

Optimal allocation of water to competing stakeholders in a shared watershed

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Abstract This paper proposes a mathematical model for allocating water to stakeholders of a shared watershed. Each stakeholder in the basin has a water demand and a water profit; however, the available water cannot meet the demands of all stakeholders. This shortage raises a conflict between stakeholders as they use a common resource. To reach an agreement between the stakeholders in water allocation, first a model was developed to obtain the highest possible profit that a stakeholder can achieve if the stakeholder is allowed to utilize as much as possible water after satisfying the basin environmental demands (flows). Then, another model was introduced which allocates water to each stakeholder such that the minimum ratio of stakeholders' profits to their highest possible profits is maximized. It is shown that the obtained solution is non-dominated in terms of considering each stakeholder profit as an objective, which means that none of the objective functions can be improved in value without degrading some of the other objective values. The proposed method is applied to the Sefidrud River basin, which is one of the biggest rivers in Iran. The stakeholders of this basin are eight administrative provinces that compete for utilizing more water while the Basin's water resources could not satisfy all stakeholders' water requirements. The model's results show that it can successfully be used for sustainable conflict resolution in a shared basin because the model satisfies the environmental water requirement in the entire basin and provides equitably the same ratio of the stakeholders' highest possible profits for them. For the case of this study, the proposed approach allocates water to the stakeholders in such a way that they could obtain at least 65 % of their highest possible profits in average.

Keywords Water allocation · Mixed-integer programming · Multi-objective optimization · Shared watersheds

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1 Introduction

Sustainable water allocation is essential for resolving water conflicts between the stakeholders of basins, caused by increasing water shortages in watersheds. In the case of transboundary river basins, sustainable water allocation has a significant importance where the stakeholders are provinces/states at the national level or countries at the international level. To achieve a sustainable water allocation, it is necessary to consider simultaneously economic, social, and environmental indicators in water allocation modelling (UNESCAP 2000). Operations Research methods have a long tradition in natural resource management (Plà et al. 2013). Hence, the water allocation problems are mainly formulated based on optimization techniques, in which single objective and multi-objective optimization techniques have received vast attentions.

A large number of single objective models have been developed for water allocation of shared rivers (e.g., Reca et al. 2001; Kucukmehmetoglu and Guldmann 2004; Devi et al. 2005; Pulido-Velázquez et al. 2006; Griffith et al. 2009; Divakar et al. 2011; Huang et al. 2012; Roozbahani et al. 2013; Fotakis and Sidiropoulos 2014). However, they cannot lead to a sustainable water allocation because they only considered one indicator out of three essential objectives (UNESCAP 2000) for achieving a sustainable water allocation scheme.

Multi-objective optimization (Cohon and Marks 1975) is broadly employed for water allocation of transboundary basins. It is an effective method to achieve reasonable results when several indicators have to be considered simultaneously (Jaramillo et al. 2005). A few multi-objective optimization models were developed for water allocation of transboundary watersheds. However, some of them have not resulted in sustainable water allocation schemes for the basins, owing to ignore the economic, social, and the environmental indicators simultaneously (e.g., Afshar et al. 2009; Fattahi and Fayyaz 2010; Ahmadi et al. 2012; Divakar et al. 2013; Rezapour Tabari and Yazdi 2014).

The purposed models by McKinney and Cai (1997), Cai et al. (2002), and Schlüter et al. (2005) for water allocation of the Aral Sea basin marginally considered three essential water allocation indicators. McKinney and Cai (1997) applied a multi-objective model to investigate annual allocations of water in the Amudarya River basin. The amount of flow to the Aral Sea, the basin's demands satisfaction, and equalizing the distribution of water deficits between stakeholders were considered as water allocation indicators of their model. Cai et al. (2002) presented a new long-term modelling framework based on multi-objective optimization for the Syr Darya River Basin, which the risk of water supply to stakeholders, water transferred to the Aral Sea, equity in water allocation, and economic efficiency in water infrastructure development were the objectives of their study. Schlüter et al. (2005) expanded the study of McKinney and Cai (1997) by creating a new water management model for the Amudarya River. Their study's indicators comprised the deficits of water delivery to all stakeholders, the planned flow to the Aral Sea, the degree of filling of the reservoirs, and the demand for stability of the system. In all three studies, weighted sum technique was utilized for finding the solutions of the developed models. The above studies on the Aral Sea addressed economic and social factors; however, they only focused on the satisfaction of the Aral Sea water requirement, which is situated in the downstream of the basin, rather than the water supply to the environment for the whole body of watershed. Due to the employment of weighted-sum technique for solving these models, varieties of weights for the objective functions were selected and thus, the models proposed many water allocation schemes for the Aral Sea basin. Note that, providing many water allocation patterns for a basin often confounds water authorities.

Wang et al. (2004) introduced a mathematical model based on Lexicographic Minimax approach for fair allocation of water to the stakeholders of the Amudarya River basin. The model minimized sequentially the largest water shortage of nodes in the basin until no shortage ratio can be decreased further without either violating a constraint or increasing an already equal or worse-off shortage ratio value that is associated with another demand. They focused on nodes' water supply instead of the whole water shares of the stakeholders. In fact, in a transboundary basin, stakeholders are administrative boundaries with various social and economic properties and many nodes in the node-link network could belong to a stakeholder. Wang et al.'s study did not consider the satisfaction of the environmental water requirement in the entire basin. In addition, they considered the maximum water demands of nodes in their models without evaluating the practical satisfaction of them if the basin wants to be managed in a sustainable way and satisfies the environmental demand. It should be noted that in some cases, the stakeholders overestimate their demands and often even if the highest priority is given to satisfy a particular stakeholder demand, the requested demand cannot be satisfied due to available water and environmental demand in the basin. Since the demand should be replaced by the highest possible water allocation by considering the demand as a cap.

Kucukmehmetoglu and Guldmann (2010) utilized a multi-objective model for water allocation of the Euphrates and Tigris River basin. The model involved all stakeholders in water allocation through maximizing the profits of all stakeholders instead of the maximization of the basin's profit. However, the environmental water satisfaction was not taken into account in this model. Moreover, they used the weighted-sum technique to find the solutions of their model and selected three different weights for the objective functions while the justification of these weights was not transparent.

In this study, we propose a multi-objective model for sharing water resources of transboundary basins between their stakeholders in a sustainable way. The proposed model maximizes the profits of stakeholders from allocated water to them while the environmental water satisfaction is considered over the entire basins. These objective functions can play as social factors while the stakeholders are satisfied with their given profits from the shared water resources. To cope with issues of assigning weights to objective functions and justifying them, instead of solving the multi-objective model, we propose a new solution method, which maximizes the minimum ratio of the profit obtained of each stakeholder to the highest possible profit that each stakeholder can achieve. The stakeholders of a transboundary basin have actually various amount of water demand due to some parameters such as their development levels, their population, and so on. The advantage of the proposed ratio is that it could imply the stakeholders' properties in water allocation modelling. The proposed model and new solution method are applied to the Sefidrud river basin, which is one of the largest transboundary rivers in Iran (Zarezadeh et al. 2012), comprised eight administrative provinces. Now, it suffers from a serious water competition between its stakeholders over water utilization.

