Water Harvesting Research Vol. 5, No. 1, Spring & Summer 2022, Original Paper p. 121-130

University of Birjand

10.22077/JWHR.2023.5803.1074

Planning the Optimal Allocation of Water Resources Using EA-MODSIM Simulation-Optimization Model

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Received: 18 November 2022/ **Revised**: 4 January 2023/ **Accepted**: 11 January 2023

Abstract

Optimal exploitation of dams' reservoirs and provision of dam downstream water demand is of great importance. The use of water resource planning models has been recently very effective. For this purpose, this paper has analyzed and investigated the optimal utilization of Galmandareh River basin water resources using a combination of MODSIM as a simulation model and election algorithm as an optimization model and the development of the EA-MODSIM model. The objective function of the problem was considered as minimizing the sum of squared deviations between the required amount and the amount released from the reservoir. Efficiency, reliability, and vulnerability in reservoir operation were also used to evaluate the proposed model. Results indicated the acceptable performance of the simulation-optimization approach used in the research to solve the problem of planning the optimal allocation of water resources at the basin. Studies showed that in the simulation-optimization approach, the amount of water demand in the basin increased by about 32% compared to the simulation model. The results of the reliability index for industrial, agricultural, and environmental demands at the dam downstream were 86, 87, and 96%, respectively. These results indicated the importance of adopting policies for the optimal exploitation of system reservoirs to increase the water supply and reduce the water resource loss at the level of the basin.

Keywords: Allocation, EA, Modeling, MODSIM.

1. Introduction

Population growth, urbanization and the industrial, commercial and agricultural development have increased water demand and the importance of the planning of water resources. Over-abstraction of water has led to a decrease in the level of reliable supply, especially for agricultural purposes. A significant part of Iran's water demand is supplied from surface water sources and through dam reservoirs. Therefore, the optimal allocation of water resources and the quantification of water demands are necessary to achieve optimal sustainability. In this regard, it is necessary to use the optimal policies for the use of reservoirs. In order to prevent the high costs of dam construction and becoming uneconomical and the waste of water resources, it is necessary to use the dam reservoirs purposively. Considering the complexities of water resources allocation and observing the priorities of allocation to water demands, it is very effective to use water resource planning models (Shourian et al., 2008; Nicklow et al., 2010; Madani et al., 2014; Li and Zhang., 2015; Zhou et al., 2015; Degefu et al., 2017)

In this regard, Che and Mays (2017), by integrating a hydrological model and genetic algorithm, developed an optimization model for flood control operation of river-reservoir systems. The results showed that the optimal release program could reduce the flood level in the 100-year flood stage for the studied river-reservoir system. In another study, Shenava and Shourian (2018) developed the ICA-MODSIM model and investigated the optimal operation of dam reservoir with regard to the increase in downstream demand and flood risk reduction. The results showed that if the optimization-simulation model was used, while the downstream demand was fully satisfied, the safe flow constraint was met. On the other hand, when the reservoir is used for water supply, there are many days in the simulation period when the reservoir is full and the river flow exceeds the safe discharge in the downstream, causing economic damage to people and livestock.

Fadaeizadeh and Shourian (2019) investigated the optimal allocation of water resources through the quantification of the agricultural needs by combining MODSIM simulation model and Particle Swarm Optimization (PSO) algorithm under the desired condition of meeting the reliability criteria. Chen et al. (2020) investigated the optimal allocation of water resources in Kunming, China, using PSO. Results showed that the allocation plans can reduce Kunming's water shortage and satisfy the interests of different sectors, thus reducing the conflicts over the use of urban water. Also, Nikoo et al. (2022) used optimal water allocation, sustainable management of water resources and the use of water balance approach to determine agricultural water allocation. In their research, they used the simultaneous application of this approach and agricultural water allocation optimization. ISM and GA optimization models were developed to obtain the optimal agricultural water allocation and also to determine the optimal irrigation scheduling.

The results showed that the ISM-GA optimization model reduced the amount of irrigation water allocation shortage for the three studied agricultural regions. In another study, Arya Azar et al. (2022) developed a new comprehensive method for the optimal allocation of surface and underground water resources using numerical models, optimization algorithms and machine learning. The results showed that machine learning models are cost-effective solutions for estimating the optimal exploitation of underground water resources in complex problems of surface and underground water supply.

