Integrated Operation of Multi-Reservoir and Many-Objective System Using Fuzzified Hedging Rule and Strength Pareto Evolutionary Optimization Algorithm (SPEA2)

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Abstract: In this paper, a many-objective optimization algorithm was developed using SPEA2 for a system of four reservoirs in the Karun basin, including hydropower, municipal and industrial, agricultural, and environmental objectives. For this purpose, using 53 years of available data, hedging rules were developed in two modes: with and without applying fuzzy logic. SPEA2 was used to optimize hedging coefficients using the first 43 years of data and the last 10 years of data were used to test the optimized rule curves. The results were compared with those of non-hedging methods, including the standard operating procedures (SOP) and water evaluation and planning (WEAP) model. The results indicate that the combination of fuzzy logic and hedging rules in a many-objective system is more efficient than the discrete hedging rule alone. For instance, the reliability of the hydropower requirement in the fuzzified discrete hedging method in a drought scenario was found to be 0.68, which is substantially higher than the 0.52 from the discrete hedging method. Moreover, reduction of the maximum monthly shortage is another advantage of this rule. Fuzzy logic reduced 118 million cubic meters (MCM) of deficit in the Karun-3 reservoir alone. Moreover, as expected, the non-hedging SOP and WEAP model produced higher reliabilities, lower average storages, and less water losses through spills.

Keywords: discrete hedging rule; fuzzy logic; optimum reservoir operation; Karun basin; SPEA2 algorithm; WEAP

1. Introduction

Iran is part of the arid and semi-arid regions of the world, with an average annual precipitation of about 250 mm, which is less than one-third of the world’s average annual rainfall. In such circumstances, optimum use of available water resources and the extracting optimize rule curve is important. The rule curve, as the main pattern of reservoir operation policy, determines the amount of water stored or released at each time step [1].

Applying hedging policies during drought periods can improve the utilization of water resources. This method is based on the fact that the higher number of drought periods with less intensity is preferred to fewer periods with higher intensity, mainly due to the nonlinear cost function of shortages. In other words, the relation between damages and deficiency is not linear [2]. The continuous hedging method was introduced in 1982 by Hashimoto et al. [3]. Later, Shih and ReVelle [4] introduced the discrete hedging method. In 1999, Neelakantan and Pandirakanthan improved the reservoir operation performance through the simulation–optimization procedure with the application of the hedging rule [5].
Considering the provision of hedging policies in recent years, many studies have been conducted to optimize utilization policies in drought periods, including the study by Dariane [2] to reduce the effect of drought. Dariane and Karami [6] presented an online optimization scheme for combined use of artificial neural networks (ANN), hedging policies, and the harmony search algorithm (HS) in developing optimum operating policies in a multiple-reservoir system. They developed a simulation–optimization methodology in which the management decision variables were passed from the optimization model to the simulation one to obtain the value of the objective function. Spiliotis et al. [7] presented a method by using the particle swarm optimization (PSO) algorithm for adopting the best hedging policy for reservoir operation. Jin et al. [8] reviewed the reservoir operation policies based on the discrete hedging method by using linear programming for the Hapcheon Reservoir in South Korea. In his research, hedging involved four phases, concern, caution, warning, and severe dehydration, in which the reservoir operation policies were determined based on the amount of available water and the tendency of the remaining reservoir in the existing phase. The amount of water in the reservoir also consisted of water stored at the beginning of the period plus the inflow into the reservoir.

In addition, in the past decades, a large number of papers have presented the fuzzy approach for improving the operation of reservoirs. For example, Russell and Campbell [9] used fuzzy logic programming to extract operational rules. Shrestha et al. [10] used a fuzzy rule-based model to derive operation rules for a multi-purpose reservoir. In this context, further research has been proposed using fuzzy logic theory to improve the efficiency in reservoir operation [11–17]. Ahmadinefar et al. [18,19] showed that the combination of hedging methods and fuzzy logic reduced the effects of drought because the rationing factors do not change suddenly when the combination is used. Rajendra et al. [20] and Kambalimath and Chandra Deka [21] reviewed fuzzy logic models for the operation of a single-purpose reservoir and hydrology and water resources domain, respectively.

In discussing many-objective optimization algorithms (problems with more than three objective functions) visualization of a high-dimensional objective space and obtaining a good convergence of the Pareto front are challenges because the proportion of non-dominated objective solutions increases when the number of objectives exceeds four. This makes ranking difficult. Zitzler and Thiele [22] introduced the SPEA algorithm. This algorithm consists of a population set and an external set. The program begins with the initial population and the outer blanket, and the following operations are performed on each repetition. The dominant answers are copied to the empty set, and the evaluation function for all the existing answers is calculated. It is worth noting that the goal is to minimize the evaluation function. The SPEA2 method is the modified version of SPEA [23].

According to the importance of operating policies in drought periods, this study attempted to optimize the operation rules for a many-objective system (more than three objective functions), including the Karun-4, Karun-3, Karun-1, and Gotvand reservoirs, by using the hedging and fuzzy approach with the SPEA2 optimization algorithm. This study can help decision makers to decide how much water should be released now and how much should be retained for future uses, which is the major task of reservoir operation. This simple choice becomes complex in the presence of uncertain future inflows and nonlinear economic benefits for released water. Combining fuzzified hedging policies optimized with the SPEA2 optimization algorithm is a useful method in occurrence of severe and frequent droughts and can improve reservoir operation rules and aid water supply operators in coping with the risk of dramatic water deficiencies to the users. This is a new strategy for optimal operation of multiple reservoirs by combining discrete hedging and fuzzy theory during drought and water scarcity for a multi-reservoir, many-objective systems. It proposes water supply policies in the form of a rule curve and reduces drought effects in meeting demands. In the discrete hedging method, the hedging coefficient changes abruptly in each phase. Using the fuzzy approach creates a transition region for this coefficient and causes the coefficient to change gradually and mitigates the intensity of drought periods. In fact, the flexibility of the hedging factors increases by using fuzzy logic.
Finally, vulnerability assessment, scarcity and reliability criteria are used to demonstrate the function of the fuzzy approach in hedging rules.

