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Derivation of Optimal Two Dimensional Rule Curve for Dualistic Reservoir Water-Supply System

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Abstract

In arid and semi-arid regions particularly vulnerable to climate change, optimizing the long-term operation of multi-purpose reservoirs is paramount. This study derived an optimum two-dimensional rule curve to jointly operate the parallel reservoirs of Mosul and Dukan, Northern Iraq. A hybridized optimization technique combining conventional dynamic programming with the shuffled complex evolution algorithm (SCE-UA) was developed to solve this problem. The results showed that the proportion of normal water supply areas increased from the beginning of the flood season (October) to its highest levels in April (58.77% of the total water supply area). The proportion decreased to its lowest in September (25.04% of the total water supply area). The newly derived 2D rule cure was compared with the current operation policy and was found to optimize the amount of water shortage by 21.1% during the operational period. It also reduced the shortage period and avoided catastrophic water shortages during droughts. In addition, the developed model optimized the amounts of water more than the joint water requirements, suffering from a significant deficit in meeting the demand during some months of the operational years. As a result, the storage in each reservoir was improved and thence can be adapted to face water shortages during future climate changes. This study proved the new hybridized model's applicability and can serve as a tool for sustainable water management.

Keywords: 2D Rule Curve; Optimization; Shuffled Complex Evolution Algorithm; Dualistic Reservoirs; Iraq.

1. Introduction

Reservoirs are among the most effective structures for developing and managing integrated water resources [1, 2]. With the economy's continuous growth, reservoirs' role has become increasingly crucial in meeting society's energy and water requirements. Consequently, reservoir operation and management are among the most complicated issues in integrated water resource development and administration [3]. A multi-reservoir system's operations can be synchronized to make optimal use of the reservoirs located along various streams, each of which has a unique capacity for water storage [4].

Thus, reservoir operation rules are essential for efficiently managing reservoirs and improving confidence in decisions about water release [5–7]. However, reservoir failure is possible, particularly during crucial times, because of excessive water overflow and insufficient water supply to meet water requirements, leading to water shortages. Therefore, rules are necessary to guarantee that the reservoir functions as intended. Rule curves are the most common representation of reservoir operating rules. This consists of a Lower Rule Curve (LRC) and an Upper Rule Curve (URC), simultaneously releasing water under the upper and lower boundaries while controlling the water level. They are extracted by combining techniques for system simulation and optimization [8, 9]. Reservoir operation is, therefore, a

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crucial element that must be planned for during the project's planning phase. As for operating a multi-reservoir system, doing so reduces the uncontrolled outflow from the system, making it more advantageous than doing so with a single reservoir [10, 11].

In previous decades, aggregation-decomposition-based parallel reservoir systems with joint demands were governed by various fundamental rules [4, 12, 13], reducing the complexity of multi-reservoir operation problems. However, for the designed operation of the multi-reservoir system, the system operating policies are defined concerning system-wide release rules and individual reservoir storage management functions [14]. Storage management functions determine the optimum storage of each reservoir, which is determined from the aggregate storage volume of the equivalent reservoir. At the same time, the entire system release rules typically specify the total release from an equivalent reservoir combined over all the reservoirs in the system. Standard Operation Procedures and hedging rule curves are frequently utilized for the entire system release rules. Standard Operation Procedures [15, 16] is a straightforward operation rule that directs reservoirs to release as much water as possible to meet delivery targets while not preserving water for later needs. With the hedging rule [14], the risk of future severe water shortages is reduced, but at the expense of more frequent minor deficits. Different rules have all been covered previously for the balancing functions. The NYC rule [14, 17] is one of these and aims to balance the likelihood of seasonal spills from each reservoir. Spacing rules, a particular case of the NYC rules, stipulate that the amount of space left in each reservoir of a parallel system must be proportional to the anticipated inflow to that reservoir [18]. The area and NYC regulations try to prevent spilling some reservoirs while leaving others empty [14]. The objective of the priority policy is to identify which reservoirs are fully used before water is released from the next reservoir with a higher rank than them [19]. A few decision variables are identified in the parametric rule, validated through the whole control period, to divide the gross storage into each reservoir at each time step [20, 21].

Optimization methods, such as linear, non-linear, and dynamic programming, are widely utilized in the field of water resources engineering to solve problems and make predictions [22]. Numerous implementations of optimization methods exist to detect optimal rule curves, for example, dynamic algorithms and other optimization techniques obtained from evolutionary theory [23, 24]. They are efficient methods to find optimal solutions, such as the genetic algorithm [25, 26], Tabu searches algorithm [27, 28], Honey-Bee Mating Optimization [29], and Harris Hawks Optimization [30], where researchers have used these methods in their research for determining optimal reservoir rule curves. Hybrid optimization techniques combine the advantages of multiple optimization methods to create a more effective optimization algorithm. Ahmadianfar et al. [31] established the hybrid optimization algorithm A-DEPSO (Adaptive Differential Evolution with Particle Swarm Optimization) to optimize unpredictable and non-convex hydropower systems by merging the differential evolution algorithm with particle swarm optimization.

Ahmadianfar et al. [32] used an efficient optimization technique called MS-DEPSO, a hybrid of differential evolution (DE) and particle swarm optimization (PSO) with a multi-strategy, to solve multi-reservoir systems that are intended to produce hydropower and provide irrigation. Karami et al. [10] Introduced and evaluated a Hybrid Algorithm (HA) that combines the Gravitational Search Algorithm (GSA) and the Particle Swarm Optimization Algorithm (PSOA) to minimize irrigation shortcomings in a multi-reservoir system. Yaseen et al. [33] used a novel hybrid algorithm of the Artificial Fish Swarm Algorithm (AFSA) and the Particle Swarm Optimization Algorithm (PSOA) to optimize the Karun-4 reservoir, improve power production, and reduce downstream water shortages. Masoumi et al. [34] used a hybrid algorithm of the gray wolf optimization technique and Shuffled complex evolution to find the optimal operation for a single reservoir in Iran and hypothetical multi-reservoir systems. Nezhad et al. [35] applied the hybrid approach by merging the shuffled complex evolution with the differential evolution called the SCE-DE algorithm in optimizing the multi-reservoir water systems.

The literature above shows no study on operating parallel reservoirs in arid and semi-arid regions using a Two-dimensional rule curve. The purpose of the present study was to derive an optimal reservoir operation policy represented by a two-dimensional rule curve for a dual reservoir system in Iraq by combining the position of the hedging rule for each water user and each reservoir in the system. The two-dimensional rule curve was applied to northern Iraq's parallel reservoirs, Mosul and Dukan reservoirs, as a case study. A hybridized optimization technique combining conventional dynamic programming with the shuffled complex evolution algorithm (SCE-UA) was developed to obtain the maximum possible economic recovery from the two parallel reservoirs.

2. Study Area and Data

In this study, two northern Iraq water supply reservoirs were used as a case study to derive the rule curve of the two-dimensional reservoir operation with dynamic programming techniques. The two parallel reservoirs are Mosul and Dukan in Iraq, as shown in Figure 1. These reservoirs have no hydraulic connection and supply water to common water users (industry and agricultural demand).