- The review of the research in the field of planning the allocation of water resources at the basin indicates an increasing attention to the simulation-optimization approach in solving water resource problems. This paper is trying to solve the problem of optimal allocation of water resources at the level of the basin using this approach. Consequently, using of simulation model with the ability to calculate the allocation per step, coding of a meta-exploration optimization algorithm, the insertion of the simulation model to evaluate, and as result the development of its model, are the main steps of this research using the MODSIM model as a comprehensive water resource management simulation model at the basin, the performance of a part of the Galmandareh River under the influence of the Galmandareh Dam that located in north-eastern of Iran, is simulated and the optimal values of the decision variables of the problem, which are the exploitation policies of the system's reservoirs, using the EA will be determined under the maximization objective.

In fact, this study mainly aims to use the MODSIM and EA together and in the form of an integrated program to optimally allocate water resources in the river basin. It should be noted that no study has been done using the combination of EA as an optimizer model in dam allocation optimization.

2. Materials and methods

2.1. Case Study

The studied system is a sub-system of Qarasu-Gorganrood basin, Northern Iran. The studied area is located at an altitude of 1078 meters above sea level. The dam is located at the Galmandareh River. One of the goals of constructing Galmandareh Dam is to supply the demand in the industry, agriculture, and environment sectors. Figure 1 shows the location of the study area in Iran.

Table 1 shows the overview of annual resources and consumption. This table shows the total amount of incoming surface flow and the total amount of requirements within the basin, as well as the characteristics of the existing structure in the studied system.

2.2. Reservoir performance simulation model, MODSIM

MODSIM is a river basin simulation model that uses the network flow programming method (NFP) to calculate water allocation values for basin management. In this model, the problem of minimizing the cost of flow network and, in other words, the optimal allocation of water between multiple uses is solved iteratively in each time step (Labadie, 2006).

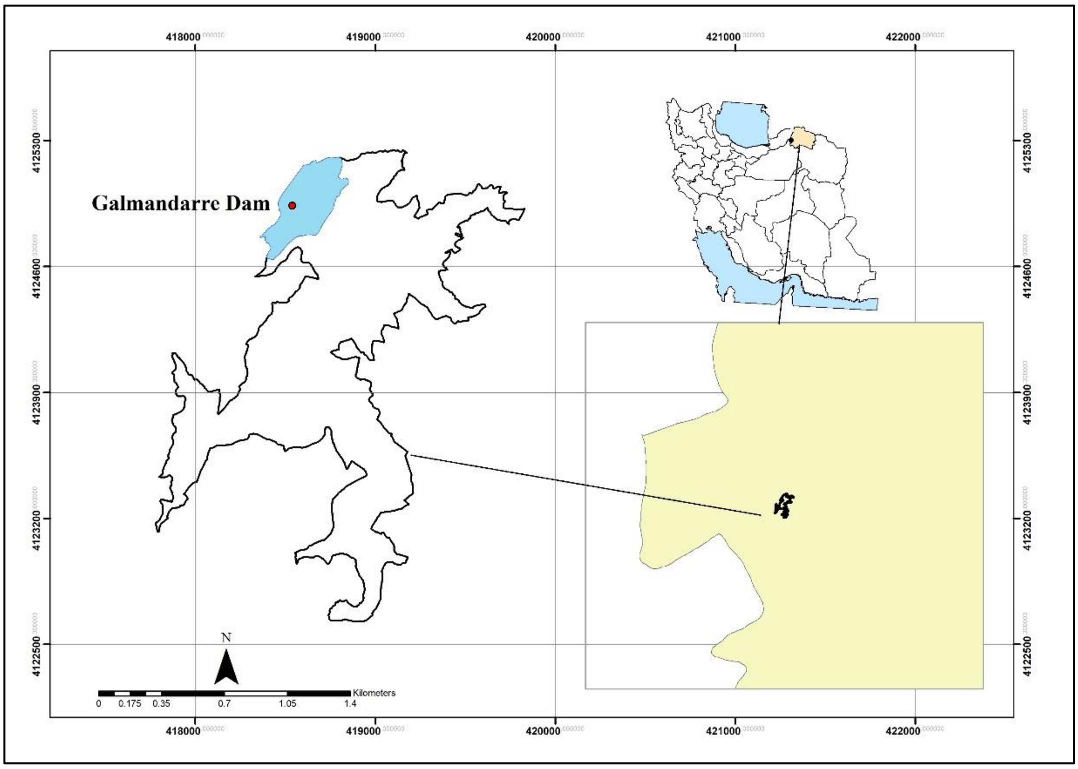

Fig. 1. Location of the Galmandareh Dam in Iran

Table 1. Water resources and demands and characteristics of the reservoirs in the system

