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# Optimization of Dam Reservoir Operation Using Grey Wolf Optimization and Genetic Algorithms: A Case Study of Taleghan Dam

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*ABSTRACT*

With the growth of population, shortage of water, and severe lack of water resources, optimization of reservoirs operation is a principal step in water resource planning and management. Therefore, in the present study, water was optimally allocated for a period from 2010 to 2020 using two simulation-optimization models based on Grey Wolf Optimization algorithm (GWO) and Genetic Algorithm (GA) and WEAP model. System operational indices including volumetric reliability, temporal reliability, vulnerability, and sustainability were used to evaluated the perforemance of optimization algorithms as well as WEAP model. The objective function of resources allocation problem was minimizing sum of the squared relative deficiencies for each month and maximizing reliability over the entire 11-year period. The results showed that optimal allocation solution found by the GWO algorithm with volumetric reliability, vulnerability, and sustainability indices which were 86.93, 0.29, and 21.48%, respectively was better and more suitable than the optimal allocation solution found by GA algorithm (which were 87.12, 0.41, and 21.34%, respectively). Finally, given an increase in the water demands , it is possible to obviate the needs of beneficiaries to an acceptable level and prevent severe draught in dry months through optimizing the use of available resources. According to the calculated indices for the WEAP model, in which volumetric reliability, vulnerability, and sustainability were equal to 87.46, 0.92, and 1.03%, respectively. It can be concluded that the use of optimization algorithm in optimal operation of the dam is more reliable than WEAP model.

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## 1. INTRODUCTION

Currently, given growing needs for water resources as a result of population growth, industry, and agriculture, it is not possible to plan only with variable and uncertain water resources. Therefore, construction of reservoirs to obviate shortage of water is an inevitable and definite matter. The uncontrolled increase in consumption and limited water resources will cause crises in the country in the very near future. In addition, Drought is an inevitable part of the world's climate. It occurs in wet as well as in dry regions. Therefore, planning for drought and mitigating its impacts is essential [1]. As a result, in addition to construction of the dam, operation of the reservoir dams should be done in such a way that the least deficiency occurs during operation period according to inflow to the dam, reservoir geometry, weather conditions, and type of consumption. Following construction of the dam, agricultural, industrial, and urban development programs and finally, structure of the basin water system will change. Changes in structure of the basin water system due to changes in the water supply system or water demand lead to changes in temporal and spatial conditions of the water system. Therefore, optimal operation of dam reservoirs is one of the essential issues in water resources management, especially surface water. Optimization allows for accurate mathematical modeling in a process, and as a result, we will be able to optimize our models using mathematical programming methods. Recently, approximation algorithms have shown

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considerable ability to achieve optimal operation of dam reservoirs [2]. Sattari et al. [3] investigated efficiency of Alavian Dam reservoir system during three phases. They defined the objective function as maximizing the total water output required for agriculture usage. They showed that the calculated capacity was relatively correct during the preliminary studies and operation was relatively satisfactory during the study period. Lack of environmental flow of the river can be evaluated as a major weakness of this model [3]. Kougias and Theodossiou [4] investigated application of harmony search (HS) algorithm in planning of a four-reservoir dam system for irrigation and hydroelectric purposes. Their objective function was maximizing daily gain of the reservoir system for 2-hour period. They showed that the HS algorithm has the potential to optimize complex problems by comparing the results obtained from this method with other methods [4]. Mehta et al. [5] compared three scenarios including changing cultivation pattern according to economic factors, changing cultivation pattern for less water consumption and a combination of changes in the irrigation system, and changing cultivation pattern in the basin in California using water evaluation and planning (WEAP) model, to provide a solution for overcoming the effects of climate change. Guo [6] used the non-dominated sorting particle swarm optimizer (NSPSO) algorithm as a modified version of particle swarm optimization (PSO) to optimize utilization of multi-purpose reservoirs. They demonstrated good performance of the algorithm.

