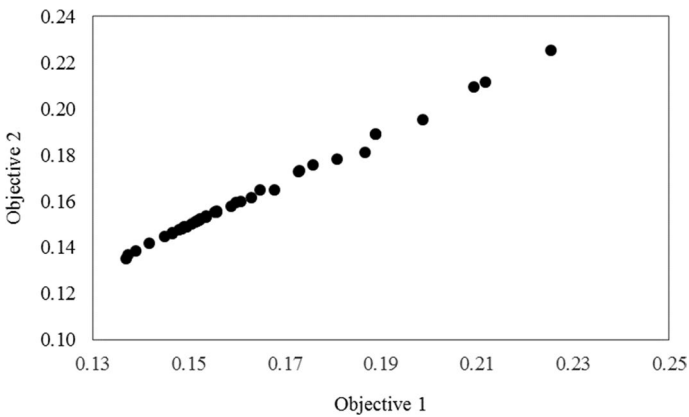
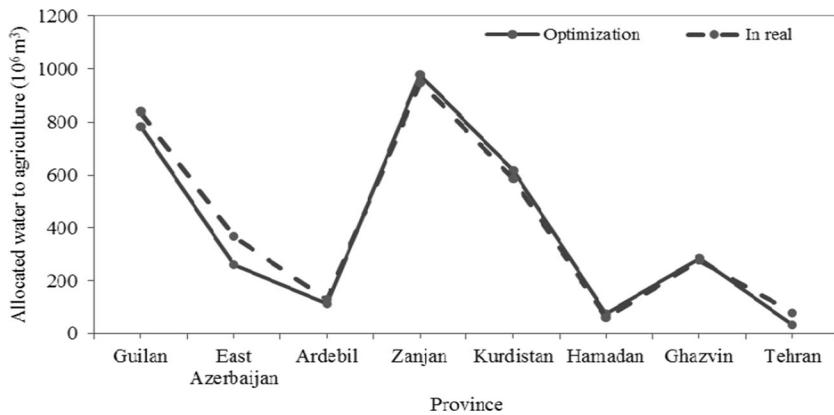


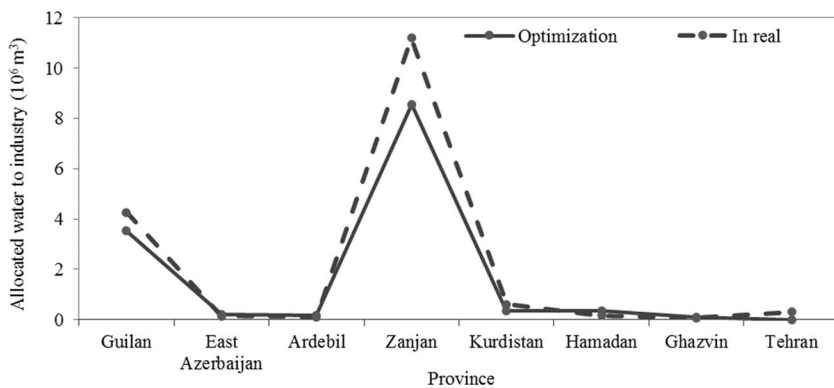
Fig. 11 Pareto front of water allocation (Objective 1 vs. Objective 2)

0.0 and 0.2, full equity is reached in the allocation of water resources in the basin and when this coefficient value is between 0.2 and 0.3, relative equity is achieved in the basin. According to the Gini coefficient values and the data in Table 1, most of the solutions are established in the range of full equity and a few of the answers are in the range of relative equity.

In the real condition, the Ministry of Energy, with the participation of regional water organizations in each province, proposed macro-policies at the catchment level. These policies were determined according to the characteristics of different provinces, including their population, type of industry, and agriculture areas. But the important point is that the implementation of such policies is only based on the conditions of the current period of operation. Thus, if there is enough water in an operational period, the operation will be done and different water demands will be supplied. Otherwise, water shortage will occur in the system. However, according to the optimal operating condition, it is possible to apply a comprehensive approach that takes into account the water demands of all stakeholders



**Fig. 12** Optimal and real water amounts allocated to agriculture for the eight provinces



**Fig. 13** Optimal and real water amounts allocated to industry for the eight provinces

in different places at different times and tries to determine different optimal objectives simultaneously.