The organization of the paper is as follows. In the next section, the water allocation model formulation is presented. The proposed method for finding the solutions of this model is explained in Sect. 3. Introducing the Sefidrud Basin and the model's implementation results are given in Sect. 4, followed by the conclusion in Sect. 5.

2 Multi-objective model formulation in water allocation

The proposed model is a multi-objective model that maximizes the profit of all stakeholders in a watershed subject to water resource availability, water balance, environmental demands,

and usage constraints. The profits are the net benefits derived from the allocated water to agricultural, urban, and industrial sectors for each stakeholder. The unfair income generation between the stakeholders of a basin is the main reason of water disputes. The unfair income generation means the uneven distribution of the basin’s income among the stakeholders, which could be generated from its shared water resources utilization, through the exploitation of the shared water resources by some stakeholders. Note that, this unfair situation can be recognized with tracking its social consequences such as unemployment rates in stakeholders. Based on this fact, the maximization of realized profits from the basin water resources for the stakeholders is selected to be the proposed model’s objective functions. The formulation of this model is based on the node-link network of a basin, with source and demand nodes. The water resources of each node are midstream produced water and transferred water from nodes upstream. Agricultural, municipal, and industrial water demands are considered in the model. Furthermore, in-stream water needs such as environmental water requirements are taken into account.

2.1 Multi-objective model objective functions

The objective functions of the model are to maximize the total net profits (Z_k) of water use for each stakeholder (k):

$$\text{Maximize } \{Z_1, Z_2, \dots, Z_K\} \tag{1}$$

where

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

where n_k is the index for the number of nodes for stakeholder k ; i_k is the index for node i that belongs to stakeholder k ; t is the index for time step which can be a month, a half year, or a year; T is the total time steps; $AP_{i_k t}$ is the agricultural profit associated with node i_k at time t , $UP_{i_k t}$ is the profit from residential water use, and $IP_{i_k t}$ is the industrial profit. Each stakeholder (province) includes several supply/demand nodes which are located in the stakeholder’s administrate boundary (see a sample river node scheme in “Appendix”). Available water resources of each node are constituted from streamflow generated in mid-stream catchment of this node and its upstream nodes, combined with the amount of transferred water from upstream nodes. $AP_{i_k t}$, $UP_{i_k t}$, and $IP_{i_k t}$ are calculated using Eqs. (3)–(5):

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

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

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

where a , u , and d represent agricultural, urban, and industrial sectors, respectively, $\varphi_{i_k}^a$, $\varphi_{i_k}^u$, and $\varphi_{i_k}^d$ are the agricultural, urban, and industrial net benefits per unit of allocated water, respectively, and $x_{i_k t}^a$, $x_{i_k t}^u$, and $x_{i_k t}^d$ are the allocated water to agricultural, urban, and industrial uses, respectively. It should be emphasized that the relationship between the water profit of a sector (φ_{i_k}) and allocated water to it ($x_{i_k t}$) is not always linear. In other words, there is not a fixed water profit for all range of water allocation to a sector. For example, in the study of water allocation to various crops in an irrigated network with limited planted crop area, the marginal value of allocated water would be different based on the stages of plants growth and their needs of water. Water stress during critical growth periods reduces yield and quality

of crops, and thus farmers are willing to pay more for water required. Therefore, the water profit of allocated water to the crops in this stage would be higher than other stages of plants growth. In this study, we aim to resolve water conflicts in watersheds where water disputes are resulted from limited water resources and high demand of stakeholders for water utilization in various sectors. In this case, we optimize the allocation of bulk water to a sector of the stakeholders and do not detail on the way that the water is utilized by clients. Therefore, it is reasonable to consider a fixed water profit for all quantitative ranges of allocated water in the present research, rather than determining the real dynamic of profit as a function of water allocated to the stakeholders in such a large scale as provinces or countries. Moreover, this paper focuses to present a multi-objective method for equitable water allocation. Thus, this oversimplified approach to model profit functions is considered.

2.2 Multi-objective model constraints

The model’s constraints are presented as follows:

1. Water balance at node i_k :

$$\vartheta_{i_k t} + \sum_{l \in UN_{i_k}} y_{(l \rightarrow i_k)t} - y_{(i_k \rightarrow j)t} - x_{i_k t}^a - x_{i_k t}^u - x_{i_k t}^d = 0 \quad \forall i_k, t \tag{6}$$

where $\vartheta_{i_k t}$ is the produced surface water in the mid-stream catchment between node i_k and nodes l ($l \in UN_{i_k}$ where UN_{i_k} is the set of node i_k ’s neighbouring nodes upstream), at time step t . $\sum_{l \in UN_{i_k}} y_{(l \rightarrow i_k)t}$ is the transferred water from the nodes l to i_k and $y_{(i_k \rightarrow j)t}$

being the released water from node i_k to node j (j is a neighbouring node for node i_k downstream). Note that, $y_{(N \rightarrow 0)t}$ is the water released from the last node (N) in the basin network which belongs to the last stakeholder downstream (E) to node 0, at time step t . The last node in our case study is sea but it can be wetlands, lakes, or seas in general.

2. Reliability of the environmental water supply in node i_k :

$$y_{(i_k \rightarrow j)t} - \varsigma_{i_k t} \times z_{i_k t} \geq 0 \quad \forall i, t \tag{7}$$

$$\sum_{t=1}^T z_{i_k t} - R \geq 0 \quad \forall i, k \tag{8}$$

where $\varsigma_{i_k t}$ is the environmental water requirement in node i_k at time step t ; $z_{i_k t}$ is a binary variable which equals 1 if the environmental water demand at node i_k of stakeholder k is satisfied at time step t , otherwise it is equal to 0, and R is the reliability level of the environmental water supply. It should be noted that water supply to the environment of node i_k is flows into the river between node i_k and its downstream node (node j). In this study, we use the definition of the reliability introduced by [Kundzewicz and Kindler \(1995\)](#) as the ratio of the times, when the volume of water supplied meets the demand, to the total time period (temporal reliability). By introducing constraints (7) and (8) into the model, the amount of transferred water from node i_k to node j at time step t ($y_{(i_k \rightarrow j)t}$) has to be greater than or equal to the water need of the environment in the node i . The reliability of the environmental water satisfaction is controlled using a binary variable ($z_{i_k t}$) in the constraint (7). The summation of this variable ($z_{i_k t}$) over the time steps has to be more than or equal to R [constraint (8)]. In fact, R is the number of time steps that the amount of transferred water from node i_k to node j has to be greater than the environmental water requirement.