Item	Value (MCM)
Total Surface Inflow	9.75
Agriculture Demand	3.99
Industry Demand	2
Environment Demand	1.3
Min Capacity	1.98
Max Capacity	28.7

The general formulation of the NFP algorithm used in each time step in MODSIM is as follows:

$$\text{Minimize} \sum_{l \in A} c_l \ q_l \quad (1)$$

Subject to:

$$\sum_{j \in O_i} q_j - \sum_{k \in I_i} q_k = 0$$

$$\text{for all } i \in N \quad (2)$$

$$l_l \leq q_l \leq u_l, \ \text{for all } l \in A$$

In these equations, A is the set of flow channels in the network, N is the set of nodes, O_i is the set of channels starting from node i (output channels), I_i is the set of channels ending at node i (input channels), q_l flow rate value in channel l, c_l flow cost coefficient in channel l (minus the weight coefficients or profit of the flow unit in channel l which is calculated based on allocation priorities between needs), l_l is the lower limit of the flow in channel l and u_l is the upper limit of the flow in channel l. Despite the MODSIM key capabilities, this model is a system exploitation simulation model with water allocation between uses at the basin scale and under known and specific allocation dimensions and policies. In other words, the model by itself is not able to determine the optimal design or operation.

2.3. Election Algorithm

Election Algorithm (EA) is inspired by the phenomenon of elections. This algorithm is a multi-agent and population-based strategy in which each search agent is called an individual (Emami and Derakhshan, 2015). For a problem with variables p_1, p_2, …, p_N, each individual p_i consists of an array of possible values for the variables:

$$P_i = [x_1 \ x_2 \ldots x_N] \quad (3)$$

The competence of each person is calculated by evaluating the function E on the values of the variables corresponding to the objective function of the problem.

Some of the best people in the population are chosen to be the candidates, and the rest form the electorate, each of them supporting a candidate. Voters are divided between candidates based on similarity of opinions.

EA is an iterative algorithm that works with a set of solutions known as the population. Advertising campaign is the core of the algorithm and includes three steps: positive advertising, negative advertising and coalition. These processes are repeated until the algorithm converges to the global optimum.

In optimization algorithms, there are parameters whose changes change the algorithm performance and will have an impact on the convergence rate and solution quality. Obtaining the best parameters is associated with trial and error. Therefore, in order to improve the EA efficiency, trials and errors were made to obtain the best value for each parameter, and these parameters are presented in Table 2.

Table 2. Value considered for the EA algorithm parameters

Initial population	50
candidates	4
voters	46
coalition rate	0.03
election rate	0.03

Due to the fact that in meta-exploration algorithms, the initial population is created randomly and also the operators in these methods cause random answers during the execution process of each algorithm, the answers obtained from the algorithm will be different in different executions. Thus, it is not possible to correctly comment on the ability of the algorithm with the result being good or bad in one run. Therefore, the algorithm must be executed more than once.

2.4. The objective function of reservoir exploitation model

In order to carry out the optimization process, the reservoir utilization model must be determined first. For this purpose, the objective function is considered in the form of minimizing the sum of squares of the difference between the required amount and the amount released from the reservoir during the operation period. The objective function is defined as follows:

$$\text{ObjectiveFunction } Z = \sum_{t=1}^{T}\left(De_t - Re_t\right)^2 + \sum_{t=1}^{T}\left(S_t - S_{t+1} + Q_t - Re_t - Ev_t\right)^2 \quad (4)$$

In this equation, Z is the objective function, T is the length of the exploitation period, De_t is the amount of demand in the month (mcm), Re_t is the reservoir output in the month (mcm). Continuity equation is also one of the most basic equations of reservoir utilization modeling, which is defined in the second part of the objective function. S_t and S_{t+1} are the reservoir's volume at the beginning and end of the period (mcm), Q_t is the flow entering the reservoir during the period and Ev_t is the amount of loss from the reservoir during the period.

In addition to the above equations, constraints should also be considered for the exploitation model; For example, the reservoir water volume cannot be less than the minimum reservoir volume or exceed its maximum volume. These constraints are included in the modeling as follows.

$$S_{min} < S_t < S_{max} \quad (5)$$

$$0 < Re_t < De_t \quad (6)$$

S_{min} and S_{max} are the minimum and maximum reservoir volume (mcm), respectively.

