



# A basin-wide approach for water allocation and dams location-allocation

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## Abstract

Construction of new dams in undeveloped transboundary basins causes two serious disputes between the stakeholders: conflicts over more water interest and over the new dams' locations. Hence, water development planning of these basins needs to be done in conjunction with the examination of stakeholders' new water shares. This study extends the model presented in Roozbahani et al. (*Water Resour Manag* 31:4539–4556, 2017) to be multi-objective and applies the methodology outlined in Roozbahani et al. (*Ann Oper Res* 229:657–676, 2015a) to solve the model. The proposed three steps approach determines the equitable allocation of the surface water of an undeveloped transboundary basin while determining optimal number, locations and capacities of new dams. The first step utilizes a mixed-integer-multi-objective model to outline the water shares of stakeholders, as well as optimal dam locations for a given number of dams. Using a sensitivity analysis, the second step pinpoints the required number of dams. The role of third step is the exploration of the dams' lowest possible capacities. Environmentally, our approach takes the entire watershed's water requirements into account. We have applied the proposed approach to the Sefidrud Basin, a transboundary basin located in Iran. The results of the approach show that, to significantly improve the security of the Sefidrud Basin's water supply, three new dams would be optimal.

**Keywords** Dams location-allocation · Water allocation · Mixed-integer program · Multi-objective models · Transboundary basin

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## 1 Introduction

The global need for more water has created an increase attention to planning and construction of dams in many countries (Petheram et al. 2017). The International Commission on Large Dams (ICLD) in its statement on the role of dams emphasizes: “A dam is the cornerstone in the development and management of water resources development of a river basin. The multipurpose dam is a very important project for developing countries, because the population receives domestic and economic benefits from a single investment.” (<https://www.icold-cigb.org/>). Dams can also mitigate water scarcity by increasing water supply and protect societies by controlling floods. However, dams could have serious negative effects on the ecosystem and the economy of shared watersheds, when the basins’ stakeholders uncooperatively construct dams within their administrative boundaries. These unsustainable developments also cause crucial conflicts over water between stakeholders. This issue is currently observed in some shared watersheds such as the Tigris–Euphrates basin (Al-Ansari 2016). Therefore, an appropriate selection of locations and capacities of future dams and also their water allocation between the stakeholders are core problems in shared watersheds.

There is a plethora of publications devoted to the problem of the optimal dam site selection. For instance, Dai (2016) used the GIS technique for this purpose. Minatour et al. (2012) suggested using analytic hierarchy processes and multi-criteria decision making. The large overview reflecting the background of this problem can be found in World Commission on Dams report (WCD 2000). The cost–benefit analysis of dam construction was implemented by International Rivers Organization (IRO 2013). Social impacts of dam construction were investigated in Ledec and Quintero (2003). However, this problem has never been considered in an optimization framework where all these aspects of catchment development (economy, ecology and social justice) were considered holistically with one integrated model.

Sustainable water allocation can be taken into consideration to solve such problem. It aims to maximize the achieved benefits of the stakeholders from the use of water, while also preserving and protecting water resources and the environment (UNESCAP 2000). It means that the selection of capacities and locations of new projects should be done in a way that it leads to fair water distribution in the basin, provides the highest profits for stakeholders, and keeps the environment healthy. It should be noted that locating and sizing new dams is also dependent upon certain engineering studies, like geology, topography, and economy. The proposed new projects by the water allocation model should be considered as an initial plan for a basin’s water resource development, which represents the potential of the basin for water harvesting and its distribution in a sustainable condition. However, the new projects should be further evaluated using engineering studies.

Single-objective optimisation (SOP) and multi-objective optimisation (MOP) methods have widely been used for detecting water allocation problems of transboundary watersheds. For instance, an SOP has been used by Cai et al. (2003), Kucukmehmetoglu and Guldmann (2004), Cai (2008), Housh et al. (2013) and Roozbahani et al. (2013) to determine how the limited water resources of transboundary basins may be shared among their stakeholders. In order to verify sustainability, it is essential to consider social, environmental, and economic factors simultaneously when assessing water allocation models (UNESCAP 2000). Therefore, because they only consider one of these factors, SOP models do not lead to sustainable water allocation. The majority of the aforementioned models employed only economic indicators, ignoring social and environmental aspects. WREMS, a cost-minimisation SOP water resource management system, was introduced by Wilson et al. (1997). The advantage of their approach was the integration of the optimisation algorithm with the data acquisition

and management system. This allowed water managers to rely more on the optimisation results.

The MOP method is an effective approach that achieves accurate results, as more than one indicator is considered concurrently (Jaramillo et al. 2005; Cohon and Marks 1975). Due to its multidisciplinary water resources management aspect, MOPs have been increasingly employed in this field. For instance, Consoli et al. (2008), Tabari and Soltani (2013), and Xevi and Khan (2005) used a MOP for reservoir operation and optimal water allocation management. It was also employed by Emch and Yeh (1998) and Park and Aral (2004) for groundwater management. Sarker and Ray (2009), Zeng et al. (2010), and García-Alonso et al. (2011) formulated crop-planning problems using an MOP. Environmental flow management has also been utilized by MOPs (Szemis et al. 2013; Yang 2011), as has urban water management (Zarghaami and Hajykazemian 2013). Udías et al. (2014) developed the MOP modelling framework which selects the optimal watershed reclamation program for Catalonia catchments. The MOP technique was also applied in an effort to optimize water supply for competing stakeholders in the Sefidrud Basin of Iran (Roozbahani et al. 2015a), which has been considered in the present paper.

The MOP method has also been utilised in water allocation within unshared watersheds. An integrated MOP model that optimally allocates limited water from a storage reservoir to different user sectors was introduced by Babel et al. (2005). Their proposed model was comprised of three modules: a reservoir operation module, an economic analysis module, and a water allocation module. The model optimised water allocation, and considered two objective functions: maximising the satisfaction and monetary outcomes of the reservoir. A weighting method was used to solve the model; for goal programming, a solution method was employed at a theoretical irrigation area of Australia's Murrumbidgee River, Berembid Weir. An MOP for water allocation in an area of saltwater intrusion at China's Pearl River Delta was developed by Liu et al. (2010). That model's objective functions included the minimization of water pollution due to social, economic and environmental aspects, and the maximization of social and economic satisfaction. A genetic algorithm was applied to determine the model's solutions. Ahmadi et al. (2012) also proposed a model based on a genetic algorithm that had multiple objectives in allocating water in Iran's Aharchay Basin. The output of the model was desirable levels of water quality and quantity for each demand sector. A multi-objective model of water allocation was proposed by Rezapour et al. (2014) to optimize resources within the basin and, consequently, restore the resources of the outer basin. The proposed models' objective functions were aimed at supplying the water demand within the basin, reducing the water output of the Iran's boundaries, and increasing the transfer of water to adjacent basins (like the Urmia Lake basin). A non-dominant sorting algorithm was used to solve the model's complex and nonlinear objective functions.

MOPs are also successfully utilised in the modelling of transboundary basin water allocation in some cases. Multiple models have been proposed for optimizing water allocation among the stakeholders of the transboundary watershed of the Aral Sea basin. McKinney and Cai (1997) developed a multi-objective model in which the water allocation criteria considered included the basin's demand satisfaction, the amount of flow to the Aral Sea, and the equalization of water deficit distribution. Another multi-objective model was used by Cai et al. (2002) for water allocation in the Syr Darya River Basin, one of the two major waterways that empty into the Aral Sea. There were several model objectives: determining the risk of uncertainty regarding water supply to stakeholders, securing Aral Sea environmental water demand satisfaction, equalizing water allocation, and realizing an economically effective in the development of a water delivery infrastructure.

Schlüter et al. (2005) similarly conducted a study of optimizing the Amu Darya River's water allocation. Deficits in the delivery of water to stakeholders were reflected by the indicators introduced in this study, as were the water level of the reservoir, the flow plan to the Aral Sea, and the total water demand. A weighted-sum method was utilized in all three studies in order to transform the MOP model into an SOP model. These Aral Sea basin studies focused on the social and economic aspects of the water allocation. The major limitation of this study was that it only examined the satisfaction of downstream demand of the Aral Sea region and ignored the environmental demand of the basin. After applying a weighted-sum method of optimization to these models, different weights were nominated for the objective functions. The models then suggested several courses of action for water allocation in the Aral Sea region. The disadvantage of the models is that providing many basin water allocation options often causes confusion among water authority managers.

Fotakis and Sidiropoulos (2014) used the genetic algorithm, which comprises the stochastic optimization approach and is based on the mechanisms of the natural selection and evolution. This algorithm is related to genetic adaptation and survival rules, which is evidenced by its title. The objective function to be maximized is total profit, which is defined as the economic benefit from irrigated crops minus water transportation and extraction costs. Griffith et al. (2009) and Muhammad and Pflug (2014) consider the random component in the environmental system and suggest using stochastic single objective programming for optimizing water allocation management. Muhammad and Pflug (2014) discuss the advantages and disadvantages of stochastic and deterministic approaches in water resource modelling.

Another transboundary watershed is the Euphrates and Tigris River basin; its main stakeholders are Syria, Iraq, and Turkey. To allocate the water in this basin, Kucukmehmetoglu and Guldmann (2010) utilized a multi-objective model that considered how each stakeholder's profit may be maximized. Consuming water in different sectors was the objective function of this model, rather than the maximization of profit for the basin. However, the model did consider the satisfaction of environmental demand. Its authors employed a weighted-sum technique and constraint method to solve their model, determining three separate weights for the analysis of the model's objective functions. These weights' justification, though, was not clear.