It should be emphasised that the satisfaction of environmental water requirement in the entire basin is essential for achieving a sustainable ecological sound water allocation. In the other word, the utilisation of water for increasing the welfare of people in the basin should not cause any degradation for the environment, which indirectly affects the welfare of people. Hence, satisfying the environmental water requirement is prioritized in this water allocation formulation.

3. Variables’ Bounds:

These constraints include upper bounds on the allocated water to agricultural activities, domestic use, and industry needs, and logical non-negativity bounds for other variables, given by

$$\xi_{ikt} - x_{ikt}^a \geq 0 \quad \forall i, t \tag{9}$$

$$\tau_{ikt} - x_{ikt}^u \geq 0 \quad \forall i, t \tag{10}$$

$$\eta_{ikt} - x_{ikt}^d \geq 0 \quad \forall i, t \tag{11}$$

$$x_{ikt}^a \geq 0 \quad \forall i, t \tag{12}$$

$$x_{ikt}^u \geq 0 \quad \forall i, t \tag{13}$$

$$x_{ikt}^d \geq 0 \quad \forall i, t \tag{14}$$

$$y_{(ik \rightarrow j)t} \geq 0 \quad \forall i, t \tag{15}$$

$$z_{ikt} = 0 \text{ or } 1 \quad \forall i, t \tag{16}$$

where ξ_{ikt} , τ_{ikt} , and η_{ikt} are the maximum agricultural, urban, and industrial water demands in node i_k , at time step t , respectively. These values are the maximum water requirements of stakeholders for various sectors in the corresponded nodes. The satisfaction of these water demands would guarantee highest socioeconomic developments for the stakeholders; however, the water resources of a basin cannot supply all of them. The maximum water demand for the domestic sector can be estimated with the prediction of demographic growth for a certain horizon. For estimating the maximum agricultural water requirement, the amount of arable lands in the basin and the water need of dominated crops in the basin can be used. The plans of local governments in the basin for developing industrial sector are reliable references for evaluating the maximum industrial water requirement.

The exogenous variables of the model include the transferred water from node i_k to node j at time step t ($y_{(ik \rightarrow j)t}$) and the integer variable (z_{ikt}) that ensures the reliability of water supply to the environment. The decision variables include the allocated water to agriculture (x_{ikt}^a), domestic use (x_{ikt}^u), and industry (x_{ikt}^d). The following proposition shows that the above multi-objective problem has infinite number of non-dominated solutions, which in each solution the profit of a stakeholder cannot be improved in value unless degrading the profits of other stakeholders. However, it should be mentioned that these solutions have little practical importance because providing too many non-dominated solutions for water allocation of a watershed could be confusing for water authorities.

Proposition 1 *If at least for one node in the basin network, for example node i ($i = 2, \dots, K - 1$), the environmental demand of node j ($j = i, \dots, K$) in time step t is less than the total produced water at all nodes upstream of j , then the proposed multi-objective water allocation model has infinite number of non-dominated solutions.*

Proof The profits are only generated from the allocated water to nodes of the stakeholders in the proposed model. Therefore, all solutions that release the lowest possible water to the node 0 (by considering the satisfaction of the environmental requirements) are a member of the non-dominated solutions set for the proposed model. Hence, this set of the non-dominated solutions contains solutions for following formulation:

$$\text{Minimize } Z = \sum_{t=1}^T y_{(\mathbb{N}_E \rightarrow 0)t} \quad (17)$$

subject to constraints (6)–(16). We assumed there is at least a node such as i that the environmental water requirement of node j ($j = i, \dots, K$) in time step t is less than the summation of produced water in the upstream nodes of j in time step t . Thus, the proposed model can allocate non-zero water to the upstream nodes in infinite ways. Note that the allocated water to the nodes (decision variables) can take any positive values.

3 The proposed method

In order to find a solution for the proposed multi-objective model, we outline a method that maximizes the minimum ratio of the profit obtained from allocating water to each stakeholder to the highest possible profit that each stakeholder can achieve. The proposed method consists of two steps. The first step finds the highest possible profit for each stakeholder. The second step distributes the basin water resources profit between the stakeholders.

3.1 Highest possible profit (HPP) models (first step of the proposed method)

In this study, we refer to f_{kt}^* as the highest possible profit of the stakeholder k in time step t . It is an input to the second step, which needs to be determined. For this purpose, a single objective model is solved for each stakeholder, which maximizes the profit of the stakeholder subject to the constraints (6)–(16), separately. We denote this approach Highest Possible Profit or HPP for short. The outputs of this model are the values of the decision variables that maximize the profit of that particular stakeholder at time step t if that stakeholder is allowed to take as much water as possible after satisfying the basin environmental demand. It should be noted that the maximum allocated water to a stakeholder could be less than its water demand with respect to the amount of its water demands and the environmental water requirements in downstream. In the case of water abundance, the HPP model allocates water to the particular stakeholder equal to its water need and transfer the leftover water to downstream stakeholders. However, when there is a water deficit in the basin, the HPP model releases firstly the water requirement of the environment, and then satisfies the water demand of the particular stakeholder as much as possible. Thus, we used “highest possible profit” term instead of “highest profit”.

3.2 Highest ratio of highest possible profit (HRHPP) models (second step of the proposed method)

The objective functions of the multi-objective model are conflicting since maximizing a stakeholder’s profit causes a reduction in other stakeholders’ profits. The proposed method is based on this idea that all stakeholders need to receive at least the highest possible ratio of their highest possible profits from the basin’s water resources. In the proposed method, instead of maximizing the profit of each stakeholder, we maximize the reachability of the

highest possible profit that is measured as the ratio of λ_t where λ_t is the minimum of the ratios of actual profit to the highest possible profit across the stakeholders in time step t . Therefore the second step of our method is formulated as follows:

$$\text{Maximize } Z = \sum_{t=1}^T \lambda_t \tag{18}$$

where

$$\lambda_t = \min(\lambda_{1t}, \lambda_{2t}, \dots, \lambda_{kt}) \tag{19}$$

subject to constraints (6)–(16). Note that λ_{kt} is given by

$$\lambda_{kt} = \frac{\sum_{i_k=1}^{n_k} (\varphi_{i_k}^a \times x_{i_{kt}}^a + \varphi_{i_k}^u \times x_{i_{kt}}^u + \varphi_{i_k}^d \times x_{i_{kt}}^d)}{f_{kt}^*} \quad \forall t, k \tag{20}$$

In order to transfer the above max-min model to a maximum model we use the following transformation:

$$\text{Maximize } Z = \sum_t \lambda_t \tag{21}$$

subject to:

$$\sum_{i_k=1}^{n_k} (\varphi_{i_k}^a \times x_{i_{kt}}^a + \varphi_{i_k}^u \times x_{i_{kt}}^u + \varphi_{i_k}^d \times x_{i_{kt}}^d) \geq (\lambda_t \times f_{kt}^*) \quad \forall k, t \tag{22}$$

and constraints (6)–(16). The constraint (22) suggests that the profit of the stakeholder k in time step t ($\sum_{i_k=1}^{n_k} (\varphi_{i_k}^a \times x_{i_{kt}}^a + \varphi_{i_k}^u \times x_{i_{kt}}^u + \varphi_{i_k}^d \times x_{i_{kt}}^d)$) has to be greater than a ratio (λ_t) of its highest possible profit (f_{kt}^*), while λ_t is the same for all stakeholders to consider equity between the stakeholders. Note that the decision variables of this model include the allocated water to agriculture ($x_{i_{kt}}^a$), domestic use ($x_{i_{kt}}^u$), industry ($x_{i_{kt}}^d$), and λ_t . We denote HRHPP (Highest Ratio of Highest Possible Profit) to this model.

