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Inter-basin hydropolitics for optimal water resources allocation

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Abstract Efficient, just, and sustainable water resources' allocation is difficult to achieve in multi-stakeholder basins. This study presents a multi-objective optimization model for water resources allocation and reports its application to the Sefidrud basin in Iran. Available water resources are predicted until 2041with the artificial neural network algorithm (ANN). This is followed by multi-objective optimization of water resource allocation. The first objective function of the optimization model is maximization of revenue, and the second objective function is the achievement of equity in water resources allocation in the basin. This study considers two scenarios in the optimization scheme. The first scenario concerns the water allocation with existing dams and dams under construction. The second scenario tackles water allocation adding dams currently in the study stage to those considered in Scenario 1. The Gini coefficient is about 0.1 under the first scenario, indicating the preponderance of economic justice in the basin. The Gini coefficient is about 0.4 under the second scenario, which signals an increase of injustice in water allocation when considering the future operation of dams currently under study.

Keywords Allocation policies · Conflict · Justice · Sustainability · Artificial neural network (ANN) · Multi-objective optimization · Gini coefficient · Sefidrud

Introduction

Water scarcity and rising water demand constitute daunting challenges in the arid regions of the world (Acquah and Ward 2019). Water resources have an important role in economic development of countries. Water resources are in a dynamic and complex balance with economic, social, and environmental factors, and their allocation among stakeholders is commonly a complex issue (Zhou et al. 2015). Water resources allocation policies and stakeholders' competition to exploit common water resources frequently cause conflicts among stakeholders. Hydropolitics provides a means for identifying these conflicts and operations (Ng et al. 2011; Sneddon and Fox 2006). Hydropolitics is the discipline that studies such conflicts. Hydropolitic also

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studies the development of water resources, transboundary waters, and international rivers (Sneddon and Fox 2006). Asah (2015) assessed the hydropolitics of the Chad Lake Basin, concluding that water resources are a security issue in the border areas, calling for the establishment of transnational entities to engage in transboundary water management. Iran is one of the arid countries in the world whose water resources are scarce, and there are conflicting objectives among stakeholders with diverging utilities. Numerous factors such as economic, social, political, environmental, and other conditions affect the allocation of water among stakeholders. This paper considers the water resources allocation in the Sefidrud river basin, Iran, relying on inter-basin hydropolitics to overcome conflicts between provinces. The hydropolitic approach has been applied in previous studies such as Rai et al. (2017) in India and Nepal and Kansal and Ekadu (2018) in Africa. This work reports its first application to water transfers in a semi-arid region.

The water resources of a basin are key determinants of regional development (Jahandideh-Tehrani et al. 2015). The planning horizon is central to the allocation of water resources, and managers must pay attention to the current water resources and to the planning of future water resources. Data mining applied to discovering patterns in large datasets involving methods at the intersection of machine learning, statistics, and database analysis is useful in the prediction of future water resources (Fallah-Mehdipour et al. 2014). This paper applies ANN linked with evolutionary algorithms to data mining and water resources predictions (Bozorg-Haddad et al. 2016, and Sarzaeim et al. 2017).

Classical optimization methods such as linear programming (LP), nonlinear programming (NLP), and dynamic programming (DP) have been successfully applied to solve well-posed water resources problems. However, they do not perform well or at all when problems have complex objective functions (say, with discrete or non-differentiable variables besetting gradient-based algorithms) and constraints, and large dimensionality (which gives rise to the curse of dimensionality in dynamic programming (Fallah-Mehdipour et al. 2012). Ghahreman and Sepaskhah (2002) employed LP to optimize water allocations from the Aradak dam (Iran). Babel et al. (2005) developed an integrated LP model for allocating water resources through reservoir operation. Divakar et al. (2011) reported a bi-objective LP model for water allocation in the Chao Phraya basin (Thailand). Iftekhar and Fogarty (2017) developed an NLP model for groundwater allocation among farms in Western Australia. Their goal was to manage groundwater in their study area.

A class of optimization methods known as evolutionary algorithms has gained ground over the last few decades. They have performed successfully where classic methods failed in solving water resources problems, such as in reservoir operation applications (Bozorg-Haddad and Mariño 2011). The GA was a pioneering evolutionary algorithm. Digna et al. (2018) implemented the GA to study development in the eastern Nile system river. Digna et al. (2018) relied on the GA to study development in the eastern Nile system river. Other applications of evolutionary algorithms in water resources systems and analysis can be found in Bozorg-Haddad et al. (2017).