2. Methodology

2.1. Discrete Hedging Method

In this study, similar to Shih and ReVelle [4] and as shown in Figure 1, three hedging levels were assumed for the operation of reservoirs. In each reservoir, the amount of total available water (TAW), i.e., the sum of the initial reservoir storage, $S_t$, and the projected inflow, $Q_t$, in period $t$, was calculated during each time step. If TAW is above $V_{1t}$, then the normal condition is assumed, and all demands are fully met. In this case, the reservoir will spill if TAW increases to above the reservoir capacity plus demand. Hedging occurs when TAW falls under $V_{1t}$. If TAW is between $V_{1t}$ and $V_{2t}$, the first water rationing phase is implemented where demand supply is cut down and only $\alpha_1$ percent of the demand is released ($0.4 \leq \alpha_1 \leq 0.85$). The second rationing phase is implemented if TAW falls further to a level between $V_{2t}$ and $V_{3t}$, and $\alpha_2$ percent of the demand is provided where $0.4 \leq \alpha_2 \leq \alpha_1 \leq 0.85$.

![Figure 1. The discrete hedging method.](image)

Therefore, decision variables for each reservoir examined in this study were: $V_{1t}$, $V_{2t}$, $V_{3t}$, $\alpha_1$, and $\alpha_2$. $V_{3t}$ is equal to the minimum reservoir capacity ($S_{\text{min}}$) according to the constraints of the problem, meaning no release occurs below this level. Hence, we must decide on four variables per month which is a total of 48 variables in a year. After determining the variables, the reservoir operation policy is applied in the following way:

\[
\begin{align*}
\text{If } S_{ti} + Q_{ti} &< V_{3t} \quad \text{Then } R_{ti} = 0 \quad (1) \\
\text{Else If } V_{3t} &< S_{ti} + Q_{ti} < V_{2t} \quad \text{Then } R_{ti} = \alpha_2 S_{ti} \times D_{ti} \quad (2) \\
\text{Else If } V_{2t} &< S_{ti} + Q_{ti} < V_{1t} \quad \text{Then } R_{ti} = \alpha_1 S_{ti} \times D_{ti} \quad (3) \\
\text{Else If } V_{1t} &< S_{ti} + Q_{ti} \quad \text{Then } R_{ti} = D_{ti} \quad (4) \\
\text{Else if } S_{\text{maxi}} &> S_{ti} + Q_{ti} \quad \text{Then } R_{ti} = D_{ti} \text{ and Spill}_{ti} = S_{ti} + Q_{ti} - S_{\text{maxi}} \quad (5)
\end{align*}
\]

where $R_{ti}$, $D_{ti}$, $S_{ti}$, $Q_{ti}$, Spill$_{ti}$ is the release, demand, storage, inflow, and spill of reservoir $i$ in period $t$. $S_{\text{min}}$ and $S_{\text{max}}$ are the minimum and maximum capacity of the reservoir $i$. If the constraints of the problem are violated, a penalty is considered for $R_{ti}$ in order to remove that choice from the optimization process and make it feasible.
2.2. Fuzzified Discrete Hedging Method

Fuzzy logic was first introduced by Zadeh in 1973. In fuzzy logic, the membership function specifies how each point is mapped to a membership value between 0 and 1 [24,25]. If the membership grade of an element is 0, then that member is completely out of the set, and if it is equal to 1, that member is completely in the set. Now, if it is between 0 and 1, this number represents the degree of gradual membership. In this research, the trapezoidal membership function was used to apply fuzzy logic. In the discrete hedging method, the hedging coefficient changes suddenly in each phase. Using the fuzzy approach creates a transition region for this coefficient and causes the coefficient to change gradually. The schematic diagram (Figure 2) shows the fuzzy hedging rule.

In Figure 2, there are two line curves (upper and lower curves) and four transition paths. When the available water is in zone 2 (between transmission lines B and C), \( \alpha_1 \) percent of demand is provided. If the available water is higher than the transmission line B, the coefficient is determined between \( \alpha_1 \) and 1 by using the fuzzy membership function. It is the first phase of hedging for slight droughts. The same trend is considered for the second phase for severe droughts. When the available water is below the transmission line C, the coefficient is determined between \( \alpha_2 \) and \( \alpha_1 \) by using the fuzzy membership function. Using transition zones around the rule curves in fuzzy logic prevents the sudden change of coefficients. In the other words, where the reservoir level is going from one zone to another, the hedging coefficients will be increased or decreased gradually. Trapezoidal membership function is shown in Figure 3.
The operation policy of each reservoir is defined by Equations (6)–(15). \( \mu \) is the degree of belongingness to a fuzzy set and Equations (6)–(9) present the parameters of determining the trapezoidal membership function. The main approach for the developed hedging rule is illustrated in Equations (10)–(15).

\[
\begin{align*}
M_{1i} &= S_{\text{mini}} + (V_{2i} - S_{\text{mini}}) \times \beta_{1i} \\
M_{2i} &= V_{2i} + (V_{1i} - V_{2i}) \times \beta_{2i} \\
M_{3i} &= M_{2i} + (V_{1i} - M_{2i}) \times \beta_{3i} \\
M_{4i} &= V_{1i} + (S_{\text{maxi}} - V_{1i}) \times \beta_{4i} \\
\text{If } S_{li} + Q_{li} \leq \text{transition zone 1} & \quad \text{Then } R_{li} = \alpha_{1li} \times D_{li} \\
\text{If } S_{li} + Q_{li} \leq \text{transition zone 2} & \quad \text{Then } R_{li} = \alpha_{2li} + D_{li} \\
\text{If } S_{li} + Q_{li} \leq \text{transition zone 3} & \quad \text{Then } R_{li} = \alpha_{3li} \times D_{li} \\
\text{If } S_{li} + Q_{li} \leq \text{transition zone 4} & \quad \text{Then } R_{li} = \alpha_{4li} \times D_{li} \\
\text{If } S_{li} + Q_{li} < V_{3li} & \quad \text{Then } R_{li} = 0
\end{align*}
\]