Pradhan and Tripathy [7] developed a model for optimal multi-purpose operation of the hydraulic reservoir in India, based on GA. Comparing the results of GA with the current policy showed the ability and effectiveness of GA [7]. Garousi-Nejad et al. [8] examined the efficiency of the FA algorithm relative to GA in reservoir operation for agricultural water supply and hydropower generation. The results show that the convergence velocity in FA is better than GA to reach the global optimum point and the value of the objective function. Sonaliy and Suryanarayana [9] used the GA for optimal utilization of Ukai reservoir in India. They showed that GA can fully satisfy the needs of downstream irrigation and minimize release of water leading to significant savings of water. Jian-Xia et al. [10] used genetic algorithm (GA) for optimal allocation of water from the reservoir. They investigated probabilistic sensitivity of GA operators, such as intersection and mutation. The results of GA showed that it could act as a suitable option in optimization problems. Ghadami et al. [11] developed a plan for optimal use of the multi-reservoir system in north of Khorasan for agricultural usage using GA. In this model, the most appropriate algorithm was determined for dam reservoir operation based on certain values of state variables including flow volume at the beginning of the year and river's water during agricultural season. Hamlat et al. [12] in a study using WEAP model, they examined and analyzed the existing water balance and the expected scenarios of water resources management in the western Algerian watershed in the future and considered the various policies in place and the parameters that might affect future demand by 2030, and showed that the needs of the domestic sector could be met by considering the expected scenarios Dehghan [13] in a study investigated allocation of water resources under management scenarios in the Gorganrood basin using the WEAP model. They showed that in the new planning of water resources allocation for the Gorganrood basin, the needs of Voshmgir Dams̉ margin industry can be met by 9.5 million cubic meters by accepting 5% reduction of system reliability. Asadi et al. [14] presented a method using a multi-objective structure and utilizing new formulations, in which, instead of meeting 100% of the needs in some months, regardless of dry months, some water of the high-water months or seasons is stored in the reservoir to be used in low-water months for adjusting the failure rate. For this purpose, the multi-objective particle swarm optimization (MOPSO) algorithm was connected to the WEAP simulator model. Finally, the results were evaluated in three scenarios: status quo, land development, and system optimization scenarios. In the status quo scenario, optimal situation was reported in the whole period except for several months. In the land development scenario, in many dry years and in all the last six years of planning in most uses, percentage of supply was zero in 3-8 consecutive dry months and it was less than 5% in other low-water years. But, percentage of supply reached by 28-60 % in these months through implementation of the optimizer model [14].

## 2. METHODOLOGY

**2. 1. Case Study** Taleghan Dam was built in 135 km northwest of Tehran with a longitude of 50° 37′ to 51° 10′ and a latitude of 36° 5′ to36° 25′ (Figure 1). It is located on Taleghan River in Sefidrud catchment. This earth dam is made of pebbles with clay core and a crown of 1,111 m long and 109 m high from the foundation and has a useful volume of 320 million cubic meters and a dead volume of 91 million cubic meters. Tables 1 and 2 represent distribution of water inflow into the reservoir dam and downstream based on monthly needs, respectively. In this study, an 11-year period was used. For estimating volume of water evaporated from the lake as well as the volume of rainfall, the Equation (2) was used as follows [6]:

$$\mathrm{Loss_t} = \mathrm{A_t} \times (\mathrm{Ev_t} - \mathrm{R_t}) \tag{1}$$

$$A_t = a \times e^{(b \times S_t)} + c \times e^{(d \times S_t)} \tag{2}$$

where, A, S , Ev, and R are the lake area (km2) , the volume of water stored in the dam (MCM), evaporation in meters, and precipitation in meters respectively, and t denoted the simulation time step..a, b, c, and d are regression coeficients of volume-suface curve and equal to 8908000 and 10-10 × 8.79 and -8621000 and -9-10 × 6.026, respectively. Equation (1) was used to estimate the evaporation from lake surface. In Equation 1, we need the surface of lake which is a variable parameter. Using Equation (2) we determined the lake surface as a function of lake volume. It is worth to mention that the lake volume was determined by water mass balance in the lake. The only question is that what is the relation between volume and surface of the lake. Using available volume-elevation-surface data and Matlab curve-fitting toolbox, we invetigate a variety of model. We used least-square method to determine the coefficient of each regression model. The best model (minimm error) was found by the Equation (2). In other word, Equation (2) is a relationship between the the lake surface (as the dependent variable) and lake volume (as the independent variable).

Based on Tables 1 and 2, sum of annual water demand for drinking, agriculture, artificial recharge, and environment is equal to 456. 49 MCM.