The Sefidrud Basin of Iran is a national transboundary basin, in which eight provinces (administrative boundaries) are stakeholders competing for water exploitation. Roozbahani et al. (2014) introduced a model of water allocation based on an MOP for this basin that maximised all the stakeholders' profits simultaneously. At the same time, environmental water supply satisfaction remained a firm constraint. In order to avoid the problem of weighting each objective function and justifying those weights, the authors presented a new solution approach for finding Pareto optimality for their model. Roozbahani et al. (2015b) developed an MOP model in which basin profit maximization, water shortage minimization, and water flow from upstream regions to downstream ones were the objective functions. In Roozbahani et al. (2015b)'s model, the environment had more influence than water supply with other stakeholders. This model was solved using the compromise programming technique. In consideration of the many different weights applied to the objective functions, ample water allocation schemes were introduced for the Sefidrud Basin by Roozbahani et al. (2015b)'s study.

Integer programming (IP) and mixed-integer programming (MIP) models have almost no tradition in water allocation; however, they have been employed for other tasks associated with water resources management. For instance, Anwar and Clarke (2001) used an MIP approach to schedule canal irrigation among a group of users who requested water at varying times of each scheduling period. Srinivasan et al. (1999) proposed a mixed-integer linear programming

(MILP) model for supporting water-supply planning and reservoir-performance optimization. Teegavarapu and Simonovic (2000) developed a mixed-integer nonlinear programming model with binary variables to study the daily hydropower operation of four cascading reservoirs.

IP and MIP have frequently been used for location-allocation problems. Location-allocation refers to those problems which aim to determine an optimal location for one or more facilities that will service demand from a given set of points (Azarmand and Neishabouri 2009). IPs and MIPs of various facility locations like logistics (Ishfaq and Sox 2011), health-care (Shariff et al. 2012), solid waste management (Caruso et al. 1993), and supply chain (Zhou et al. 2002) were the basis of many location-allocation models. Kallrath (2005) provided a detailed review of an MIP application in industrial mathematics, planning, and management; in the same paper, he reviewed some works on multi-criteria optimization and more references can be found *ibid*.

Many studies have been reviewed in literature regarding the application of MOP models in water-allocation modelling. For instance, Edirisinghe et al. (2000) provides a detailed review of papers devoted to the determination of optimal reservoir capacity based on different optimisation algorithms, including deterministic and stochastic programming. However, there are just a few studies which simultaneously address water allocation and the location-allocation of new dams in an under-developed watershed, to our knowledge. This study sheds some light on this problem. The first attempt to formulate these problems holistically was implemented by the authors in Roozbahani et al. (2017). This study combines the approaches used in Roozbahani et al. (2015a, 2017) to offer an integrated model to optimally determine the water share of stakeholders, locations of dams and capacities of dams. In this work, we also employed the three-step optimization procedure. In the first step, the SOP model was utilized for maximising the profit of the entire basin. In the current work, we moved towards a more socially fair approach, in which the incomes of all stakeholders were maximized using the MOP approach. This new method resulted in more uniform spatial distributions of the dams, allowing more access to the water resources by the stakeholders located in the upper part of the basin. This methodology allows water managers to facilitate social justice in the region, which is a major justification of the present study.

This paper is closely related to Roozbahani et al. (2017) in terms of model and it is closely related to Roozbahani et al. (2015b) in terms of solution approach. It utilizes a three-step method that distributes the resources of a transboundary watershed to its stakeholders, and specifies proposed dam capacities and locations in order that the individual profit of each stakeholder is maximized. This approach prepares a blueprint of a basin's optimal water allocation, along with proposed dam capacities and locations, without appealing to any time-consuming engineering studies. The aim of this approach is fourfold: to decide on optimal dam count, select the locations in which they should be constructed, calculate their capacities, and allocate water to a shared watershed's stakeholders. It will accomplish this in such a way that each stakeholder achieves the highest profit from water usage, while the basin's complete environmental demand is satisfied.

In the first step of our algorithm, a mixed-integer, multi-objective model is run for several different numbers of dams, so that the water resources of the basin can be equitably allocated to stakeholders, and the capacities and locations of the proposed dams can be optimized. The second step of the approach uses a sensitivity analysis to determine the basin's optimal dam count. The third step explores new minimum capacities for the dams that were selected by the second step—while still granting the same profit for the stakeholders, which was calculated by the first step.

The paper is structured as follows. Section 2 describes the three-step approach. The case study of the Sefidrud Basin is explained in Sect. 3. The results are discussed in Sect. 4, and we conclude the paper in Sect. 5.

## 2 The formulation of the three-step approach

This section firstly introduces the notations used in mathematical models. It then explains the proposed algorithm's steps for locating and determining the capacities of the new dams in conjunction with water allocation. The formulation is adapted from Roozbahnai et al. (2015a, 2017), hence some of the constraints and decision variables are same as the models presented in them.

### 2.1 Notations

Notion used in the present paper is consistent with the notation accepted in two previous papers devoted to the water allocation management in the Sefidrud Basin mentioned above (Roozbahnai et al. 2015a, 2017). Below the equations for model constraints will be referred as equation numbers in these two publications. However, for the clarity of model formulation the set of variables used in the modelling formulation is provided below.

#### 2.1.1 Sets and indices

All indices which have been used in this paper are outlined as follows:

- a agricultural sector superscript;
- u urban sector superscript;
- d industrial sector superscript;
- k stakeholder index;
- t time step index, either month or year;
- T total time steps;
- $\kappa$  stakeholder set;
- $\nu_k$  set of nodes in stakeholder k ( $k \in \kappa$ );
- $n_k$  stakeholder k number of nodes index;
- $i_k$  stakeholder k node i index;
- $\pi_{i_k}$  set of nodes (l) that are the upstream neighbor of node  $i_k$ ;
- $i'_{i_k}$  node that is the downstream neighbor of node  $i_k$ ;
- $\tau$  set of time periods.

#### 2.1.2 Decision variables

The decision variables in our model are outlined as follows:

- $x_{i_k t}^a$  is allocated water to the agriculture sector in node  $i_k$  from surface water at time t ( $k \in \kappa, i \in \nu_k, t \in \tau$ );
- $x_{i_k t}^u$  is allocated water to the urban sector in node  $i_k$  from surface water at time t ( $k \in \kappa, i \in \nu_k, t \in \tau$ );
- $x_{i_k t}^d$  is allocated water to the industry in node  $i_k$  from surface water at time t ( $k \in \kappa, i \in \nu_k, t \in \tau$ );

$z_{i_k}^\Delta$  is a binary variable that is 1 if there is a dam in node  $i_k$  ( $k \in \kappa, i \in \nu_k$ );

$C_{i_k}^\Delta$  is the capacity of the dam in node  $i_k$ ; it is 0 if there is no dam in node  $i_k$  ( $k \in \kappa, i \in \nu_k$ ).

### 2.1.3 Exogenous variables

All exogenous variables which have been used in this paper are outlined as follows:

$AP_{i_k t}$  is agricultural profit of node  $i_k$  at time  $t$  ( $k \in \kappa, i \in \nu_k, t \in \tau$ );

$UP_{i_k t}$  is urban profit of node  $i_k$  at time  $t$  ( $k \in \kappa, i \in \nu_k, t \in \tau$ );

$IP_{i_k t}$  is industrial profit of node  $i_k$  at time  $t$  ( $k \in \kappa, i \in \nu_k, t \in \tau$ );

$S_{i_k t}$  is stored water in node  $i_k$  at time  $t$  ( $k \in \kappa, i \in \nu_k, t \in \tau$ ) if there is a dam in node  $i_k$ , and 0 otherwise;

$R_{(i_k \rightarrow i'_k)t}$  is released water from node  $i_k$  to node  $i'$  at time  $t$  ( $k \in \kappa, i \in \nu_k, t \in \tau$ );

$R_{(l \rightarrow i_k)t}$  is released water from node  $l$  to node  $i_k$  at time  $t$  ( $k \in \kappa, i \in \nu_k, l \in \pi_i, t \in \tau$ );

$z_{i_k t}^\psi$  is a binary variable that is 1 when there is a dam in node  $i_k$  at time  $t$  ( $k \in \kappa, i \in \nu_k, t \in \tau$ ) if full;

$z_{i_k t}^\varepsilon$  is a binary variable; takes 1 if the environmental water demand in node  $i_k$  at time  $t$  is met.

### 2.1.4 Input and modelling parameters

The inputs and parameters are listed as follows:

$\rho_{i_k}^a$  is the agricultural net benefit of allocating 1 unit water to agriculture in node  $i_k$  ( $i \in \nu_k$ );

$\rho_{i_k}^u$  is the urban net benefit of allocating 1 unit water to domestic sector in node  $i_k$  ( $i \in \nu_k$ );

$\rho_{i_k}^d$  is the industrial net benefit of allocating 1 unit water to industry in node  $i_k$  ( $i \in \nu_k$ );

$v_{i_k t}$  is the produced water in node  $i_k$  ( $i \in \nu_k$ ) at time  $t$ ; precisely, it is the produced water between nodes  $l \in \pi_{i_k}$  and node  $i_k$ ;

$n$  is the number of required dams;

$M$  is a big number;

$R^\psi$  is the reliability level showing the number of time periods that dams' reservoirs must be full;

$R^\varepsilon$  is the reliability level showing the number of time periods that the environmental water needs must be met;

$\xi_{i_k t}$  is agricultural water demands in node  $i_k$ , at time  $t$  ( $i \in \nu_k, t \in \tau$ );

$\psi_{i_k t}$  is urban water demands in node  $i_k$ , at time  $t$  ( $i \in \nu_k, t \in \tau$ );

$\eta_{i_k t}$  is industrial water demands in node  $i_k$ , at time  $t$  ( $i \in \nu_k, t \in \tau$ );

$S_{i_k t}$  is environmental water demand of node  $i_k$ , at time  $t$  ( $i \in \nu_k, t \in \tau$ ); it has to flow in rivers;

$IV_{i_k}$  is the volume of water at the beginning of the planning horizon in dam  $i_k$  ( $k \in \kappa, i \in \nu_k$ ) if there is a dam in node  $i_k$ , otherwise, it is 0.

