

Determining Location and Capacity of Dams through Economic and Environmental Indicators

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Abstract Construction of dams is a conventional way to deal with the problem of water scarcity in undeveloped basins. The economic and the environmental effects of dams are often evaluated locally rather than in a basin frame. The distinctive feature of this paper is to propose a basin-wide approach, comprised three steps for determining dams' locations and dams' capacities based on optimization modelling. Our approach provides an environmentally sound plan for surface water development that also results in the highest profit for the basin, for the sake of achieving sustainable development. The first step of our approach runs a mixed-integer linear model to give optimal locations and capacities of new dams for various number of dams along with satisfying the environmental water requirements in the entire basin. The second step uses a sensitivity analysis to finalize the number of dams in the basin by comparison of the basin profits, given by the various number of dams. Finally, the third step of the algorithm investigates the possibility of dams' capacities reduction, for the selected number of dams while they still provide the same basin profit, given from the first step, using another mixed-integer linear model. The introduced approach was applied to the Sefidrud Basin, Iran and its results showed that three dams could lead to an environmentally sound sustainable economic development for the Basin.

Keywords Mixed-integer programming · Dam location-allocation · Surface water development · Economic and environmental indicators

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1 Introduction

Water is becoming more scarce and valued due to water demands increase caused by population growth. The climate change also makes the trends of rainfall more severe and less assured. In these circumstances, dams find a high status in basins water management, not only for increasing the reliability of water supply to requirements, but also for raising water security in watersheds. The conventional method of choosing the locations and capacities of dams relies on geology, engineering, economic, and the environmental studies. In that case, the economic and the environmental consequences of dams' constructions are assessed independently for each dam and most attention is focused on their local economic and the environmental effects. In these circumstances, the impacts of dams on the economy and the environment of the entire basin were neglected. Based on sustainable water development standpoints, the combined effects of all dams on the economy and the environment of the entire basin should be assessed in the first instance.

This paper introduces an environmentally rigorous three-step approach for dams' location-allocation in an undeveloped basin. The word "allocation" in the "location-allocation" formula means the capacity of a dam, whereas the word "location" is referred to the position of the dam, in other words, in which node it is proposed to be constructed. The aim of this approach is to specify the optimal locations and capacities of new dams by taking into consideration their integrated consequences on the economic and the environment of the entire basin. Put differently, the approach ascertains the locations and capacities of new dams in a way that the basin is led to sustainable economic development, while the environmental water requirements have to be satisfied in the entire basin. In the first step, a mixed-integer linear model runs for various numbers of new dams to yield the optimal locations and capacities of dams. Second step utilises a sensitivity analysis to find the ideal number of dams for the basin. Third step searches for new lower capacities for the dams while they provide the same profit for the basin, given from the first step. The proposed approach prepares a faithful perspective of water resources development for the basin, however, the capital outlay for the construction of dams is not considered in the present approach, due to no possibility of assessing it for all possible dams' locations in the watershed. Moreover, finalizing the location and capacity of a new dam needs supplementary studies similar tectonic and geological ones and somehow a proposed location is rejected due to a geological problem in that spot. Therefore, the results of the approach can be viewed as an initial plan of water development in a watershed and its results need to be verified by the future detailed supplementary hydro-engineering studies. In addition, the results of the approach help to decrease the cost of detailed hydro-engineering studies, due to focusing of these engineering studies on the specific locations, identified by the model presented in this work, rather than all possible dams' spots in the watershed. The novelty of this study is to use optimisation techniques for determining dams' locations and dams' capacities, which were not employed for these purposes so far.

The paper structure is as follows. Section 2 consists of a review of the literature. Section 3 describes the proposed model. The Sefidrud Basin, which is the case study area, is briefly described in Section 4. The results of the model implementation are presented in Section 5, followed by conclusions and discussion in Section 6.

2 Literature Review

Operations Research has a known reputation for solving associated issues of natural resource industries (Plà et al. 2014). Optimisation techniques have supported many studies

conducted in area of water resources management such as scheduling canal irrigation (Anwar and Clarke 2001), operating reservoir systems (Srinivasan et al. 1999; Tabari and Soltani 2013), urban water management (Qin and Xu 2011; Zarghaami and Hajykazemian 2013), the environmental water management (Szemis et al. 2013; Yang 2011), and groundwater management (Park and Aral 2004; Singh et al. 2013). These techniques have also been used to handle water allocation problems such as conjunctive use of surface and groundwater resources (Singh and Panda 2012), water allocation of unshared basins (Karimi and Ardakanian 2010; Ahmadi et al. 2012), and water conflicts resolution in transboundary basins (McKinney and Cai 1997; Wang et al. 2004; Kucukmehmetoglu and Guldmann 2010; Roozbahani et al. 2015a). Although, there are copious studies in the literature on the applications of optimisation techniques for water resources management, to the best of our knowledge, there were no studies for treating the problem of determining dams' locations and dams' capacities by optimisation modelling.

In fact, the problem considered in the present work, focusing on identification of optimal position and volume of dams in a basin, can be classified as a location-allocation problem. Location-allocation refers to mathematical models that determine the optimal location for facilities. These models take into consideration the location and demand of customers, the capacity of the facilities, and transport costs. These factors are utilized in order to calculate the number of facilities to be developed, together with their capacity and location. Location-allocation models have been applied in various areas such as a healthcare facility planning (Shariff et al. 2012), logistics (Ishfaq and Sox 2011), supply chain (Zhou et al. 2002), solid waste management (Caruso et al. 1993), and many others. The concepts used in this study resemble the well-studied location-allocation models but has substantive district features. The aim of the present study is to determine how the optimization approach can contribute to the solution of problem what the best locations and volumes of dams are in a particular watershed.

3 Proposed Approach

This section firstly introduces notations and variables that are used in mathematical models, developed in the present work. Then, it explains the proposed approach.