The cited works employ optimization methods to search the decision space featuring one single objective, whereas water allocation of resources under inter-basin hydropolitics includes multiple stakeholders with conflicting utilities. The latter type of problems requires the application of multi-objective optimization to determine optimal options for all the stakeholders simultaneously.

The main goal of multi-objective optimization is to determine a set of optimal solutions satisfying all objectives simultaneously. This type of optimization is especially useful when objectives involve tradeoffs. In traditional optimization methods, techniques such as the weighting approach are used in LP and NLP to produce a single optimal solution based on the applied weights. On the other hand, evolutionary algorithms yield a set of non-dominated solutions, or Pareto fronts, as the optimal solutions. The non-dominated sorting genetic algorithm (NSGA), multi-colony ACO (MOACO), and multi-objective PSO (MOPSO) are examples of multi-objective evolutionary optimization algorithms (Fallah-Mehdipour et al. 2012). This paper applies NSGA-II (e.g., Peng et al. 2019, and Saadatpour 2020) to determine optimal water allocation considering the hydropolitics of regional water transfers.

This paper predicts future water resources at the basin scale with ANN. The NSGA-II is applied to optimal allocation of water considering hydropolitic conditions within the basin. The ANN-NSGA-II method is applied to the Sefidrud basin, Iran.

Materials and methods

This section introduces coupled simulation and optimization to obtain optimal allocation of water considering hydropolitic conditions in inter-basin water transfer. The Sefidrud river basin, Iran, serves as a case study illustrating this work's methodology. ANN is employed for the predictions of available water resources through year 2041. Water evaluation and planning (WEAP) system is coupled with the multi-objective optimization non-dominated sorting genetic algorithm (NSGA) II for optimal water allocation. Hydropolitic conditions form part of the formulation of the objective functions and constraints of the water allocation optimization problem. Figure 1 presents flowchart of this paper's methodology.

Artificial neural network (ANN)

The ANN predicts phenomena based on large and representative datasets (Bozorg-Haddad et al. 2016). ANN is a machine learning method that searches for relations between input and output data. ANN constructs a mathematical relation between input and output data. It educates and identifies relations between inputs and outputs and predicts outputs for new inputs. ANN establishes nonlinear mathematical relations that are developed through a procedure of training, validation, and testing (Sarzaeim et al. 2017; Kelleher and Tierney 2018).

The non-dominated sorting genetic algorithm (NSGA-II)

The NSGA-II was introduced by Deb et al. (2002). The NSGA-II is a popular method for multi-objective optimization, which operates on the basis of non-dominated sorting and elitism. It generates a random population of possible solutions to a multi-objective optimization problem followed by evaluation of the objective functions. The next population of possible solutions is generated based on the mutation and crossover operators followed by newly evaluated objective functions corresponding to the new population of possible solutions. The first-generation population and the newly generated population are classified and ranked by non-dominated sorting into Pareto fronts. After sorting and classification, the objective functions of the previous and the new populations are evaluated and compared to assess if there is improvement from the previous to the next population. If improvement is not established by performance criteria, the search for optimal Pareto fronts ends. Otherwise, a new population of possible solutions is generated, and the search process continues until satisfying a termination criterion (Aboutalebi et al. 2015). More details about the NSGA-II can be found in Sarzaeim et al. (2018).

Inter-basin hydropolitics

Water conflicts commonly arise when a water system does not supply the water demands of all stakeholders (Madani et al. 2014). Hydropolitics is the discipline that studies such water conflicts at different spatial scales (Waterbury 1979). There are 310 international river basin and 150 countries sharing them (McCracken and Wolf 2019). This study presents the hydropolitics of water allocation in the Sefidrud basin, Iran.