## 2.2 The steps of the proposed approach

The proposed approach is analogous to Roozbahni et al. (2015a) and consists of the following three steps:

*Step 1* In this step, a model called Multi-Objective Water and Dams Allocation (MOWDA) is run to determine the water shares of stakeholders, in addition to specifying the locations

and capacities of the given number of dams. The objective functions of the MOWDA model are to maximize all stakeholders' profits and the model runs for different numbers of dams.

*Step 2* A sensitivity analysis is undertaken to decide on the basin's optimal number of required dams. It should be noted that the MOWDA model is run for multiple scenarios in Step 1.

*Step 3* The stakeholders' profits, which were determined in Step 1 for a selected number of dams (those determined in Step 2), are placed into a model in Step 3 called Minimum Capacity (MinCap). The MinCap model determines the capacity of dams such that the summation of dams' capacities is minimized while still providing the same profits for the stakeholders that were achieved in Step 1. In many instances, the obtained capacities for selected dams by Steps 1 and 3 are similar. However, in the case of having multiple optimal solutions (in terms of the capacities), the MinCap model chooses the one that leads to the minimum summation of dams' capacities. Here it is assumed that the constructions of dams with lesser capacities is always preferable to the construction of larger dams, disregarding their geographical location.

### 2.2.1 Step one: running the MOWDA model for various scenarios

The MOWDA model is based on a multi-objective algorithm which maximises all stakeholders' profits in a catchment that is subject to the availability of water resources, environmental demands, water balance, and usage constraints. It also determines the optimal capacities and locations of the given number of dams so that they provide the highest possible profits to stakeholders. The profits are computed as the net benefits determined by the volume of water allocated to the agricultural, community (urban and domestic), and industrial sectors of each stakeholder. Unequal income distribution among the basin's stakeholders is the central cause of the region's water disputes. This unjust situation can be detected by indicators related to its social aftermaths, such as level of unemployment in the areas corresponding to different stakeholders. The profits gained from the redistributed surface water resources, calculated for each stakeholder, is selected as the objective functions of the MOWDA model. This model uses the node-link network of the Sefidrud Basin, with its water supply and demand nodes. The surface water resource volume in each midstream-area node of the basin is calculated as a balance between water accumulated in this node, water released from nodes located upstream, and water released downstream. This model considers three types of water demand: that which is related to agricultural, community, and industrial water use. The environmental water requirements are also taken into account. It should be emphasised that this study only focuses on surface water allocation in transboundary basins. This decision was made because the water conflicts in these basins are mainly over surface water utilisation as a shared water resource between all stakeholders.

#### The objective functions of the MOWDA model

The MOWDA model's objective function is the total net profit ( $Z_k$ ) from water use for each stakeholder  $k$  which are maximized. The multi-objective mathematical form akin to Roozbahni et al. (2015a), is stated as:

$$\text{Maximize } \{Z_1, Z_2, \dots, Z_K\} \quad (1)$$

where

$$Z_k = \sum_{i_k=1}^{n_k} \sum_{t=1}^T (AP_{i_k t} + UP_{i_k t} + IP_{i_k t}) \quad k = 1, 2, \dots, K \quad (2)$$



$AP_{i_k t}$ ,  $UP_{i_k t}$ , and  $IP_{i_k t}$  are obtained using Eqs. (3)–(5):

$$AP_{i_k t} = \rho_{i_k}^a \times x_{i_k t}^a \quad \forall i_k, t, k \tag{3}$$

$$UP_{i_k t} = \rho_{i_k}^u \times x_{i_k t}^u \quad \forall i_k, t, k \tag{4}$$

$$IP_{i_k t} = \rho_{i_k}^d \times x_{i_k t}^d \quad \forall i_k, t, k \tag{5}$$

**The constraints of the MOWDA model**

The MOWDA model’s constraints are constituted from 6 groups:

1. Water balance at node  $i_k$  [Eq. (5) from Roozbahani et al. (2017)]
2. Number of dams in the basin [Eq. (6) *ibid*]

This constraint limits the number of dams in the watershed. For instance,  $n = 1$  indicates that the model allows only one dam to be allocated in the basin and optimizes the allocation of water to the stakeholders where water can be accumulated only in this dam. It should be noted that  $n$  is an input (a parameter) of the MOWDA model.

3. Stored water in dam  $i_k$  and its capacity [Eqs. (7–10) *ibid*]

The first constraint in this group points to shows that the stored water in dam  $i_k$  at time  $t$  ( $S_{i_k t}$ ) must be less than or equal to its maximum capacity ( $C_{i_k}^\Delta$ ). The second indicates that the stored water in dam  $i_k$  in time  $t$  ( $S_{i_k t}$ ) must be greater than or equal to its capacity ( $C_{i_k}^\Delta$ ) when  $z_{i_k t}^\psi$  is equal to 1. In accordance with the last one (Eq. 10 *ibid*),  $z_{i_k t}^\psi$  has to be equal 1 in at least  $R^\psi$  time steps out of total time steps. The last 3 constraints determine the capacity of dam  $i_k$  ( $C_{i_k}^\Delta$ ). When  $z_{i_k t}^\psi$  is 1 in time  $t$ , Constraint (8 *ibid*) is changed to  $S_{i_k t} \geq C_{i_k}^\Delta$  while Constraint (7 *ibid*) forces the stored water to be less than dam  $i_k$ ’s capacity ( $S_{i_k t} \leq C_{i_k}^\Delta$ ). In these circumstances, the model limits the capacity of dam  $i_k$  ( $C_{i_k}^\Delta$ ) to be equal to its stored water in time step  $t$  ( $S_{i_k t}$ ). Similar situations have to be repeated for  $R^\psi$  time steps.

In fact, the model assigns a value for the capacity of dam  $i_k$  such that it would be full in  $R^\psi$  time steps. This formulation is based on a fact that water authorities prefer to construct dams that operate with full capacities in most time steps. For example, in the algorithm tries to avoid to propose dams, which operate with half capacity in 60% of times. Furthermore, this formulation warrants water security in the basin where dams have to be full at  $R^\psi$  time steps over total time steps.

Note that  $z_{i_k}^\Delta$  is 0 when there is no dam in node  $i_k$ . In these circumstances, Constraint (9, *ibid*) changes into  $\sum_{t \in \tau} z_{i_k t}^\psi \geq 0$  that is also satisfied when  $z_{i_k t}^\psi$  is zero. Furthermore, Constraint (10, *ibid*) forces the capacity of dam  $i_k$  ( $C_{i_k}^\Delta$ ) equal to 0, and as a result [regarding to Constraint (7, *ibid*)], the water that is stored ( $S_{i_k t}$ ) is also 0 for all  $t$ . In these cases, Constraint (5, *ibid*) is converted to  $v_{i_k t} + \sum_{l \in \pi_{i_k}} R_{(l \rightarrow i_k)t} - R_{(i_k \rightarrow i'_k)t} - x_{i_k t}^a - x_{i_k t}^u - x_{i_k t}^d = 0$  which is the water balance for nodes without a dam.

4. Reliability of environmental water supply [Eqs. (11, 12) *ibid*]

Water supplied to the environment of node  $i_k$  empties into the river between node  $i_k$  and its downstream node ( $i'_k$ ). This study uses the definition of reliability that Kundzewicz and Kindler (1995) proposed. In this paper, the reliability of water supply is defined as the ratio of intervals between the time that the volume of water supplied meets the demand and the total considered time period (known as temporal reliability). Using Constraints (11 *ibid*) and

(12 *ibid*) in the model, the amount of water transferred from node  $i_k$  to node  $i'_k$  at time step  $t$  ( $R_{(i_k \rightarrow i'_k)t}$ ) must be greater than or equal to the water required for satisfying the environmental demand in the node  $i_k$  at time  $t$  ( $\zeta_{i_k t}$ ). A binary variable ( $z_{i_k t}^\varepsilon$ ) is used in Constraint (11 *ibid*) in order to control the reliability of the environmental water supply. The result is 1 if the environmental water requirement is satisfied, and 0 otherwise. The sum of the variables ( $z_{i_k t}^\varepsilon$ ) over the time steps should exceed or be equal to  $R^\varepsilon$  (Constraint (12 *ibid*)).  $R^\varepsilon$  in fact equals the total time steps when the amount of water transferred from node  $i_k$  to node  $i'_k$  exceeds the environmental water requirement.

It should be emphasised that satisfying the environmental water need throughout the basin is crucially important to securing its sustainable ecological conditions. Using water to increase the welfare of people living in the basin, in other words, should not be implemented, due to the degradation of the environment, as this also affects the population's wellbeing. Thus, environmental demand satisfaction is a priority in model formulation accepted in this work.