The HRHPP model gives the highest value to λ_t while it is mainly constrained by the stakeholders’ water resource limitation and also the stakeholders’ released water to downstream for satisfying the environmental water needs in time step t . It means that the model cannot increase the value of λ_t from a particular value due to the imposed limitation of a stakeholder to the model while the profits of other stakeholders can be more than $\lambda_t \times f_{kt}^*$ with regard to the constraint (22). Thus, λ_t would increase if we ignore that particular stakeholder as one competing stakeholder in the basin. Hence the solution obtained might be a dominated solution. To make sure that the solution is non-dominated, we introduce a multi-stage solution for the HRHPP model as follows:

The first stage is to solve the HRHPP¹ model by considering the constraints (6)–(16) and (22). We use abbreviation HRHPP^s (HRHPP^s is the HRHPP model for the stage s) to denote to the model in the first stage. The solution of this model gives the highest value for λ_t that satisfies all imposed constraints of stakeholders to the model. Let λ_t^1 (λ_t^s is the value of λ_t for the stage s) be the solution of HRHPP¹ model and g_t^1 be the set of stakeholders that $\lambda_t^1 = \lambda_{g_t^1}$ (for all t). The second stage is to find a new value for λ_t^s by ignoring g_t^1 from the model. For this purpose, we set the value of λ_t^1 ($t = 1, \dots, T$) in the constraint (22) for only g_t^1 ($t = 1, \dots, T$) and solve the HRHPP² model. In other words, the HRHPP² model

satisfies the water demand of the stakeholders which belong to g_t^1 ($t = 1, \dots, T$) in a way that their profits are at least $\lambda_t^1 \times f_{g_t^1}^*$ ($t = 1, \dots, T$). In this circumstance, the HRHPP² model is given by

$$\text{Maximize } Z = \sum_t^T \lambda_t \tag{23}$$

subject to:

$$\sum_{i_k=1}^{n_i} \left(\varphi_{i_k}^a \times x_{i_k t}^a + \varphi_{i_k}^u \times x_{i_k t}^u + \varphi_{i_k}^d \times x_{i_k t}^d \right) \geq (\lambda_t \times f_{kt}^*) \quad \forall k \text{ without } g_t^1, t \tag{24}$$

$$\sum_{i_m=1}^{n_i} \left(\varphi_{i_m}^a \times x_{i_m t}^a + \varphi_{i_m}^u \times x_{i_m t}^u + \varphi_{i_m}^d \times x_{i_m t}^d \right) \geq (\lambda_t^1 \times f_{mt}^*) \quad \forall m \in g_t^1, t \tag{25}$$

and constraints (6)–(16), where m is index for stakeholders which belong to g_t^1 set. Note that λ_t^1 ($t = 1, \dots, T$) are constants in the constraint (25). The solution of the HRHPP² model gives the value of λ_t^2 and also the set of stakeholders which belong to g_t^2 set. Other stages of this method are exactly similar to the stage 2. Put differently, in each stage, the stakeholders whose profit cannot increase anymore due to its limitation, are ignored from the model (are fixed in the constraints) and the new value of λ_t is maximized. These steps continue until the ratios of the stakeholders’ profits to their highest possible profits stay constant. The flowchart of the solution method is presented in ‘‘Appendix’’. The following proposition shows that the solution of the proposed method is non-dominated.

Proposition 2 *The solution obtained from the HRHPP models is non-dominated.*

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

$$\pi = \text{Min} \left(\sum_{t=1}^T y_{(N_E \rightarrow 0)t} \right) \tag{26}$$

subject to (6)–(16).

In other words, in the obtained solution there is some water released to the node 0 while it could be allocated to the stakeholders with unsatisfied demand and increase the λ_t values. However, the proposed method runs the HRHPP model until none of λ_{kt} can be increased any more. This contradict completes the proof.

4 The application of the models

4.1 Case study area: the Sefidrud Basin

The multi-objective water allocation model and the proposed solution method are employed to resolve water disputes in the Sefidrud Basin, north-western of Iran. The area of the Basin is 59,217 km² and encompasses eight administrative provinces, namely, Kordestan (Province 1), Hamedan (Province 2), Zanzan (Province 3), East Azarbaijan (Province 4),

Table 1 The areas, the future agricultural demand, and the water profit for agriculture sectors of the stakeholders (MGC 2011)

Province	Area (%)	Future demand (MCM)	Agricultural water profit ^a
1	23	1,029	440
2	3	126	440
3	31	1,967	1,515
4	20	753	1,836
5	7	447	1,836
6	2	410	1,417
7	7	431	1,417
8	7	2107	1,933
Sum	100	7,270	–

^a Unit: Rial/M³, Rial is the Iranian money currency (1 US dollar = 9,000 Rial, in the same date that the agricultural water value was assessed)

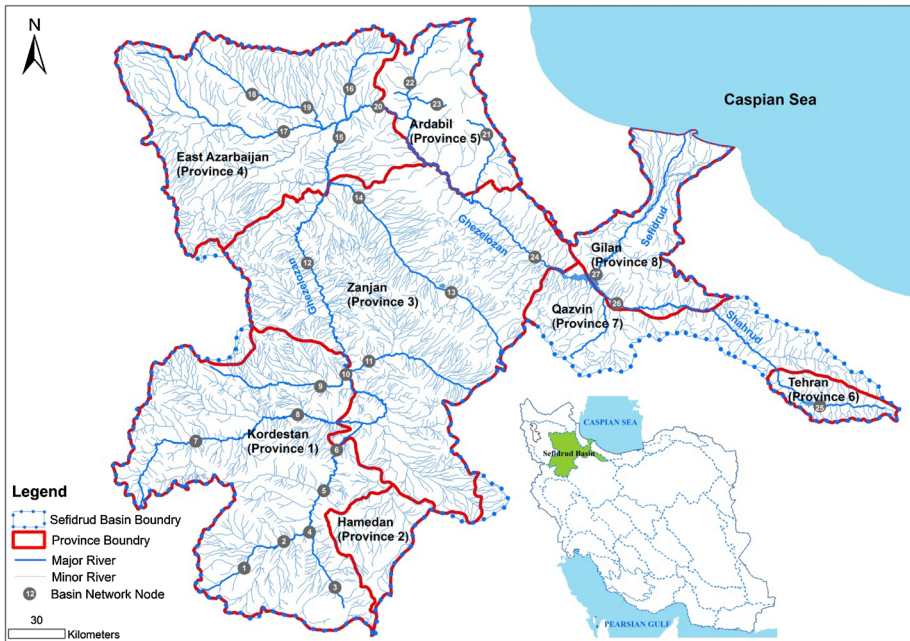


Fig. 1 The location of the Sefidrud Basin and its stakeholders

Ardabil (Province 5), Tehran (Province 6), Qazvin (Province 7), and Gilan (Province 8). Table 1 shows the area of each province in the Basin. Figure 1 shows the Basin’s location in Iran and its stakeholders. The Basin current population is 2.1 million and it is estimated to increase to 2.24 million in 2025 (MGC 2011). According to the definition of a transboundary basin, introduced by Breils et al. (2008), the Sefidrud Basin is a transboundary basin.