2.5. Optimal allocation planning using simulation-optimization approach EA-MODSIM model development

The main approach of this research is to use the MODSIM and EA together and in the form of an integrated program for the optimal allocation of water resources in the river basin. Despite the capabilities of the MODSIM model, it is basically a water resource system exploitation simulation model with the allocation of water resources between uses at the basin and under known allocation dimensions and policies for different elements of water storage, transfer and diversion. In other words, the model by itself is not able to determine the appearance, design and determine the optimal dimensions of the mentioned components or determine the policies for the optimal exploitation of the reservoirs. Rather, it studies and examines the behavior of a water resources system at the level of the basin under specific and predetermined scenarios. Therefore, in order to achieve the desired development image or the optimal exploitation policies of the desired reservoirs in a water resources system, it is necessary to connect this model to an optimization algorithm with the decision variables or exploitation of the mentioned components. Based on this, the MODSIM at the basin level in solving the problem and EA for water allocation have been integrated. The purpose of solving the problem considered in the system under investigation is to optimize the water storage values in the system's reservoirs in the daily time step as the problem's exploitation variables.

By using the programming capability in MATLAB, the values of the desired variables can be considered equal to the desired values every time the model is run, and the results of the simulation of the system's behavior can be analyzed according to the mentioned values. By programming the EA algorithm in MATLAB and inserting the MODSIM model into it, the decision variables' values are considered equal to the values produced by EA in each iteration. Then, for this set of operation variable values, by running the simulation model, the net profit functions due to water allocation to the nodes of the system corresponding to the operation policy of the reservoirs are calculated. Candidates converge to the values that include the maximum value of the objective function, which is equal to the net profit from operating the system during the planning horizon and considering the constraints of the problem. The constraints of this optimization model include constraints on the upper and lower limits of the decision variables, as well as the constraints of establishing the continuity condition and flow limits in the network channels at each time step. Therefore, by connecting the EA to MODSIM and developing the EA-MODSIM model, the problem of planning the optimal allocation of water resources at the basin level can be solved with the simulation-optimization approach. The performance of the EA-MODSIM model is shown in Figure 2.