#### 5. Stored water in dam $i_k$ in first and last time steps [Eqs. (13, 14) *ibid*]

$S_{i_k t_1}$  and  $S_{i_k t_l}$  represent the stored water in dam  $i_k$  in the first and last time steps, respectively. Constraint (13 *ibid*) indicates that if there is a dam in node  $i_k$  ( $z_{i_k}^\Delta = 1$ ) then its stored water in the first time step is  $IV_{i_k}$ .  $IV_{i_k}$  is an input parameter that may be equal to the average annual river discharge in node  $i_k$ . This constraint allocates an unreasonable value for the stored water at the first time step. Constraint (14 *ibid*) demands that the stored water in the last time step ( $S_{i_k t_l}$ ) be greater than or equal to the stored water in the time step 1 ( $S_{i_k t_1}$ ). This constraint is inserted into the model in order to balance the stored water of dam  $i_k$  during the time steps.

#### 6. Variables' domains [Eqs. (15–26) *ibid*]

These constraints represent upper limits of the amount of water allocated to agricultural activities, domestic (communal) use, and the needs of regional industry. Proposition 1, formulated in Roozbahani et al. (2015a), shows that the non-dominated solutions in the MOWDA model are infinite. In each solution, a stakeholder's profit cannot increase in value unless the profits of other stakeholders are degraded.

### 2.2.2 The solution method of the MOWDA model

In order to find the solutions of the MOWDA model, a new solution method is outlined. The solution method has been adapted from Roozbahani et al. (2015a) where they used the same methodology for allocation water to stakeholders assuming there is no dam in the basin. This method is based on maximizing "the minimum ratio of the profit obtained from allocating water to each stakeholder to the highest possible profit that each stakeholder can achieve" (Roozbahani et al. 2014). The solution method is based upon the idea that the highest benefits possible (the objective functions of the MOWDA model) must be granted equitably to every stakeholder from the basin's water. In this method, equity is defined similarly to the definition in Roozbahani et al. (2014): an equivalent percentage of the greatest water profits for all stakeholders. Hence, the solution model maximises the stakeholders' minimum water profits. This method is elaborated through three sub-steps.

#### First sub-step: the highest possible profit (HPP) model

$f_{kt}^*$  refers to the highest possible profit (HPP) of stakeholder  $k$  in time step  $t$ , and is an input for the second sub-step that is calculated in the first sub-step. For this purpose, the HPP model is separately solved for each stakeholder. In this way, the profit of the stakeholder

is maximized subject to constraints mentioned above. This model’s output determines the best possible water allocation to stakeholder  $k$  subject to only satisfying the environmental demand. Note that the water that is allocated to a stakeholder may not exceed the stakeholder’s demand. Thus, the “highest possible profit” term is used instead of simply “highest profit.” The formulation of the HHP model is as follows:

$$\text{Maximize } Z_k = \sum_{i_k=1}^{n_k} \sum_{t=1}^T (AP_{i_{kt}} + UP_{i_{kt}} + IP_{i_{kt}}) \quad k = 1, 2, \dots, K$$

subject to constraints formulated above.

**Second sub-step: the highest ratio of highest possible profit (HRHPP) model**

The second step is to develop an HRHPP model that maximizes the minimum ratio of stakeholders’ profits in time step  $t$  to the highest possible profit each stakeholder can reach in time step  $t$ . This ratio for time step  $t$  is denoted by  $\lambda_t$ . The formulation of the HRHPP model akin to Roozbahani et al. (2015a) is as follows:

$$\text{Maximize } Z = \sum_{t=1}^T \lambda_t \tag{6}$$

where

$$\lambda_t = \min(\lambda_{1t}, \lambda_{2t}, \dots, \lambda_{kt}) \tag{7}$$

subject to Constraints [(5–26) *ibid*] where  $\lambda_{kt}$  is defined by

$$\lambda_{kt} = \frac{\sum_{i_k=1}^{n_k} (\rho_{i_k}^a \times x_{i_{kt}}^a + \rho_{i_k}^u \times x_{i_{kt}}^u + \rho_{i_k}^d \times x_{i_{kt}}^d)}{f_{kt}^*} \quad \forall t.k \tag{8}$$

In the following, we change the max–min model above to a maximum model:

$$\text{Maximize } Z = \sum_t \lambda_t \tag{9}$$

subject to:

$$\sum_{i_k=1}^{n_k} (\rho_{i_k}^a \times x_{i_{kt}}^a + \rho_{i_k}^u \times x_{i_{kt}}^u + \rho_{i_k}^d \times x_{i_{kt}}^d) \geq (\lambda_t \times f_{kt}^*) \quad \forall t.k \tag{10}$$

and Constraints [(5–26) *ibid*]. Constraint (10) guarantees that the profit of stakeholder  $k$  in time step  $t$  ( $\sum_{i_k=1}^{n_k} (\rho_{i_k}^a \times x_{i_{kt}}^a + \rho_{i_k}^u \times x_{i_{kt}}^u + \rho_{i_k}^d \times x_{i_{kt}}^d)$ ) must be greater than a ratio ( $\lambda_t$ ) of its highest possible profit ( $f_{kt}^*$ ), while equity is ensured by  $\lambda_t$ , which is the same for all stakeholders.

**Third sub-step: the final water profit (FWP) model**

Sub-step three of the solution method is to develop the FWP model, which is a single-objective model that uses the results of sub-step two to allocate water to the stakeholders (when the value of  $\lambda$  for each time step is obtained) and apportion the remaining water among stakeholders according to their water profits. This model’s objective function is the maximization of the overall basin’s profit (OBP), while the profits of all stakeholders in time step  $t$  must be greater than  $\lambda'_t \times f_{kt}^*$ .  $\lambda'_t$  is a constant value at time step  $t$ , which is the given

solution of the HRHPP model for  $\lambda$  at time step  $t$ . Put differently,  $\lambda'_t$  is equal to the value of  $\lambda_t$  for time  $t$ , given from sub-step two. The FWP model formulation is as follows:

$$\text{Maximize } OBP = \sum_{k \in \kappa} \sum_{i_k \in \nu_k} \sum_{t \in \tau} (AP_{i_k t} + UP_{i_k t} + IP_{i_k t}) \tag{11}$$

subject to:

$$\sum_{i_k=1}^{n_i} (\rho_{i_k}^a \times x_{i_k t}^a + \rho_{i_k}^u \times x_{i_k t}^u + \rho_{i_k}^d \times x_{i_k t}^d) \geq (\lambda'_t \times f_{kt}^*) \quad \forall k.t \tag{12}$$

and Constraints [(5–26) *ibid*].

The solutions of the proposed solution method are non-dominated, as shown in the following proposition.

**Proposition 1** *The solution obtained by the proposed solution approach is non-dominated.*

**Proof** If the obtained solution is dominated, the amount of  $\sum_{t=1}^T R_{(N_E \rightarrow 0)t}$  in the obtained solution is greater than  $\pi$  where:

$$\pi = \text{Min} \left( \sum_{t=1}^T y_{(N_E \rightarrow 0)t} \right) \tag{13}$$

subject to Constraints [(5–26) *ibid*].

In this solution, in other words, some excess water is released to the node 0, while it could be allocated to the stakeholders at a time step. As there is at least one dam in the basin, excess water released to node 0 could be stored in the dam and allocated to one of the stockholders in another time step. This would increase the  $\lambda_t$  values or the profit [expression (11)] in the third sub-step of our solution method. This contradiction completes the proof.

### 2.2.3 Step two: ascertaining the number of required dams

A sensitivity analysis is proposed for discovering a basin’s optimal number of required dams. To this end, the solutions of the MOWDA model in terms of  $\lambda_t$ , the overall profit of the basin, the stakeholders’ profits, and the summation of proposed dams’ capacities for various scenarios are taken into consideration in choosing the optimal number of dams. It should be noted that the dams’ locations and capacities are indicated in this selection of the optimal number of required dams.

### 2.2.4 Step three: exploring for lower capacities for selected dams

Step two finds the optimal number of dams. In Step three, the MinCap model runs to find new dam capacities (selected in Step two), such that the summation of dams’ capacities is minimized while the stakeholders’ profits are equal to or greater than the values achieved by the MOWDA model. It should be mentioned that the MOWDA model might have multiple optimal solutions. Concerning Constraints (8)–(10), the capacity of dam  $i_k$  ( $C_{i_k}^\Delta$ ) must equal the amount of stored water in at least  $R^\psi$  time steps. Therefore, any value between  $R^\psi$  and total time steps for dam  $i_k$  may be selected in the MOWDA model, which maximizes the stakeholders’ profits in time step  $t$ . For this reason, there could be multiple optimal solutions in the MOWDA model (i.e. various capacities of dams), which would all provide the same

**Table 1** The area, population, agricultural demands (for 2025), and produced surface water resources of the Sefidrud Basin’s stakeholders

Province	Area in the basin (%)	Population in 2007 (%)	Agricultural demand (MCM)	Surface water (MCM)
1	23.3	12.8	1029	1039
2	3.4	1.5	126	55
3	30.9	22.9	1967	1233
4	19.5	11.2	753	1407
5	6.8	4.5	447	680
6	1.9	0.3	410	464
7	7.4	1.6	431	587
8	6.8	45.2	2107	749
Sum	100	100	7270	6214

values for stakeholders’ profits. Minimizing the summation of the dams’ capacities is the MinCap model’s objective function, given by

$$Z_{MinCap} = \sum_{k \in \kappa} \sum_{i_k \in \nu_k} C_{i_k}^{\Delta} \tag{14}$$

This objective function is subjected to

$$\sum_{i_k \in \nu_k} \sum_{t \in \tau} (AP_{i_k t} + UP_{i_k t} + IP_{i_k t}) \geq SP_{kt} \quad \forall k.t \tag{15}$$

and Constraints [(5–26) *ibid*], where  $SP_{kt}$  is the profit achieved by stakeholder  $k$  in time step  $t$  by the MOWDA model.