Objective functions

The optimization problem herein addressed involves objective functions and the constraints of a water

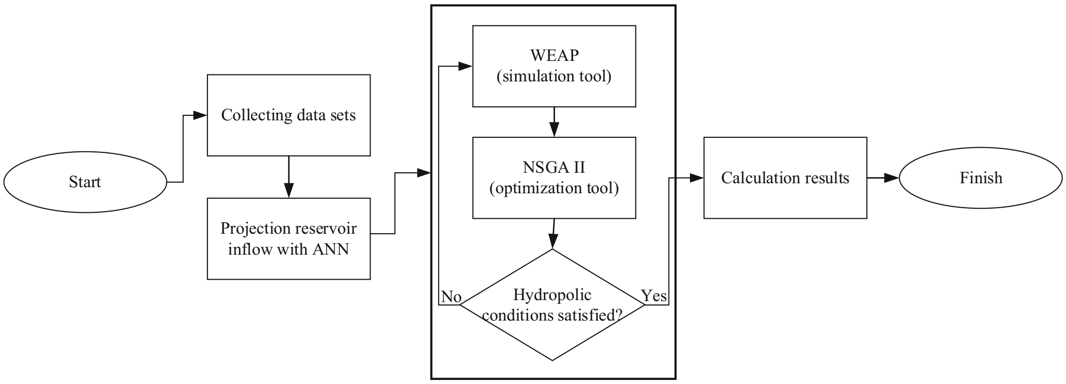


Fig. 1 Flowchart of the applied method

allocation problem. This work applies hydropolitic conditions to regional water transfers. The Sefidrud river basin encompasses several provinces with conflicting water demands. Each province constitutes a stakeholder with specific water-use characteristics. The first objective function in this work is to maximize the revenue from water resources allocation. Water is a valuable good, especially in arid and semi-arid areas beset by water scarcity, where conflicts between stakeholders seeking to supply their water needs are common. Water resources allocation influences economic performance. This paper represents the economic objective by Eq. (1):

Maximize

$$F_1 = \sum_{p=1}^{m} \sum_{c-1}^{**n} q_{pc} \times AEB_{pc} \quad p = 1, \ldots, m; c = 1, \ldots., n \tag{1}$$

in which p denotes the index for stakeholders (i.e., provinces in this instance), c denotes the index for water use by each stakeholder, q_{pc} denotes the amount of water received by stakeholder p for water use c, and AEB_{pc} represents the average revenue of water use c and stakeholder p (Rial/m^3). The decision variables in this study are the amount of water allocated to stakeholder p for consumptive use c (q_{pc}). The amount of water allocated to stakeholder p is $Q_p = \sum_{c=1}^{n} q_{pc}$. The amount of water allocated to water use c is $Q_{\mathrm{c}} = \sum_{p=1}^{m} q_{pc}$.

Gini (1921) introduced the Gini coefficient, which ranges between 0 and 1, to measure income inequality. A higher Gini index indicates greater inequality, with high income individuals receiving much larger percentages of the total income of the population. The Gini coefficient is calculated with the Lorenz curve (Fig. 2). It is defined by the ratio of the area comprised between the absolute equitable line and the Lorenz curve to the total area under the absolute equitable line. The absolute equitable line denotes an equitable distribution of income. In Fig. 2 the Gini coefficient is equal to the ratio of the area of A to the area A plus B. The Gini coefficient is herein applied to measure the inequality of water allocation in a river basin. The second objective is to achieve equability of water allocation and is given by the minimization of the Gini index of water allocation as written in Eq. (2):

Minimize:

$$F_2 = \frac{1}{2p\sum_{p=1}^{m} {}^{Q_p}/_{AEB_p}} \times \sum_{p=1}^{m} \sum_{k=1}^{o} \left| \frac{Q_p}{AEB_p} - \frac{Q_k}{AEB_k} \right| \quad p = 1, \ldots, m; k = 1, \ldots, o \tag{2}$$

where Q_p denotes the total volume of water received by stakeholder p, AEB_p represents the average revenue from water use by stakeholder p (million Rial), k denotes a counter that is randomly selected among the stakeholders to calculate the amount of water and the revenue from water use received by the stakeholder k, and AEB_{k} denotes the average revenue of stakeholder k.