## 2. 2. Grey Wolf Optimization Algorithm (GWO)

GWO [15] was inspired by life of grey wolves. They have a special interest in social hierarchy. The leaders of males and females are called as alpha. Alpha is mainly responsible for deciding on hunting, where to sleep, when to wake up, and so on. Alphaś decisions are dictated to the rest of the community showing that organization and discipline in an association are more important thanpower. Beta is at the second level in the grey wolf hierarchy. Beta wolves are follower wolves helping the alpha in decision-making or other association activities. The lowest rank in grey wolves belongs to the omega grey wolf. The omega plays the role of a sacrificial sheep. The omega wolf must always serve other dominant wolves. They are the last wolves in the community that are allowed to eat. If the wolf is neither alpha, nor beta, and omega, so it is called as delta. They must serve the alpha and beta wolves. Social hierarchy in the group of grey wolves is shown in Figure 2. The most important hunting phases in the grey wolveś association include the followings: 1. Pursuing 2. Reaching the hunt 3. Surrounding 4. Forming the attack position 5. Attacking for mathematically modeling this process, the Equations (3)-(6) are used as follow:

$$\vec{X}_{(t+1)} = \overrightarrow{Xp}_{(t)} - (\vec{A} \times \overrightarrow{D_t}) \quad (3)$$

where $t$ is the number of iterations, $\vec{A}$ and $\vec{D}$ are the coefficient vectors, $\overrightarrow{Xp}$ is the position of the prey, and $\vec{X}$ is the position of the gray wolves.

$$\vec{D} = \left|(\vec{C} \times \overrightarrow{Xp}_t) - \vec{X}_t\right| \quad (4)$$

$$\vec{A} = a(2r_1 - 1) \quad (5)$$

$$\vec{C} = 2r_2 \quad (6)$$

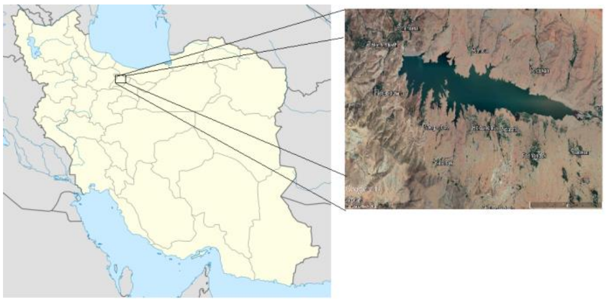

**Figure 1.** Location of the Taleghan Dam

**TABLE 1.** The average monthly water flow to Taleghan Dam (during 2010-2020) MCM

| Statisticial Summary of inflow | April | May | June | July | August | September | October | November | December | February | January | March |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Mean** | 76.80 | 102.10 | 73.62 | 29.50 | 13.71 | 9.89 | 8.66 | 16.25 | 13.05 | 11.49 | 13.73 | 30.17 |
| **Standard Deviation** | 25.10 | 35.46 | 37.58 | 12.42 | 4.75 | 4.36 | 1.86 | 8.28 | 5.11 | 3.70 | 4.59 | 9.56 |
| **Min** | 41.11 | 64.10 | 32.22 | 15.74 | 6.94 | 4.01 | 3.91 | 7.68 | 5.81 | 4.12 | 8.30 | 20.33 |
| **Max** | 129.21 | 178.81 | 174.41 | 57.48 | 21.41 | 18.94 | 10.82 | 33.92 | 22.14 | 16.53 | 23.96 | 46.19 |

**TABLE 2.** Water demand in different months in Taleghan Dam

| Demand | April | May | June | July | August | September | October | November | December | February | January | March |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Drinking** | 14.88 | 16.98 | 19.77 | 22.75 | 22.40 | 21.35 | 18.72 | 16.45 | 14.52 | 14.00 | 13.65 | 14.52 |
| **Agriculture** | 7.5 | 28.3 | 27.5 | 24.8 | 23.3 | 14.1 | 23.1 | 1.4 | 0 | 0 | 0 | 0 |
| **Artificial recharge** | 1.1 | 0 | 0 | 0 | | 0 | 0 | 0 | 4.7 | 5.6 | 4.3 | 4.3 |
| **Environment** | 7.9 | 12 | 9.3 | 5.4 | 6.4 | 4.3 | 4.7 | 5.1 | 3.9 | 3.9 | 4.1 | 9 |
| **Sum** | 31.38 | 57.78 | 56.57 | 52.95 | 52.1 | 39.75 | 46.52 | 22.95 | 23.12 | 23.5 | 22.05 | 27.82 |

where, component "a" is linearly decreased from 2 to 0 during the repetition period, and r1 and $r2$ are the random vectors in the range of [0 and 1]. For mathematically modeling hunting behavior of the grey wolf, α (the best candidate solution), β (the second best candidate solution), and δ (the third best candidate solution) are used assuming that they have the best knowledge about prey position. So, the three best solutions obtained so far are kept and other search agents like omega are forced to update their position according to position of the best search agents. Equation (7) is used to update the position of the wolves:

$$\vec{X}_{(t+1)} = \frac{\overrightarrow{X1}_t+\overrightarrow{X2}_t+\overrightarrow{X3}_t}{3} \tag{7}$$

Here, X is the position of any wolf at iteration t+1.