The annual average precipitation in the north part of the Sefidrud Basin (Province 8) is about 1,000mm while it is from 200 to 400mm in its south (Provinces 1–7). The annual average temperature in the Basin is between –5 and 25 °C, which tends to be warmer in the south than the north. The Sefidrud River is the main waterway in this Basin. It goes through

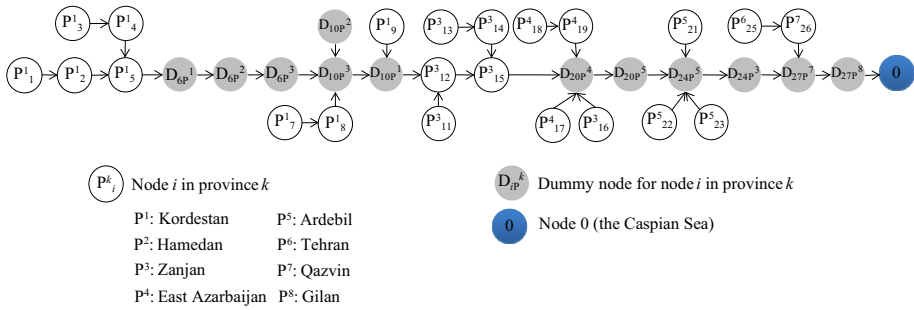


Fig. 2 The Sefidrud Basin network

the Provinces 1–8 and finally releases to the Caspian Sea. The total water supply of the Basin is 7,615 million cubic meters (MCM) whose share of surface water is 81.6% (MGC 2011). The agricultural water requirement accounts for 91% of the Basin’s water demands while the shares of municipal and industrial sectors are 8 and 1% (MGC 2011), respectively. Because of their very low shares in total water use, the water uses of municipal and industrial sectors were assumed to be zero in our case study. The annual agricultural water demand for 2025 is estimated to be 7,270 MCM that it is expected to be the future water demand of the Basin (MGC 2011). Table 1 shows the future demand of the Basin, as well as the agricultural water profit for each province.¹ The comparison of the Basin water resources and the province’s future demands shows that the Basin faces with a huge water shortage. Therefore, the provinces struggle uncooperatively to utilize more water for satisfying their demands. This competition causes a water conflict in this basin.

Figure 2 shows the Sefidrud Basin network. It includes supply/demand nodes scattered among eight provinces. The main streamflow gauge stations in the basin were considered to be nodes in the network. These supply/demand nodes provide the surface water for the agricultural uses in their vicinities. We also replaced shared nodes in the network with dummy nodes to calculate easily the water share of associated stakeholders in the shared nodes.²

In this study, the environmental water requirement in each node is calculated, utilizing the modified Montana method (Torabi Palatkaleh et al. 2010a). Montana (Tennant 1976) is the most renowned method for determining the environmental water requirement, which was developed in the USA. Tennant (1976) established some classes of flow classifications to associate habitat quality with various percentages of mean annual flow. These classes, which are for various conditions of habitat quality on a seasonal basis, are presented in Table 2. Note that, the Modified Montana method (Torabi Palatkaleh et al. 2010a) estimates the environmental water need based on a percentage of the mean monthly flow in the node, instead of the mean annual flow. In this work, the percentages for “Fair or degrading” environmental status are taken into account (10% mean monthly flow for October to March and 30% mean monthly flow for April to September). These percentages are officially accepted by the Iranian water authorities to be considered for calculating the environmental water requirements of rivers in Iran (Torabi Palatkaleh et al. 2010b).

¹ The reader is referred to Roozbahani et al. (2013) for the detailed description of water resources and water demands in this Basin.

² More details about the nodes’ runoff and demand are available in Roozbahani et al. (2013).

Table 2 Percentages of mean annual flow required for maintaining the specific habitat quality (Torabi Palatkaleh et al. 2010a)

Environmental status	Percentage of mean annual flow	
	Low flow season	High flow season
Optimum range	60–100	60–100
Outstanding	40	60
Excellent	30	50
Good	20	40
Fair or degrading	10	30
Poor	10	10
Severe degradation	<10	<10

4.2 Results

The stakeholders' demands in 2025 (Table 1) represent their water requirements for maximum socio-economic developments (MGC 2011) and thus, we considered them in this study. In addition, the Basin discharge during 1975–2007 has no statistically significant trend, positive or negative (MGC 2011), therefore, we used the discharge of the Basin for this period in the present study. With regards to the numbers of years in this period and given that the model is monthly, the number of time steps is 600 (50 years \times 12 months = 600 time steps). Demand satisfaction in 90% of time steps was considered a major reliability criterion for supplied water to the environment in the Basin (Torabi Palatkaleh et al. 2010b). Thus, the amount of R in the HPP models and the HRHPP model is equal to $0.90 \times 600 = 540$. All models were solved using IBM ILOG CPLEX Optimization Studio (IBM). The results of the HPP and the HRHPP models will be discussed in the next sub-sections.

4.2.1 The results of the HPP models

Since eight provinces constitute the Sefidrud Basin, eight mixed-integer linear programming models (the HPP models) were developed. In this section, numbered models refer to the HPP models for the corresponding provinces. For an example, Model 1 maximizes the profit of Province 1. Table 3 shows the annual average profits of Provinces given by the HPP models. The minimum profit of each province is bold faced and underlined. As shown in this table, Model 1; which brings about the highest possible profit for Province 1, causes the minimum profits of Provinces 2, 3, and 6. Model 3, which maximizes the profit of Province 3, brings about the minimum profits of Provinces 1, 4, 5 and 8. Table 3 shows that the profit of Province 1 is mainly in conflict with the profit of Provinces 2, 3, and 6 and Province 3's profit is mainly in conflict with Province 1, 4, 5, and 8 profits. There is also a conflict of interest between Province 7 and Province 6. Table 3 clearly illustrates the water conflicts in the Basin. In other words, selfish utilizing water by a province directly causes a reduction on the profits of other provinces. It should be noted that the aim of the HPP models' developments is to compute the highest possible profits of the stakeholders when there is no any obligation or limitation for the satisfaction of the stakeholders. Therefore, it is assumed when for instance the HPP model wants to maximize the profit of the stakeholder 8 (placed downstream), it has a dominated control on water resource of the Basin and could transfer all of it to downstream even in time steps with no sufficient water.