The constraints of the water allocation problem are given by Eqs. (3), (4), (5), (6), and (7):

Constraints:

The available water in the basin is the total amount of water available for use from rivers, reservoirs, and withdrawal from aquifers. The total amount of water allocated to the provinces cannot exceed the total available water. The available water constraint is defined by Eq. (3):

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

A sustainable riverine system must meet the minimum environmental requirements of the basin. Equation (3) ensures that the environmental requirements are met by the water allocation in a study region, which involves multiple water users (Madani et al. 2014). The environmental (riverine) water demand was herein calculated with the Montana method (Tennant 1976), which sets the environmental water demand equal to a percentage of the average annual flow, and varies with the season of the year (Fallah-Mehdipour et al. 2019). The available water (AW) equals the available surface water (TSW) and groundwater (AG) minus the environmental demand (ED) and domestic demand (DD). The available water is given by Eq. (4):

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

Under hydropolitic conditions the AW is divided among provinces, which in turn allocate the water to their customers. Thus, the amount of water allocated to each consumer sector in each province cannot exceed the total water allocated to that province. The set of constraints in this case is defined by Eq. (5):

$$\sum_{c=1}^{n} q_{pc} \leq Q_p \quad p = 1, 2 \ldots, m \tag{5}$$

The amount of water allocated to each consumer sector cannot exceed the total requirements of that sector. This constraint is defined by Eq. (6):

$$WA_{pc} \leq De_{pc} \quad For\ all\ p, c \tag{6}$$

WA_{pc} and De_{pc} denote the amount of allocated water to stakeholder p and water use c and the water demand of stakeholder p and water use c, respectively. The

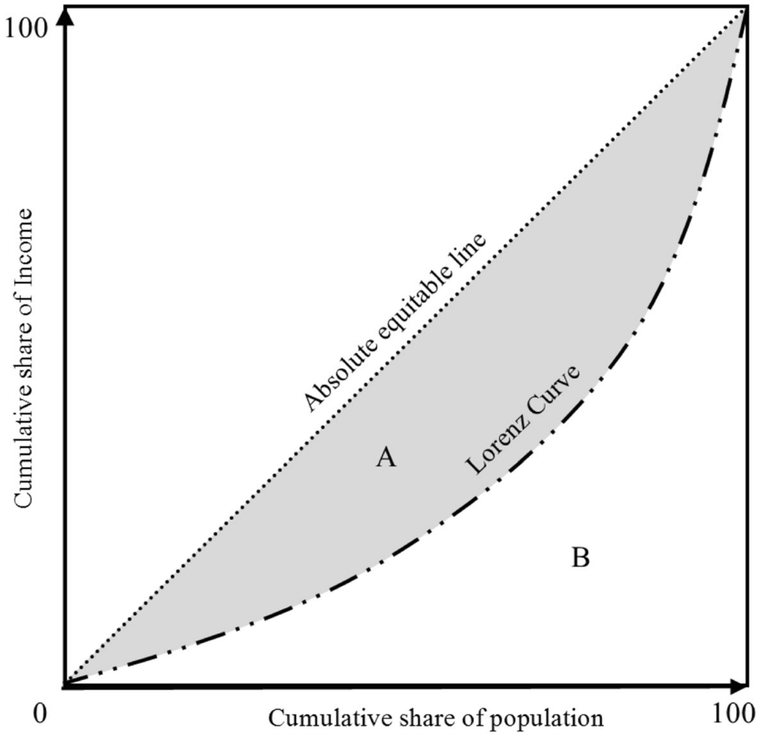


Fig. 2 Schematic of the Lorenz curve for calculation of the Gini index

amount of water allocated to each sector and each stakeholder must be larger than zero. This constraint is defined by Eq. (7):

$$WA_{pc} > 0 \quad for\ all\ p, c \tag{7}$$

Case study

The Sefidrud basin is located in North of Iran. The area of the basin is about 59,400 km^2 (Madani et al. 2014). This basin area is located at the intersection of the Alborz and Zagros Mountains and includes eight provinces: Guilan, East Azerbaijan, Ardebil, Zanjan, Kurdistan, Hamadan, Qazvin, and Tehran. The basin is located within 46°37′ to 51°13′ E and 35°00′ to 38°00′ N (see Fig. 3). This basin comprises two sub-basins called Ghezlouzan and Shahrood, which discharge to Sefidrud Lake and harbor the Sefidrud river. As of 2020 82 dams have been constructed in the Sefidrud basin. There are 17 dams under construction, and 67 dams are in the study stage. The Sefidrud river discharges to the Caspian Sea in northern Iran. The rainfall in this basin ranges from 245 mm in the Tarom-Oliya plain (Zanjan province) to 1250 mm in the Fomenat plain of Guilan province (Iran Ministry of Energy 2020).