The agriculture used the most water resources in the basin. Figure 12 shows the amount of water received by each province for agriculture under the real and optimal conditions. Zanjan has the highest amount of water, while Hamadan has the lowest amount of water used for agriculture in the basin, which indicates the direct relationship with the area and the profit from the allocated water for each province. Zanjan Province has arid and semi-arid climate, which requires more water for agriculture than other provinces. Guilan has a better profit from agriculture, resulting in higher agricultural water use. The order of agricultural water use for the remaining provinces follows (from high to low): Kurdistan, Ghazvin, East Azerbaijan, Tehran, Ardebil and Hamadan.

The water allocated to the agriculture and industry of each province under the real and optimal conditions is shown in Figs. 12 and 13. The water allocation was based on the profit and equity. Zanjan Province has the most dams and the largest area in the Sefidrud basin, and hence has more surface water.

Figures 14 and 15, respectively, show the profits of agriculture and industry under the real and optimal conditions. The profits were calculated based on the *AEB* and the

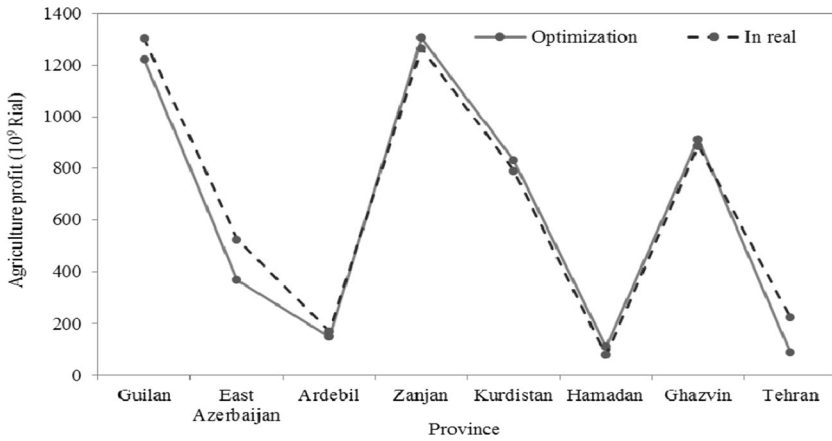


Fig. 14 Profits of agriculture for the optimal and real conditions of the eight provinces

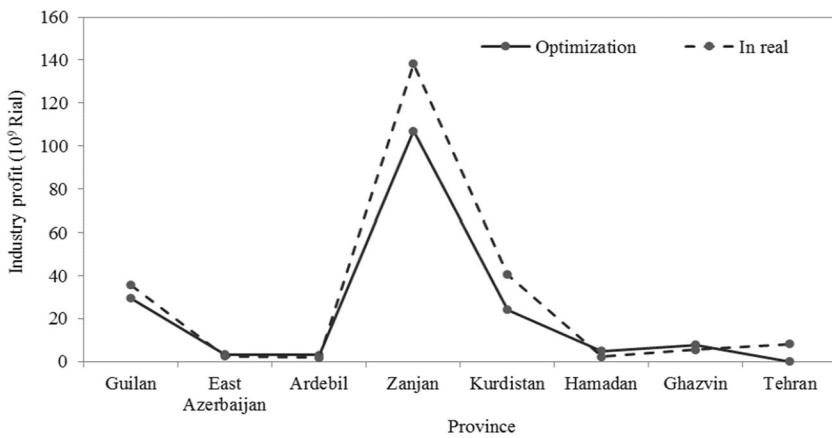


Fig. 15 Profits of industry for the optimal and real conditions of the eight provinces

amount of water received by each user of a province. Thus, provinces that receive more water or have a higher *AEB* have more profits from agriculture and industry. Zanjan Province with a larger crop area (Table 2) and more control of surface water by dams (Fig. 4) and Guilan Province with the highest *AEB* have the most benefits from the allocation of water resources to agriculture. According to Table 2, although Ghazvin Province has a smaller crop area than the East Azerbaijan and Kurdistan Provinces, it has more agricultural benefits than those provinces due to its higher *AEB*. The provinces of Kurdistan, East Azerbaijan, Ardebil, Hamadan, and Tehran have more agricultural profits. Since Zanjan Province has the largest industry in the basin, it has the highest profit from this water consumption. The profits of other provinces in the industry are shown in Fig. 15.