X1 is the position of the alpha at iteration t, X2 is the position of the beta at iteration t, X3 is the position of the omega at iteration t

where, $\overrightarrow{X1}$, $\overrightarrow{X2}$, and $\overrightarrow{X3}$ were defined as follow:

$$\overrightarrow{X1}_t = \left|\overrightarrow{X\alpha}_t - (\overrightarrow{A1} \times \overrightarrow{D\alpha}_t)\right| \tag{8}$$

$$\overrightarrow{X2}_t = \left|\overrightarrow{X\beta}_t - (\overrightarrow{A2} \times \overrightarrow{D\beta}_t)\right| \tag{9}$$

$$\overrightarrow{X3}_t = \left|\overrightarrow{X\delta}_t - (\overrightarrow{A3} \times \overrightarrow{D\delta}_t)\right| \tag{10}$$

where, $\overrightarrow{X\alpha}$ , $\overrightarrow{X\beta}$ , and $\overrightarrow{X\delta}$ are the positions of the first three best solutions initeration t. $\overrightarrow{A1}$, $\overrightarrow{A2}$, and $\overrightarrow{A3}$ are introduced before (Equation (5)) and $\overrightarrow{D\alpha}$ , $\overrightarrow{D\beta}$ and $\overrightarrow{D\delta}$ are defined as follow, respectively.

$$\overrightarrow{D\alpha}_t = \left|\left(\overrightarrow{C1} \times \overrightarrow{X\alpha}\right) - \vec{X}\right| \tag{11}$$

$$\overrightarrow{D\beta}_t = \left|\left(\overrightarrow{C2} \times \overrightarrow{X\beta}\right) - \vec{X}\right| \tag{12}$$

$$\overrightarrow{D\delta}_t = \left|\left(\overrightarrow{C3} \times \overrightarrow{X\delta}\right) - \vec{X}\right| \tag{13}$$

where $\overrightarrow{C1}$, $\overrightarrow{C2}$, and $\overrightarrow{C3}$ are introduced before (Equation (6)).

**2. 3. Genetic Algorithm (GA)** This algorithm was first proposed by Holland [16] and then, it was developed as a powerful optimization tool. This method is based on the Darwin's theory and conflict of survival, stating that always the creatures who are the most stable can survive. The GA starts from a set of initial random solutions called as population. Each population is made up of a set of chromosomes, each of which is a solution to the problem, and each chromosome is made up of a set of genes, or indeed problem-solving variables. Size of the population influences performance of GA so that, if the population is too small, due to not searching all the solution space, the algorithm may not converge to the desired solution, and if it is too large, although more space is searched, but convergence speed for optimal solution will be slow and execution time of the program will be longer. There are two types of operators in the GA: evolutionary operators, such as selection and genetic operators, such as crosses and mutations. Selection process is based on the degree of suitability of the objective functions corresponding to each chromosome in each generation, and the criterion for selecting chromosomes is based on their suitability.

**2. 4. WEAP Software** WEAP is a software tool used for integrated planning of water resources providing a comprehensive, flexible, and user-friendly framework for policy planning and analysis [17]. Many areas are exposed to heavy challenges of freshwater management. Allocation of the limited water resources has raised concerns about environmental quality, climate diversity planning, and uncertainty. In addition, the necessity for developing and implementing sustainable water usage strategies has increasingly imposed pressure on water resources̓ policy-makers. The need node in WEAP depends on issues, such as water consumption patterns, equipment efficiency, reuse strategy, costs, and water allocation schemes. Furthermore, the supply side refers to issues, such as surface runoff, groundwater resources, reservoirs, and water transfer. WEAP is distinguished from natural simulation (e.g., need for evapotranspiration; runoff, base flow) and engineering components of the water system (e.g., reservoirs, groundwater pumping) by a comprehensive approach. This allows the designer to have access on a more comprehensive view of the wide range of factors that must be considered in water resources management for the current and future usage. The results obtained from