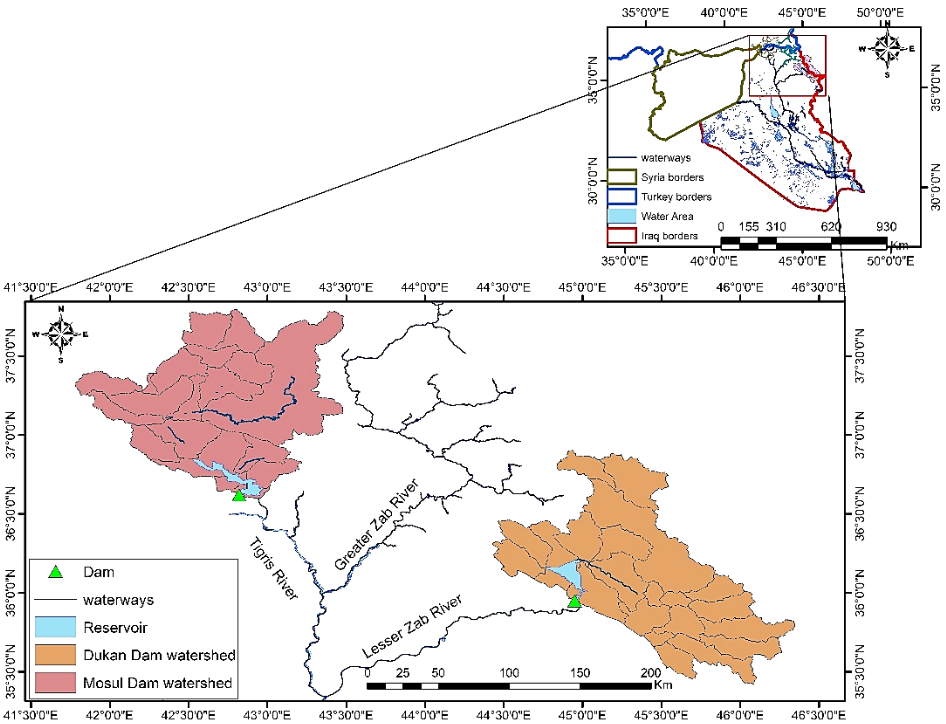


Figure 1. Location of the study area

Mosul and Dukan reservoirs are located on Iraq's Tigris and lesser Zab rivers. The geographical coordinates of these reservoirs are 36° 37′ 49″ N 42° 49′ 23″ E, and 35°57'15" N 44°57'10" E, respectively. Reservoirs in Mosul and Dukan have storage capacities of 11100 million m^3 and 6890 million m^3 at normal reservoir water levels, respectively. The presence of the Greater Zab River within the study area will meet part of the common water requirements. Therefore, the monthly average of the water requirements from 2001 to 2020 was subtracted from the total shared water requirements in the study area. The selected portion was used in the optimization process, as illustrated in Figure 2. The hydrological and physical characteristics of each reservoir are shown in Table 1, and the average monthly water inflow of these reservoirs for many years is shown in Figure 3. In this paper, the average monthly data for measured inflow, water demand, evaporation rate (mm), and precipitation for the parallel reservoirs for the past 20 years (2001–2020) are used as input data to construct an optimal two-dimensional reservoir rule curve.

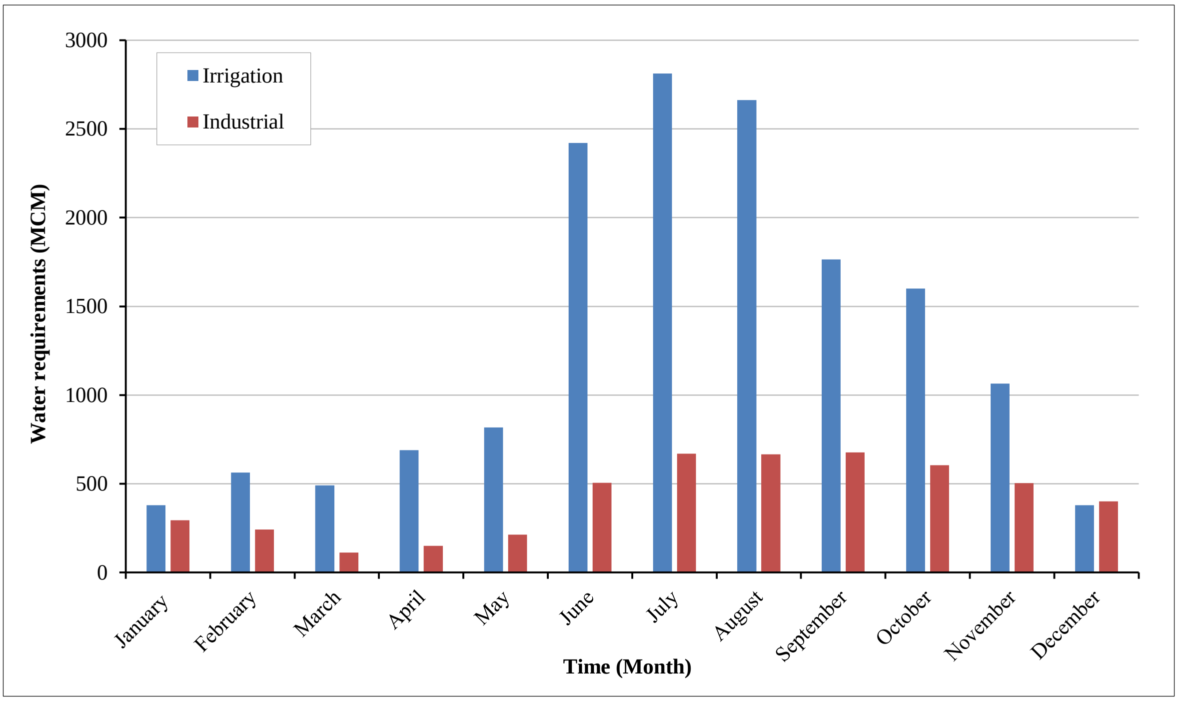


Figure 2. Average monthly water demand of Mosul and Dukan reservoir for the period (2001 -2020)

Table 1. Hydrological and physical Characteristics of Mosul and Dukan dam [36-38]

No.	Characteristics	Mosul	Dukan	Unit
1-	Catchment area	46700	11690	Km^2
2-	Monthly mean inflow	1315806762	34850414	m^3
3-	Reservoir Capacity	11100000000	6890000000	m^3
4-	Dead storage	2950000000	790000000	m^3
5-	Max. Reservoir water level	335	515	m.a.s.l
6-	Normal Reservoir water level	330	511	m.a.s.l
7-	Min. Reservoir water level	300	479	m.a.s.l

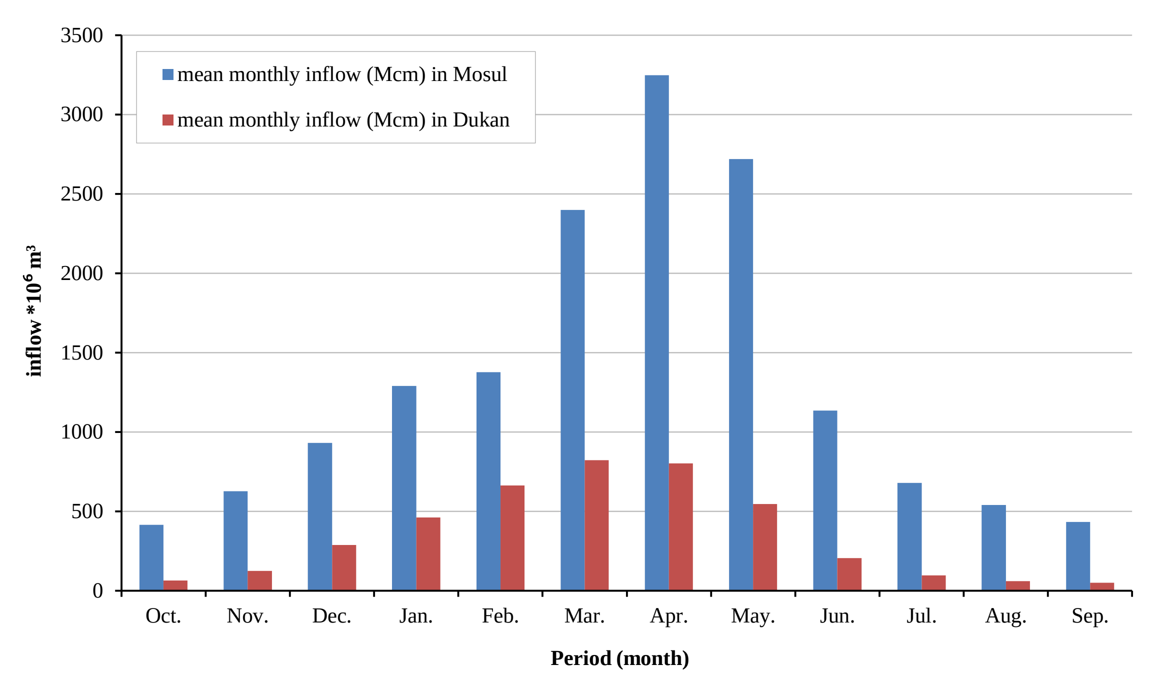


Figure 3. Average monthly inflow of Mosul and Dukan reservoir (2001 -2020)