3.1 Notations

3.1.1 Sets and Indices

a : is the superscript for the agricultural sector;

u : is the superscript for the urban sector;

d : is the superscript for the industrial sector;

k : is the index for stakeholder;

t : is the index for time step, which can be a month, a half year, or a year;

κ : is the set of stakeholders, for instance $\{1, 2, 3, \dots, K\}$ where K is the maximum number of stakeholders;

v_k : is the set of nodes in stakeholder $k(k \in \kappa)$;

i_k : is the index for node i that belongs to stakeholder k ;

π_{ik} : is the set of nodes that are adjacent neighbour of node i_k and are located in the upstream of node i_k ;

i'_k : is the node that is adjacent neighbour of node i_k and is located in the downstream of node i_k ;
 τ : is the set of time steps, for instance $\{1, 2, 3, \dots, T\}$ where T is the maximum number of time steps.

3.1.2 Decision Variables

$x_{ik,t}^a$: is water allocated to agriculture in node i_k at time t ($k \in \kappa, i \in \nu_k, t \in \tau$);
 $x_{ik,t}^u$: is water allocated to urban sector in node i_k at time t ($k \in \kappa, i \in \nu_k, t \in \tau$);
 $x_{ik,t}^d$: is water allocated to industry in node i_k at time t ($k \in \kappa, i \in \nu_k, t \in \tau$);
 z_{ik}^Δ : is a binary variable that has assigned value of 1 if there is a dam in node i_k ($k \in \kappa, i \in \nu_k$) and 0 otherwise;
 $C_{i_k}^\Delta$: is the capacity of the dam in node i_k , it is 0 if there is no dam in node i_k ($k \in \kappa, i \in \nu_k$);

3.1.3 Others Variables

$AP_{ik,t}$: is agricultural profit associated with node i_k at time t ($k \in \kappa, i \in \nu_k, t \in \tau$);
 $UP_{ik,t}$: is urban profit associated with node i_k at time t ($k \in \kappa, i \in \nu_k, t \in \tau$);
 $IP_{ik,t}$: is industrial profit associated with node i_k at time t ($k \in \kappa, i \in \nu_k, t \in \tau$);
 $S_{ik,t}$: is water stored 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 water transferred from the node i_k to node i'_k at time t ($k \in \kappa, i \in \nu_k, t \in \tau$);
 $R_{(l \rightarrow i_k)_t}$: is water transferred from the 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 a dam in node i_k at time step t ($k \in \kappa, i \in \nu_k, t \in \tau$) if full and 0 otherwise;
 $z_{i_k,t}^\varepsilon$: is a binary variable, which equals 1 if the environmental water demand in node i_k at time step t is satisfied and 0 otherwise.

3.1.4 Input and Internal Modelling Parameters

$\rho_{i_k}^a$: is a marginal agricultural net benefit of allocating 1 unit water to agriculture in node i_k ($k \in \kappa, i \in \nu_k$);
 $\rho_{i_k}^u$: is a marginal urban net benefit of allocating 1 unit water to the domestic sector in node i_k ($k \in \kappa, i \in \nu_k$);
 $\rho_{i_k}^d$: is a marginal industrial net benefit of allocating 1 unit water to industry in node i_k ($k \in \kappa, i \in \nu_k$);
 $\nu_{i_k,t}$: is water produced in node i_k ($k \in \kappa, i \in \nu_k, t \in \tau$) at time t . It actually is the water harvested between nodes $l \in \pi_i$ and node i_k ;
 n : number of required dams;
 M : is a large constant number;
 R^ψ : is the reliability level that shows the number of times that dams' reservoirs must be full;
 R^ε : is the reliability level that shows the number of times that the environmental water needs must be satisfied over the total period the algorithm is implemented;
 $\xi_{i_k,t}$: is agricultural water demand in node i_k , at time t ($k \in \kappa, i \in \nu_k, t \in \tau$);
 $\psi_{i_k,t}$: is urban water demand in node i_k , at time t ($k \in \kappa, i \in \nu_k, t \in \tau$);
 $\eta_{i_k,t}$: is industrial water demand in node i_k , at time t ($k \in \kappa, i \in \nu_k, t \in \tau$);

$\varsigma_{i_k t}$: is environmental water demand of node i_k at time $t(k \in \kappa, i \in \upsilon_k, t \in \tau)$, it has to flow in rivers;
 IV_{i_k} : is the initial volume of water in dam $i_k(k \in \kappa, i \in \upsilon_k)$ if there is a dam in node i_k otherwise it is 0.

3.2 Three-Step Approach of the Proposed Algorithm

The proposed algorithm consists of three steps. During Step 1 the algorithm runs a model called Maximum Profit (MaxPro) for several numbers of dams (n) (scenarios), given to the model. In each run, the model maximises the basin's profit by considering the given number of dams (n). For each scenario, the MaxPro model presents the best locations and capacities of dams and water shares of the basin's stakeholders. For Step 2 algorithm provides the decision on the number of required dams for the basin by undertaking a sensitivity analysis on the outputs of the MaxPro model for various scenarios (numbers of dams). During Step 3, a model called Minimum Capacity (MinCap) runs to find out the possibility of decreasing dams' capacities for the selected scenario (by Step 2), while they still provide the same profit for the basin, achieved from MaxPro model during implementation of Step 1. The objective function of the MinCap model is to minimize the summation of dams' capacities. These three steps are described in details in the following sub-sections.

3.2.1 Step 1: Multiple Running of MaxPro Model for Several Scenarios

MaxPro is a mixed-integer linear programming model. It maximises the basin's profit achieved from water allocated to various sectors such as agricultural, urban, and industrial in the entire basin. The model's objective function is subjected to water availability, water balance, environmental demands, and water use constraints. The model formulation is based upon a node-link network of the basin. In this network, nodes represent the sources (produced water) and demands and arcs represent the water flow. The water resources of each node are comprised of midstream produced water and transferred water from upstream nodes. Agricultural, municipal, and industrial water demands are considered as the total water demands of the nodes. In addition, satisfaction of the environmental requirement in each node is a firm constraint in the model. Each node is considered as a potential location for construction of a dam. In this study, the main runoff gauges in a basin are expected to be nodes because runoff gauges are practically positioned in narrow gorges between mountains or hills where the geometry is relatively stable and they are treated as suitable spots for dam construction.