\( S, Q, V, R, D, \) and \( \alpha \) were defined before in Section 2.1. \( \beta_{1li}, \beta_{2li}, \beta_{3li}, \) and \( \beta_{4li} \) are the membership function parameters and are obtained by applying optimization algorithm. Hence, based on this method, with \( V_{1i}, V_{2i}, \alpha_{1}, \) and \( \alpha_{2}, \) there are eight decision variables for optimization in each time period.

2.3. SPEA2 Optimization Algorithm

The SPEA algorithm consists of a population set and an external set [22]. The program begins with the initial population and the blank outer set, and the following operations are performed on each repetition. The dominant answers are copied to the empty external set, and the evaluation function for all the existing answers is calculated as follows (Figure 4). It is worth noting that the goal is to minimize the evaluation function. For each solution \( i \) in the external, \( S(i) \) is assigned between 0 and 1. This is the ratio of solutions that are dominated by \( i \) to the population size plus 1 and represents the evaluation function of that answer. For the solutions \( j \) in the population set, the evaluation function is obtained from the sum of \( S(j) \) for solutions dominant \( j \) plus 1. Finally, depending on the evaluation function, the mating, combination and mutation operators are performed, and the new set replaces the previous one.

![Figure 3. Trapezoidal membership function for fuzzy hedging coefficients.](image-url)
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Finally, depending on the evaluation function, the mating, combination and mutation operators are performed, and the new set replaces the previous one.

The SPEA2 method is the modified version of SPEA. In this algorithm, \( S(i) \) and \( R(i) \) are computed as follows.

\[
S(i) = \left| \{ j \mid j \in P_t + P_{t-1} \setminus j > j \} \right| \tag{16}
\]

\[
R(i) = \sum_{P_t + P_{t-1}, j \succ i} S(j) \tag{17}
\]

To calculate the evaluation function of each solution, the \( D(i) \) parameter, which also contains the distance information from the nearest neighbor, \( k \), is added to \( R(i) \). For this purpose, the distance between the solution i and all solutions in the population and the external set j is calculated and incrementally arranged in a list. The solution \( k \) is represented by \( \sigma_i \), where \( k \) is the root of total number of solutions in population and external sets. Finally, \( D(i) \) and the evaluation function \( F(i) \) are calculated as follows.

\[
D(i) = \frac{1}{\sigma_i + 2} \tag{18}
\]

\[
F(i) = R(i) + D(i) \tag{19}
\]

In this research, the number of iterations was considered as 3000.

2.4. Water Evaluation and Planning (WEAP)

WEAP is a software tool that was developed for integrated water resources simulation. It can cover a wide range of issues, such as water protection, rights and allocation priorities, simulation of surface water and groundwater, reservoir operation, hydropower generation, pollution control, ecosystem demands, vulnerability assessment, and benefit–cost analysis of the project [26].

![Figure 4. Optimization process in the SPEA2 algorithm.](image-url)
Water allocation in this program is based on priorities that can range from 1 to 99. Reservoirs are also considered as a demand site with a priority of 99 so they will fill only when there is additional water in the system. The objective function is maximization of the coverage rate for all demand sites. WEAP uses linear programming and iterates for each priority so that demands with priority 1 are supplied first and before priority 2. Hence, the program is run at least once for each priority. If one demand site can be able to supply its water from several sources, the resources are also prioritized. The WEAP simulation model is able to optimize allocations among different users in each time step. It is not capable of maximizing throughout the time and has no hedging mechanism by itself, and thus acts similar to the standard operating procedures (SOP) method in this regard. Here, the output of this model was mainly used as a base solution for comparison purposes.

3. Case Study

The study area was the Karun basin in southwestern Iran. Five reservoirs, including the Karun-4, Karun-3, Karun-1, Godarlandar, and Gotvand reservoirs, along with their demand site were used in this paper to evaluate the methods (Figure 5). It should be noted that the Godarlandar reservoir does not play a role in downstream flow regulations; therefore, it was removed from the optimization process, leaving a system of four reservoirs.
The whole Karun basin area is about 67,100 km$^2$, where 68% is in the mountains and 32% is in the plains. Karun River, with a length of 950 km, is the longest river in the country and one of the longest in the Middle East. The river originates from the Zagros Mountains and drains into Persian Gulf after passing the Khuzestan Plain. The river is also considered the largest river in Iran in terms of annual discharge [27].

The schematic of the study area is shown in Figure 6.
Data and System Specifications

The time series studied in this paper were monthly data during the 1961–1962 to 2013–2014 water years, from which the initial 43 years were considered for optimization of decision parameters and the last 10 years were used for testing the performance of the optimized rule curves. Table 1 shows a summary of the reservoir information.