## 4 Conclusions

The increase in water demand induced by climate change, population growth, agricultural expansion, industrial development, and urbanization has raised sustainability concerns, which emphasizes the necessity for effective management of the limited water resources. In this study, a multi-objective model was developed for water allocation in the Sefidrud River basin to resolve water conflicts associated with transboundary water resources by maximizing the economic profits of the water resources system for all stakeholders and minimizing the Gini coefficient, which accounted for the socioeconomic aspect of water allocation. The optimum solutions were determined by NSGA-II. Results showed that Zanjan Province received the most water allocated to both agriculture and industry. Guilan Province with a high *AEB* and Zanjan Province with the largest crop area had the highest profits from the water allocation for agriculture and industry in the basin. This study demonstrated that optimizing water allocation, especially for the three major provinces (including Zanjan, Guilan, and East Azerbaijan) in the basin, helped to protect the environment and ecosystem and resolve the hydropolitical issues for this transboundary river basin.

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**Data availability** All of the required data have been presented in our article. The data that support the findings of this study are available from the corresponding author upon reasonable request.

**Declaration**

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

## References

- Aboutalebi, M., Bozorg Haddad, O., & Loáiciga, H. A. (2015). Optimal monthly reservoir operation rules for hydropower generation derived with SVR-NSGAI. *Journal of Water Resources Planning and Management*, *141*(11), 04015029
- Akbari-Alashti, H., Bozorg-Haddad, O., Fallah-Mehdipour, E., & Mariño, M. A. (2014). Multi-reservoir real-time operation rules: A new genetic programming approach. *Proceedings of the Institution of Civil Engineers: Water Management*, *167*(10), 561–576. <https://doi.org/10.1680/wama.13.00021>
- Asgari, H.-R., Bozorg-Haddad, O., Pazoki, M., & Loáiciga, H. A. (2016). Weed optimization algorithm for optimal reservoir operation. *Journal of Irrigation and Drainage Engineering*, *142*(2), 04015055. [https://doi.org/10.1061/\(ASCE\)IR.1943-4774.0000963](https://doi.org/10.1061/(ASCE)IR.1943-4774.0000963)
- Bozorg-Haddad, O., Afshar, A., & Mariño, M. A. (2009a). Optimization of non-convex water resource problems by honey-bee mating optimization (HBMO) algorithm. *Engineering Computations (swansea, Wales)*, *26*(3), 267–280. <https://doi.org/10.1108/02644400910943617>
- Bozorg-Haddad, O., Moradi-Jalal, M., Mirmomeni, M., Kholghi, M. K. H., & Mariño, M. A. (2009b). Optimal cultivation rules in multi-crop irrigation areas. *Irrigation and Drainage*, *58*(1), 38–49. <https://doi.org/10.1002/ird.381>
- Bozorg-Haddad, O., Ashofteh, P. S., Rasoulzadeh-Gharibdousti, S., & Mariño, M. A. (2013a). Optimization model for design-operation of pumped-storage and hydropower systems. *Journal of Energy Engineering*, *140*(2), 04013016
- Bozorg-Haddad, O., RezapourTabari, M. M., Fallah-Mehdipour, E., & Mariño, M. A. (2013b). Groundwater model calibration by meta-heuristic algorithms. *Water Resources Management*, *27*(7), 2515–2529
- Bozorg-Haddad, O., Ashofteh, P. S., & Marino, M. A. (2015). Levee layouts and design optimization in protection of flood areas. *Journal of Irrigation and Drainage Engineering*, *141*(8), 04015004