3. Materials and Methods

3.1. Two-Dimensional Reservoir Operation

When the reservoir's water storage level is low, the hedging rule can effectively avoid a water supply shortage by actively and moderately reducing the reservoir's water supply and ensuring the reservoir's smooth operation during the dry season. Therefore, the regulation of hedging water supply is significant for the water supply operation of multi-reservoir systems, which has attracted many scholars to study it [39, 40]. In this paper, the hedging water supply rules were used in the two-dimensional reservoir operation diagram to determine the water supply decision of the reservoir group for the common water users. Common water users often include multiple water demand items such as domestic water, industrial water, and agricultural water. Figure 4 is a schematic of a two-dimensional reservoir operation diagram for a particular operation period. The horizontal and vertical coordinates represent the maximum water storage of reservoirs 1 and 2, respectively, and X_1 and X_2 represent the positions of hedging water supply for demand 1 and demand 2 concerning the position of maximum storage for reservoir 1 in a specific operation period.

Similarly, X_3 and X_4 represent the positions of hedging water supply for demand 1 and demand 2 concerning the position of maximum storage for reservoir 2 in a specific operation period. In different operation periods, the two-dimensional reservoir operation diagram presents different forms with the different locations of the hedging water supply lines. Four hedging water supply lines divide the two-dimensional reservoir operation diagram into nine water supply operating areas and three water supply rules. According to the position of the combination of two reservoir storage rules, the water supply task from a two-dimensional reservoir rule was one of three: normal, one demand is hedged, and the two demands are hedged.

Using a combination of dynamic programming and shuffled complex evolution (SCE-UA), the optimal position of the hedging water supply line for each reservoir's water user (industrial and agricultural) was determined.

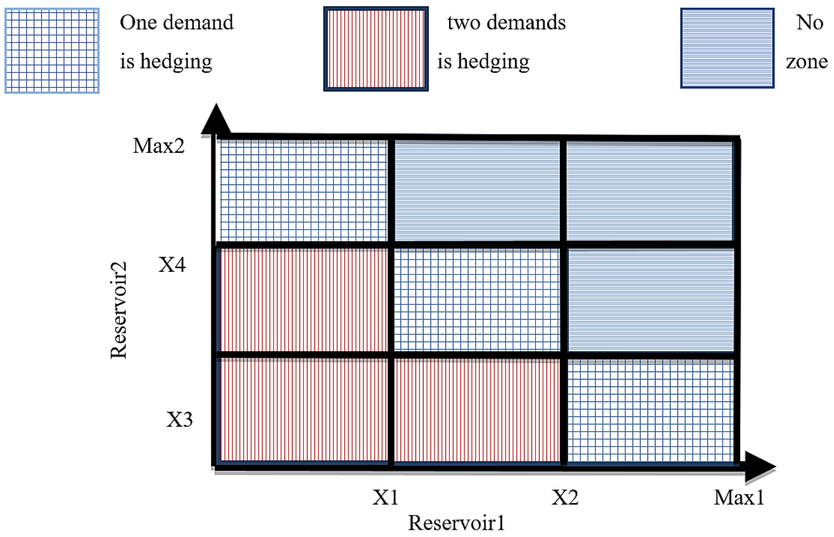


Figure 4. Two-dimensional reservoir rule curve

3.2. Methodology

In this study, the methodology used to derive the two-dimensional operating rule for the reservoirs within the study area is briefly explained in the diagram illustrated in Figure 5. In this methodology, hybrid algorithms were relied upon, resulting from the combination of the dynamic algorithm and the complex evolutionary algorithm. In West Asia in general and Iraq in particular, this is the first study concerned with applying a two-dimensional operating rule on reservoirs to meet the joint demand; in addition, the results obtained were not compared with the results of previous studies.

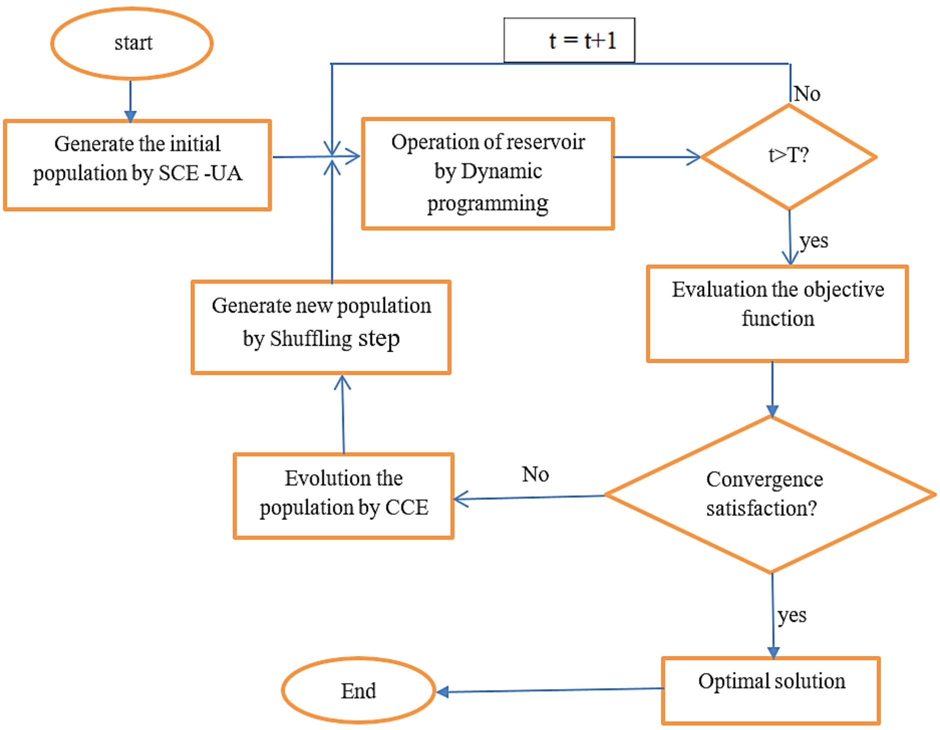


Figure 5. Flowchart of deriving 2D rule curve

3.3. Formulation of 2D Rule Curve

3.3.1. Objective Function

The reliability of the water supply measured the water supply risk of the dual reservoir and indicates the frequency of the water shortage events, but cannot express the degree of water shortage. So, many scholars, such as Hashimoto et al. [41], introduced the water supply resilience coefficient (RES), an index about the capability of reservoirs to recover from hedging water supply to normal water supply. Then the optimization objective function was maximized in terms of reliability and resiliency of water supply:

$$\text{Max } R = W_{ind} (w_1 \times Rel_{ind} + w_2 \times Res_{ind}) + W_{agri} (w_1 \times Rel_{agri} + w_2 \times Res_{agri}) \ldots \quad (1)$$

where w_1 and w_2 are the weighting factors between different water supply risk indexes, W_{ind} and W_{agri} are the weighting factors between industry and agriculture. Rel_{ind} and Rel_{agri} are the water supply reliability for industry and agriculture water demand; Res_{ind} and Res_{agri} are the water supply resiliency coefficient for industry and agriculture water demand. The risk indexes (reliability and resiliency) were determined by the following formulas [42]

$$Rel = 1 - \frac{T_F}{N} \quad (2)$$

$$Res = \frac{T_N}{T_F} \quad (3)$$

In Equations 2 and 3, N represents the total duration of the water supply period; T_F represents the total number of hedging water supplies during the water supply period; T_N represents the number of times the hedging water supply returns to normal water supply during the water supply period.