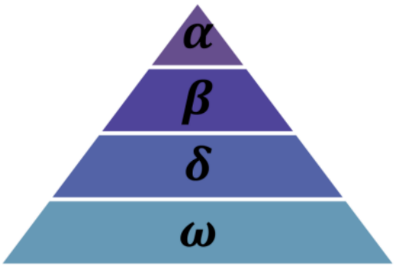


**Figure 2.** Social hierarchy in the group of grey wolves

WEAP are a very useful tool for assessing different options for water management and development. In this study, WEAP software was used to allocate the available water resource among different demand sites. In other words, the amount of supplied water to each demand site by SOP algorithm was calculated by WEAP software. Inputs data including river inflow, precipitation, evaporation, demands, and dam physical properties were collected and used as inputs of WEAP software. The time horizon of investigation was set to 2010-2020. The results of supplied water to each demand site were then exported to Excel and the reservoir performance indicators of SOP algorithm were calculated.

**2. 5. Indicators of Reservoir Performance** For checking performance of GA and GWO algorithms, indicators of reliability, vulnerability, and sustainability were used. The index of reliability offers the possibility that the system has normal operation (no failure) during its performance period. This index can be defined in two volume and time forms as follows:

**2. 6. Volumetric Reliability** Volumetric Reliability is referred to the ratio of volume of water released during the whole period t ($Re_t$) to the amount of water needed in downstream of the reservoir ($D_{et}$) and is obtained based on the Equation (14) as follows:

$$\delta_v = 100 \times \left(\frac{Re_t}{De_t}\right) \tag{14}$$

**2. 7. Time Reliability** Time Reliability is referred to a percent of time, at which the reservoir is able to meet the demand (facing no failure) and calculated as follows (Equation (15)):

$$\delta_t = 100 \times \left[1 - \frac{NDef}{T}\right]$$
$$NDef = Number\ (\alpha \times Det > Ret) \tag{15}$$

where, $N_{Def}$ and T are the number of periods facing the failure and the total operating periods, respectively. α is the confident coefficient indicating how much failure is acceptable in reliability calculation. In this study, α=0.9 was used. It means all deficits lower than 10 percent are considered as full allocation. Generally, the confident coefficient for domestic use is 0.95, for environmental needs is 0.9, and for agriculture is 0.85. In this study, because we investigate the total allocation as a whole, we used α=0.9 which can be considered as an average value for α.

**2. 8. Vulnerability Index** Vulnerability Index represents the extent of system failures and is obtained using the Equation (16) as follows [18]:

$$\eta = \max_{t=1,2,\dots,T}\left(\frac{De_t - Re_t}{De_t}\right) \tag{16}$$

where, $De_t$ and $Re_t$ represent the required and released water volumes in t-th period, respectively and T shows the entire number of periods of operation.

**2. 9. Sustainability** Loucks [19] introduced sustainability index, φ, as follows (Equation (17)):

$$\Phi = \delta\, \gamma\, (1 - \eta) \tag{17}$$

where, δ, η, and γ are Reliability and Vulnerability, and Resilience, respectively. Resilience is calculated by the Equation (18) stated as follows:

$$\gamma = 1/f/fs \tag{18}$$

where, fs is the number of failure periods continually, and f is the number of entire time periods.

**2. 10. Mathematical Model of Optimal Operation of Reservoir** In this study, The objective function of resources allocation problem was minimizing sum of the squared relative deficiencies for each month (Modified vulnerability index) and maximizing reliability.

the objective function and constraints are defined as follows:

$$min\ F = \frac{1}{T}\sum_{t=1}^{T}\left(\frac{R_t - D_t}{D_t}\right)^2 + \frac{1}{\delta_t} + P \tag{19}$$

Subject to:

$$S_{t+1} = S_t + Q_t + Loss_t + Re_t + Spill_t \tag{20}$$

$$R_{min} \le R_t \le R_{max} \tag{21}$$

$$S_{min} \le S_t \le S_{max} \tag{22}$$

$$P = \begin{cases} \sum_{t=1}^{T} \frac{S_{min} - S_t}{S_{min}} & if\ (S_t < S_{min}) \\ \sum_{t=1}^{T} \frac{S_t - S_{max}}{S_{max}} & If\ (S_t < S_{max}) \end{cases} \tag{23}$$

where, $R_t$ is the volume of the released water, $D_t$ is the amount of the required water, $\delta_t$ is the time reliability, $S_{t+1}$ is the volume of the stored water in the reservoir in the next period, $S_t$ is the volume of the stored water in the reservoir in the current period, and $R_{min}$ and $R_{max}$

represent the minimum and maximum released water from reservoir, respectively. $S_{min}$ and $S_{max}$ are the minimum and maximum volumes of the stored water, respectively; P is the penalty function related to the reservoir volume, $Q_t$ is the volume of water inflow to the reservoir. $Loss_t$ refers to the amount of reservoir loss. $Spill_t$ presents the volume of water overflow, and t is the number of period.