The Objective Function of MaxPro Model The objective function of MaxPro is to maximize the total net benefits of water uses in the entire basin from surface water resources:

$$\text{Maximize } Z_{\text{MaxPro}} = \sum_{k \in \kappa} \sum_{i_k \in \upsilon_k} \sum_{t \in \tau} (AP_{i_k t} + UP_{i_k t} + IP_{i_k t}) \quad (1)$$

The variables $AP_{i_k t}$, $UP_{i_k t}$, and $IP_{i_k t}$ are calculated using eqs. (2)–(4):

$$AP_{i_k t} = \rho_{i_k}^a \times x_{i_k t}^a \quad \forall k, i_k, t \quad (2)$$

$$UP_{i_k t} = \rho_{i_k}^u \times x_{i_k t}^u \quad \forall k, i_k, t \quad (3)$$

$$IP_{i_k t} = \rho_{i_k}^d \times x_{i_k t}^d \quad \forall k, i_k, t \quad (4)$$

The relationship between the water profit of each sector (agricultural, urban or industrial) and water allocated to it is not always linear and there is not a fixed water profit for all range of

water allocation to a sector. We aim to find the optimal locations and capacities of new dams by maximising the basin achieved profit from bulk water allocation to a sector of the stakeholders in the basin. 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. The algorithm requires this inevitable simplification.

The Constraints of the MaxPro Model The model’s constraints are presented as follows:

1. Flow balance at node i :

$$S_{i_k(t+1)} = S_{i_k t} + \nu_{i_k t} + \sum_{l \in \pi_{i_k}} R_{(l \rightarrow i_k)t} - R_{(i_k \rightarrow l')_t} - x_{i_k t}^a - x_{i_k t}^u - x_{i_k t}^d \quad \forall k, i_k, t \tag{5}$$

2. Number of dams in the basin:

$$\sum_{k \in \kappa} \sum_{i_k \in \nu_k} z_{i_k}^\Delta = n \tag{6}$$

Constraint (6) specifies the number of dams in the model. For instance, $n = 1$ (as a given parameter to the model) means the model considers only one dam in the basin and optimizes allocating water to the stakeholders. The maximum number of dams is equal to the maximum number of nodes in the basin, when dams are proposed in all nodes.

3. Stored water in dam i_k and its capacity:

$$-S_{i_k t} + C_{i_k}^\Delta \geq 0 \quad \forall k, i_k, t \tag{7}$$

$$S_{i_k t} - C_{i_k}^\Delta + M \times (1 - z_{i_k t}^\psi) \geq 0 \quad \forall k, i_k, t \tag{8}$$

$$\sum_{t \in \tau} z_{i_k t}^\psi - R^\psi \times z_{i_k}^\Delta \geq 0 \quad \forall k, i_k \tag{9}$$

$$-C_{i_k}^\Delta + M \times z_{i_k}^\Delta \geq 0 \quad \forall k, i_k \tag{10}$$

Constraints (7), (8), and (9) work together to determine the capacity of dam i_k and the variable $z_{i_k t}^\psi$ has a key role for that purpose. As it showed above, Constraint (7) points to the fact that the water stored in dam i_k at time t ($S_{i_k t}$) has to be less than or equal to its capacity ($C_{i_k}^\Delta$). Constraint (8) indicates the water stored in dam i_k at time t ($S_{i_k t}$) has to be greater than or equal to its capacity ($C_{i_k}^\Delta$) when $z_{i_k t}^\psi$ is equal to 1. When $z_{i_k t}^\psi$ is 1 at time t , Constraint (8) is changed to $S_{i_k t} \geq C_{i_k}^\Delta$ while Constraint (7) is $S_{i_k t} \leq C_{i_k}^\Delta$. In this circumstance, the model forces the capacity of dam i_k ($C_{i_k}^\Delta$) to be equal to the stored water in dam i_k at time t ($S_{i_k t}$). By Constraint (9), it is asked to the model to consider the value of $z_{i_k t}^\psi$ equal to 1 in at least R^ψ time

steps out of total time steps. Put differently, the model assigns a value to the capacity of dam i_k ($C_{i_k}^\Delta$) that in fact is the stored water in dam i_k in R^{ψ} time steps. The nature of the model's objective function is to increase the profit of the basin by allocating more water to various water uses. Therefore, this formulation gives the efficient value for the capacity of dam i_k . The main goal of this algorithm is to provide an optimum initial plan for water development of the basin and the optimization of reservoirs operations is out of scope of this study.

Note that $z_{i_k}^\Delta$ is 0 when there is no dam in node i_k . In this circumstance, Constraint (9) 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. In addition, Constraint (10) makes the capacity of dam i_k ($C_{i_k}^\Delta$) equal to 0 and consequently (regarding to Constraint (7)), the stored water ($S_{i_k t}$) are also 0 for all time steps. In these circumstances, Constraint (5) converts to $\nu_{i_k t} + \sum_{l \in \pi_{i_k}} R_{(l \rightarrow i_k)t} - R_{(i_k \rightarrow l)t} - x_{i_k t}^a - x_{i_k t}^u - x_{i_k t}^d = 0$ that is water balance for nodes without dams.

4. Environmental water supply reliability:

$$R_{(i_k \rightarrow i'_k)t} - \zeta_{i_k t} \times z_{i_k t}^\varepsilon \geq 0 \quad \forall k, i_k, t \tag{11}$$

$$\sum_{t \in \tau} z_{i_k t}^\varepsilon - R^\varepsilon \geq 0 \quad \forall k, i_k \tag{12}$$

Regarding Constraints (11) and (12), the transferred water from node i_k to node i'_k at time t ($R_{(i_k \rightarrow i'_k)t}$) has to be greater or equal to the environmental water need in the node i_k ($\zeta_{i_k t}$). The reliability of the environmental water supply is controlled utilising a binary variable ($z_{i_k t}^\varepsilon$) in Constraint (11) which is 1 if the environmental water requirement is satisfied. The summation of $z_{i_k t}^\varepsilon$ over the time steps has to be greater than or equal R^ε (Constraint (12)). The definition of the reliability introduced by Kundzewicz and Kindler (1995) is used in this study. It is the ratio of the times that the volume of water supplied meets the demand, to the total time period, which is called the temporal reliability.