The detailed flowchart of the proposed algorithm is presented in Fig. 1.

### 3 Case study area: the Sefidrud Basin

The Sefidrud Basin is one of the largest transboundary basins located in the Northwest part of Iran (based on the definition of Breils et al. (2008)). The case study and attributes of the basin has been explained in Roozbahani et al. (2017). Figure 1 in Roozbahani et al. (2017) present the location of the basin in Iran and Table 1 gives some information about the area, population, agricultural demands, and produced surface water resources of the Sefidrud Basin’s stakeholders.

According to the estimate made for 2025 by MGC (2011), the total annual water demand in the Sefidrud Basin is 7270 million cubic meters (MCM). The agricultural sector is the primary user of water resources, accounting for 91% of the total demand. The water demands of the municipal and industrial sectors are about 8% and 1%, respectively, of the total demand. Because their total water use shares were low, the water use of the urban and industrial sectors were considered to be zero in this case study. The agricultural demands of the Basin’s stakeholders are displayed in Table 1. As shown, the largest agricultural demand in the Basin belongs to Province 8 with 2107 MCM demand, while it has about 6.8% and 45.2%, respectively, of contained area and population of the Basin.

According to MGC (2011), the potential of the average long-term surface water supply (50 years) in the Sefidrud Basin is about 6214 MCM, as shown in Table 1. This table also

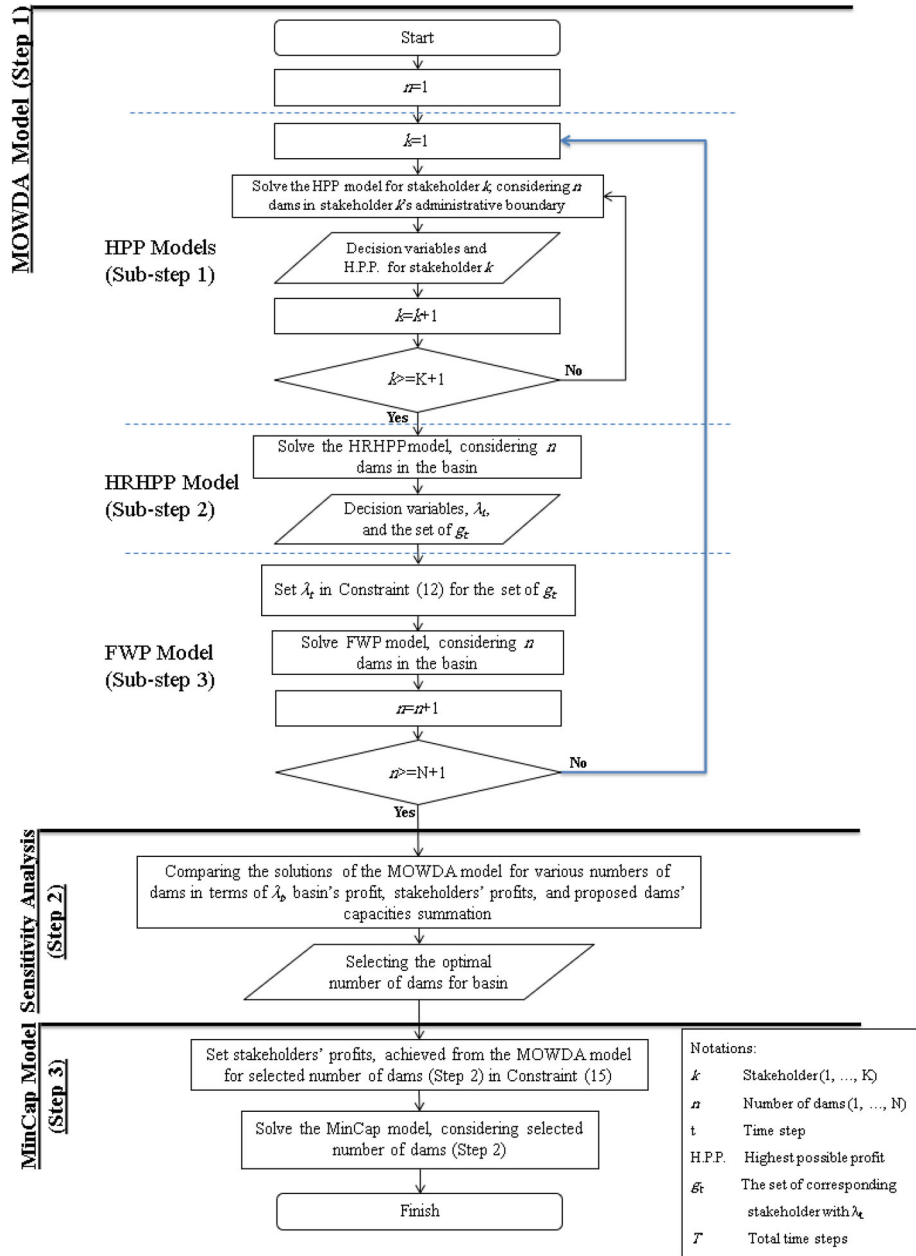


Fig. 1 The flowchart of the proposed approach

provides the source of the surface waters from the Sefidrud Basin stakeholders. As this table demonstrates, Province 8 has the highest water demand (2107 MCM), but its share from the Basin surface water supply is 749 MCM. According to this table, Provinces 4 and 3, with

1407 and 1233 MCM, respectively, have the largest share of surface water production in the Basin.

Figure 2 in Roozbahani et al. (2017) shows the network scheme representing the Sefidrud River Basin's water resource system and its nodes. The network divides the Basin's catchment into regions, as in Letcher et al. (2007). Supply/demand nodes correlate to 27 mainstream flow gauges in the Basin. Shared nodes between stakeholders in the network are replaced with dummy nodes. In this way, the associated stakeholders' water shares in the shared nodes are computed.

Each node's environmental water demand is obtained by employing the modified Montana algorithm (Torabi Palatkaleh et al. 2010a). Montana (Tennant 1976) is used to determine the environmental water requirement, and was developed in the USA. Tennant (1976) proposed some flow classification clusters, which linked habitat quality with different percentages of average annual discharge in the catchment under consideration. The environmental water demand is computed by the modified Montana method based on a percentage of the average monthly, rather than annual, flow in each node. In this study, the "fair or degrading" percentages of environmental status are considered as a critical threshold (for instance, a 10% average monthly flow for the period from October to March, and a 30% average monthly flow from April to September). The Iranian water authorities officially accepted these thresholds for computing the environmental water demands in Iran's catchments (Torabi Palatkaleh et al. 2010b). The environmental water requirements for each node were presented in Roozbahani et al. (2013).

## 4 The results of the approach implementation to the case study

In this section, the results of the approach implementation to the Sefidrud Basin are demonstrated. The Basin's anticipated water demand in 2025 is shown in Table 1. There were no trends indicated that were statistically significant (either positive or negative) in the Basin discharge from 1957 to 2007 (MGC 2011). This fact allowed us to use the annually recorded node discharges from that time period (50 time steps) for this study. The demand satisfaction threshold in 90% of time steps was utilized as an important water reliability supply criterion in the Basin (MGC 2011). The amount of  $R$  is  $0.90 \times 50 = 45$ .  $R^\psi = 45$  is also considered in this study, as it was similarly done by Roozbahani et al. (2017). This means the model has to allocate the capacity of dam  $i_k$  such that it will be full in at least 90% of time steps. CPLEX 12.6 solver (IBM) was used to solve all models, and those results are discussed below.

### 4.1 The results of the MOWDA model (step 1)

This subsection presents the results of the HPP, HRHPP, and the FWP model implementations.

#### 4.1.1 The results of the HPP models (sub-step one)

As the Sefidrud Basin contains eight Provinces, eight linear MIP models (the HPP models) were developed for each Province. Below, the numbers of the models correspond to the numbers of Provinces. For instance, the profit of Province 1 is maximized in Model 1. Table 2 shows the summation of Provinces' profits provided by the HPP models for scenarios 1–5. The results of the HPP models are presented in the electronic companion of this article (Tables A-1 to A-8) in detail.

**Table 2** The summation of profits of stakeholders per the HPP models (in billion Rials)

Province	Scenario (number of dams)					
	0	1	2	3	4	5
1	175	1125	1132	1139	1145	1148
2	40	201	202	203	204	205
3	1748	9459	9512	9556	9585	9605
4	1176	5458	5468	5474	5475	5475
5	611	2933	2934	2935	2937	2937
6	222	1730	1733	1734	1734	1736
7	510	2651	2652	2653	2654	2655
8	3807	16,401	16,402	16,403	16,404	16,405

The results presented in Table 2 demonstrate that the construction of one dam within a Province makes a significant increase in its achieved profits. For instance, the highest possible profit of Province 1 without any dams (scenario 0) is 175 billion rials (BR). It rises to 1125 BR after considering only one dam in Province 1. The same circumstances can be noticed for all stakeholders. The second point to note in Table 2 is that the increase in the number of dams does not always result in a significant rise in the stakeholders' profits. For example, the highest possible profits of Province 7 for scenarios 1 and 5 are 2651 and 2655 BR, respectively. This means that the consideration of four more dams in the Basin brings a profit of only 4 BR for this province. This situation is seen for Provinces 2, 4, 5, 6, and 8, as well. The conditions for Provinces 1 and 3 are a bit different, as the consideration of more dams in the Basin causes more profits for them. These achievements from Table 2 demonstrate the high potential of Provinces 1 and 3 for water resource development, in comparison with other stakeholders.