## 3. RESULTS AND DISCUSSION

In order to obtain a reliable reults, two population size (number of wolves), were used to optimize the problem. Different performance indices were tested with population size of 200 - 500 with 2500 iterations. The results are shown in Tables 3 and 4.

For considering different modes that can be used in GA operator of roulette wheel selection, gene mutation operator with probability between 0.2 - 0.3 and cross – over operator with probability between 0.8-0.9 were evaluated in program execution.Values of the objective function and reservoir performance indicators are given in Table 4 for the whole operation period (132 months).

Values of the objective function and reservoir performance indices are given in Table 5 for the whole statistical period (132 months) and the iteration of 2500.

**TABLE 3.** Results of GWO algorithm

| GWO algorithm | | |
|---|---|---|
| **Objective function** | **Iteration** | **Population** |
| 0.040879 | 2500 | 200 |
| 0.03306 | 2500 | 500 |

**TABLE 4.** The results of applying GA

| GA algorithm | | | | | Number |
|---|---|---|---|---|---|
| **Objective function** | **pc** | **pm** | **Iteration** | **Population** | |
| 0.041035 | 0.8 | 0.2 | 2500 | 200 | 1 |
| 0.040612 | 0.9 | 0.3 | 2500 | 200 | 2 |
| 0.0392 | 0.8 | 0.2 | 2500 | 500 | 3 |
| 0.03886 | 0.9 | 0.3 | 2500 | 500 | 4 |
| 0.040641 | 0.8 | 0.3 | 2500 | 200 | 5 |
| 0.039974 | 0.8 | 0.3 | 2500 | 500 | 6 |

According to this table, the volumetric reliability of the best solution found by GWO with 86.93 is close to the best GA solution with 87.12 while GWO minimizes the objective function with 0.03306 better than GA with 0.03886. According to the objective function (minimize vulnerability index and maximize time reliability index), the vulnerability index of the best solution found by GWO with 0.2903 is highly lower than best solution found by GA with 0.4131 which means GWO is highly better than GA. In addition, time reliability of the best solution found by GWO with 68.93 is better than the best solution found by GA with 66.66 which means GWO is better than GA. also sustainability index (which is an overall index, see Equation (17)) of GWO with 21.48 is higher than GA with 21.34 and confirms the better performance of the GWO.

In Figure 3, as can be seen, although performance of both methods was acceptable and they were able to meet the required demand in downstream of dam with good accuracy, GWO has better performance than GA. As can be seen in Figure 3, the optimum solution found by GA, has more severe droughts than the optimum solution found by GWO.

Figure 4 shows the average annual water shortage (demand minus release) of Taleghan Dam obtained from GWO and GA algorithms. According to Figure 4, severity of shortages in GA is higher than GWO. The maximum amount of dam volume shortage in GA and GWO is equal to 7.89 and 6.77 MCM, respectively. Low amount of shortages in GWO indicates good performance of this algorithm. According to Table 6, it can be concluded that although WEAP model has more suitable performance than GWO algorithm regarding its time reliability index, volumetric reliability index, and shortage, but higher value of the objective function and more vulnerability and less sustainability than GWO algorithm are reasons for poor performance of WEAP.

Figure 5 shows the average monthly water release in two models. Results of applying models showed that during the 11-year period and according to the two models of WEAP and GWO, the reservoir can adjust 399.14 and 391.64 million meter cubic water annually for release on average. Based on Figure 5, the average release of water in April, May, June, and July is more in the WEAP model than GWO model. The condition is completely opposite in August, September, and October, revealing that the GWO model provides more supplies in

**TABLE 5.** Objective function values and reservoir performance indices in operation of the Taleghan Dam reservoir using the GWO and GA algorithms

| Sustainability (%) | Vulnerability(%) | Time reliability α(%)=0.9 | Volumetric reliability(%) | Total Deficit (MCM) | Objective function | Model |
|---|---|---|---|---|---|---|
| 21.48 | 0.2903 | 68.93 | 86.93 | 655.92 | 0.03306 | GWO |
| 21.34 | 0.4131 | 66.66 | 87.12 | 646.377 | 0.03886 | GA |