Serving many stakeholders with different priorities, different water uses, who rely in multiple manners on water use across geographical areas, may cause tensions in a river basin. This calls for consideration of the hydropolitic conditions in the transboundary basin herein under study.

Results and discussion

This work considers two future development scenarios in the Sefidrud basin. The first scenario concerns the water allocation with existing dams and dams under construction. The second scenario tackles water allocation adding dams currently in the study stage to those considered in Scenario 1.

Streamflow was predicted at the Bianlou, Gilvan, Loshan, and Pol Astaneh gages with ANN. The ANN method was implemented to determine the amount of future water available to meet basin uses. The optimal number of neurons was determined to equal to 40 with a 12-step time delay. Predictions were evaluated with the goodness-of-fit criteria. Eighty percent of the data were used for training and the remaining 20% for testing. Table 1 lists the results corresponding to the four gages.

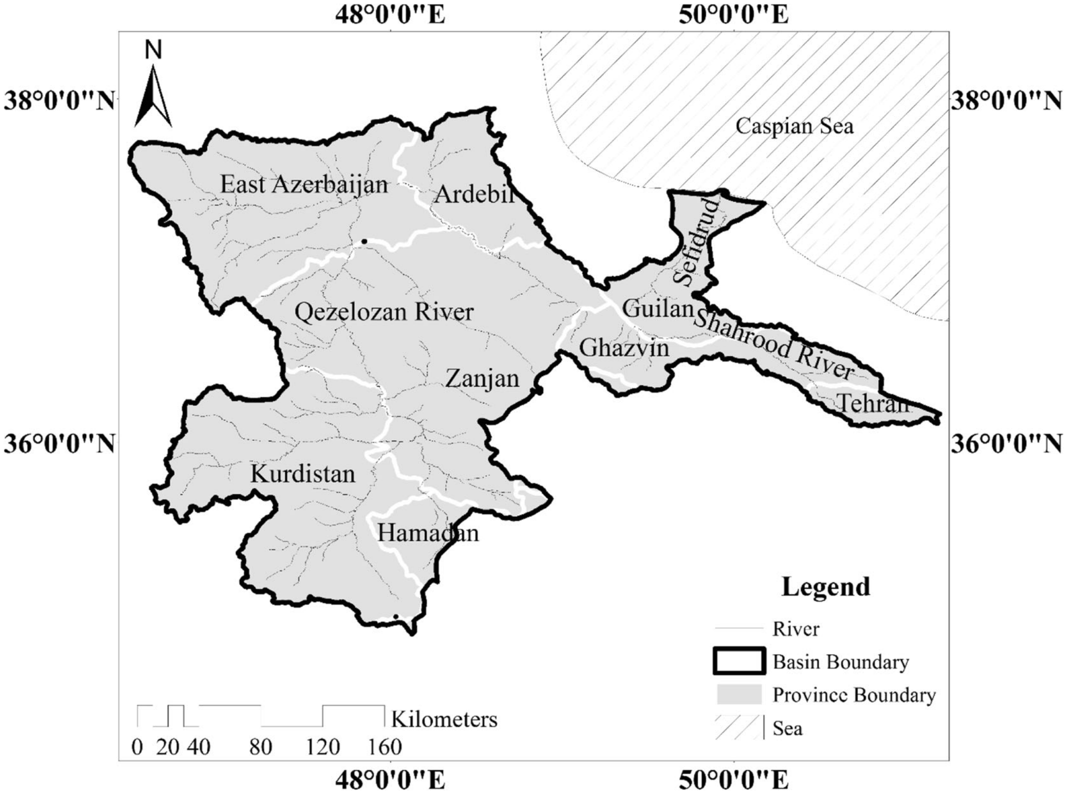


Fig. 3 The study area

It is seen in Table 1 that the ANN performed better at the Bianlou and Gilvan stations. The reason for this is the relative low variation in the measured streamflow at these stations. Figure 4 a–d display the ANN simulated and observed runoff at the Bianlou, Gilvan, Loshan, and Pol Astaneh stations.