- Bozorg-Haddad, O., Hoseini-Ghafari, S., Solgi, M., & Loáiciga, H. A. (2016a). Intermittent urban water supply with protection of consumers' welfare. *Journal of Pipeline Systems Engineering and Practice*, 7(3), 04016002. [https://doi.org/10.1061/\(ASCE\)PS.1949-1204.0000231](https://doi.org/10.1061/(ASCE)PS.1949-1204.0000231)
- Bozorg-Haddad, O., Zarezadeh-Mehrizi, M., Abdi-Dehkordi, M., Loáiciga, H. A., & Mariño, M. A. (2016b). A self-tuning ANN model for simulation and forecasting of surface flows. *Water Resources Management*, 30(9), 2907–2929
- Bozorg-Haddad, O., Solgi, M., & Loáiciga, H. A. (2017). *Meta-heuristic and evolutionary algorithms for engineering optimization*. Wiley. ISBN: 978-1-119-38705-3.
- Bozorg-Haddad, O., Athari, E., Fallah-Mehdipour, E., & Loáiciga, H. A. (2018a). Real-time water allocation policies calculated with bankruptcy games and genetic programming. *Water Science and Technology: Water Supply*, 18(2), 430–449
- Bozorg-Haddad, O., Athari, E., Fallah-Mehdipour, E., Bahrami, M., & Loáiciga, H. A. (2018b). Allocation of reservoir releases under drought conditions: A conflict-resolution approach. In *proceedings of the institution of civil engineers-water management* (pp. 1–26). Thomas Telford Ltd.
- Dai, C., Qin, X. S., Chen, Y., & Guo, H. C. (2018). Dealing with equality and benefit for water allocation in a lake watershed: A Gini-coefficient based stochastic optimization approach. *Journal of Hydrology*, 561, 322–334
- Davijani, M. H., Banihabib, M. E., Anvar, A. N., & Hashemi, S. R. (2016). Optimization model for the allocation of water resources based on the maximization of employment in the agriculture and industry sectors. *Journal of Hydrology*, 533, 430–438
- De Stefano, L., Duncan, J., Dinar, S., Stahl, K., Strzepek, K. M., & Wolf, A. T. (2012). Climate change and the institutional resilience of international river basins. *Journal of Peace Research*, 49(1), 193–209
- Deb, K., Pratap, A., Agarwal, S., & Meyarivan, T. A. M. T. (2002). A fast and elitist multiobjective genetic algorithm: NSGA-II. *IEEE Transactions on Evolutionary Computation*, 6(2), 182–197
- Degefu, D. M., & He, W. (2016). Allocating water under bankruptcy scenario. *Water Resources Management*, 30(11), 3949–3964
- Fallah-Mehdipour, E., Bozorg-Haddad, O., Beygi, S., & Mariño, M. A. (2011). Effect of utility function curvature of Young's bargaining method on the design of WDNs. *Water Resources Management*, 25(9), 2197–2218. <https://doi.org/10.1007/s11269-011-9802-5>
- Fallah-Mehdipour, E., Bozorg Haddad, O., & Mariño, M. A. (2013). Extraction of optimal operation rules in an aquifer-dam system: Genetic programming approach. *Journal of Irrigation and Drainage Engineering*, 139(10), 872–879
- Fallah-Mehdipour, E., Bozorg-Haddad, O., & Loáiciga, H. A. (2018). Calculation of multi-objective optimal tradeoffs between environmental flows and hydropower generation. *Environmental Earth Sciences*, 77(12), 453
- Farhadian, M., Bozorg Haddad, O., Seifollahi-Aghmiuni, S., & Loáiciga, H. A. (2015). Assimilative capacity and flow dilution for water quality protection in rivers. *Journal of Hazardous, Toxic, and Radioactive Waste*, 19(2), 04014027
- Ghasemi, M. M., Karamouz, M., & Shui, L. T. (2016). Farm-based cropping pattern optimization and conjunctive use planning using piece-wise genetic algorithm (PWGA): A case study. *Modeling Earth Systems and Environment*, 2(1), 25
- Gini, C. (1921). Measurement of inequality of incomes. *The Economic Journal*, 31(121), 124–126
- Helpman, R., & Coooter, E. (1974). Optimal income taxation for transfer payments under different social welfare criteria. *The Quarterly Journal of Economics*, 4(88), 656–670
- Iftekhhar, SMd., & Fogarty, J. (2017). Impact of water allocation strategies to manage groundwater resources in Western Australia: Equity and efficiency considerations. *Journal of Hydrology*, 548(1), 145–156
- Karimi, S. S., Yasi, M., & Eslamian, S. (2012). Use of hydrological methods for assessment of environmental flow in a river reach. *International Journal of Environmental Science and Technology*, 9(3), 549–558
- Liu, H., Sang, X., Yan, Z., Zhou, Z., Su, J., & Chen, G. (2015). Evaluation of the Balance of Water Resources in Multiple Spatial Scale Based on Lorenz Curves and Gini Coefficients. In *2nd international conference on green materials and environmental engineering*. Atlantis Press, December 20–21, Phuket, Thailand.
- Madani, K., Zarezadeh, M., & Morid, S. (2014). A new framework for resolving conflicts over transboundary rivers using bankruptcy methods. *Hydrology and Earth System Sciences*, 18(8), 3055–3068
- MGC (Mahab Ghods Company) (2011) National water master plan study: The Sefidrud basin. *Iranian Ministry of Energy*, Tehran, Iran.
- Mianabadi, H., Mostert, E., Zarghami, M., & van de Giesen, N. (2014). A new bankruptcy method for conflict resolution in water resources allocation. *Journal of Environmental Management*, 144, 152–159