3.3.2. Constraints

Identifying the appropriate constraints to specify the feasible region that satisfies the system's objective function is essential. As such, the following constraints were set as follows:

1- Reservoir water balance equation:

$$S_{t+1}^i = S_t^i + I_t^i - R_t^i - Sp_t^i - E_t^i \quad (4)$$

where S_{t+1}^i, S_t^i Are the water storage volume of reservoir *i* in *t* period and t + 1 period, respectively; I_t^i, R_t^i, Sp_t^i and E_t^i are the inflow volume, water supply, abandoned water of reservoir *i* in *t* period and net evaporation losses by volume, respectively. The net evaporation losses were determined by multiplying the net evaporation rate by each reservoir's average water surface area. The average water surface area is a water storage function in each reservoir (i) (Figures 6 and 7). The impact of net evaporation losses may be positive or negative because the net evaporation equals to evaporation rate in (mm) minus the precipitation rate in (mm).

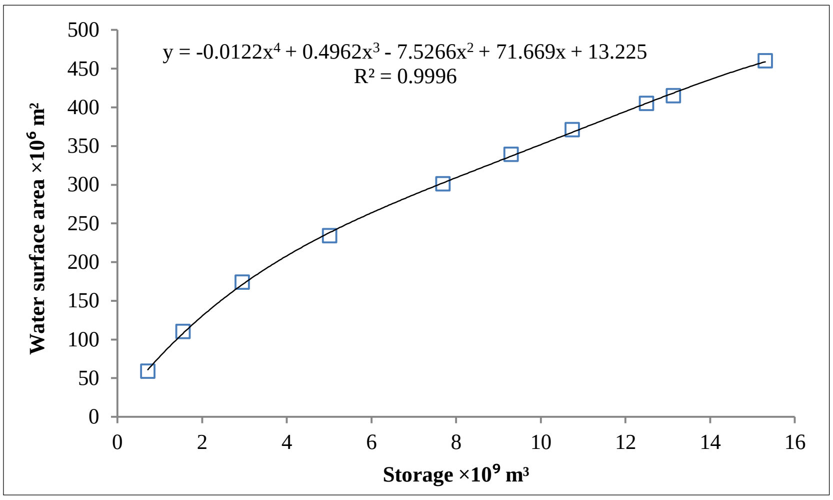


Figure 6. The relationship between water surface area and storage for Mosul dam

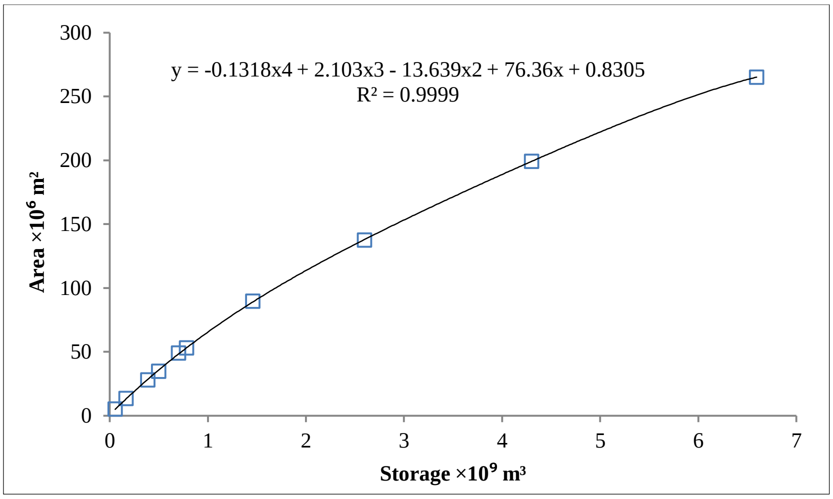


Figure 7. The relationship between water surface area and storage for Dukan dam

2- The position of hedging water supply for each water use for each reservoir must be greater than minimum storage and less than or equal to maximum storage.

$$S_{min}^{i} \leq H_{t}^{i}]_{ind} \leq S_{max}^{i} \tag{5}$$

$$S_{min}^{i} \leq H_{t}^{i}]_{Agri} \leq S_{max}^{i} \tag{6}$$

3- The position of the storage combination of the two reservoirs for computing the water supply according to the two-dimensional reservoir rule curve is as follows:

Case1:

- If $H_{t}^{M}]_{Ind} \leq S_{t}^{M} \leq S_{max}^{i}$ *and* $H_{t}^{D}]_{Ind} \leq S_{t}^{D} \leq S_{max}^{D}$, then (7)

$$R_{ind} = D_{ind} \tag{7-a}$$

$$R_{Agri} = D_{Agri} \tag{7-b}$$

$$R_{T} = R_{ind} + R_{Agri} \tag{7-c}$$

Case2:

- If $H_{t}^{M}]_{Agri} \leq S_{t}^{M} < H_{t}^{M}]_{Ind}$ *and* $H_{t}^{D}]_{Ind} \leq S_{t}^{D} \leq S_{max}^{D}$, then (8)

$$R_{ind} = D_{ind} \tag{8-a}$$

$$R_{Agri} = D_{Agri} \tag{8-b}$$

$$R_{T} = R_{ind} + R_{Agri} \tag{8-c}$$

Case3:

- If $S_{min}^{M} \leq S_{t}^{M} < H_{t}^{M}]_{Agri}$ *and* $H_{t}^{D}]_{Ind} \leq S_{t}^{D} \leq S_{max}^{D}$, then (9)

$$R_{ind} = D_{ind} \tag{9-a}$$

$$R_{Agri} = \alpha_{1} * D_{Agri} \tag{9-b}$$

$$R_{T} = R_{ind} + R_{Agri} \tag{9-c}$$

Case4:

- If $H_{t}^{M}]_{Ind} \leq S_{t}^{M} \leq S_{max}^{M}$ *and* $H_{t}^{D}]_{Agri} \leq S_{t}^{D} < H_{t}^{D}]_{Ind}$ then (10)

$$R_{ind} = D_{ind} \tag{10-a}$$

$$R_{Agri} = D_{Agri} \tag{10-b}$$

$$R_{T} = R_{ind} + R_{Agri} \tag{10-c}$$

Case5:

- If $H_{t}^{M}]_{Agri} \leq S_{t}^{M} < H_{t}^{M}]_{Ind}$ *and* $H_{t}^{D}]_{Agri} \leq S_{t}^{D} < H_{t}^{D}]_{Ind}$, then (11)

$$R_{ind} = D_{ind} \tag{11-a}$$

$$R_{Agri} = \alpha_{1} * D_{Agri} \tag{11-b}$$

$$R_{T} = R_{ind} + R_{Agri} \tag{11-c}$$

Case6:

- If $S_{min}^{M} \leq S_{t}^{M} < H_{t}^{M}]_{Agri}\ and\ H_{t}^{D}]_{Agri} \leq\ S_{t}^{D} < H_{t}^{D}]_{Ind}$, then (12)

$$R_{ind} =\ \alpha_2 * D_{ind} \quad (12\text{-a})$$

$$R_{Agri} = \alpha_1 *\ D_{Agri} \quad (12\text{-b})$$

$$R_T = R_{ind} + R_{Agri} \quad (12\text{-c})$$

Case7:

- If $H_{t}^{M}]_{Ind} \leq S_{t}^{M} \leq S_{max}^{M}\ and\ S_{min}^{D} \leq S_{t}^{D} < H_{t}^{D}]_{Agri}$, then (13)

$$R_{ind} =\ D_{ind} \quad (13\text{-a})$$

$$R_{Agri} = \alpha_1 *\ D_{Agri} \quad (13\text{-b})$$

$$R_T = R_{ind} + R_{Agri} \quad (13\text{-c})$$

Case8:

- If $H_{t}^{M}]_{Agri} \leq S_{t}^{M} < H_{t}^{M}]_{Ind}\ and\ S_{min}^{D} \leq S_{t}^{D} < H_{t}^{D}]_{Agri}$, then (14)

$$R_{ind} =\ \alpha_2 * D_{ind} \quad (14\text{-a})$$

$$R_{Agri} = \alpha_1 *\ D_{Agri} \quad (14\text{-b})$$

$$R_T = R_{ind} + R_{Agri} \quad (14\text{-c})$$

Case9:

- If $S_{min}^{M} \leq S_{t}^{M} < H_{t}^{M})_{Agri}\ and\ S_{min}^{D} \leq S_{t}^{D} < H_{t}^{D})_{Agri}$, then (15)

$$R_{ind} =\ \alpha_2 * D_{ind} \quad (15\text{-a})$$

$$R_{Agri} = \alpha_1 *\ D_{Agri} \quad (15\text{-b})$$

$$R_T = R_{ind} + R_{Agri} \quad (15\text{-c})$$

4- Reservoir water storage at any period does not exceed the upper and lower limits of its water storage capacity:

$$S^{i}_{min} \leq S^{i}_{t+1} \leq S^{i}_{max} \quad (16)$$

5- The water supply from each reservoir at any period must be greater than zero and less than or equal to the maximum water supply.

$$0 \leq R_t^i\ \leq\ R_{max}^i \quad (17)$$

6- Coefficients of hedging water supply requirements:

$$0 \leq\ \alpha_1\ \leq\ \alpha_2\ \leq 1 \quad (18)$$

7- The position of hedging water supply for industrial water users must be larger than the hedging water supply for agricultural water users for each reservoir in the system:

$$S_{min}^{i} \leq H_t^i]_{Agri} \leq H_t^i]_{ind} \leq S_{max}^{i} \quad (19)$$

where $H_{t}^{M}]_{Ind}$ is position of the Mosul reservoir's hedging rule curve for industrial purposes over a specified period; $H_{t}^{M}]_{Agri}$ is position of the Mosul reservoir's hedging rule curve for agriculture purposes over a specified period; $H_{t}^{D}]_{Ind}$ is position of the Dukan reservoir's hedging rule curve for industrial purposes over a specified period; $H_{t}^{D}]_{Agri}$ is position of the Dukan reservoir's hedging rule curve for agriculture purposes over a specified period; R_{ind} is water supply for industrial; R_{Agri} is water supply for agriculture; R_T is total water supply for different water users according to the two-dimensional reservoir rule curve; D_{ind} is common water requirement for industrial purposes; D_{Agri} is common water requirement for agricultural purposes; R^i_{max} is maximum water supply from the reservoir (i); α_1 , α_2 is rationing factor of water supply for agriculture and industrial water user, respectively.

3.4. Solution of Reservoir Operation Model

The Shuffled Complex Evolution (SCE-UA) algorithm was selected for this study as, in general, it is a well-known optimization algorithm in water resource management [43, 44], especially for the operation of reservoirs. Furthermore, a global optimization algorithm was proposed by Naeini et al. [44]. Duan et al. [45] combined the advantages of the simplex method, random search, competitive biological evolution, and hybrid partitioning methods to solve nonlinearly constrained optimization problems. Optimization begins by uniformly sampling a population of points from the acceptable parameter range. These points are subdivided into complexes, each with its own members. Then, iterative evolution is performed by sampling points from each complex to produce a sub-complex, which is subsequently developed many times using the simplex approach. This evolutionary process is repeated for each complex several times before the complexes are shuffled to exchange the information gathered throughout the evolution process. As previously stated, the effectiveness of SCE-UA is dependent on a restricted set of parameters that the user must specify, namely, population size, number of complexes for each point in the population, number of members for each complex, number of sub-complexes, number of iterations for the evolution of sub-complexes, and the number of iterations for the evolution of each complex, for which Naeini et al. [44] advised utilizing the default values of these parameters. In the current optimization process, the values of the algorithm parameters were taken by trial and error, which gives the optimal objective function, so at the small values of these parameters, it is difficult to reach the optimal state of the issue due to a large number of constraints within the problem. Still, there is no variation in the optimal value with the iteration at the higher values. It was found that selecting the following values of the algorithm parameters gave the optimum objective function, i.e., the number of complexes was (8), the number of members was (51), the number of sub-complexes was (10), iterations for the evolution of sub-complexes were (7), iterations for the evolution of each complex were (10), and the population size was (408).

The decision variables of the optimization process were the position of the hedging rule curve for each month of the year for each water use at each dam and the rationing factors (α1 and α2). So, the number of decision variables was 50, so the variables from one to 12 and from 13 to 24 represent the positions of the hedging rule for industrial demand in the Mosul and Dukan dams, respectively. Likewise, the variables from 25 to 36 and 37 to 48 represent the positions of the hedging rule for agricultural demand in the Mosul and Dukan dams, respectively. Similarly, variables 49 and 50 represent the rationing factors for each water user and the two dams above.

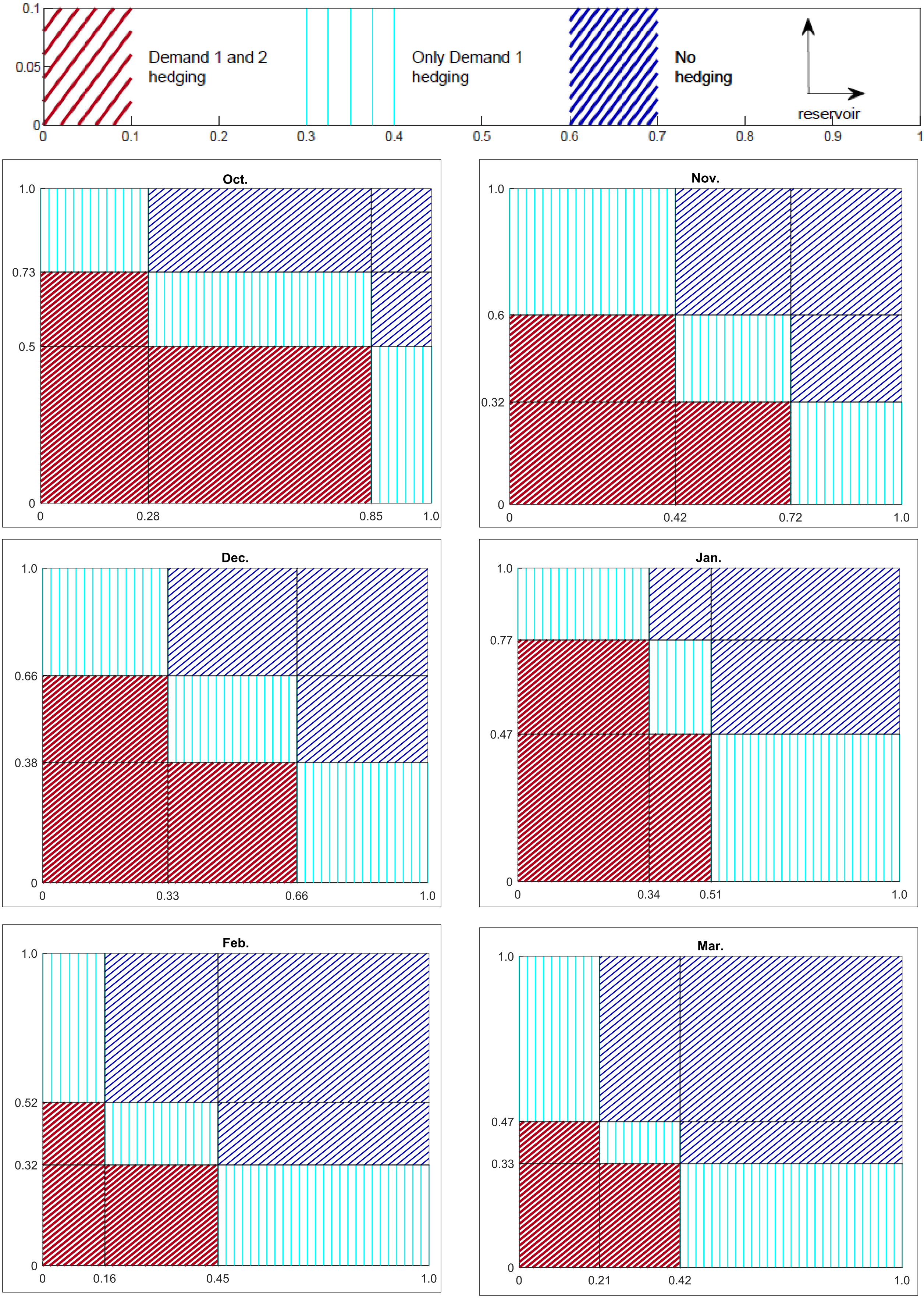
4. Results and Discussion

The analytical hierarchy process (AHP) was used in this paper to determine the weight factors (W_{ind} and W_{agri}) for different water users in the objective function. For this purpose, the comparison matrix was selected according to the priority between water users (industrial and agriculture), as illustrated in Table 2. Weights were calculated by the square root method. Similarly, the water supply risk index weighting factors (w1 and w2) in the objective function were divided into twenty intervals, each with a step of 0.05. The values that yielded the highest value of the objective function were chosen. These values were $w_1 = 0.9$ and $w_2 = 0.1$.