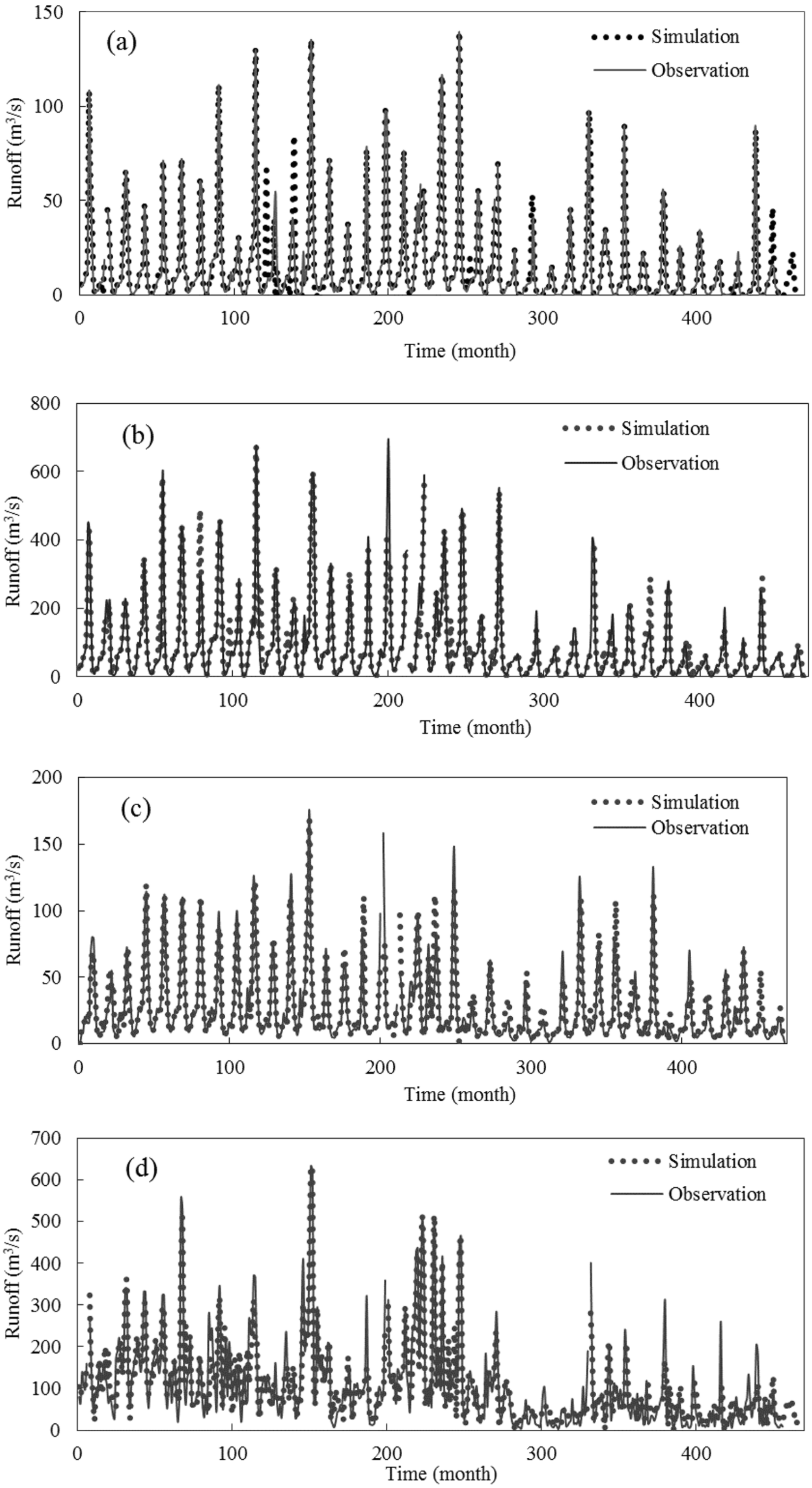
Optimization of water allocation was conducted following the prediction of future available water with the ANN. The required databases were created and input to the MATLAB software to carry out the bi-objective optimization with the NSGA-II algorithm, which returns Pareto front of solutions as output. Recall that the first objective function maximizes the revenue of water resource allocation and the second establishes equability in the allocation of water resources. Maximization of revenue calls for allocation of more water to provinces with high productivity. The second objective seeks to achieve equability of meeting water needs in the provinces. These two objective functions introduce tradeoffs between revenue maximization and equity satisfaction. Optimization was carried out for water allocations to the provinces with the NSGA-II algorithm under the two scenarios. The Pareto fronts obtained are displayed in Fig. 5 a and b.