5. Stored water in dam i_k in first and last time steps:

$$S_{i_k t_1} - IV_{i_k} \times z_{i_k}^\Delta \leq 0 \quad \forall k, i_k \tag{13}$$

$$S_{i_k t_1} - S_{i_k t_l} \leq 0 \quad \forall k, i_k \tag{14}$$

where $S_{i_k t_1}$ and $S_{i_k t_l}$ are the stored water in dam i_k in the first and last time step, respectively. Constraint (13) points out that if there is a dam in node i_k ($z_{i_k}^\Delta=1$) then the stored water of dam i_k in the first time step is IV_{i_k} . IV_{i_k} is an input data to the model that could be equal to the annual average of river discharge in node i_k . This constraint limits the model to consider an unreasonable

value for the stored water at the first time step. Constraint (14) insures that the stored water in the last time step ($S_{i_k,t}$) is greater than or equal to the water stored in the time step 1 (S_{i_k,t_1}). This constraint is considered to make the stored water in dam i_k during time steps balanced.

6. Variables' Bounds:

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

$$\xi_{i_k,t} - x_{i_k,t}^a \geq 0 \quad \forall k, i_k, t \quad (15)$$

$$\tau_{i_k,t} - x_{i_k,t}^u \geq 0 \quad \forall k, i_k, t \quad (16)$$

$$\eta_{i_k,t} - x_{i_k,t}^d \geq 0 \quad \forall k, i_k, t \quad (17)$$

$$x_{i_k,t}^a \geq 0 \quad \forall k, i_k, t \quad (18)$$

$$x_{i_k,t}^u \geq 0 \quad \forall k, i_k, t \quad (19)$$

$$x_{i_k,t}^d \geq 0 \quad \forall k, i_k, t \quad (20)$$

$$R \left(i_k \rightarrow i'_k \right)_t \geq 0 \quad \forall k, i_k, t \quad (21)$$

$$C_{i_k}^\Delta \geq 0 \quad \forall k, i_k, t \quad (22)$$

$$S_{i_k,t} \geq 0 \quad \forall k, i_k, t \quad (23)$$

$$z_{i_k}^\Delta = 0 \text{ or } 1 \quad \forall k, i_k, t \quad (24)$$

$$z_{i_k,t}^\varepsilon = 0 \text{ or } 1 \quad \forall k, i_k, t \quad (25)$$

$$z_{i_k,t}^\psi = 0 \text{ or } 1 \quad \forall k, i_k, t \quad (26)$$

In this formulation, the volumes of returned flow and the reservoirs' water losses have been neglected due to their insignificant effects to the final outputs of the algorithm and avoiding excessive model's complication.

3.2.2 Step 2: Carrying Out a Sensitive Analysis to Determine the Number of Required Dams

Sensitivity analysis is suggested here as a method for finding the number of required dams in a basin. For this purpose, the changes in the basin's profit with increase of the number of dams are evaluated. In order to perform this analysis, the results of the MaxPro model, related to the basin's profit for various scenarios (number of dams), are analyzed. The number of required dams are determined as excessive if increasing the number of dams after that value does not significantly change the basin's profit. The selection of the optimal number of required dam includes determination of both locations and capacities of these dams.

3.2.3 Step 3: Searching Minimum Capacities for Dams

The MaxPro model might produce non-unique but multiple optimal solutions for selected scenario by Step 2. Regarding Constraint (7), (8), and (9), the capacity of dam i_k ($C_{i_k}^\Delta$) has to be equal to the stored water in at least R^ψ times. Therefore, the model could select any value between R^ψ and total time steps for dam i_k , which maximizes the basin's profit. By this fact, MaxPro might have multiple optimal solutions (various capacities of dams), giving the same value for the model objective function. In order to find the minimum capacities for dams, the MinCap model is implemented. The MinCap model aims to find new capacities for dams such that the basin's profit is equal or greater than the achieved value by the MaxPro model. The MinCap's objective function is to minimize the summation of dams' capacities given by

$$\text{Minimize } Z_{MinCap} = \sum_{k \in K} \sum_{i_k \in U_k} C_{i_k}^\Delta \quad (27)$$

subject to

$$\sum_{k \in K} \sum_{i_k \in U_k} \sum_{t \in T} (AP_{i_k t} + UP_{i_k t} + IP_{i_k t}) \geq P_{MaxProModel} \quad (28)$$

and constraints (2) to (26), where $P_{MaxProModel}$ is the achieved value from the objective function of MaxPro model for the selected scenario. As mentioned above, the capital investments necessary for the construction of dams have not been considered in the present approach. The results of the MinCap model are treated as auxiliary information, which could help to decrease these investments for dams construction by narrowing the potential areas and limiting the capacities for these projected dams.

4 Case Study: The Sefidrud Basin

The proposed three-step approach is applied to the Sefidrud Basin, which is an under-developed basin in northern Iran. The Basin drainage area is 59,217 Km² (MGC 2011) and includes territories of eight provinces; Kordestan (Province 1), Hamedan (Province 2), Zanjan (Province 3), East Azarbaijan (Province 4), Ardabil (Province 5), Tehran (Province 6), Qazvin (Province 7) and Gilan (Province 8). Figure 1 shows the Basin's location in Iran and its stakeholders. The areas and population of each province are presented in Table 1. This information can expose the level of the stakeholders' dependency to the Basin water resources for development.