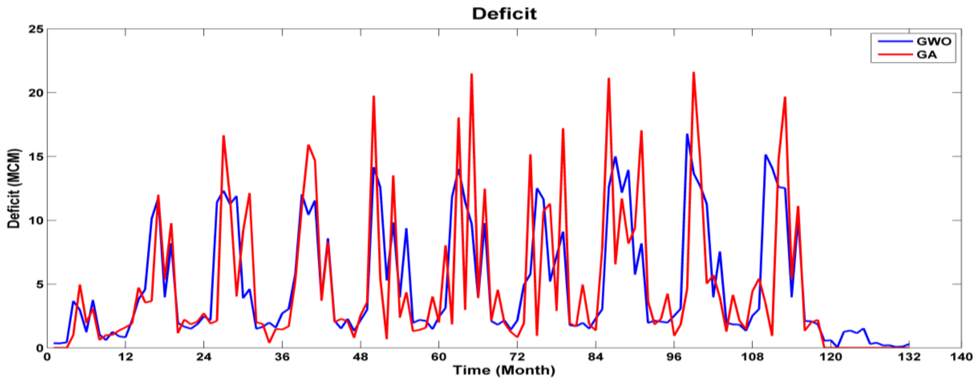


**Figure 3.** Release value through GWO and GA algorithms

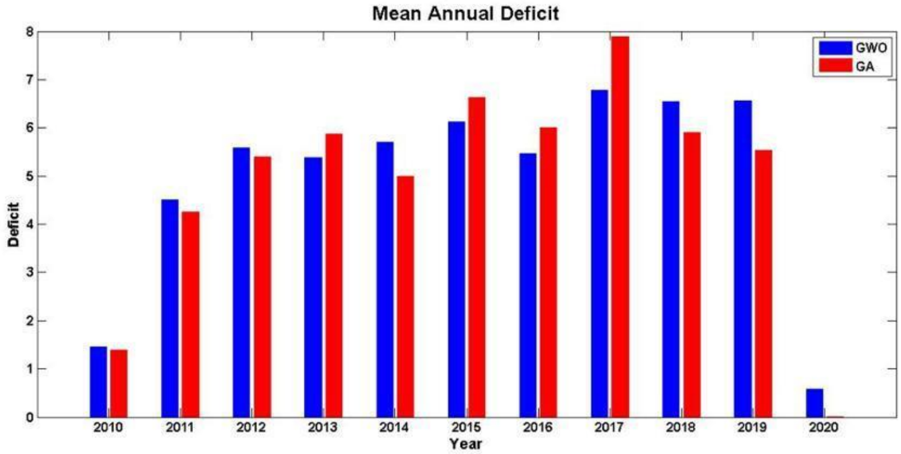


**Figure4.** Mean values of annual water deficit obtained from GWO and GA algorithms for Taleghan Dam (2010-2020)

**TABLE 6.** Objective function values and reservoir performance indices in operation of the Taleghan Dam reservoir using the GWO algorithm and WEAP model

| Sustainabilit (%) | Vulnerability(%) | Time reliability α=0.9 (%) | Volumetric reliability (%) | Shortage (MCM) | Objective function | Model |
|---|---|---|---|---|---|---|
| 21.48 | 0.29 | 68.93 | 86.93 | 655.92 | 0.03306 | GWO |
| 1.03 | 0.92 | 71.9 | 87.46 | 627.97 | 0.09 | WEAP |