The optimal Pareto front extracted for the first scenario shows that operation of dams under construction would achieve equability of water allocation in the Sefidrud basin. The second scenario, on the other hand, indicates the revenue in the basin increases, yet the degree of equability of water allocation decreases. The reason for this tradeoff between revenue and equity is the large number of dams planned in the Sefidrud basin. There are 67 dams under study, 17 are under construction, and 82 are in operation. The distribution of dams under construction among the provinces is as follows: East Azerbaijan, Zanjan, Ardabil, Kurdistan, Guilan,

Table 1 Training and testing results of the ANN

Station	Training		Testing	
	R^2	RMSE	R^2	RMSE
Bianlou	0.91	2.73	0.9	3.54
Gilvan	0.93	1.63	0.85	2.64
Loshan	0.83	1.93	0.81	2.35
Pol Astaneh	0.79	3.11	0.78	4.26

Fig. 4 ANN simulated and observed runoff at the **a** Bianlou, **b** Gilvan, **c** Loshan, and **d** Pol Astaneh stations



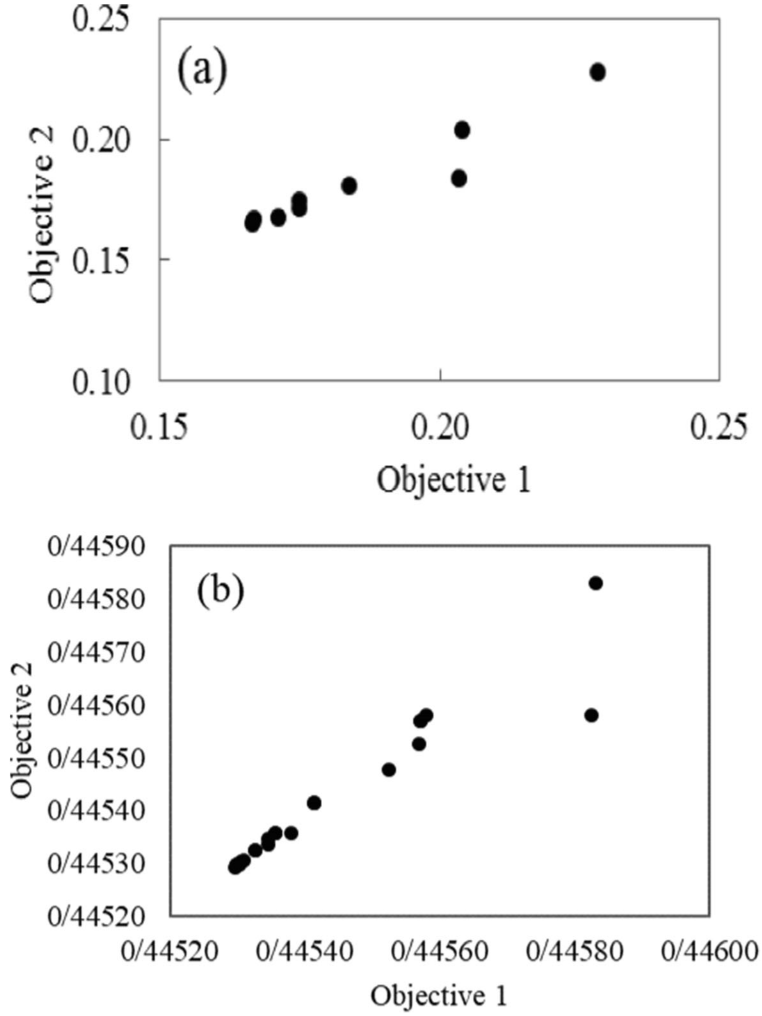


Fig. 5 Pareto fronts of water allocation under **a** Scenario 1 and **b** Scenario 2. Objective 1 is expressed in millions of Rials. Objective 2 represents the value of Gini index for water allocation

and Hamadan provinces have respectively 4, 6, 2, 2, 2, and 1 dam under construction, respectively. The distribution of dams under study among the provinces is as follows: East Azerbaijan, Zanjan, Kurdistan,