Table 1. Specifications of reservoirs and power plants.

| Parameter                                      | Karun-4 | Karun-3 | Karun-1 | Gotvand |
|------------------------------------------------|---------|---------|---------|---------|
| Normal water level, masl *                     | 1028    | 845     | 532.5   | 372     |
| Top of active storage, masl                     | 996     | 800     | 490     | 185     |
| Total reservoir capacity, MCM                   | 2279    | 2718    | 2438    | 4671    |
| Active storage, MCM                             | 834.2   | 1624.5  | 1614    | 3050.5  |
| Hydropower plant capacity, MW **                | 1000    | 2000    | 2000    | 2000    |
| Number of HP units                              | 4       | 8       | 8       | 8       |
| Design discharge, cms +                         | 684     | 1370.5  | 1471    | 1686.3  |
| Design head, m ++                               | 162     | 161     | 154     | 130     |
| HP efficiency, %                                | 92      | 92.4    | 90      | 93      |
| Peak power duration, h ~                        | 4       | 4       | 4       | 6       |
| Average head loss, m                            | 3       | 4.5     | 8       | 4       |

* meters above sea level, ** megawatts, + cubic meters per second, ++ meters, ~ hours.

The priority of demands for the Karun-4, Karun-3, and Karun-1 reservoirs is as follows: 1-hydropower, 2-municipal, 3-environmental, and 4-agricultural demands. In the Gotvand reservoir, energy production is the secondary objective after all others. Therefore, due to high agricultural and municipal demands and in order to increase the reservoir efficiency for the secondary demand (hydropower), two outlets were devised. The height of the penstock (for releasing water for hydropower generation) is 181 masl and the height of the reservoir lower outlet for other uses (e.g., agriculture, municipal, etc.) is 161 masl. All other demands are released through the penstock for energy generation as long as possible. In dry periods, where the storage level falls below the penstock level (i.e., 181 m), the demand is released through the lower outlet of the reservoir. Table 2 shows the monthly average municipal and agricultural demands in each reservoir site.

Table 2. Municipal and agricultural demands (MCM).

| Sector     | Karun-4 | Karun-3 | Karun-1 | Gotvand |
|------------|---------|---------|---------|---------|
| Municipal  | 0.4     | 9.8     | 0.8     | 116.2   |
| Agricultural| 1.3     | 0.4     | 8.6     | 497.2   |

The returned water from agricultural fields is not usually estimated accurately and there is no report regarding this parameter in the area. Hence, in the present study, the rate of return flow was considered as 20% of the diverted flow. Moreover, according to the recommendation of Tennant [28], the monthly minimum streamflow for environmental concerns at the downstream of each reservoir was assumed as the 10% of average monthly natural streamflow.

To calculate the reservoir’s hydropower requirement, following parameters are needed:

1. Hydropower plant capacity (MW), design head (m), and head loss (m), which can be expressed as a constant or a function of other parameters.
2. Number of units of power plants and the peak hours, which can be different for each month.
3. Efficiency (%), flood level (m of sea level), and design discharge rate (cms).
4. Moreover, the net head (m), the required discharge rate for firm energy production (cms), and the hydropower demand are obtained from Equations (20)–(22).
\[
H_{\text{net},t} = \frac{H_t + H_{t+1}}{2} - \text{TWL} - \text{HL} \\
Q_{\text{req},t} = \left( \frac{P \times 1000}{9.81 \times \eta} \right) \\
D_t = Q_{\text{req},t} \times \text{PT} \times \text{Nday} \times \frac{3600}{10^6}
\]

where \(H_t, \text{TWL}, \text{HL}, H_{\text{net},t}, P, \eta, D_t, \text{PT}, \) and \(\text{Nday}\) are the reservoir level at the beginning of period \(t\) (masl), tail water level (masl), head loss (m), net head (m), power plant installation capacity (MW), plant efficiency (%), required water for hydropower demand (MCM), and daily peak hours and number of days in a month, respectively.

### 4. Applications

In this study the objective functions were the minimization of the normalized deficits for each demand as described by Equations (23)–(26).

\[
\begin{align*}
\text{Min } TSD_{\text{mun}} &= \sum_{i=1}^{4} \sum_{t=1}^{T} \left( \frac{D_{\text{mun},i} - R_{\text{mun},i}}{D_{\text{mun},i}} \right)^2 \text{ Municipal} \\
\text{Min } TSD_{\text{agr}} &= \sum_{i=1}^{4} \sum_{t=1}^{T} \left( \frac{D_{\text{agr},i} - R_{\text{agr},i}}{D_{\text{agr},i}} \right)^2 \text{ Agriculture} \\
\text{Min } TSD_{\text{env}} &= \sum_{i=1}^{4} \sum_{t=1}^{T} \left( \frac{D_{\text{env},i} - R_{\text{env},i}}{D_{\text{env},i}} \right)^2 \text{ Environmental} \\
\text{Min } TSD_{\text{hyd}} &= \sum_{i=1}^{4} \sum_{t=1}^{T} \left( \frac{D_{\text{hyd},i} - R_{\text{hyd},i}}{D_{\text{hyd},i}} \right)^2 \text{ Hydropower}
\end{align*}
\]

In the above equations, the index \(i\) represents the reservoir number (1 to 4), \(R_{ti}\) and \(D_{ti}\) are the reservoir release and demand, respectively.

Constraints and assumptions of the problem are given as follows.

\[
S_{t+1,i} = S_{ti} + Q_{ti} - R_{ti} - \text{Spill}_{ti} - E_{ti} \quad \text{mass balance} \\
S_{\text{mini}} < S_{ti} < S_{\text{maxi}} \quad \text{capacity constraint} \\
0.4 < \alpha_{2i} < 0.85 \quad \text{assumptions of hedging} \\
S_{\text{mini}} < V_{2i} < V_{li} < S_{\text{maxi}} \quad \text{assumptions of hedging} \\
S_{ti} = 0.9 \times S_{\text{maxi}} \quad \text{initial storage} \\
\]

If \(R_{\text{hyd},i} > R_{\text{mun},i} + R_{\text{agr},i} + R_{\text{env},i} \Rightarrow \text{extra} = R_{\text{hyd},i} - (R_{\text{mun},i} + R_{\text{env},i})\)

\[
Q'_{ti+1} = Q_{ti+1} - 0.9 \times Q_{ti} + \text{Spill}_{ti} + 0.2 \times R_{\text{agr}} + R_{\text{env}} + \text{extra}
\]