Table 2. Comparison matrix for water user

Water user	Industrial	Agriculture	Weight
Industrial	1	2	0.667
Agriculture	0.5	1	0.333

In determining the optimum position of the hedging rule for each water use and common water supply from the two-dimensional reservoir rule curve, the shuffled complex evolution algorithm was hybridized with dynamic programming (DP). Accordingly, the optimal allocation process between Mosul and Dukan reservoirs was set up through the two-dimensional reservoir rule curve, as shown in Figure 8. Subsequently, the optimal storage of Mosul and Dukan reservoirs was obtained, as shown in Figures 9 and 10. The forward process was used in DP to evaluate the objective function as in Equation 1. The storage of Dukan was divided into ten stages, with ten states for each stage based on the existing maximum and minimum storage. The water supply of Dukan reservoir was determined by one-dimensional dynamic programming, and the water supply process of Mosul reservoir was determined by the constraint that the sum of the water supplies of the two reservoirs is equal to the water supply to the common water users as determined by the two-dimensional reservoir rule curve. In the two-dimensional reservoir rule curve (Figure 8), the horizontal axis represents the water storage capacity of the Mosul reservoir, and the vertical axis represents the water storage capacity of the Dukan reservoir. It divided the water storage of two reservoirs into three water supply rules. In operating these dualistic reservoirs, one year was divided into twelve operation periods, and the shape and area of each water supply rule changed from one operation period to another.



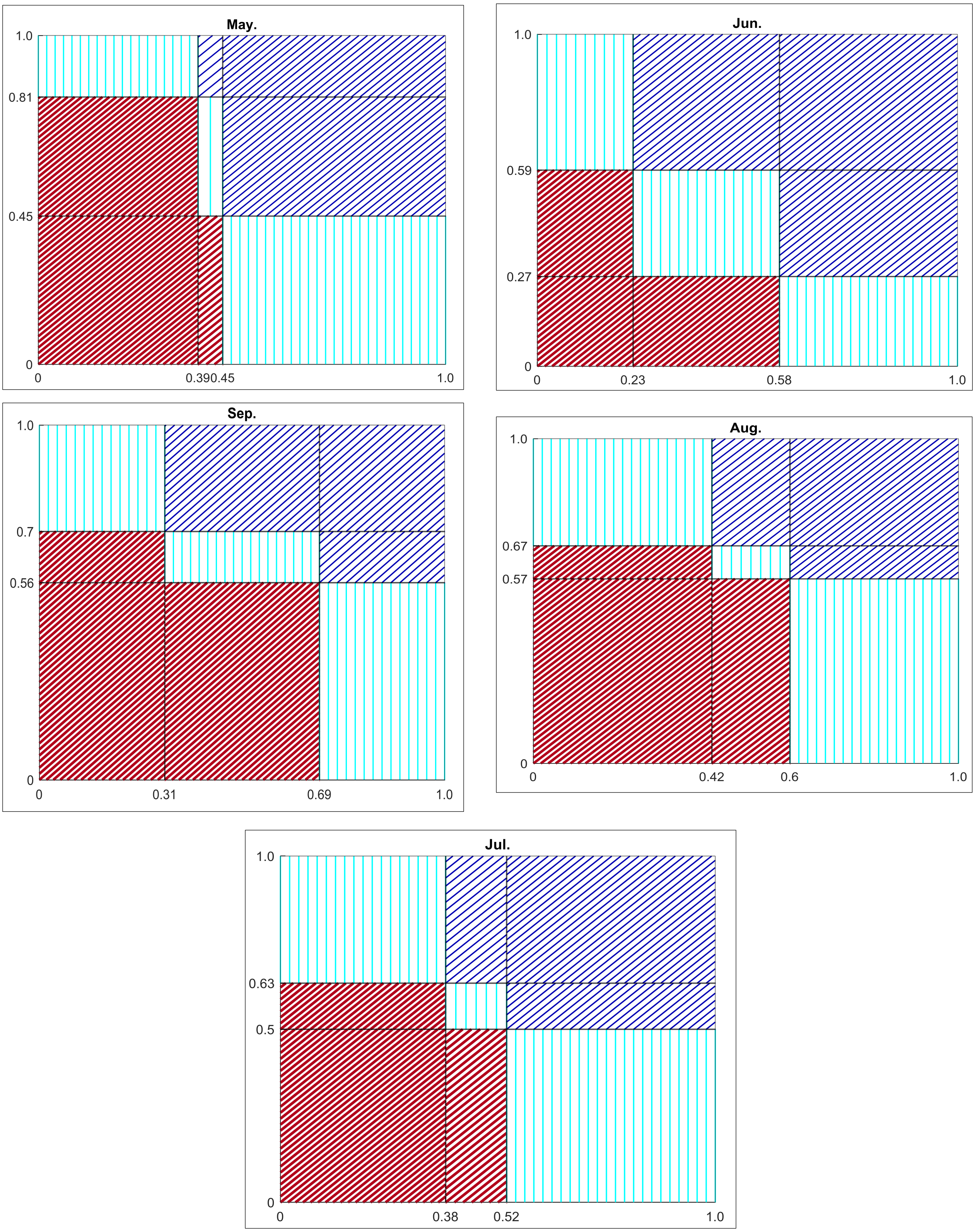


Figure 8. Optimal 2D rule curve of Mosul and Dukan reservoirs for 2001-2020

The proportion of normal water supply area increased from the beginning of the flood season (October) to reach its highest levels in April (58.77% of total water supply area), then began to decrease to reach its lowest levels in September (25.04% of total water supply area), due to the fact that the amount of water entering the reservoirs was much greater than that during the period within the flood season. In addition, the increase in water demand in post-flood season periods is more significant than during the flood season. In the pre-flood period, this proportion is more significant than that in the post-flood period, mainly because the storage in the reservoirs before the flood season decreases to minimum levels due to the reasons mentioned above, as illustrated in Figure 8.