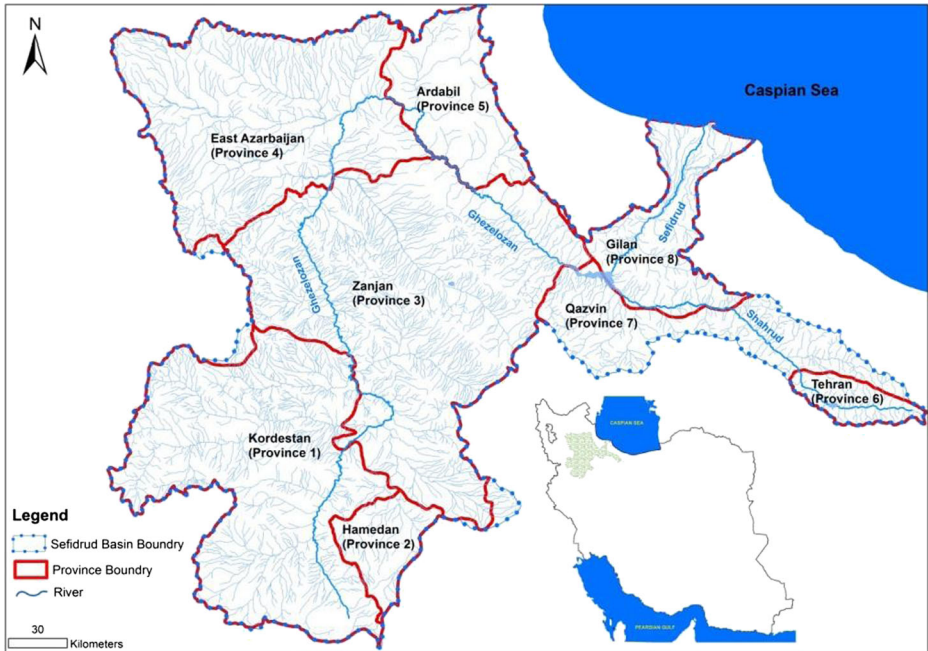


Fig. 1 The location of the Sefidrud Basin and its stakeholders

The Sefidrud River is main waterway in the Basin, whose head tributaries, Ghezelozan and Shahrud, originate from Province 1 (Kordestan) and Province 6 (Tehran), respectively. The Ghezelozan River passes through Province 2 (Hamedan), Province 3 (Zanjan), Province 4 (East Azarbaijan) and Province 5 (Ardabil) and at the lower part flows into Province 8 (Gilan). The Shahrud River, after passing through Province 7 (Qazvin), flows into Province 8 (Gilan). The Ghezelozan and Shahrud rivers are called the Sefidrud River after joining. The Sefidrud River goes through Province 8 (Gilan) and finally flows into the Caspian Sea (Fig. 1). The overall basin discharge is 7615 million cubic meters (MCM), which surface and ground water shares are 6214 MCM and 1337 MCM, respectively (MGC 2011). The agricultural water requirement accounts for 91% of the Basin's water demands while municipal (urban) and industrial sectors shares are 8% and 1% (MGC 2011), respectively. Therefore, agriculture is the main consumer of water resources and a dominant source of revenue

Table 1 The area and population of provinces in the Sefidrud Basin

Province	Area Contained in the Sefidrud Basin (%)	Population in 2007 (%)
1	23.3	12.8
2	3.4	1.5
3	30.9	22.9
4	19.5	11.2
5	6.8	4.5
6	1.9	0.3
7	7.4	1.6
8	6.8	45.2
Sum	100	100

in this Basin. The municipal and industrial water demands are ignored in the present study, which means eqs. (3), (4), (16), (17), (19) and (20) irrelevant for this region. The Basin agricultural water demand for 2007 was 3701 MCM and it is estimated to increase to 7270 MCM for 2025 (MGC 2011).

The surface water is the primary resource of agricultural water satisfaction. The future basin agricultural demands and the agricultural water profit for each province are shown in Table 2. The data on “marginal profit” of water for the agricultural sector were available for this study (MGC 2011). Moreover, the future agricultural demand of the Basin depends on the potential of irrigated area in the stakeholders (provinces), which could have a relation with contained area of the stakeholders in the Basin. The detailed description of water resources and water demands of this Basin can be found in the paper of Roozbahani et al. (2013). Note that, the groundwater resources of the Basin are the main resources of supplying the others water needs such as industrial and urban requirements while their needs are not substantial in comparison with the agriculture.

There are 27 main runoff gauges in the basin, which were considered to be supply/demand nodes in the Basin network. The recorded data of these gauges were used to calculate the nodes' surface water volume. These supply/demand nodes provide the surface water for the agricultural uses in their vicinities. Shared nodes in the network were replaced with dummy nodes to calculate easily the water share of associated stakeholders in shared nodes. More details about the nodes' runoff and demand are available in Roozbahani et al. (2013). Figure 2 shows the Sefidrud Basin nodal network.

The environmental water supply was considered for each node in this study. The modified Montana method was used for calculating the environmental water demand (Torabi Palatkaleh et al. 2010). The Modified Montana method estimates the environmental water requirement based on a percentage of the average monthly streamflow in a node. In this work, the environmental water requirements were calculated based on 10% of unimpaired the basin flows for October to March and 30% of unimpaired the basin flows for April to September of unimpaired basin flows. These percentages are officially accepted by the Iranian water authorities for calculating the environmental water requirements of rivers in Iran (Torabi Palatkaleh et al. 2011). More details about the application of the Modified Montana method in the Sefidrud basin can be found in the paper of Roozbahani et al. (2015b). In this study, the monthly environmental water requirements were calculated first and then the sum of them, as yearly environmental water requirement was utilized in the model.

Table 2 The current and future basin agricultural demand

Province	Future Demand (MCM)	Agricultural Water Profit (Rial ^a /M3)
1	1029	440
2	126	440
3	1967	1515
4	753	1836
5	447	1836
6	410	1417
7	431	1417
8	2107	1933
Sum	7270	-

^aRial is the Iranian money currency

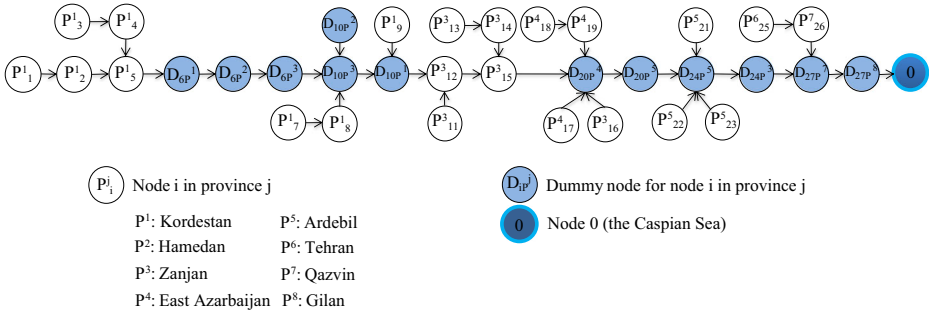


Fig. 2 The network’s view of the Sefidrud Basin

5 Results

The Basin’s water demand in 2025 (MGC 2011) represents the water requirements of the stakeholders for maximum social-economic developments (Table 2) and it was considered an input of the present model. No statistically significant trend (positive or negative) were observed in in the Basin discharge during 1957 to 2007 (MGC 2011). Thus, the yearly-recorded discharges for the nodes during 1957 to 2007 (50 time steps) is employed for assessing future scenarios, which means that the potential changes in streamflow associated to the climatic, demographic and infrastructural changes were not considered in the approach described in the present paper. The threshold of demand satisfaction in 90% of time steps is a major reliability criterion for water supply systems in the Basin (MGC 2011). Thus, the amount of R^e is $0.90 \times 50 = 45$. In addition, the security supply parameter $R^{st}=45$ is considered in this study. It means the model has to find a value for the capacity of dam i that it will be full in at least 90% of time steps. The parameterised models (MaxPro and MinCap) were solved using CPLEX 12.6 solver (IBM Corp 2013) and the results will be presented and discussed in the following subsections.