- Mianabadi, H., Mostert, E., Pande, S., & van de Giesen, N. (2015). Weighted bankruptcy rules and trans-boundary water resources allocation. *Water Resources Management*, 29(7), 2303–2321
- Oftadeh, E., Shourian, M., & Saghafian, B. (2016). Evaluation of the bankruptcy approach for water resources allocation conflict resolution at basin scale, Iran's lake urmia experience. *Water Resources Management*, 30(10), 3519–3533
- Orouji, H., Bozorg-Haddad, O., Fallah-Mehdipour, E., & Mariño, M. A. (2014). Extraction of decision alternatives in project management: Application of hybrid PSO-SFLA. *Journal of Management in Engineering*, 30(1), 50–59. [https://doi.org/10.1061/\(ASCE\)ME.1943-5479.0000186](https://doi.org/10.1061/(ASCE)ME.1943-5479.0000186)
- Roozbahani, R., Abbasi, B., Schreider, S., & Ardakani, A. (2014). A multi-objective approach for trans-boundary river water allocation. *Water Resources Management*, 28(15), 5447–5463
- Roozbahani, R., Schreider, S., & Abbasi, B. (2015). Optimal water allocation through a multi-objective compromise between environmental, social, and economic preferences. *Environmental Modelling & Software*, 64, 18–30
- Sabbaghpour, S., Naghashzadehgan, M., Javaherdeh, K., & Bozorg-Haddad, O. (2012). HBMO algorithm for calibrating water distribution network of Langarud city. *Water Science and Technology*, 65(9), 1564–1569. <https://doi.org/10.2166/wst.2012.045>
- Shokri, A., Bozorg-Haddad, O., & Mariño, M. A. (2013). Algorithm for increasing the speed of evolutionary optimization and its accuracy in multi-objective problems. *Water Resources Management*, 27(7), 2231–2249. <https://doi.org/10.1007/s11269-013-0285-4>
- Solgi, M., Bozorg Haddad, O., Seifollahi-Aghmiuni, S., & Loáiciga, H. A. (2015). Intermittent operation of water distribution networks considering equanimity and justice principles. *Journal of Pipeline Systems Engineering and Practice*, 6(4), 04015004. [https://doi.org/10.1061/\(ASCE\)PS.1949-1204.0000198](https://doi.org/10.1061/(ASCE)PS.1949-1204.0000198)
- Solgi, M., Bozorg Haddad, O., & Loáiciga, H. A. (2016). The enhanced honey-bee mating optimization algorithm for water resources optimization. *Water Resources Management*. <https://doi.org/10.1007/s11269-016-1553-x>
- Solgi, M., Bozorg Haddad, O., & Loáiciga, H. A. (2020). A multi-objective optimization model for operation of intermittent water distribution networks. *Water Supply*, 20(7), 2630–2647
- Soltanjilili, M., Bozorg-Haddad, O., & Mariño, M. A. (2011). Effect of breakage level one in design of water distribution networks. *Water Resources Management*, 25(1), 311–337. <https://doi.org/10.1007/s11269-010-9701-1>
- Tennant, D. L. (1976). Instream flow regimens for fish, wildlife, recreation and related environmental resources. *Fisheries*, 1(4), 6–10
- Van der Zaag, P., Seyam, I. M., & Savenije, H. H. (2002). Towards measurable criteria for the equitable sharing of international water resources. *Water Policy*, 4(1), 19–32
- Wang, L. Z., Fang, L., & Hipel, K. W. (2003). Water resources allocation: A cooperative game theoretic approach. *Journal of Environmental Informatics*, 2(2), 11–22
- Wang, X. J., Zhang, J. Y., Shahid, S., Guan, E. H., Wu, Y. X., Gao, J., & He, R. M. (2016). Adaptation to climate change impacts on water demand. *Mitigation and Adaptation Strategies for Global Change*, 21(1), 81–99
- Yu, S., & Lu, H. (2018). An integrated model of water resources optimization allocation based on projection pursuit model–Grey wolf optimization method in a transboundary river basin. *Journal of Hydrology*, 559, 156–165
- Zeng, Y., Li, J., Cai, Y., & Tan, Q. (2017). Equitable and reasonable freshwater allocation based on a multi-criteria decision making approach with hydrologically constrained bankruptcy rules. *Ecological Indicators*, 73, 203–213
- Zhou, Y., Guo, S., Xu, C. Y., Liu, D., Chen, L., & Wang, D. (2015). Integrated optimal allocation model for complex adaptive system of water resources management (II): Case study. *Journal of Hydrology*, 531, 977–991