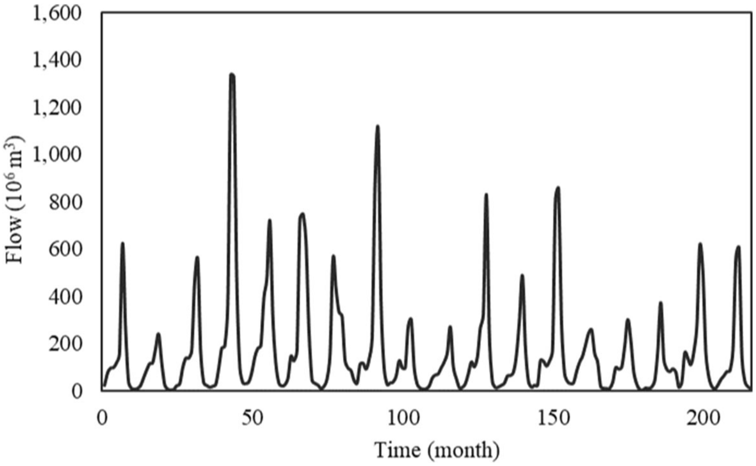


Fig. 6 The volume of water entering the Sefidrud reservoir.A

Ardabil, Qazvin, Guilan, and Hamadan have 15, 29, 8, 9, 3, 2, and 1 dam under study, respectively.

According to Fig. 6, since 1999 the volume of water entering the Sefidrud dam has declined. Therefore, the large number of dams under construction indicates that their operation in most parts of the basin area would have adverse impacts on water allocation among the provinces.

Water resources management in the Sefidrud basin is determined based on requests from the stakeholder provinces. The response to increasing water demand, population, and economic growth of the cities and provinces within the basin by water resource managers has not prioritized the implementation of integrated water resources management based on sustainable development and balancing the use of water resources. Rather, water resources management in the Sefidrud basin has strived to maximize water supply by constructing dams in the basin. Inward-looking water management by the provinces and the proliferation of dams have caused conflicts between the provinces in their quest to meet their water demands. Some key adverse impacts of this lack of non-integrated water management has been failed to deliver sufficient water to downstream provinces and to meet environmental requirement in many river reaches.

Bringing into operation the under study dams would raise the inequity of water resources allocation in the basin. This would also heighten conflict between the provinces concerning water use. Provincial water conflicts and occurrence of streamflow below the environmental requirement are challenges at the root of the hydropolitics of this basin deserving prompt attention. Otherwise, conflicts may intensify over scarce water and the worsening degradation of the riverine environment.

Conclusions

This study presented an optimization of water resources allocation under hydropolitic conditions affecting province-scale water use in the Sefidrud basin of Iran. This study considered two water allocation scenarios. The second scenario resolves the effect that dams under construction and under study would have on regional water supply. Conflicts between provinces arising from their desire to meet water demands have threatened the Sefidrud basin's riverine environment. Self-serving interests on the part of the provinces and lack of integrated water resources management have created complex hydropolitic conditions and inequity of water resources allocation in the study basin. Past studies and their results indicate conflicts at varying scales, and levels compromise sustainability of the basin and the water resources system. This work has shown the tradeoff between water supply and inequity in water resources allocation affecting the stakeholder provinces. At present, the stakeholders in the Sefidrud basin neglect the ecosystem sustainability of the basin. Bringing dams under construction and under study into operation points to worsening environmental problems and water conflicts in this basin.

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Data availability All of the required data have been presented in our article.

Compliance with ethical standards

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

Abbreviations *Variable,* Description; F_1, First objective function; C, Index for water use by each stakeholder; q_{pc}, Amount of water received by stakeholder p for water use c; AEB_{pc}, Average revenue of water use c and stakeholder p; Q_c, Amount of water allocated to water use c; Q_p, Amount of water allocated to province p; F_2, Second objective function; AEB_p, Average revenue from water use by stakeholder p; k, Counter that is randomly selected among the stakeholders; AW, Available water; TSW, Surface water; AG, Groundwater; ED, Environmental demand; DD, Domestic demand; WA_{pc}, Amount of allocated water to stakeholder p and water use c; De_{pc}, Water demand of stakeholder p and water use c

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