#### 4.1.2 The results of the HRHPP model (sub-step two)

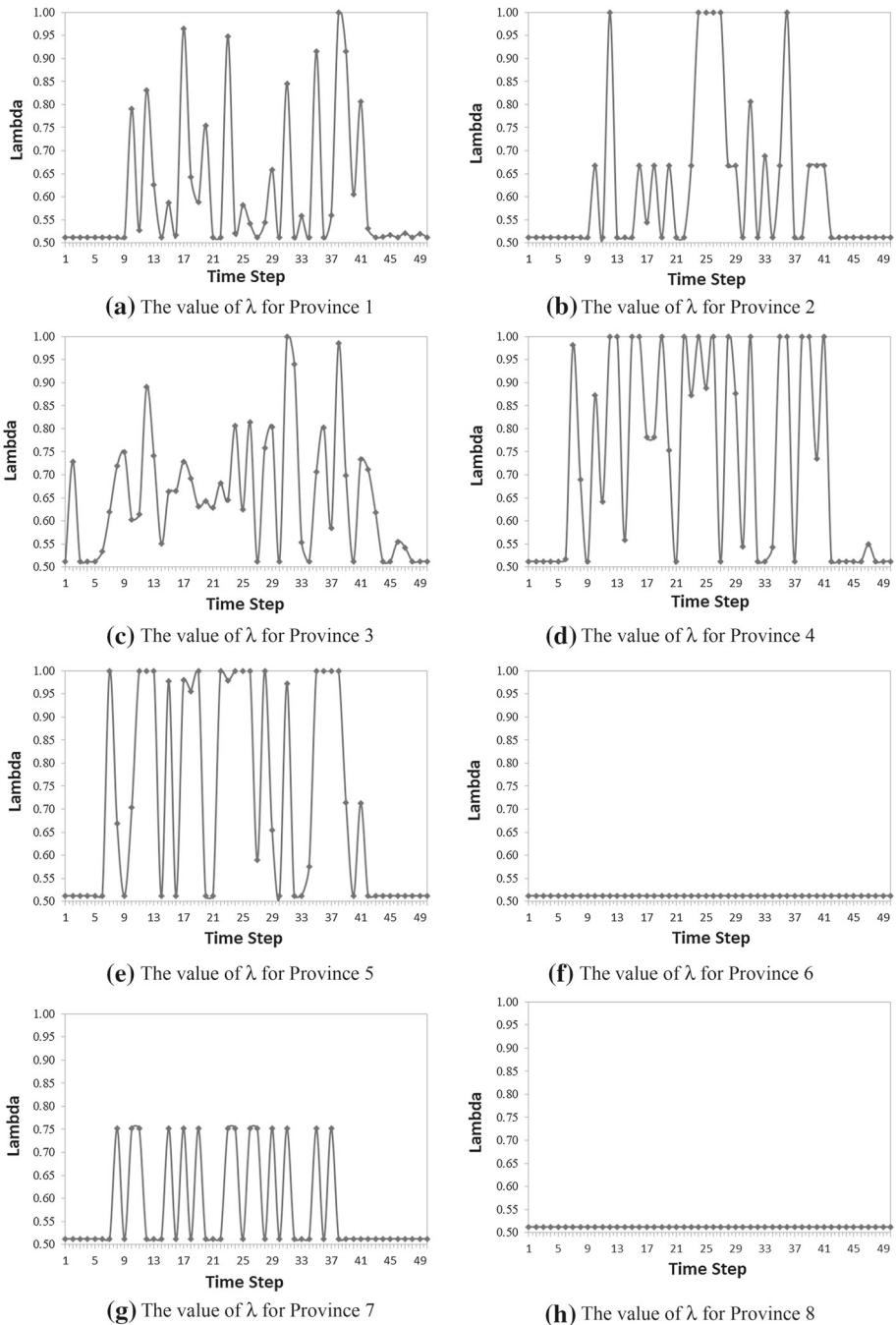
The results of the HRHPP model for scenarios 1–5 are presented in the electronic companion to this article (Tables B-1 to B-5) in detail. The minimum value of  $\lambda_t$  over time steps for scenario 1, given by the HRHPP model, is 0.512. This means that by considering one dam in the Sefidrud Basin, the stakeholders could achieve at least 0.512 of their highest possible profits over time steps. The minimum value of  $\lambda$  raises to 0.548, 0.561, 0.563, and 0.572 by taking into account 2, 3, 4, and 5 dams in the Basin, respectively.

Figure 2 demonstrates the variations of the stakeholders'  $\lambda$  values over time steps for scenario 1, for example. As shown in this figure, the values of  $\lambda$  for Provinces 1, 2, 3, 4, 5, and 7 fluctuate between 0.512 and 1 over a period of 50 years, while they are constantly equal to 0.512 for Provinces 6 and 8. This shows that the conditions of Provinces 6 and 8 limit the HRHPP model's minimum value of  $\lambda$  to 0.512 for scenario 1.

#### 4.1.3 The results of the FWP model (sub-step three)

Table 3 and Figs. 3, 6, 7, and 8 present the Sefidrud Basin's proposed dams with their optimal locations and capacities for scenarios  $n = 1$ ,  $n = 2$ ,  $n = 3$ ,  $n = 4$ , and  $n = 5$ , respectively, derived from the FWP model. As shown in Table 3 and these figures, Nodes 10 and 20 play significant roles in the Sefidrud Basin water planning and development, because the model



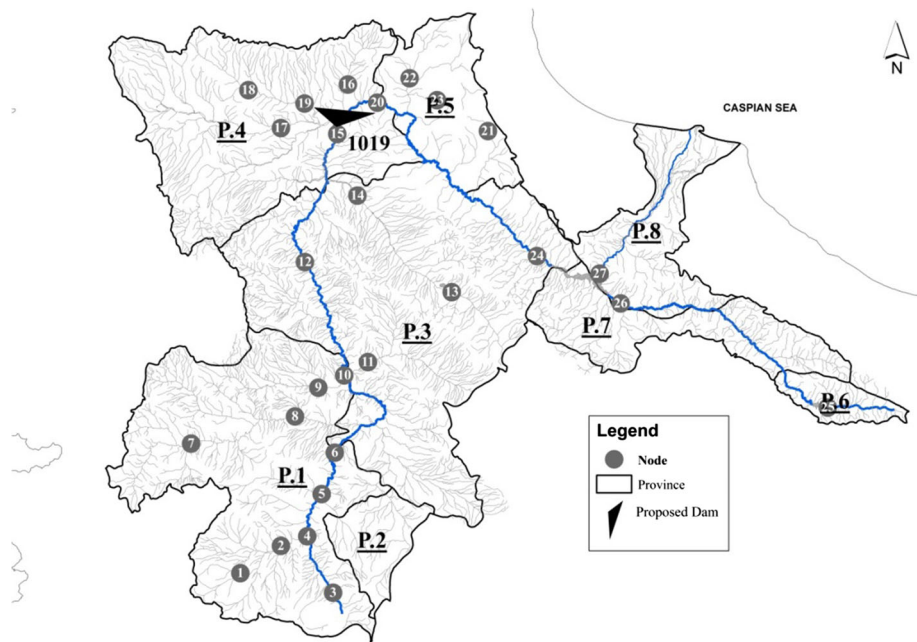


**Fig. 2** The stakeholders'  $\lambda$  values, given by the HRHPP model for the scenario 1

proposes them for constructing dams for scenario 4. The second important node is Node 15, which is proposed for dam construction for scenario 3. Nodes 27, 12, and 7 are other nodes which are proposed for dam construction by scenarios 2 (Node 27) and 1. As shown in these

**Table 3** The locations and capacities (MCM) of proposed dams by the FWP model

Node	Province	River	Scenarios				
			n = 1	n = 2	n = 3	n = 4	n = 5
7	1	Ghezeloan	0	0	0	0	115
10	1, 2, 3	Ghezeloan	0	405	531	326	306
12	3	Ghezeloan	0	0	0	437	0
15	4	Ghezeloan	1019	0	191	0	559
20	4, 5	Ghezeloan	0	823	879	907	1503
27	7, 8	Sefidrud	0	0	0	102	773
Dams' capacities summation			1019	1228	1601	1772	3265

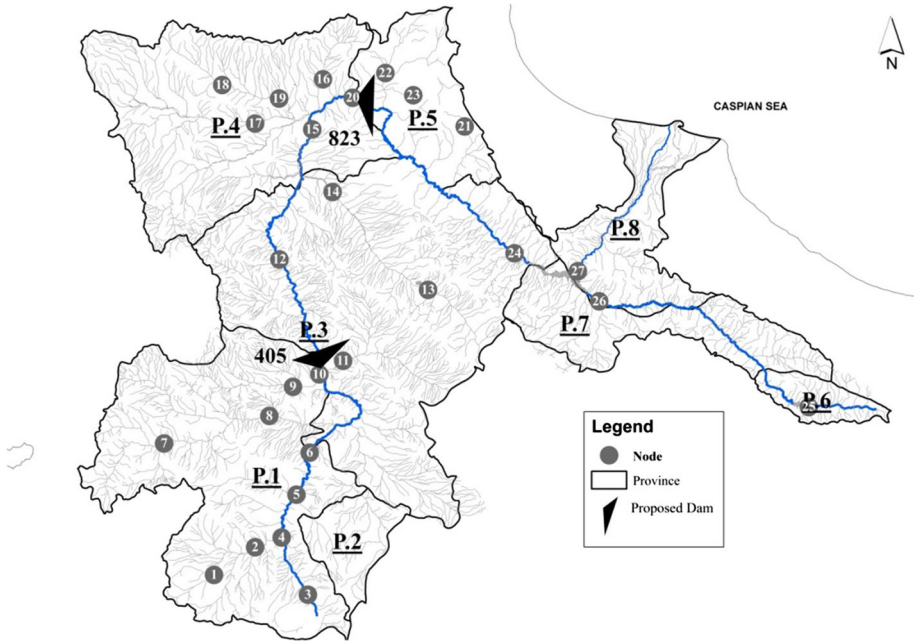


**Fig. 3** Location and size of scenario 1's proposed dam for the scenario 1, derived by the FWP model. The bold number next to the symbol used for dam shows the proposed capacity for the dam