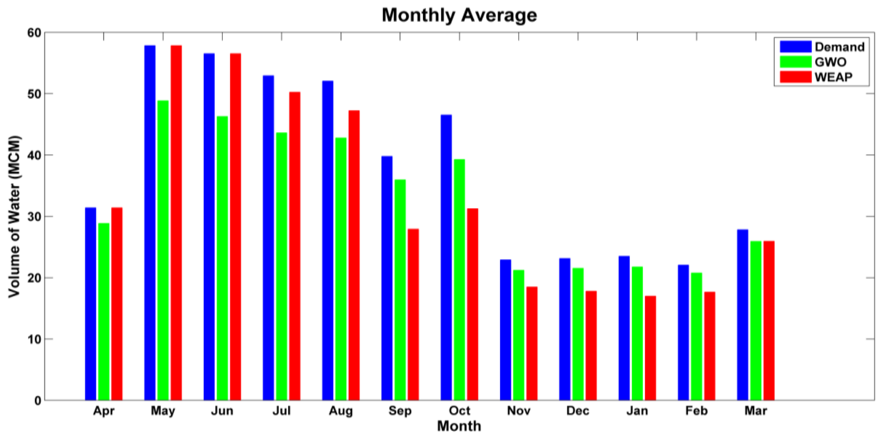


**Figure 5.** Average monthly release in WEAP and GWO and monthly demand of the dam

August, September, and October by saving water in April, May, June, and July. Using the operating procedure of less release of water in these months, GWO causes more water reservation in the reservoir, which in turn causes uniform distribution of water deficit in these months and decreases severity of water deficit in the critical months. In WEAP model (SOP), the aim is to supply 100% of monthly demands. Based on this policy in dry periods, by consumption of the available water in the reservoir, the elevation of the reservoir decreases and as a result, the amount of evaporation is decreased in comparison by optimal solution found by GWO. Therefore, water deficit in WEAP model decreases in comparison by GWO, and consequently, the volumetric reliability obtained by WEAP model is better than the GWO's. On the other hand, due to the less water available in the reservoir, the obtained vulnerability of the system in WEAP model is considerably more than GWO's.

## 4. CONCLUSION

Meta-heuristic optimization algorithms have been extensively used by scientists and engineers to optimize water resource system during last two decades. In the present study, first, performance of the GWO algorithm was investigated in compared to the GA and the GWO algorithm was selected as appropriate method. Then, the GWO algorithm was compared with WEAP model and results showed that in the GWO algorithm, always a desirable amount of water would be stored in the reservoir and used in each period faces acceptable amount of water deficit and as a result, preventing severe shortages in drought events. The results of the present study are consistent with the results of other study. Vulnerability index was obtained as 0.29 and 0.92 in GWO algorithm and WEAP model, respectively. Also, sustainability of the system was higher in the GWO algorithm with 21.48 than the WEAP model with 1.03. Optimal usage of water in condition where the recent droughts have caused water deficit in the country naturally and also, irregular usage of underground waters has caused many worries; accordingly, it is suggested to use the water resources in the reservoirs scientifically.

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## Persian Abstract

**چکیده**

با افزایش جمعیت، کمبود آب و کمبود شدید منابع آبی، بهینه سازی عملکرد مخازن یک گام اصلی در برنامه ریزی و مدیریت منابع آب است. در مطالعه حاضر، با استفاده از دو مدل بهینه سازی – شبیه سازی بر اساس الگوریتم بهینه سازی گرگ خاکستری (GWO) و الگوریتم ژنتیک (GA) و مدل WEAP ، منابع آب برای یک دوره آماری از سال ۲۰۱۰ تا سال ۲۰۲۰ تخصیص داده شد. از شاخص های عملکرد سیستم شامل قابلیت اطمینان حجمی، قابلیت اطمینان زمانی، آسیب پذیری و پایداری برای ارزیابی الگوریتم های بهینه سازی و همچنین مدل WEAP استفاده شد. تابع هدف مساله تخصیص منابع آب، به حداقل رساندن مجموع کمبودهای نسبی مربع برای هر ماه و به حداکثر رساندن قابلیت اطمینان در کل دوره ۱۱ ساله بود. نتایج نشان داد که راه حل تخصیص بهینه توسط الگوریتم GWO با شاخص های قابلیت اطمینان حجمی ، آسیب پذیری و پایداری به ترتیب با ۸۶.۹۳ ، ۰.۲۹ ، و ۲۱.۴۸ بهتر از راه حل تخصیص بهینه توسط الگوریتم GA با ۸۷.۱۲ ، ۰/۴۱ و ۲۱/۳۴ درصد می باشد. در نهایت، با توجه به افزایش تقاضای آب، می توان نیازهای ذینفعان را تا حد قابل قبولی کاهش داد و از طریق بهینه سازی استفاده از منابع موجود ، از خشکسالی شدید در ماه های خشک جلوگیری کرد. با توجه به شاخص های محاسبه شده برای مدل WEAP، که در آن قابلیت اطمینان حجمی، آسیب پذیری و پایداری به ترتیب برابر با ۸۷/۴۶ ، ۰/۹۲ و ۱/۰۳ درصد می باشد، می توان نتیجه گرفت که استفاده از الگوریتم بهینه سازی در عملکرد بهینه سد مناسب تر است از مدل WEAP می باشد.