Table 4 illustrates the ratio of provinces' profits given by the HPP models to their highest possible profit. For an example, the ratio of Province 1's profit, given by Model 8, to the

Table 3 The stakeholders’ profits given by the HPP models (unit: billion Rials)

Province	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
1	175	57^a	59	60	62	62	62	57
2	5	40	7	7	7	7	7	7
3	627	749	1,748	773	807	768	721	701
4	637	713	427	1,176	689	706	658	671
5	316	361	211	330	611	369	337	331
6	84	86	108	110	108	222	86	99
7	186	186	136	139	136	121	510	125
8	3,605	3,672	3,004	3,305	3,527	3,681	3,483	3,807

^a The minimum profit of each province is bold faced and underlined

Table 4 The percentage of provinces’ profits given by the HPP models to their highest possible profits

Province	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
1	100	32	33	34	36	36	36	32
2	14	100	18	19	19	18	19	18
3	36	43	100	44	46	44	41	40
4	54	61	36	100	59	60	56	57
5	52	59	34	54	100	60	55	54
6	38	39	49	50	49	100	39	45
7	36	36	27	27	27	24	100	24
8	95	96	80	87	93	97	91	100

highest possible profit of Province 1 is equal 32%. It means when Model 8 maximizes the profit of Province 8, the allocated water to Province 1 by this model only makes profit for Province 1 equal to 32% of its highest possible profit. As shown in this table, Province 8’ profit has fluctuated around 20% (often less than 10%) of its highest possible profit (3,807 Billion Rials) while for other provinces it is at least more than 40%. For an example, the fluctuation of Province 2 is varied from 81 to 86%. In short, the water share of Province 8 from the Basin’s surface water resource, which is located at the Basin downstream, does not significantly depend on the allocated water to other provinces, while this in not the case for others. The reason of this circumstance is that all HPP models have to satisfy the environmental water requirement of all nodes in the entire Basin in 90% of times. Hence, all models release water from upstream regions to downstream area (Province 8) to satisfy this constraint, regardless of water shortages in upstream regions. However, Province 8 could use surplus water, which exceeds the environmental water requirement of the last node in the network for supplying its water requirements.

4.2.2 HRHPP models results

The solutions of the HRHPP¹ and HRHPP² models show the Basin water resources can equitably be shared between Provinces 1 and 8 in two stages. In the first stage, solving the HRHPP¹ model, the given value to λ_t by the model for 411 time steps out of 600 time steps are equal to the calculated ratios of the stakeholders’ profits to their highest possible profits

Table 5 The given value of λ_{445}^1 by the HRHPP¹ model and the ratio of stakeholders' profits to their highest possible profits

Time step	λ_{445}^1 ^a	Province							
		1	2	3	4	5	6	7	8
445	0.698	0.749	0.698	0.897	1.000	1.000	0.698	0.698	1.000

^a Given value by the model

Table 6 The given value to λ_{445}^2 by the HRHPP² model and the ratio of stakeholders' profits to their highest possible profits calculated manually

Time step	λ_{445}^2	Province							
		1	2	3	4	5	6	7	8
445	0.970	0.970	0.698	0.970	1.000	1.000	0.698	0.698	1.000

using the decision variables. In other words, the HRHPP¹ model shares water between the stakeholders in a way that they receive exactly the same ratio of their highest possible profits in these time steps. For 189 time steps, the values of λ_t^1 are set to the constraint (22) in the HRHPP² model for the corresponding stakeholders, which limit the value of λ_t^1 . Similarly, λ_t^1 are set to the constraint (22) in HRHPP² model, but for all stakeholders in aforementioned 411 time steps.

For instance, the outputs of the models corresponding to the value of λ for two time steps, 445 and 537 are presented. Table 5 illustrates the given value to λ_{445}^1 by the HRHPP¹ model for time step 445 (λ_{445}^1) and the ratio of stakeholders' profits to their highest possible profits using the outputs of the model.

As shown in this table, the given value to λ in time step 445 by the model is 0.698 when the ratios of the stakeholders' profits to their highest possible profits are between 0.698 to 1.000. This ratio for Province 2, 6, and 7 is equal to λ . It shows the corresponding constraints of Provinces 2, 6, and 7 constrict the model to give values more than 0.698 to λ . The model allocates water to Provinces 1, 3, 4, 5, and 8 in a way that the ratios of their profits to their highest possible profits are more than 0.698 (0.749, 0.897, 1, 1, and 1, respectively) due to the constraint (22) which allows the model to allocate more water to other provinces. Therefore, the HRHPP² model is solved to find a fair λ (λ_{445}^2) for these provinces. Table 6 shows the result of the HRHPP² model corresponding to the value of λ_{445}^2 and the ratio of stakeholders' profits to their highest possible profits calculated manually using the values of the model's decision variables.

As illustrated in the table, the given value to λ_{445}^2 by the model is 0.970 and the ratios of Provinces 1, 3, 4, 5, and 8 profits to their highest possible profits are 0.970, 0.970, 1, 1, and 1, respectively. These results describe that the HRHPP² model shares water between these provinces as a manner that Provinces 1 and 3 can make more profits and consequently higher ratios in comparison with the results of the HRHPP¹ model. As shown in Tables 5 and 6, the ratios of Provinces 4, 5, and 8 profits to their highest possible profits in both tables are 1. It means that the available water resources for these provinces are more than their water requirements. The amount of releasing water to the Caspian Sea in this time step confirms previous explanation when the environmental water requirement for the last node in the Basin network is 18.7 MCM and the water released to the Caspian Sea is 191 MCM.

Table 7 The given value of λ_{537}^1 by the HRHPP¹ model and the ratio of stakeholders’ profits to their highest possible profits calculated manually

Time step	λ_{537}^1	Province							
		1	2	3	4	5	6	7	8
537	0.229	0.229	0.229	0.229	0.229	0.229	0.229	0.229	0.229

Table 8 The yearly averages of allocated water to provinces by the HRHPP² model

Province →	1	2	3	4	5	6	7	8	Basin
Water allocated (MCM)	288	56	760	397	207	113	221	1,194	3,234
Shortage (%)	72	56	61	47	54	73	49	43	56

Table 7 illustrates the given value to λ_{537}^1 by the HRHPP¹ model. As shown, the value of λ_{537}^1 and the ratio of stakeholders’ profits to their highest possible profits are equal. It means that in this time step the model allocates water to the stakeholders as a manner that they make profits only 0.229 of their highest possible profits from utilizing their water share.

Here we report the final results of water allocation obtained from the HRHPP² model. The yearly average of allocated water to each province is shown in Table 8. As presented in Table 8, the total surface water allocated to stakeholders is 3,234 MCM.