The simulation method for a fuzzified discrete hedging approach is presented in Figure 7. The steps are as follows:

1. For the first month (\(t = 1\)), the initial reservoir storage (\(S_{1i}\)) is equal to \(S_{\text{maxi}}\) and \(\text{Spill}_{1i} = 0\).
2. The releases (\(R_{ti}\)) are obtained in each period according to the rule curve based on optimized coefficients (according to Equations (1)–(5) for discrete hedging and 10 to 15 for the fuzzified discrete hedging method).
3. The mass balance equation (Equation (27)) is calculated, and spill and reservoir storage are determined in the next month.
4. The above steps are repeated until the last month of the time series.
5. Results

5.1. Calibration Stage

In this section, the results of the fuzzified discrete hedging rule are compared with the discrete hedging rule, the SOP method, and the WEAP model. The convergence graph of the fuzzified discrete hedging rule is illustrated in Figure 8. According to this figure, the SPEA2 optimization algorithm had almost the same trend for all four objective functions. The agricultural and municipal functions had the most and the least convergence rates, respectively.

Table 3 shows the coefficients obtained in the calibration process for the hedging and fuzzy hedging methods for each reservoir. According to the table, the \( V_{1P} \) coefficients for the fuzzified discrete hedging rule were less than the discrete hedging level for all months. As shown in Figure 1, the value of \( V_{1P} \) indicates the starting point of the hedging, and the lower the value, more needs are fully met. The same is true for \( V_{2P} \). Moreover, \( \alpha \) coefficients were generally higher with the fuzzified discrete hedging rule compared to the discrete hedging rule. Alpha coefficients are the percentages of the supply in hedging phases. Therefore, higher alpha values indicate lower hedging intensity.
Table 3. Discrete hedging and fuzzified discrete hedging coefficients.

| Method          | Reservoir | Coef. | Mar   | Apr   | May   | June  | July  | Aug   | Sep   | Oct   | Nov   | Dec   | Jan   | Feb   | Avg  |
|-----------------|-----------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|------|
| Karun-4         | $V_{1P}$ | 2052  | 2085  | 1962  | 1951  | 1963  | 2028  | 1905  | 2101  | 2001  | 1463  | 1839  | 1861  | 1934  |      |
| Karun-3         | $V_{1P}$ | 1296  | 1352  | 1895  | 2061  | 2392  | 1647  | 1209  | 1654  | 1990  | 1984  | 1769  | 1758  | 1751  |      |
| Gotvand         | $V_{1P}$ | 1754  | 2041  | 2130  | 1633  | 1997  | 1505  | 2438  | 2409  | 1620  | 1883  | 2285  | 1246  | 1912  |      |
| Karun-1         | $V_{1P}$ | 3738  | 2833  | 1913  | 2677  | 3401  | 3059  | 3586  | 4668  | 4320  | 3327  | 2870  | 2794  | 3266  |      |
| Karun-4         | $V_{2P}$ | 1841  | 1504  | 1445  | 2001  | 1514  | 1480  | 1646  | 1881  | 1719  | 1641  | 1445  | 1742  | 1655  |      |
| Karun-3         | $V_{2P}$ | 1094  | 1306  | 1094  | 1202  | 1094  | 1510  | 1094  | 1459  | 1094  | 1414  | 1292  | 1190  | 1237  |      |
| Gotvand         | $V_{2P}$ | 1976  | 1710  | 1710  | 2450  | 2662  | 2562  | 3452  | 3208  | 1710  | 3224  | 1710  | 1710  | 2340  |      |

Figure 8. Convergence graph of the fuzzified discrete hedging rule.

Fuzzy Hedging and Discrete Hedging Coefficients.
5.2. Test Stage

The performance of rule curves derived in the calibration (optimization) stage was evaluated using a test period with data independent from those used in the calibration. This was done through different criterions, as explained in the following sections.

5.2.1. Reliability

To define the reliability, assume that the system outputs are divided into two sets of satisfactory (S) and failure (F) conditions. The probability that the reservoir provides the outflow required to satisfy various water demands is called reliability ($\alpha$) as defined by Equation (34) [3].

$$\alpha = \text{Prob} [X_t \in S]$$  \hspace{1cm} (34)

Although a system with higher reliability is preferred, it should be noted that higher reliability does not always mean a better performance. For a better and comprehensive evaluation, more criterions are needed. Thus, the maximum monthly deficiency, the monthly average storage volume, and the total spills were used along with the reliability in this paper. Table 4 shows the average monthly reliability values for the test period.

| Method               | Reservoir | Municipal | Agriculture | Environmental | Hydropower | Average  |
|----------------------|-----------|-----------|-------------|---------------|------------|----------|
| **Fuzzified discrete hedging** |           |           |             |               |            |          |
| Karun-4              | 1         | 1         | 1           | 0.967         | 0.992      |          |
| Karun-3              | 1         | 1         | 1           | 0.933         | 0.983      |          |
| Karun-1              | 1         | 1         | 1           | 0.95          | 0.988      |          |
| Gotvand              | 1         | 0.767     | 1           | -             | 0.922      |          |
| **average**          | 1         | 0.942     | 1           | 0.951         | 0.971      |          |
| **Discrete hedging** |           |           |             |               |            |          |
| Karun-4              | 1         | 1         | 1           | 0.983         | 0.996      |          |
| Karun-3              | 1         | 1         | 1           | 0.883         | 0.971      |          |
| Karun-1              | 1         | 1         | 1           | 0.913         | 0.978      |          |
| Gotvand              | 1         | 0.75      | 1           | -             | 0.917      |          |
| **average**          | 1         | 0.938     | 1           | 0.926         | 0.966      |          |
| **SOP**              |           |           |             |               |            |          |
| Karun-4              | 1         | 1         | 1           | 0.97          | 0.993      |          |
| Karun-3              | 1         | 1         | 1           | 0.948         | 0.987      |          |
| Karun-1              | 1         | 1         | 1           | 0.942         | 0.986      |          |
| Gotvand              | 1         | 0.775     | 1           | -             | 0.925      |          |
| **average**          | 1         | 0.944     | 1           | 0.953         | 0.973      |          |
| **WEAP**             |           |           |             |               |            |          |
| Karun-4              | 1         | 1         | 1           | 0.968         | 0.992      |          |
| Karun-3              | 1         | 1         | 1           | 0.926         | 0.982      |          |
| Karun-1              | 1         | 1         | 1           | 0.958         | 0.99       |          |
| Gotvand              | 1         | 0.817     | 1           | -             | 0.939      |          |
| **average**          | 1         | 0.954     | 1           | 0.951         | 0.976      |          |