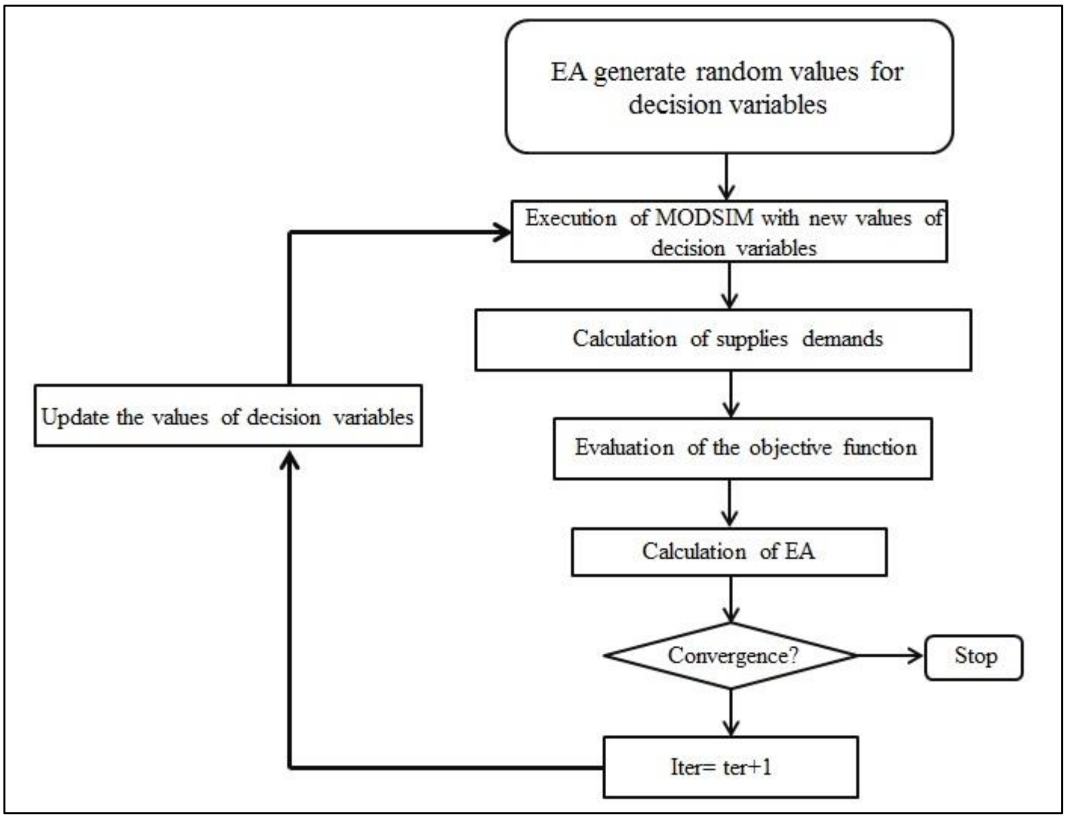

Fig. 2. Flowchart of the EA-MODSIM coupled model

2.6. Efficiency criteria in reservoir operation

Reservoir exploitation always seeks to increase the reliability of water supply and reduce vulnerability in meeting demands. Hoshimoto et al. (1982) introduced reliability and vulnerability indices in reservoir exploitation. These indicators can be used as a basis for comparing different reservoir exploitation methods. Volumetric reliability is defined as the ratio of the released water volume to the required volume during the exploitation period. According to what was said, equation 7 was used to calculate the volumetric reliability.

$$Rel = \frac{\sum_{t=1}^{12} \mathrm{Re}_t}{\sum_{t=1}^{12} De_t} \quad (7)$$

In this equation, Rel is the volume reliability index that is usually expressed as a percentage. In exploiting the reservoir, the amount of failures has different importance. For example, five shortages of 1 mcm are less important than one shortage of 5 mcm. Vulnerability index has been proposed to investigate this issue.

Vulnerability is the maximum relative deficiency created during the exploitation period, which is expressed by the following equation.

$$Vul = Max \frac{(De_t - \mathrm{Re}_t \mid De_t > \mathrm{Re}_t)}{De_t} \quad (8)$$

Vul is the vulnerability index in this equation.

Any exploitation policy that can provide more reliability and less vulnerability will be more suitable.

3. Results and Discussion

By using the series of monthly observations of the Galmandareh River at the hydrometer station and comparing their modeled values, it is possible to perform general calibration and validation of the resource and consumption simulation model. Effective parameters in MODSIM for model calibration are backwater coefficients from demand nodes and release rules and water storage priorities in system reservoirs. By changing these parameters, the observed and calculated values of the time series of the river discharge at the location of the indicator station of the basin have been adapted to each other. Figure 3 shows, as an example of the model validation results, the time series of observations and simulation at Tangrah station located on Galmandareh River.