5.1 The Results of the MaxPro Model

Figures 3, 4, 5, and 6 present the optimal locations and capacities of proposed dams in the Sefidrud Basin for scenarios $n = 1, n = 2, n = 3,$ and $n = 4,$ respectively. These figures illustrate several examples of the MaxPro model’s output. As shown in these figures, node 20 has a significant role in the Sefidrud Basin development, because for various scenarios, the MaxPro model proposes it for constructing a dam. Note that, node 20 is a share node between Provinces 4 and 5. The second proposed node by MaxPro for a dam construction is node 27, located in Province 8. This province is located in the Basin downstream area where water requirement and marginal value of water are the highest (Table 2). The location of node 20 is close to node 27 and thus, it seems proposed dam in this node has an important role in satisfying water requirement of node 27. Table 3 summarises the locations and capacities of proposed dams for various scenarios.

The results from MaxPro clearly illustrate the concept behind the model’s formulation. The objective function of MaxPro is to maximize the total net benefits of water uses in the entire basin from surface water resources. Thus, more water should be allocated to nodes with higher marginal value of water. To give more gains from water, it is favourable to have dams with large reservoirs in order to increase the available water

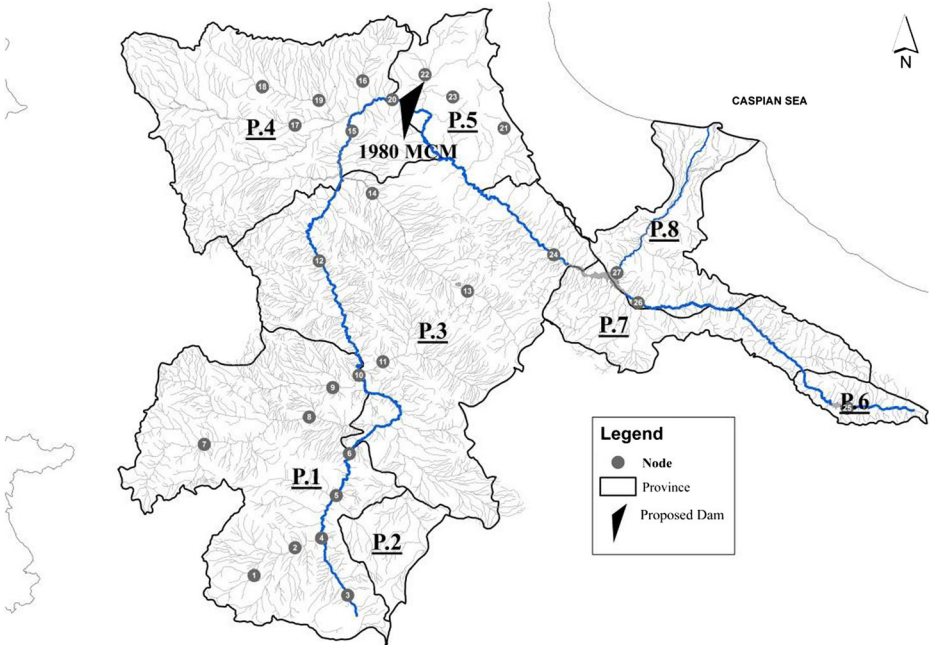


Fig. 3 Location and capacity (derived from MaxPro model) of the proposed dam for the scenario 1

supply of the Basin, then, they should be located in spots where they could have more capacities based on constraints (7) to (10). As a results, MaxPro proposes nodes for dams

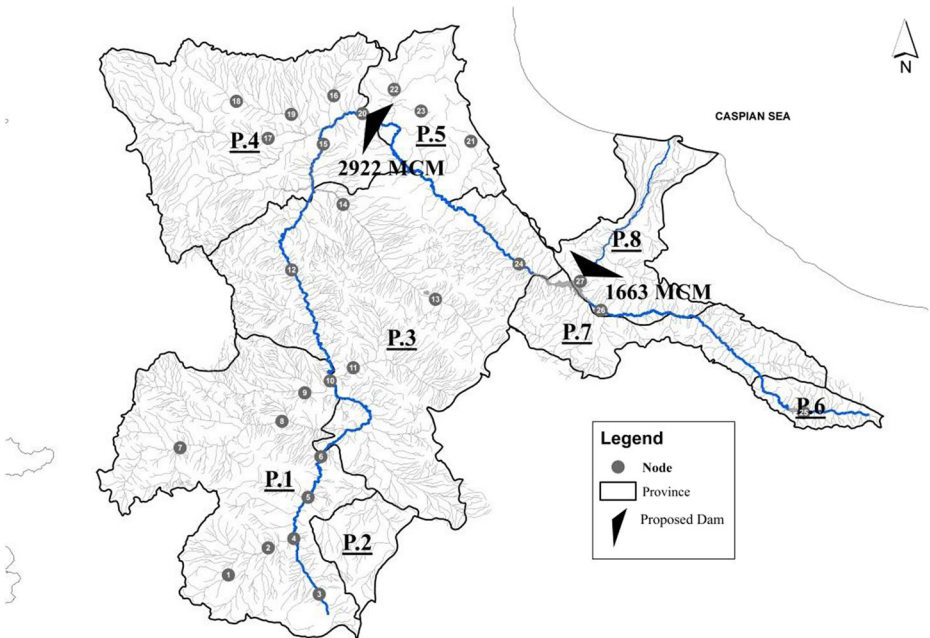


Fig. 4 Location and capacity (derived from MaxPro model) of the proposed dam for the scenario 2