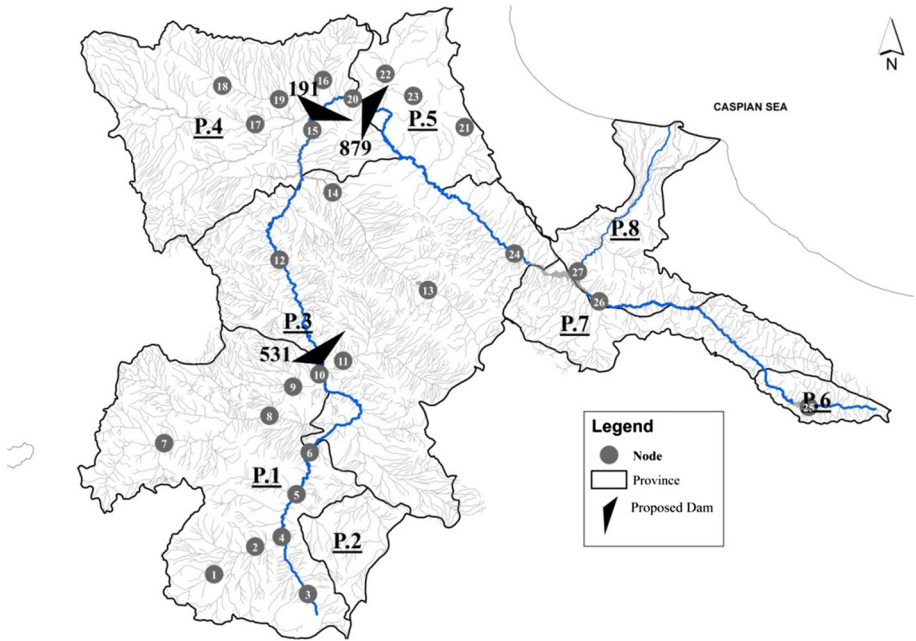
figures, most dams proposed by the FWP model are located on the Ghezeloan River (a major tributary of the Sefidrud River), due to the large number of the stakeholders located in its catchment. This point shows that the water authority of the Basin needs to put more attention on water planning and the development of the Ghezeloan River. Moreover, most dams are proposed to be constructed in the administrative boundaries of Provinces 3 and 4.

**4.1.4 The results of the FWP model (sub-step three)**

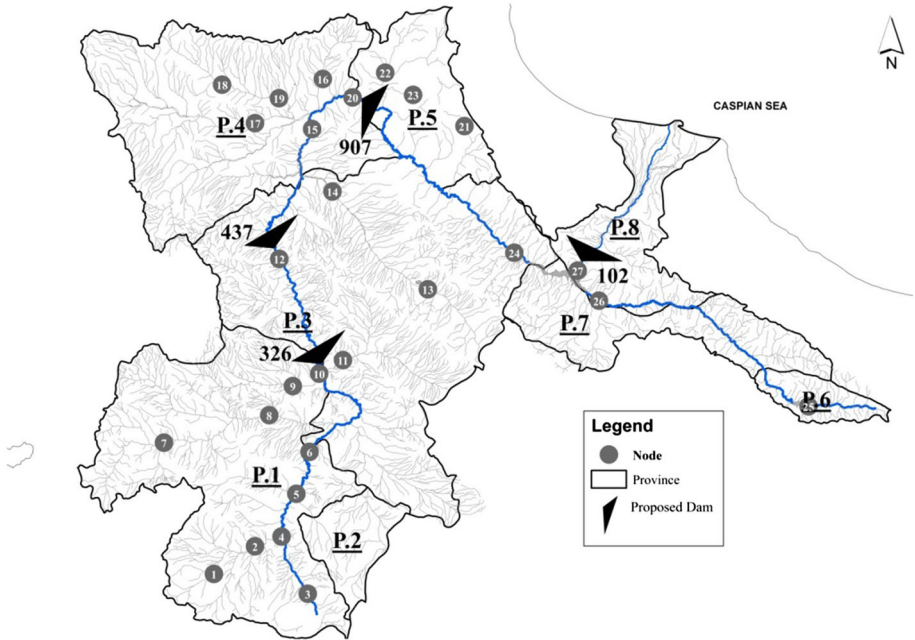
Table 3 and Figs. 3, 4, 5, 6, and 7 present the Sefidrud Basin's proposed dams with their optimal locations and capacities for scenarios n = 1, n = 2, n = 3, n = 4, and n = 5,



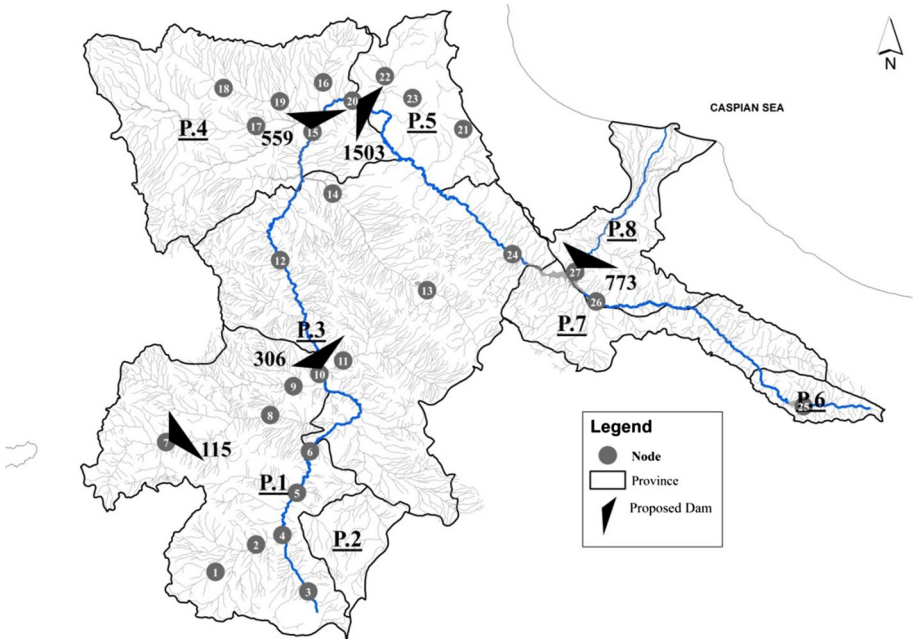
**Fig. 4** Location and size of scenario 2’s proposed dam, derived by the FWP model. The bold number next to the symbol used for dam shows the proposed capacity for the dam



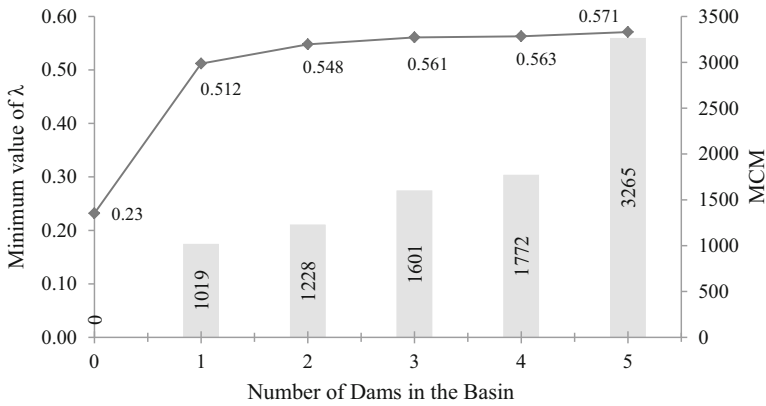
**Fig. 5** Location and size of the proposed dam for the scenario 3, derived by the FWP model. The bold number next to the symbol used for dam shows the proposed capacity for the dam



**Fig. 6** Location and size of the proposed dam for the scenario 4, derived by the FWP model. The bold number next to the symbol used for dam shows the proposed capacity for the dam



**Fig. 7** Location and size of the proposed dam for the scenario 5, derived by the FWP model. The bold number next to the symbol used for dam shows the proposed capacity for the dam



**Fig. 8** Comparing the minimum value of  $\lambda$  over time steps achieved by various scenarios (number of dams) and the summation of dams' capacities

respectively, derived from the FWP model. As shown in Table 3 and these figures, Nodes 10 and 20 play significant roles in the Sefidrud Basin water planning and development, because the model proposes them for constructing dams for scenario 4. The second important node is Node 15, which is proposed for dam construction for scenario 3. Nodes 27, 12, and 7 are other nodes which are proposed for dam construction by scenarios 2 (Node 27) and 1. As shown in these figures, most dams proposed by the FWP model are located on the Ghezelozan River (a major tributary of the Sefidrud River), due to the large number of the stakeholders located in its catchment. This point shows that the water authority of the Basin needs to put more attention on water planning and the development of the Ghezelozan River. Moreover, most dams are proposed to be constructed in the administrative boundaries of Provinces 3 and 4.