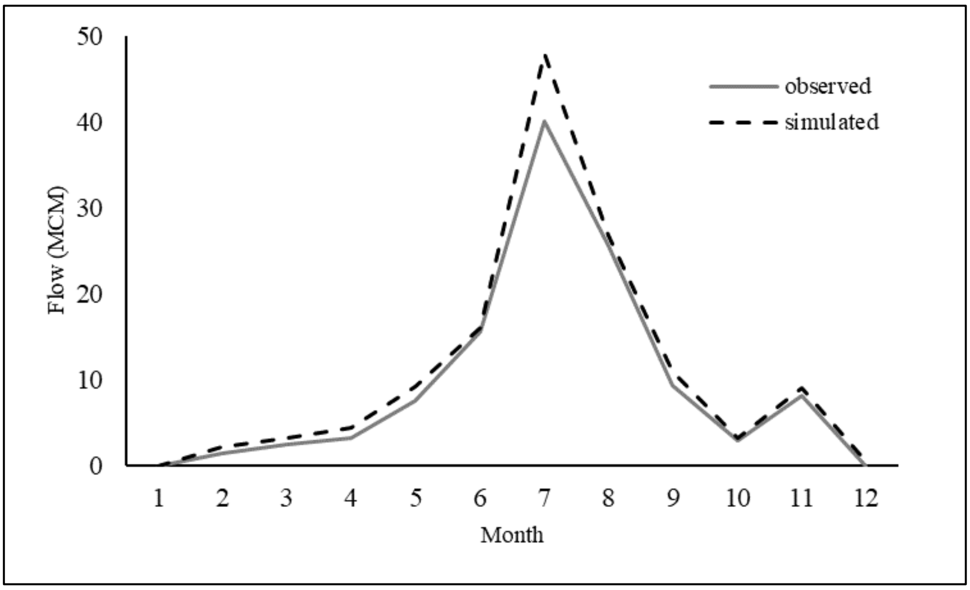

Fig. 3. Comparison of the simulated and observed monthly outflow

- The results obtained in this section show the acceptable performance of the simulation model. Obviously, due to the large number and complex interaction of effective parameters on each other and the changes of variables during the simulation period, it is very difficult and time-consuming to fully adapt the time series of observed and calculated discharge in water resources models. Based on this, the simulation model of the basin, which has been verified according to the above results, has been accepted for use in allocation optimization calculations. The results of the research and the acceptable performance of the EA-MODSIM model are in line with the results of Fadaeizadeh and Shourian (2019). These similar results show the role of optimum operation of the reservoirs to meet multiple purposes and to get maximum benefit from their application in water resources management problems.

Table 3- Comparison of the water supply in the simulation and simulation-optimization models (MCM)

Item	Demand	Simulation Optimization Supply	Simulation Supply
Agriculture	3.99	3.47	2.62
Industrial	2	1.73	1.19
Environmental	1.3	1.25	1.05
Total	7.29	6.45	4.86

In order to investigate the changes in the water resource allocation by using the simulation-optimization approach and providing a basis for comparing the results, first the simulation model is implemented under the status quo and its results are presented. Then, by combining the EA with MODSIM in MATLAB, the exploitation policies of the system reservoirs have been optimized as decision variables, and the status of meeting the demands has been compared with the base conditions (simulation). In the mentioned problem, the objective function is considered as minimizing the sum of the squares of the difference between the required amount and the amount released from the reservoir, during the exploitation period.

In Table 3, the results of the demand of the basin are presented in the conditions of simple simulation and the use of EA-MODSIM simulation-optimization model.

According to the results presented in Table 3, it can be seen that out of the average annual flow of 9.75 mcm entering the basin, the reservoir system in optimal conditions is able to allocate 6.45 mcm of water to the required nodes. The remaining flow in the amount of 3.3 mcm downstream has been removed from the system. While in simulating, the amount of water demands and the output flow are equal to 4.86 and 4.89 mcm, respectively. In other words, the use of the optimization approach has led to an increase in supply the basin's demands and a decrease in the outflow from the basin.

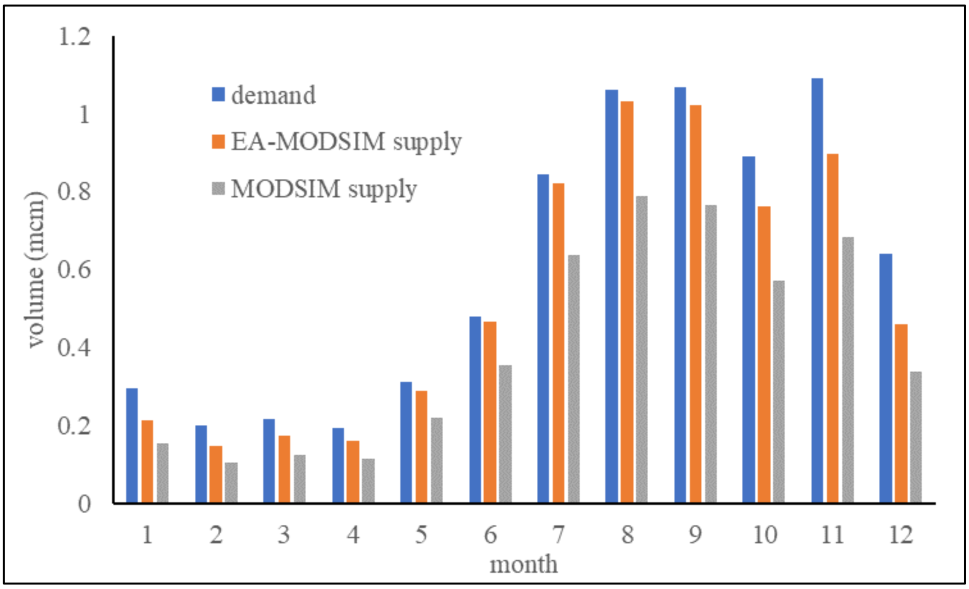

Fig. 4. Average supply for the basin total demands in simulation and simulation-optimization models