According to this Table, the results indicate that the response of the model was based on the priorities of objective functions. The reliabilities of the SOP method were higher than all other methods, as expected. The hedging policy spreads deficit between periods to reduce its severity. Hence, it reduces reliability and improves vulnerability. However, results show that reduction in reliability was not high and the fuzzified discrete hedging rule had better performance compared to the non-fuzzified hedging rule. The average reliability of the hydropower requirement in the fuzzified discrete hedging method was 0.951, which is better than the 0.926 from the discrete hedging method. This difference and improvement in the reliability of the hydroelectricity was more than others (0.933 versus 0.883) in the Karun-3 reservoir. Moreover, in the Gotvand reservoir, the reliability for the agricultural demands was better using the fuzzy discrete hedging method than the regular
discrete hedging method. In addition, as can be seen from Table 4, the reliability values of the WEAP were very close to the SOP method because of the similar basis.

Considering the impact of unprecedented drought and climate change in the studied area, as well as possible projects for transferring the headwaters of the Karun River to neighboring provinces such as Isfahan and Yazd, the scenario of reducing the natural inflows by 30% was also investigated. Accordingly, Table 5 shows the average monthly reliabilities for the test period, assuming a drought and water transmission scenario.

Table 5. Average monthly reliability for the test period assuming a drought and water transmission scenario.

| Method               | Reservoir | Municipal | Agriculture | Environmental | Hydropower | Average |
|----------------------|-----------|-----------|-------------|---------------|------------|---------|
| Fuzzified discrete hedging | Karun-4   | 1         | 1           | 1             | 0.62       | 0.905   |
|                      | Karun-3   | 1         | 1           | 1             | 0.643      | 0.911   |
|                      | Karun-1   | 1         | 1           | 1             | 0.761      | 0.94    |
|                      | Gotvand   | 1         | 0.75        | 1             | -          | 0.917   |
| average              |           | 1         | 0.938       | 1             | 0.675      | 0.918   |
| Discrete hedging     | Karun-4   | 1         | 1           | 1             | 0.45       | 0.863   |
|                      | Karun-3   | 1         | 1           | 1             | 0.504      | 0.876   |
|                      | Karun-1   | 1         | 1           | 1             | 0.603      | 0.901   |
|                      | Gotvand   | 1         | 0.65        | 1             | -          | 0.883   |
| average              |           | 1         | 0.913       | 1             | 0.519      | 0.881   |
| SOP                  | Karun-4   | 1         | 1           | 1             | 0.581      | 0.895   |
|                      | Karun-3   | 1         | 1           | 1             | 0.662      | 0.916   |
|                      | Karun-1   | 1         | 1           | 1             | 0.761      | 0.94    |
|                      | Gotvand   | 1         | 0.851       | 1             | -          | 0.95    |
| average              |           | 1         | 0.963       | 1             | 0.668      | 0.925   |
| WEAP                 | Karun-4   | 1         | 1           | 1             | 0.536      | 0.884   |
|                      | Karun-3   | 1         | 1           | 1             | 0.591      | 0.898   |
|                      | Karun-1   | 1         | 1           | 1             | 0.694      | 0.924   |
|                      | Gotvand   | 1         | 0.782       | 1             | -          | 0.927   |
| average              |           | 1         | 0.946       | 1             | 0.607      | 0.908   |

As can be seen from the table, the tangible superiority of fuzzified discrete hedging method in dealing with the drought period was evident in comparison with other algorithms. For example, the average reliability of hydropower using the fuzzified discrete hedging method was 0.675 versus 0.519 using the discrete hedging method. In addition, the improvement of the reliability in the Karun-3 reservoir was more than other reservoirs (0.620 versus 0.450). In addition, a similar trend to Table 4 was observed for the agricultural demands of the Gotvand reservoir. As in the previous table, the WEAP reliability values were very close to the SOP values. As expected, the WEAP and SOP methods performed better than both of the hedging rules. However, the fuzzified discrete hedging method produced better rules in terms of reliability than the regular discrete hedging method.

5.2.2. Maximum Monthly Deficiency

The maximum monthly deficiency is given in Table 6. Results indicate the overall superiority of the fuzzified hedging method over other methods. For example, the maximum deficiency of hydropower demand in the fuzzified method was 334 (Karun-1) versus 410 MCM (Karun-3) in the non-fuzzified hedging method, 520 MCM (Karun-1) in the SOP method, and 469 MCM in the WEAP method. In addition, the sum of maximum deficiencies of the fuzzified method for hydropower was 626 MCM versus 856 MCM for the regular discrete method, 1018 MCM for the SOP method, and 988 MCM for the WEAP model. However, both hedging methods showed deficits in agricultural water demand in the Gotvand reservoir, which was absent in the SOP and WEAP models. Overall, we can
conclude that the fuzzified hedging method performs better than all other methods and both hedging methods accomplish more than the non-hedging SOP or WEAP methods.