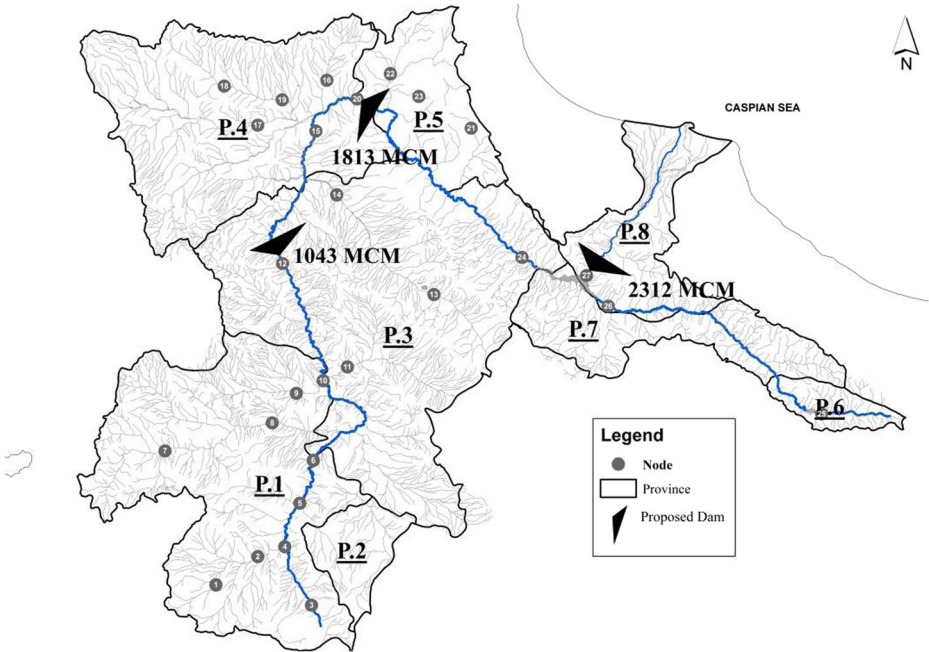


Fig. 5 Location and capacity (derived from MaxPro model) of the proposed dam for the scenario 3

construction where the river’s discharge is larger and the stored water could produce more profit for the Basin’s economy.

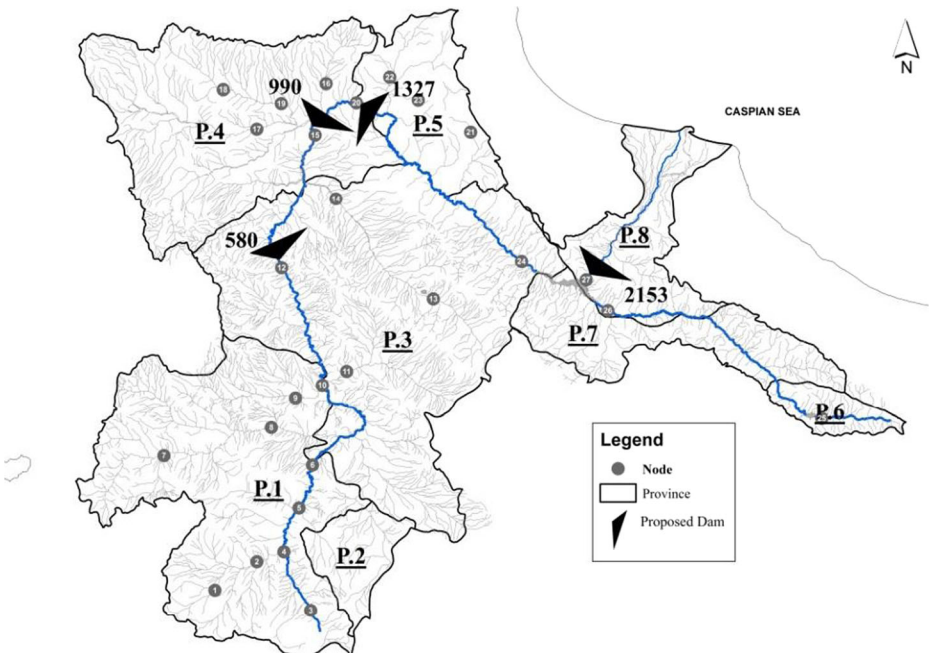


Fig. 6 Location and capacity (derived from MaxPro model) of the proposed dam for the scenario 4

Table 3 The locations and capacities of proposed dams by MaxPro model (up to 4 dams)

Location		Dam Capacity (MCM)			
Province	Node	$\underline{n = 1}$	$\underline{n = 2}$	$\underline{n = 3}$	$\underline{n = 4}$
3	12	0	0	1043	580
4	15	0	0	0	990
4, 5	20	1980	2922	1813	1327
7, 8	27	0	1663	2312	2153
Dams' capacities summation		1980	4585	5168	5050

5.2 Sensitivity Analysis

The main idea of the proposed sensitivity analysis is based on the comparison of the marginal incomes associated to the construction of each additional dam in the basin. If the total income in the basin increases insignificantly with construction of each additional dam, this construction is economically non-sustainable, due to large capital cost associated with this construction.

Figure 6 compares the Basin's profits achieved by various numbers of dams. As shown in this figure, the Basin's profit rises by 28.66% when 1 dam is proposed in the Basin in comparison with the profit of the Basin without dam ($n = 0$). The profit steadily increases to 29.78% by adding one dam more ($n = 2$). Growing the profit continues to go up with a lower slope to 30.25% when the model considers three dams in the Basin ($n = 3$). When four dams are proposed in the Basin, the Basin's profit grows slowly from 30.25% to 30.55% (only for 0.30%). Figure 6 shows that the profit still had a rise by adding 5, 6, and 7 dams to the Basin, however, it is not significant (about 0.20% increase). Finally, it is tested for $n = 27$ (without considering the dummy nodes) and observed the Basin's profit in maximum development would be 31.10% more than the undeveloped Basin's profit, which is also very small increase.