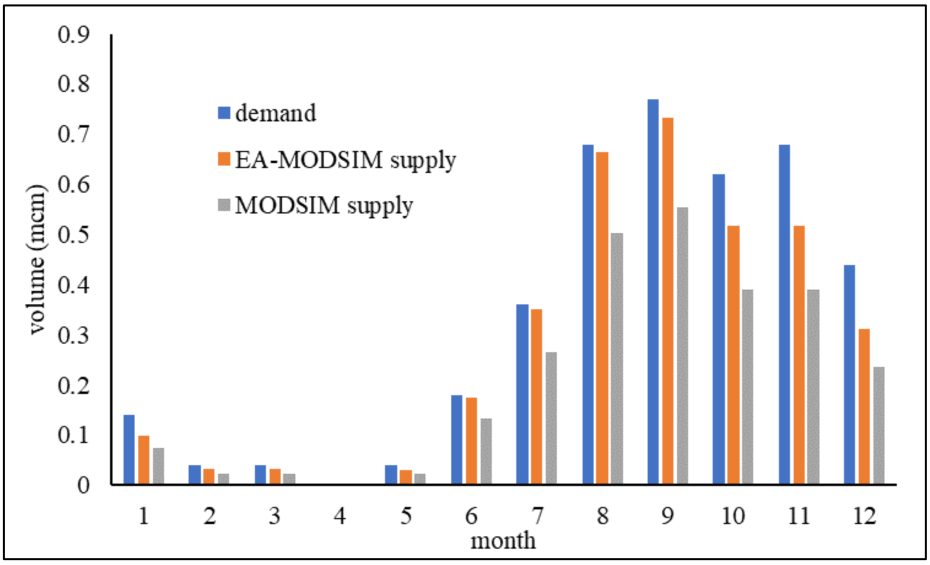

Fig. 5. Average supply for the basin agricultural demands in simulation and simulation-optimization models

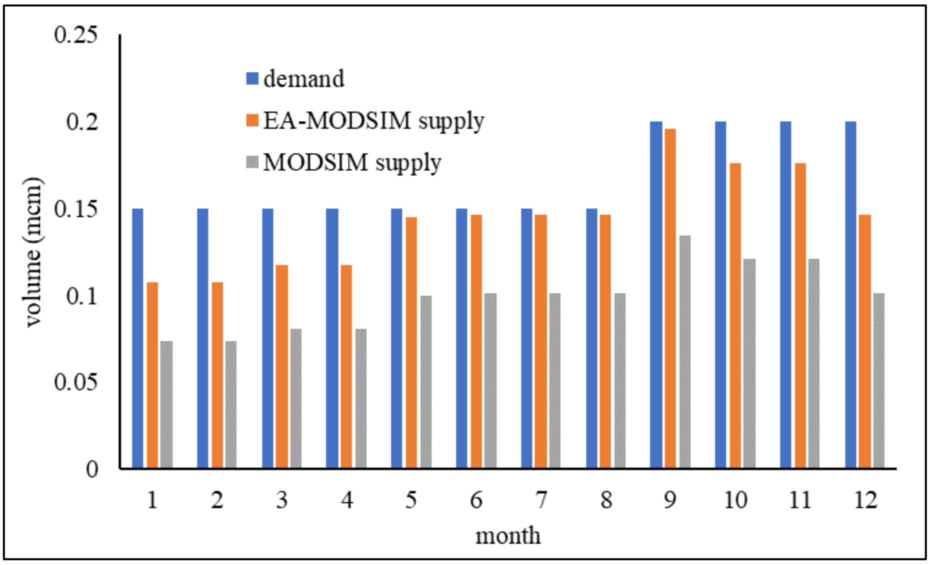

Fig. 6. Average supply for the basin industrial demands in simulation and simulation-optimization models