According to Table 8, Provinces 8 and 2 have the largest and the smallest portions of the Basin’s surface water with 1,194 and 56 MCM, respectively. In addition, Provinces 8 and 6 have the smallest and the largest water shortages in the Basin with 43 and 73 %, respectively. The monthly averages of allocated water to the provinces are also presented in Fig. 3. In this figure, we compare the monthly averages of allocated water to the provinces by the HRHPP models with maximum and minimum allocated water to them by the HPP models. For an example, Fig. 3a corresponds to Province 1. The light blue curve represents the allocated water to Province 1 by Model 1 which maximizes the profit of Province 1. The dark blue curve represents the allocated water to Province 1 by the HRHPP models and finally the red curve represents the allocated water to Province 1 by a model that maximizes the profits of all stakeholders except Province 1. As shown in Fig. 3, the competition over water utilization concentrates on the spring and summer (months 7–12) while the main parts of the stakeholders’ water requirements in the autumn and winter (months 1–6) are satisfied. Note that month 1 is from 23rd September to 23rd October.

4.3 Water development opportunities

As shown in Tables 1 and 8, the Basin’s water demand in 2025 is 7,270 MCM while the Basin’s surface water resource is only able to satisfy 3,234 MCM and the Basin confronts with 4,036 MCM water deficit. The Basin water development through dam construction is an option to tackle the Basin’s water shortage issue; however, undoubtedly, the negative effects of water development in the Sefidrud Basin need to be examined by its water authority before any water development action. The capacity of the Basin for water development was also evaluated using the HRHPP² model’s results. Water released to the Caspian Sea (the model’s output) and the monthly environmental water supply in the last node in the Basin network are presented in Fig. 4. The total difference of these values was considered as the water

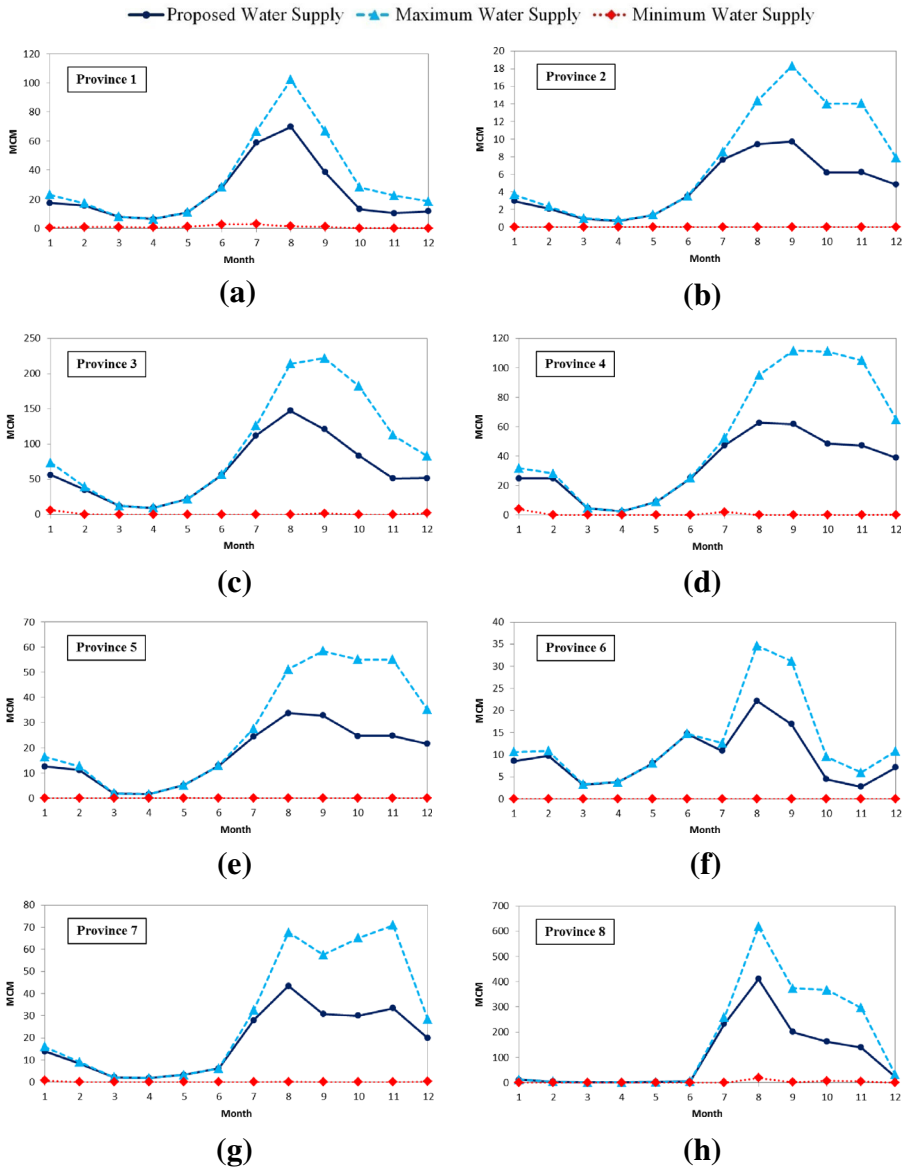


Fig. 3 The maximum, minimum, and proposed (by the HRHPP² model) water supplied to the stakeholders (the values are the average of 50 years). **a** Maximum (possible), minimum, and proposed allocated water to Province 1. **b** Maximum (possible), minimum, and proposed allocated water to Province 2. **c** Maximum (possible), minimum, and proposed allocated water to Province 3. **d** Maximum (possible), minimum, and proposed allocated water to Province 4. **e** Maximum (possible), minimum, and proposed allocated water to Province 5. **f** Maximum (possible), minimum, and proposed allocated water to Province 6. **g** Maximum (possible), minimum, and proposed allocated water to Province 7. **h** Maximum (possible), minimum, and proposed allocated water to Province 8

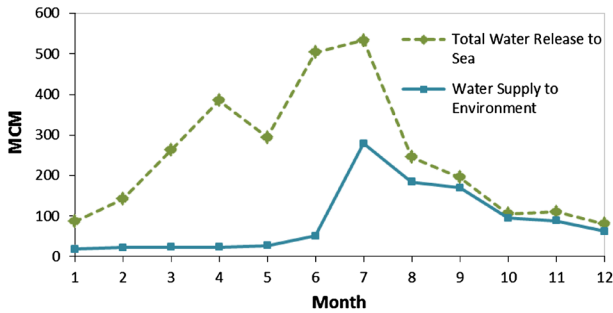


Fig. 4 The comparison of monthly averages water released into the Caspian Sea and the water supply to the environment in last node in the Basin network (the values are the average of 50 years)

development capability for the Basin. The annual average of water released to the Caspian Sea (without considering the water supply to the environment) is 1,852 MCM where the portions of months 1–6 (autumn and winter) and months 7–12 (spring and summer) are 79 and 21 %, respectively. This result shows the Basin water authority is able to plan for regulating 1,852 MCM through constructing new dams. By considering the volumes of allocated water to stakeholders (3,234 MCM) and the total capacity of the new dams (1,852 MCM), the potential of the Basin surface water resource for satisfying the water demands is 5,086 MCM. In other words, the Basin’s stakeholders are able to use 5,086 MCM out of 6,214 MCM of the Basin’s surface water resources when the satisfaction of the environmental water demand is considered to be a sustainable water development criterion for the water allocation modelling.