Table 6. Maximum monthly deficiency during the test period (MCM).

| Method              | Reservoir | Municipal | Agriculture | Environmental | Hydropower |
|---------------------|-----------|-----------|-------------|---------------|------------|
| Fuzzified discrete hedging | Karun-4  | 0         | 0           | 0             | 90         |
|                     | Karun-3  | 0         | 0           | 0             | 292        |
|                     | Karun-1  | 0         | 0           | 0             | 334        |
|                     | Gotvand  | 0         | 419         | 0             | -          |
| sum                 | 0         | 419       | 0           | 626           |
| Discrete hedging    | Karun-4  | 0         | 0           | 0             | 145        |
|                     | Karun-3  | 0         | 0           | 0             | 410        |
|                     | Karun-1  | 0         | 0           | 0             | 301        |
|                     | Gotvand  | 0         | 188         | 0             | -          |
| sum                 | 0         | 188       | 0           | 856           |
| SOP                 | Karun-4  | 0         | 0           | 0             | 134        |
|                     | Karun-3  | 0         | 0           | 0             | 364        |
|                     | Karun-1  | 0         | 0           | 0             | 520        |
|                     | Gotvand  | 0         | 0           | 0             | -          |
| sum                 | 0         | 0         | 0           | 1018          |
| WEAP                | Karun-4  | 0         | 0           | 0             | 140        |
|                     | Karun-3  | 0         | 0           | 0             | 379        |
|                     | Karun-1  | 0         | 0           | 0             | 469        |
|                     | Gotvand  | 0         | 1.8         | 0             | -          |
| sum                 | 0         | 0         | 0           | 988           |

5.2.3. Average Storage

Table 7 shows average storages during the test period of all methods (WEAP is left out for similarity to SOP). As can be seen, in the SOP method storages were lower since in each time period it tried to release the demand and had no hedging or storage of water for future possible needs. The fuzzified hedging also kept storage at low levels and had lower storages than the regular hedging while performing better in terms of meeting the demands, as explained earlier. As a rule of thumb, lower storage means less water loss due to spillage, which is discussed in the following section.

Table 7. Average storages during the test period (MCM).

| Method              | Reservoir | Mar | Apr | May | June | July | Aug | Sep | Oct | Nov | Dec | Jan | Feb | Avg. |
|---------------------|-----------|-----|-----|-----|------|------|-----|-----|-----|-----|-----|-----|-----|-----|
| Fuzzified discrete hedging | Karun-4  | 2020 | 1859 | 1751 | 1841 | 1827 | 1871 | 2018 | 2203 | 2265 | 2264 | 2164 | 2110 | 2016 |
|                     | Karun-3  | 2139 | 1898 | 1664 | 1518 | 1672 | 1791 | 1982 | 2261 | 2374 | 2183 | 2275 | 2190 | 1996 |
|                     | Karun-1  | 1473 | 1355 | 1292 | 1400 | 1386 | 1441 | 1621 | 2128 | 2061 | 2041 | 1471 | 1511 | 1598 |
|                     | Gotvand  | 4403 | 4216 | 3677 | 3780 | 4044 | 4178 | 4093 | 4058 | 4371 | 4004 | 4513 | 4341 | 4140 |
| Discrete hedging    | Karun-4  | 2127 | 1966 | 1819 | 1828 | 1830 | 1890 | 2015 | 2157 | 2267 | 2276 | 2265 | 2219 | 2055 |
|                     | Karun-3  | 2211 | 2028 | 1846 | 1777 | 1892 | 1939 | 2075 | 2269 | 2271 | 2315 | 2269 | 2197 | 2091 |
|                     | Karun-1  | 2168 | 1923 | 1716 | 1778 | 1807 | 1884 | 2008 | 2170 | 2301 | 2351 | 2342 | 2259 | 2059 |
|                     | Gotvand  | 4624 | 4547 | 4128 | 4234 | 4380 | 4395 | 4299 | 4283 | 4431 | 4638 | 4671 | 4671 | 4442 |
| SOP                 | Karun-4  | 2049 | 1888 | 1757 | 1767 | 1789 | 1847 | 2012 | 2191 | 2251 | 2273 | 2193 | 2137 | 2013 |
|                     | Karun-3  | 1844 | 1702 | 1585 | 1610 | 1636 | 1689 | 1845 | 1978 | 2023 | 2046 | 1972 | 1926 | 1821 |
|                     | Karun-1  | 1578 | 1424 | 1334 | 1524 | 1556 | 1562 | 1748 | 2160 | 2135 | 2199 | 1671 | 1646 | 1711 |
|                     | Gotvand  | 4294 | 4122 | 3607 | 3638 | 3887 | 4083 | 3948 | 4003 | 4396 | 4030 | 4487 | 4301 | 4066 |

5.2.4. Spill

The total spill volumes during the test period for the four reservoirs are shown in Table 8. As expected, the SOP method resulted in the least spillage thanks to its lower reservoir storages. Next stands the fuzzified method with 192,384 MCM of total spillage.
The regular discrete hedging method had the highest total spillage with an amount equal to 283,975 MCM. It was evident that although non-hedging methods did better in terms of reliability and spillage, they did suffer from large amounts of deficits that could result in huge amounts of damages.