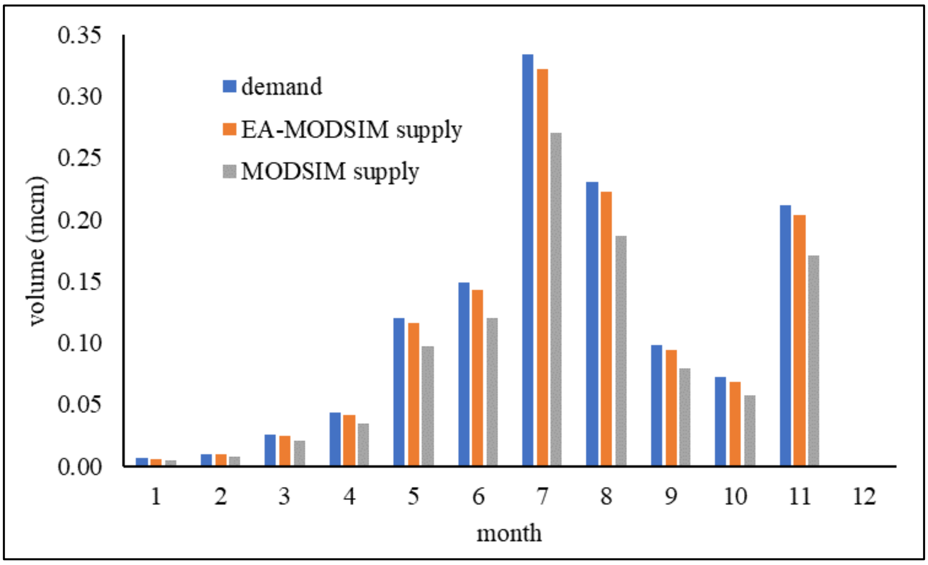

Fig. 7. Average supply for the basin environmental demands in simulation and simulation-optimization models

This difference in the increase of supplies and the decrease in the output flow is due to the increase of the discharge at the place of consumption and water recycling in the basin. These results show an improvement of about 32% in the supply of the water demands of the basin using the simulation-optimization approach. The results of simulation and simulation-optimization models are presented in the figures below.

In the following, the results of evaluation criteria for both simulation and simulation-optimization approaches are presented in Table 4.

Table 4- Results of efficiency simulation and simulation-optimization models

	Simulation			Simulation-Optimization		
Efficiency Criteria	Environmental	Agriculture	Industrial	Environmental	Agriculture	Industrial
Reliability (%)	81	65	60	96	87	86
Vulnerability	0.2	0.87	0.53	0.8	0.28	0.27

MODSIM simulation model is a basic priority allocation model. This means that in order to calculate the amount of water allocation to the demand and storage nodes in the system at each time step, it is necessary to know the priority of allocation to the node. Determining this priority number for system reservoirs can be done with two approaches. The priority of storing water in the reservoir should be in such a way that the water release is done only to supply of water demands of the reservoir downstream and after providing them, the water is stored in the reservoir. Or it should be in such a way that the reservoir is also used to supply of water demands of all or several considered nodes downstream of the basin that are far away from the reservoir. In this situation, the priority of storing water in the reservoir should be less than the intended demands. The first mode is implemented in the simulation model of the current situation of the basin, where dams are generally operated to supply of water demands in their region. But in the simulation-optimization model, the priority of the reservoirs is defined in such a way that the reservoirs participate in providing the demand of the entire basin.

In the simulation conditions, the reservoir behavior generally shows a simple classical behavior, which is discharged when the water release is required to supply the downstream nodes and the storage volume is increased during the water seasons. But on the other hand, in the conditions of optimal operation, the fluctuations of the storage volume of the system reservoirs are much more and have shown a more complex behavior. The reason for this is the system performance of the reservoir to supply the entire basin demands and not just the demands of its downstream. Of course, it is obvious that the implementation of such a model in practice for releasing water from reservoirs may not be easily possible and more detailed technical and hydraulic considerations should be considered in this field. But the optimal policy obtained for the exploitation of reservoirs can be used as a suitable model for planning the allocation of water resources at the level of the basin.

4. Conclusion

This paper has solved the problem of planning the optimal allocation of water resources at the basin level by using the simulation-optimization approach, in which the MODSIM comprehensive basin simulation model was used as the simulation and EA was used as the optimization. The proposed EA-MODSIM model was tested for allocating the water resources of Galmandareh Dam to water uses in the downstream basin. According to the results of the simulation-optimization approach compared to the simulation, it was observed that the amount of supply to the demands of the basin increased by about 32%. Policies for optimal use of reservoirs in simulation-optimization conditions express their complex behavior in one approach. These results show the importance and impact of appropriate decision-making for planning the allocation of water resources at the level of Iran’s basin. The results of the model are consistent with the general expectations in the field of water resources systems analysis and indicate the influence of various factors in complex decision-making at the macro level of water resources management in the behavior and performance of the system.

5. Disclosure statement

No potential conflict of interest was reported by the authors

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