5 Conclusions

A mixed-integer multi-objective model was proposed for sustainable water allocation of a multi-stakeholder river basin. The proposed model maximizes the profits of stakeholders simultaneously, while, water requirement of the environment in the entire basin satisfied. A new approach has been introduced for solving the proposed model due to the difficulties of assigning weights to objective functions and justifying them. The approach, first, finds the highest possible profits for the stakeholders (the HPP model) and then maximizes sequentially the minimum ratio of stakeholders’ profits achieved by their water shares to their highest possible profits in each time step until obtaining a non-dominated solution (the HRHPP model).

The multi-objective model and the proposed approach have been applied to the Sefidrud Basin. It is an underdeveloped watershed and all its stakeholders (eight provinces) confront with rising water requirements for developing various sectors. Thus, there are severe competitions between the stakeholders for utilizing more water in their territories, especially between upstream and downstream stakeholders. The results of the HPP model showed that the profit of Province 1 is mainly in conflict with the profit of Provinces 2, 3, and 6 and Province 3’s profit is mainly in conflict with Province 4, 5, and 8 profits. Moreover, the water share of Province 8, which is located at the Basin downstream, does not significantly depend on the allocated water to other provinces. The results of the HRHPP model’s implementation showed that the Basin’s water resources could equitably be allocated to its stakeholders in two stages. The water shares of the stakeholders based on the HRHPP² model are 288, 56, 760, 397, 207, 113, 221, and 1,194 MCM for Provinces 1–8, respectively. In addition, based

on the outputs of the HRHPP² model, the maximum potential of the Basin for water development (new dams water regulating) is 1,852 MCM. The approach's implementation results presented a fair distribution of incomes in the Sefidrud Basin when it allocated more water to the upstream provinces in comparison with the current water allocation scheme of the Basin which more water is utilized by downstream stakeholder (Province 8).

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Appendix

See Figs. 5 and 6.

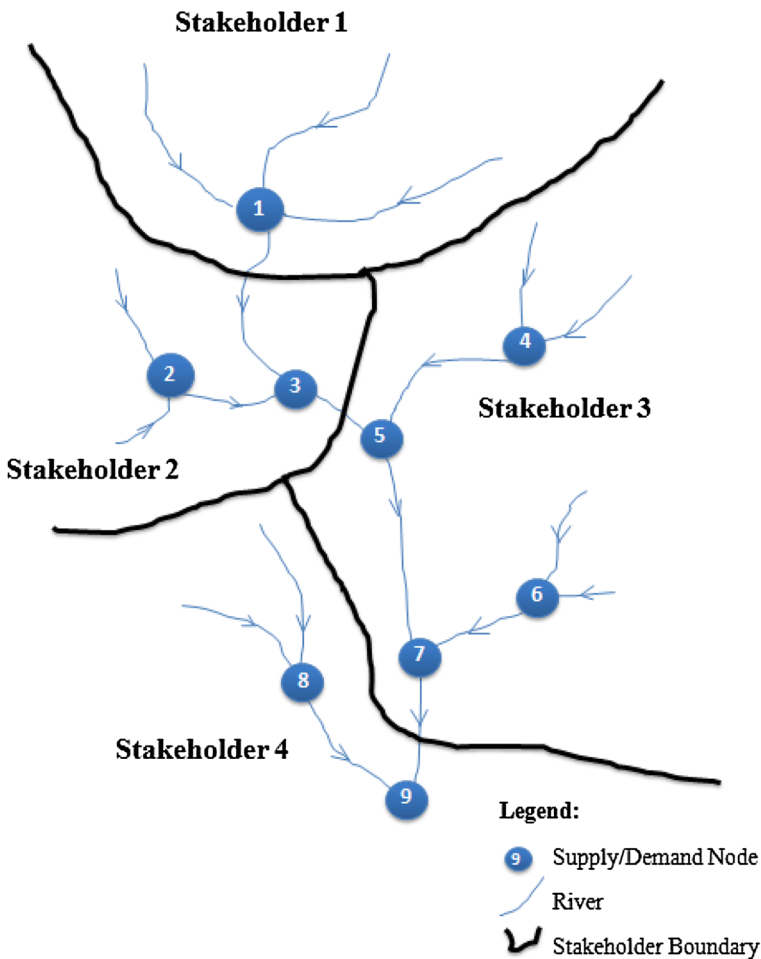


Fig. 5 A sample of river node scheme

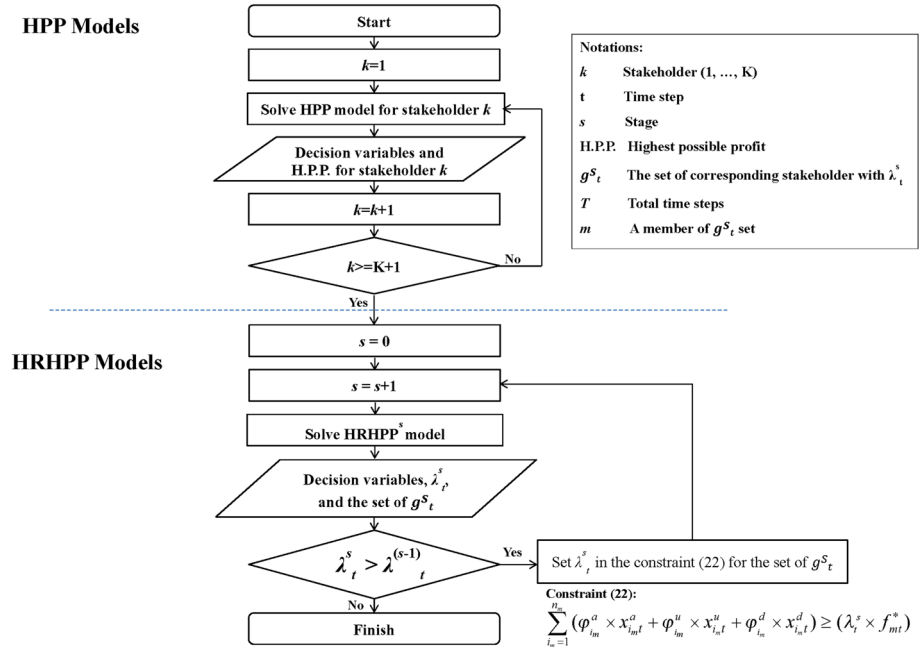


Fig. 6 Solution method flowchart

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