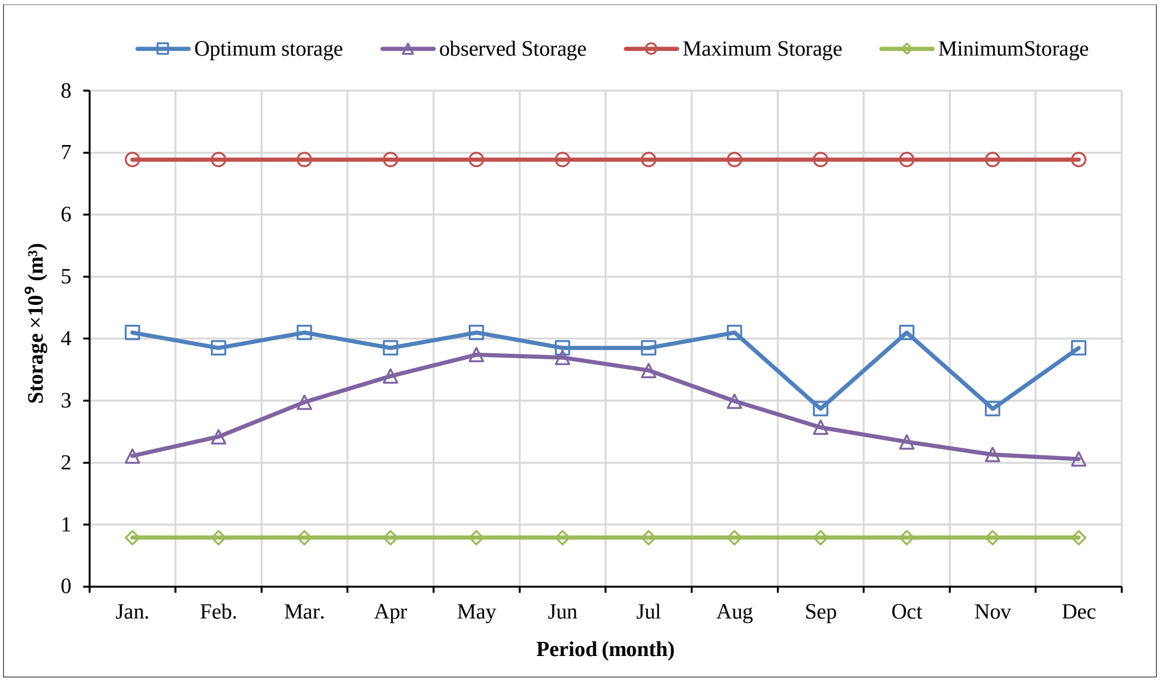


Figure 9. Optimum, Maximum, Minimum and observed storage for Dukan Dam (2001-2020)

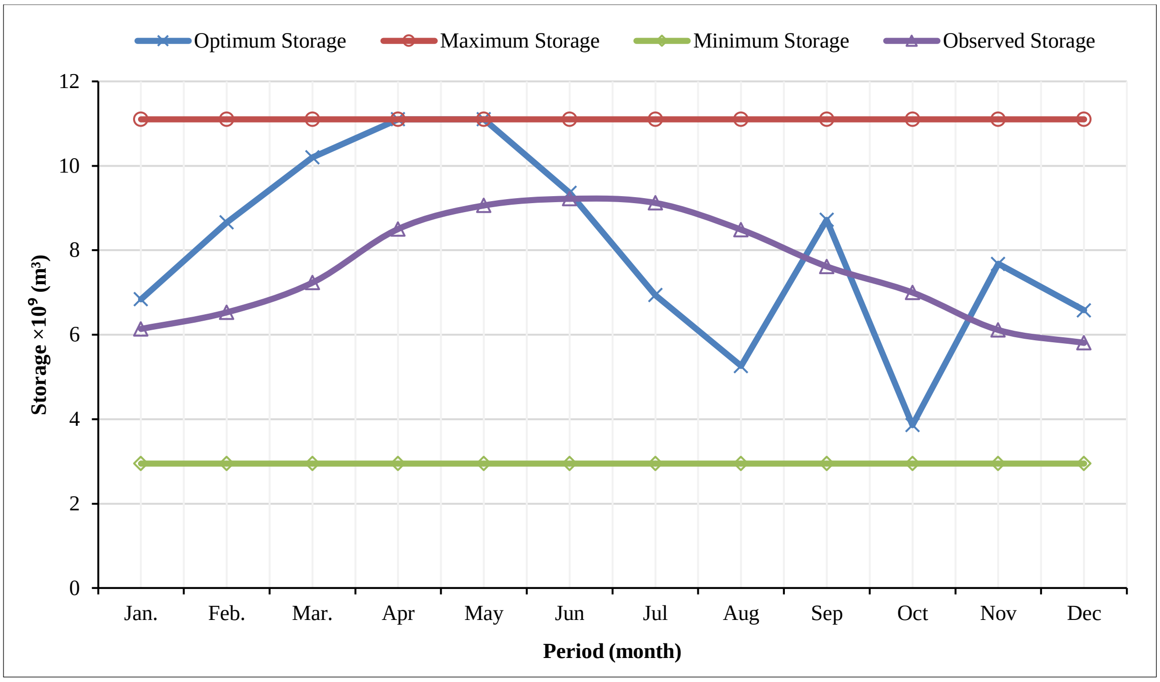


Figure 10. Optimum, Maximum, Minimum and observed storage for Mosul Dam (2001-2020)

The changing trend of the proportion of the hedging water supply area was just opposite that of the normal water supply area, which was caused by the different influence of the hedging water supply rule on the water storage process of the reservoir and the normal water supply rule. The maximum objective function obtained from the derivation of the 2D reservoir rule curve was 0.83, with the best values of reliability and resiliency for industry and agriculture. These values were 0.9167, 1.0, 0.67, and 0.25, respectively. The optimal values of the rationing factors (α1 and α2), derived from the optimization process, were 0.67 and 0.87, respectively. The optimization model was written in Matlab 2022a software. Figures 9 and 10 show that the reservoir storage rate will increase throughout the operating year in the Dokan Dam and most months in the Mosul Dam reservoir. This is because the Dukan Dam reservoir releases the least amount of water to meet the common requirements, and the complete opposite is true for the Mosul Dam reservoir. Through this, it is clear that the policy proposed through this research is better if each reservoir is operated separately. The relationship between the simulated water supply generated by dynamic programming and the water requirement is illustrated in Figure 11. From this plot, it was observed that the Two- dimensional rule curve developed has satisfied very well as it was able to release the required demand.

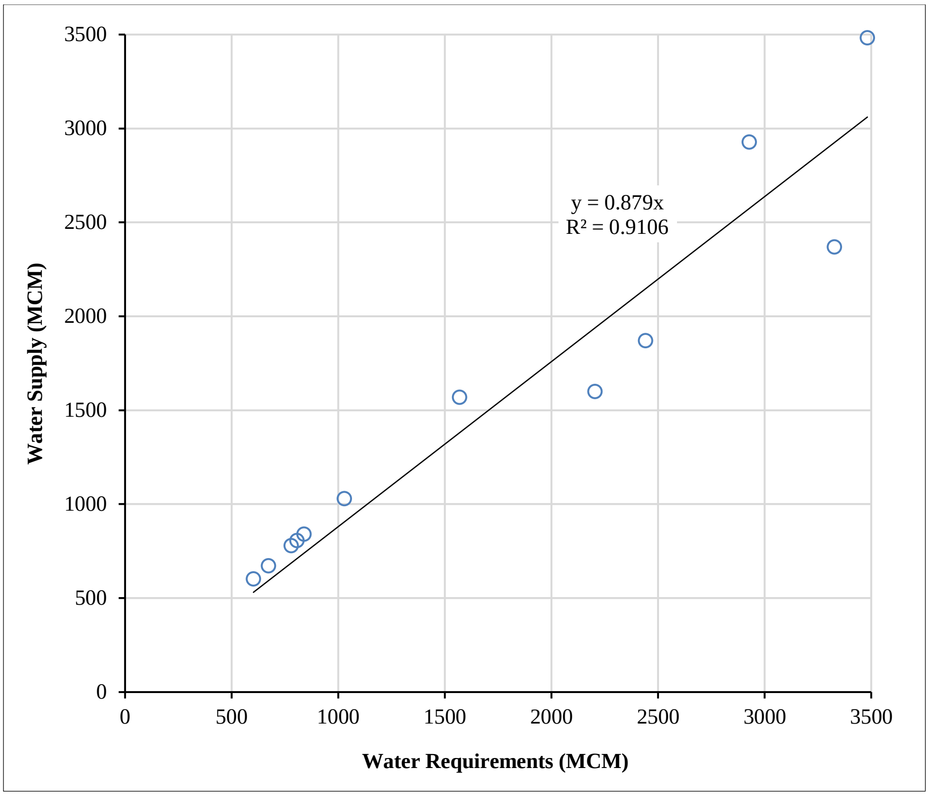


Figure 11. Relationship between water supply from Mosul and Dukan dam with joint water requirements

Table 3 depicts the percentage of excess and shortage in water supply, as well as the positive and negative impact on the storage of Mosul and Dukan reservoirs, for two operation rule curves with the operation period. These operation rules represent the current operation rules of the Mosul and Dukan dams and the proposed operation in this study. Columns 2 and 3 in Table 3 represent the change in the percentage of water supply concerning the joint water requirement according to the current rule curve policy and the proposed rule curve policy, and columns 3 and 4 represent the change in percent in the amount of storage between the two policies for two dams. It is clear from this Table that the proposed operating curve in the study reduces the amount of water shortage by 21.1% during the operational year, a significant percentage due to the predominant water scarcity in the region. In addition, they were reducing the operating periods that suffer from scarcity. Therefore, in general, the storage levels of the Mosul and Dukan dams will improve, except for a few months in the reservoir of the Mosul Dam. They will decrease compared to the current operating levels. The reason for this decrease is that the releases from the Mosul Dam will meet all the requirements of the shared water.