#### 4.2 Sensitivity analysis (step 2)

Figure 8 compares the minimum value of  $\lambda$  over time steps achieved by various scenarios (number of required dams) with the Summation of Dams' Capacities (SDC). As shown in this figure, the minimum value of  $\lambda$  is 0.23 when no dam is in the Basin ( $n = 0$ ,  $SDC = 0$ ). It rises to 0.512 when one dam is considered ( $n = 1$ ) with 1019 MCM reservoir capacity in the Basin. The consideration of two dams ( $n = 2$ ,  $SDC = 1228$ ) in the Basin increases the minimum value of  $\lambda$  from 0.512 to 0.548. The achievement of this value of  $\lambda$  requires the construction of one dam with 405 MCM capacity in node 10, and another with 823 MCM capacity in node 20. Put differently, the equity of water sharing in the Basin rises by 0.036 ( $0.548 - 0.512$ ) if the surface water storing potential of the Basin increases by 209 ( $1228 - 1019$ ) MCM. The minimum value of  $\lambda$  continues to increase with a lower slope to 0.561 when the model considers three dams ( $n = 3$ ,  $SDC = 1601$  MCM) in the Basin. There is not a significant jump in the minimum value of  $\lambda$  when four dams ( $n = 4$ ,  $SDC = 1772$  MCM) are considered for the Basin water development. In this situation, the minimum value of  $\lambda$  grows slowly from 0.561 to 0.563 (only 0.002). The increasing trend of minimum value of  $\lambda$  continues by considering five dams ( $n = 5$ ,  $SDC = 3265$  MCM) in the Basin and it reaches the value of 0.571 in these circumstances. For obtaining this amount of increase in the value of  $\lambda$  ( $0.571 - 0.563 = 0.008$ ), a rise in reservoir capacity equal to 1493 ( $3265 - 1772$ ) MCM is required. This fact shows a further increase in the value of  $\lambda$  needs huge

**Table 4** The average annual of stakeholders' profits for various scenarios

Number of dams	Province profit (billion Rials)								Basin profit (billion Rials)	SDC (MCM)
	1	2	3	4	5	6	7	8		
n = 1	13	3	127	79	44	22	36	285	610	1019
n = 2	14	3	131	79	45	23	37	274	605	1228
n = 3	14	3	133	79	44	23	37	270	604	1601
n = 4	14	3	133	79	44	23	38	273	607	1772
n = 5	14	3	134	80	45	23	38	270	607	3265

reservoir capacities in the Basin. The minimum value of  $\lambda$  for scenario 27 ( $n = 27$ , without considering the dummy nodes) is 0.62, which shows that the maximum possible development in the Basin (dams construction on all feasible nodes) would not increase the value of  $\lambda$  very much further than the given values for scenarios 1–5, when it needs a huge water storing capacity in the Basin.

Table 4 presents the profits of the stakeholders for various numbers of dams in the Basin. As shown in this table, the Basin profit for scenarios 1, 2, 3, 4, and 5 are 610, 605, 604, 607, and 607 BR. Based on these data, the Basin's highest profit is achieved by considering one dam in the Basin, when the model presents the lowest level of water sharing equity in the Basin. In this case, the FWP model satisfies more water demands of Province 8, which has the highest water value in the Basin. The profit of Province 8 decreases when increasing the minimum value of  $\lambda$ . The Basin's profit does not demonstrate a significant variability by increasing the numbers of dams. It varies between 604 and 610 BR for various scenarios, while the requested water storing capacities vary between 1019 MCM and 3265 MCM. According to Table 4, the increase in the number of dams has an effect on the achieved profits of Provinces 3 and 8, while the profits of other provinces have not changed significantly.

According to Fig. 8 and Table 4, an increase in the numbers of dams in the Sefidrud Basin by more than three does not result in significant additional water sharing equity and Basin profit, while it does contribute to a significant cost for the dams' construction. Hence, three dams lead to a reasonable water allocation scheme for the Sefidrud Basin. It is very important to note that this result could be modified if new information, such as practical reservoir capacities and the cost of dam construction for various nodes in the Basin, are added to the model.

#### 4.3 The results of MinCap Model (step 3)

The MinCap model was run for scenario 3, and its results were same as those of the MOWDA model for this scenario. That is, for this case study, there are no lower capacities resulting in the same profits that were achieved by the MOWDA model. Table 5 presents the annual average of allocated water to the stakeholders for scenario 3, derived from the MinCap model's results. To sum up, the water shares of Provinces 1–8 are 408, 79, 1087, 536, 298, 200, 305, and 1734 MCM, respectively, if three dams in node 10 with storing capacity 531 MCM, node 15 with storing capacity 191 MCM, and node 20 with storing capacity 879 MCM will be constructed.

**Table 5** The annual average of allocated water to the stakeholders given by the MinCap model for scenario 3 (MCM)

Scenario	Province								Sum
	1	2	3	4	5	6	7	8	
n = 3	408	79	1087	536	298	200	305	1734	4646

## 5 Conclusion

We introduced a novel approach for optimal planning and management of water in an undeveloped basin. The proposed approach consists of three steps. The first step determines the optimal water allocation and the locations and sizes of new dams in the basin for various numbers of dams. It utilises the MOWDA model, a multi-objective model to determine capacities and locations of new dams so that they bring the greatest possible profits for all stakeholders, simultaneously. The MOWDA model must be run for several scenarios (that is, for various dam counts). A three-step solution method was also introduced that transforms the MOWDA model into three single-objective models, the HPP, HRHPP, and FWP models. The solution method relies on the necessity of a stakeholder's allocated water reaching as near as possible to its maximum feasible profit.

In the approach's second step, the optimal dam count for the basin is selected. For this purpose, a sensitivity analysis approach was implemented. Multiple ideal solutions were possible in the MOWDA model for a selected scenario, so the third step included the proposal of the MinCap model. This model tested whether providing the same profit for the basin that was achieved by MOWDA was possible for a selected scenario with lower dam capacities.

The approach was applied to the Iranian Sefidrud Basin, an area where water disputes between stakeholders is a problem for the water authority. There are eight administrative Provinces (stakeholders) in this watershed, competing seriously for more water shares and locating new reservoirs in their administrative boundaries. The implementation of the HPP model demonstrated that water resource development is a need for the Basin, while the profit of Province 1 increased from 175 to 1125 BR, considering only one dam in the Basin. Similar situations were observed for other Provinces as well. Moreover, the results of the HPP model demonstrated that Provinces 1 and 3 in the Basin have a higher potential for water resource development in comparison with other stakeholders, due to the significant rise of their profit with one dam considered. The results of the HRHPP model showed that by taking into account one, two, three, four, and five dams in the Basin, the stakeholders could achieve at least 0.512, 0.548, 0.561, 0.563, and 0.572 of their highest possible profits, respectively. The FWP model used the outputs of the HRHPP model in terms of  $\lambda$  and determined optimal capacities and locations of new Basin dams for scenarios 1–5. The outputs of the FWP model showed that nodes 10, 20, 27, 12, and 7 have significant roles in the Sefidrud Basin's water planning and development.

The employment of a sensitivity analysis approach as the second step of the suggested approach demonstrated that only three dams are needed for water resource development in the Sefidrud Basin. Dams in excess of three did not increase water-sharing equity or Basin profit significantly. The MinCap model results implementation as the third step of the approach illustrated that lower dam capacities that bring about the same profits as those the MOWDA model achieved do not exist for a selected scenario. Therefore, the major conclusion from this study is the recommendation to construct three dams in nodes 10 (with 531 MCM capacity),

15 (with 191 MCM capacity), and 20 (with 879 MCM capacity). This should lead the Basin to its optimal water resource development and an equitable water allocation scheme, which guarantees the resolution of water conflicts in the Basin. In this circumstance, the water shares of Provinces 1–8 are 408, 79, 1087, 536, 298, 200, 305, and 1734 MCM, respectively.

In summary, the first contribution reported in this paper is the novel approach for water allocation problem modelling of a transboundary basin, which is based on multi-objective, mixed-integer programming. It leads to the significantly more socially fair distribution of water resources than the single-objective paradigm employed by Roozbahani et al. (2017). It is clearly seeing that the results of the present research suggest migration of the proposed dam sides from well-developed downstream areas of the Basin to the upstream provinces where population is in less economically advantageous situation. The second contribution is the introduction of a new solution method to find an effective Pareto optimality solution for the developed multi-objective model. The third contribution is the combination of the location-allocation formulation with water allocation modeling. Finally, yet importantly, the problem of finding the capacity of new dams was formulated without the need for cost-capacity function for each proposed dam location in the Basin.

This paper presents a novel multistage algorithm which can be used for the selecting the optimal site/capacity selection in the transboundary basins. It can be widely used in water resources as well as in the solutions of general problems of resource allocation (supply chains) with storages. The sensitivity analysis has been implemented to the series of model parameters in order to establish how robust the suggested scenarios of dams construction are. It can be concluded that the model and algorithm presented in this paper can be productively used in practice of water resource management.

Moreover, based on our best search, the current study is a pioneering research, which focuses on the preliminary assessment of the optimal locations and capacities of new dams in a transboundary basin, along with optimal water allocation of the basin at the same time. The proposed formulation of the problem, together with the suggested technique for solving the multi-objective optimization model, is an innovative, which were not applied in the previous studies. The process of investigating potential dam sites in the usual engineering approach typically involves an iterative process of increasingly detailed studies, without taking the long view of dams' effects on the economy and the ecosystem of the entire basin to the decision makers. The proposed method could make sure that the water development of the basin is sustainable and would bring peace instead of conflicts for the stakeholders, while it prepares the highest possible profits for all stakeholders along with lowest negative effects on the ecosystem.

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