Table 8. Total spillage (MCM).

| Reservoir | Fuzzified Discrete Hedging | Discrete Hedging | SOP  |
|-----------|---------------------------|-----------------|------|
| Karun-4   | 17,900                    | 109,320         | 15,987|
| Karun-3   | 16,201                    | 15,841          | 18,907|
| Karun-1   | 26,913                    | 26,554          | 24,980|
| Gotvand   | 131,370                   | 132,260         | 53,078|
| Sum       | 192,384                   | 283,975         | 112,952|

The following steps must be performed for practical implementation of the model:

1. Input data collection such as inflow and minimum and maximum capacity for each reservoir
2. Determining demands for all reservoirs such as municipal, agricultural, environment, flood control, and hydropower demands for each reservoir
3. Prioritizing objective functions for each reservoir
4. Specifying how reservoirs relate to each other and writing of equations
5. Writing mass balance equations, reservoir constraints, and restrictions related to hedging
6. Writing equations related to the membership functions of the fuzzy method (sensitivity analysis can be performed for the study area on a variety of membership functions)
7. Assigning initial values for hedging, fuzzy, and SPEA2 parameters (please note that, different values do not affect the final result, but their logical selection helps to speed up the algorithm.)
8. Selecting appropriate evaluation criteria or an appropriate number of repetitions for stopping the algorithm. (This criterion should be selected so that the parameters are well calibrated. The convergence diagram of the functions can be used for this purpose.)
9. Model implementation
10. Extraction of hedging coefficients and the threshold for beginning phases one and two of hedging
11. Determining operation policy of the system

6. Conclusions

In this paper, the performance of the many-objective algorithm SPEA2 was evaluated using fuzzified and regular discrete hedging rules. It was compared to the non-hedging methods of SOP and WEAP using a four-reservoir system in the Karun basin in Iran with four objective functions related to meeting municipal, agricultural, environmental, and hydropower water demands. Results indicated that using fuzzy logic improves the performance of the discrete hedging rule. The hedging methods were able to reduce the overall vulnerability of the system by reducing the maximum water demand shortages. In addition, the fuzzified hedging method performed better than the regular algorithm in all aspects, including reliability, vulnerability, and losses through spills. Moreover, as expected the non-hedging SOP and WEAP methods produced higher reliabilities, lower average storages, and less water losses through spills. The key index in comparing the reservoir operation methods in here is the maximum vulnerability, which may cause great amounts of system damages and losses. The proposed many-objective algorithm SPEA2 coupled with fuzzified discrete hedging in a multi-reservoir, multi-user site proved to be superior to non-fuzzified hedging and non-hedging methods, including the SOP and WEAP.
Description of Parameters

| Parameter | Description |
|-----------|-------------|
| $V_{1t}$ | the upper threshold for phase one hedging (MCM) |
| $V_{2t}$ | the upper threshold for phase two hedging (MCM) |
| $V_{3t}$ | the lower threshold for phase two hedging (MCM) |
| $\alpha_1$ | ratio of demand met in phase one hedging |
| $\alpha_2$ | ratio of demand met in the phase two hedging |
| $R_{ti}$ | release of reservoir $i$ in period $t$ (MCM) |
| $D_{ti}$ | demand from reservoir $i$ in period $t$ (MCM) |
| $S_{ti}$ | storage of reservoir $i$ at the beginning of period $t$ (MCM) |
| $Q_{ti}$ | inflow of reservoir $i$ in period $t$ (MCM) |
| $Spill_{ij}$ | spill of reservoir $i$ in period $t$ (MCM) |
| $S_{min i}$ | minimum capacity of reservoir $i$ (MCM) |
| $S_{max i}$ | maximum capacity of reservoir $i$ (MCM) |
| $\beta_{1ti}$, $\beta_{2ti}$, $\beta_{3ti}$, $\beta_{4ti}$ | the membership function parameters obtained by using optimization algorithm |

**SPEA2 optimization algorithm**

| Parameter | Description |
|-----------|-------------|
| $S(i)$ | the ratio of solutions which are dominated by $i$ dividing with the population size plus 1 |
| $P_t$ | population size |
| $P_i$ | external sets |
| $R(i)$ | in-crowd answers |
| $D(i)$ | contains the distance information from the nearest neighbor $k$ |
| $F(i)$ | the evaluation function |

**Specifications of reservoirs**

| Parameter | Description |
|-----------|-------------|
| $H_t$ | reservoir level at the beginning of period (m) |
| TWL | tail water level (m) |
| HF | head loss in penstock (m) |
| $P_{dep}$ | power plant installation capacity (MW) |
| $\eta$ | efficiency (%) |
| $D_t$ | required water for hydropower demand (millions of cubic meters) |
| PT | peak power time (hour) |
| Nday | number of days in a month |
| Applications | TSD<sub>mun</sub> | TSD<sub>agr</sub> | TSD<sub>env</sub> | TSD<sub>hyd</sub> |
|--------------|-----------------|----------------|-----------------|-----------------|
|              | deficits for municipal demands | deficits for agricultural demands | deficits for environmental demands | deficits for hydropower demands |

\[
\begin{align*}
S_{ti} & : \text{storage at the beginning of period } t \text{ of reservoir } i \text{ (MCM)} \\
S_{t+1i} & : \text{storage at the end of period } t \text{ of reservoir } i \text{ (MCM)} \\
Q_{ti} & : \text{reservoir } i \text{ inflow in period } t \text{ (MCM)} \\
\text{Spill}_{ti} & : \text{reservoir } i \text{ spill in period } t \text{ (MCM)} \\
E_{ti} & : \text{reservoir } i \text{ evaporation in period } t \text{ (MCM)} \\
S_{\text{min } i} & : \text{minimum storage capacity of reservoir } i \text{ (MCM)} \\
S_{\text{max } i} & : \text{maximum storage capacity of reservoir } i \text{ (MCM)} \\
R_{\text{hyd } i} & : \text{release for hydropower demands in reservoir } i \text{ (MCM)} \\
R_{\text{env } i} & : \text{release for environmental demands in reservoir } i \text{ (MCM)} \\
R_{\text{agr } i} & : \text{release for agricultural demands in reservoir } i \text{ (MCM)} \\
R_{\text{muni } i} & : \text{release for municipal demands in reservoir } i \text{ (MCM)} \\
\end{align*}
\]

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