According to Fig. 7, the increase of the numbers of dams in the Sefidrud Basin, more than three does not result in significant additional profit for the Basin and three dams lead the

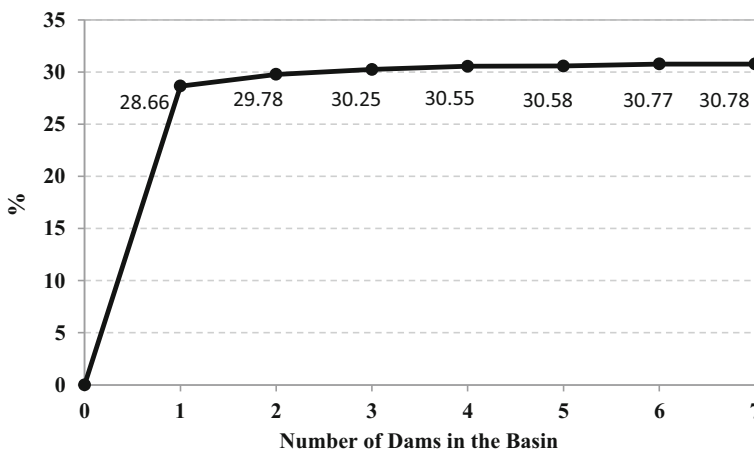


Fig. 7 The Basin profits rise by considering dams in the Basin in comparison with the Basin profit without any dams (%). The y-axis shows $\frac{\text{Basin's profit} - \text{Basin's profit without any dam}}{\text{Basin's profit without any dam}} \times 100$

Table 4 The percentage of water supply to the stakeholders for Scenarios 1 to 3 (%)

Scenario	Stakeholder							
	P.1	P.2	P.3	P.4	P.5	P.6	P.7	P.8
1	9	14	53	88	81	31	67	99
2	9	14	55	89	82	37	72	99
3	10	14	56	90	83	33	73	99

Basin's profit to a reasonable raise. Hence, the results of the models for scenarios, which recommend construction of 1, 2, and 3dams were selected.

5.3 The Results of the MinCap Model

The MinCap model was run for scenarios 1, 2, and 3 as Step 3 of the proposed approach. The results of the model were same as the MaxPro model's results for these scenarios. In other words, for this case study, there are no lower dams' capacities (for scenarios 1, 2, and 3) which bring about same profits, achieved by the MaxPro model. The main reason of giving this result is the huge water shortage in the Basin. According to the objective function, the MaxPro model has to supply more water to demands for making maximal profit, while the total water supply is less than total demands. Therefore, the MaxPro model looks for the lowest possible values for dams capacities in order to increase delivered water to demands and as a result, achieves the highest profit.

Table 4 presents the percentage of water supply to the stakeholders for Scenarios 1 to 3, derived from the MinCap model's results. As shown in this table, the stakeholders can be classified into three categories. The first category includes stakeholders, whose water shares stay steady by increasing the number of dams. Provinces 2 and 8 belong to this category. The second category includes stakeholders whose water shares rise with the increase of the number of the proposed dams. The members of this category are Provinces 1, 3, 4, 5, and 7. The member of the third category are those whose water shares do not have a stable situation and their water shares go up and down by increasing the number of dams in the Basin. Province 6 is the only member of the third category. In short, providing new reservoirs in the Basin raise available water and has non-negative effects on the water shares of Provinces 1, 2, 3, 4, 5, 7, and 8. However, The construction of new dams could produce algorithm a negative effect on the water share of Province 6.

6 Conclusion

In the nutshell, this paper introduced a three-step approach for optimal water planning and management of an undeveloped basin. The first step employed the MaxPro model to find out the locations and capacities of the new dams such that they cause the highest profit for the basin. The MaxPro model was ran for various scenarios (numbers of dams). The required number of dams for the basin was selected by the second step, using a sensitivity analysis. To cope with the possibility of multiple ideal solutions for the MaxPro model (for selected scenario), the MinCap model was proposed in the third step. MinCap tested the possibility of providing the same profit for a basin, achieved by MaxPro for selected scenario with lower dams' capacities.

Our proposed approach was examined to the Sefidrud Basin, which is an under developing basin in Iran. Applying the MaxPro model to the Sefidrud Basin showed water development (dams) have a significant effect on raising the Basin's profit. For instance, the profit of Basin went up over 28.66%, 29.78%, and 30.25% by considering 1, 2, and 3 dams in the Basin. As it was observed, constructing more than three dams would not substantially increase the Basin's profit. Thus, the construction of three dams in nodes 12 (1043 MCM capacity), 20 (1813 MCM capacity), and 27 (2312 MCM capacity) would be sufficient for this basin.

In the first instance, it is important to note again that the algorithm suggested in the present paper does not pretend to be a final tool for indication of the proposed locations and capacities of dams to be constructed in the basin. It is necessary to emphasize that the final decision should be made only after a series of on-site engineering studies, which will allow local authorities to investigate the constructional opportunity for developing these dams and implement the necessary cost-benefit analysis. The major implication of the present modelling work is to propose the construction sites and potential capacities, which maximize the income in region and, in the same time, does not produce negative influence to the environmental flow. However, the importance of such modelling exercise should not be underestimated. The model implementation brings water authorities two major messages. Firstly, the proposed model recommends that the optimal number of reservoirs to be projected in the basin is three. The larger number cause negligibly small increase in the regional marginal income, which definitely unable to compensate the capital investments associated to this construction work. It is quite important message, for engineers who will implement the further study. Same time the algorithm also proposes what are desirable volumes of these reservoirs, which will allow plan the engineering study accordingly. The total volume of these dams, estimated as about 5000 MCM is also important contribution to the further development of the dam construction project.

Second important message is that the proposed model recommended construction of the dam in the lowland provinces of the Sefidrud basin, which is natural for the methods, whose priority is maximization of the income. Obviously, the purely economic objective function will emphasize importance of the development of the basin reaches where the marginal value of water is relatively high. Being economically viable these proposed sited may cause some problems of social nature by increasing the difference in the developmental levels of upland and downstream nodes. It means that the further modelling study should be implemented by adding a new component to the algorithms objective function, which will reflect the level of the social justice in the region.

Finally, another important result of the proposed modelling approach is that it treats the problems of dam construction holistically, in the entire basin's scale whereas engineering studies actually evaluate the effects of dam construction locally, for the selected sites. It could be quite effective tool for the planning further development of underdeveloped watershed.

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