Table 3. Comparison between the Current Rule curve operation and Proposed Rule curve operation

Month	%of shortage in water supply according to the 2D Rule curve	%of shortage in water supply according to the Current Rule curve	%of Changed in the storage of the Mosul dam	%of Changed in the storage of the Dukan dam
Jan.	0.00	0.79	0.11	0.94
Feb.	0.00	0.78	0.33	0.59
Mar.	0.00	1.63	0.41	0.38
Apr.	0.00	1.82	0.31	0.13
May.	0.00	1.18	0.22	0.10
Jun.	0.00	-0.46	0.02	0.04
Jul.	0.00	-0.50	-0.24	0.10
Aug.	-0.29	-0.45	-0.38	0.37
Sep.	-0.23	-0.33	0.14	0.12
Oct.	-0.27	-0.37	-0.45	0.76
Nov.	0.00	-0.15	0.26	0.35
Dec.	0.00	0.48	0.13	0.87

5. Conclusion

This study aimed to derive a two-dimensional rule curve to operate parallel reservoirs in southwest Asia with joint demand. A two-dimensional rule curve was developed for the Mosul and Dukan reservoirs, the largest multi-purpose reservoirs in Iraq. The reservoir serves various functions, the most important of which are flood control, domestic water supply, industrial uses, environmental flows, and agricultural uses. The 2D reservoir operation rule curve was derived by a hybridized algorithm (SCE-DP) coupling conventional dynamic programming with the shuffled complex evolution algorithm, and the optimal allocation of water supply from the Musol reservoir was calculated based on it. The results showed that the proportion of normal water supply areas is lower in the dry season than in the flood season.

After comparing the newly derived base curve with the current operating policy, it shows that the current operating policy is not appropriate to meet the joint demand because it provides scarcity and abundance in supplying water to meet the joint demand during the same operational year, and the reason is that it is based on downstream demand. On the other hand, The newly derived operating policy is more suitable for water supply to achieve common demand in countries that have a dry or semi-arid climate in general and in Iraq in particular, as it reduces the amount of abundant water and reduces the water shortage in the dry season as a result of the impact of climate changes, and as a result, increases the capacity of reservoirs concerned with the operation. Finally, the hybrid algorithm showed its efficiency in deriving complex operating policies by being simple and fast.

6. Declarations

6.1. Author Contributions

Conceptualization, N.K. and T.S.; methodology, N.K.; software, N.K.; validation, N.K.; formal analysis, N.K., T.S., and M.A.M.; investigation, N.K., T.S., and M.A.M.; resources, N.K.; data curation, N.K.; writing—original draft preparation, N.K.; writing—review and editing, N.K., T.S., and M.A.M.; visualization, N.K.; supervision, T.S. and M.A.M. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in the article.

6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6.4. Conflicts of Interest

The authors declare no conflict of interest.

7. References

[1] Kumar, V., & Yadav, S. M. (2022). Multi-objective reservoir operation of the Ukai reservoir system using an improved Jaya algorithm. Water Supply, 22(2), 2287–2310. doi:10.2166/ws.2021.374.

[2] Liu, B., Xia, J., Yang, L., Cui, C., Wang, L., & Li, T. (2020). Improved dynamic simulation technique for hydrodynamics and water quality of river-connected lakes. Water Supply, 20(8), 3752–3767. doi:10.2166/ws.2020.125.

[3] Simonovic, S. (1987). The implicit stochastic model for reservoir yield optimization. Water Resources Research, 23(12), 2159–2165. doi:10.1029/WR023i012p02159.

[4] Fang, H., Li, X., Shang, W., & Wang, L. (2022). Improved multi-reservoir operation rules of water supply system based on target storage curves. Water Supply, 22(6), 5753–5770. doi:10.2166/ws.2022.214.

[5] Connaughton, J., King, N., Dong, L., Ji, P., & Lund, J. (2014). Comparing simple flood reservoir operation rules. Water (Switzerland), 6(9), 2717–2731. doi:10.3390/w6092717.

[6] Ahmadi, M., Haddad, O. B., & Loáiciga, H. A. (2015). Adaptive Reservoir Operation Rules Under Climatic Change. Water Resources Management, 29(4), 1247–1266. doi:10.1007/s11269-014-0871-0.

[7] Diao, Y., Wang, C., Wang, H., & Liu, Y. (2021). Construction and application of reservoir flood control operation rules using the decision tree algorithm. Water (Switzerland), 13(24), 3654. doi:10.3390/w13243654.

[8] Chang, Y. T., Chang, L. C., & Chang, F. J. (2005). Intelligent control for modeling of real-time reservoir operation, part II: Artificial neural network with operating rule curves. Hydrological Processes, 19(7), 1431–1444. doi:10.1002/hyp.5582.

[9] Chen, L., McPhee, J., & Yeh, W. W. G. (2007). A diversified multiobjective GA for optimizing reservoir rule curves. Advances in Water Resources, 30(5), 1082–1093. doi:10.1016/j.advwatres.2006.10.001.

[10] Karami, H., Farzin, S., Jahangiri, A., Ehteram, M., Kisi, O., & El-Shafie, A. (2019). Multi-Reservoir System Optimization Based on Hybrid Gravitational Algorithm to Minimize Water-Supply Deficiencies. Water Resources Management, 33(8), 2741–2760. doi:10.1007/s11269-019-02238-3.

[11] Al-Aqeeli, Y. H., & Mahmood Agha, O. M. A. (2020). Optimal Operation of Multi-reservoir System for Hydropower Production Using Particle Swarm Optimization Algorithm. Water Resources Management, 34(10), 3099–3112. doi:10.1007/s11269-020-02583-8.

[12] Xu, W., Zhang, C., Peng, Y., Fu, G., & Zhou, H. (2014). A two stage Bayesian stochastic optimization model for cascaded hydropower systems considering varying uncertainty of flow forecasts. Water Resources Research, 50(12), 9267–9286. doi:10.1002/2013WR015181.

[13] Peng, A. B., Peng, Y., Zhou, H. C., & Zhang, C. (2015). Multi-reservoir joint operating rule in inter-basin water transfer-supply project. Science China Technological Sciences, 58(1), 123–137. doi:10.1007/s11431-014-5641-y.

[14] Oliveira, R., & Loucks, D. P. (1997). Operating rules for multi-reservoir systems. Water Resources Research, 33(4), 839–852. doi:10.1029/96WR03745.

[15] Maass, A., Hufschmidt, M. M., Dorfman, R., Thomas, Jr, H. A., Marglin, S. A., & Fair, G. M. (1962). Design of water-resource systems: New techniques for relating economic objectives, engineering analysis, and governmental planning. Harvard University Press. doi:10.4159/harvard.9780674421042.

[16] Stedinger, J. R. (1984). The Performance of LDR Models for Preliminary Design and Reservoir Operation. Water Resources Research, 20(2), 215–224. doi:10.1029/WR020i002p00215.

[17] Clark, E. J. (1956). Impounding reservoirs. Journal (American Water Works Association), 48(4), 349-354.

[18] Johnson, S. A., Stedinger, J. R., & Staschus, K. (1991). Heuristic operating policies for reservoir system simulation. Water Resources Research, 27(5), 673–685. doi:10.1029/91WR00320.

[19] Zeng, X., Hu, T., Xiong, L., Cao, Z., & Xu, C. (2015). Derivation of operation rules for reservoirs in parallel with joint water demand. Water Resources Research, 51(12), 9539–9563. doi:10.1002/2015WR017250.

[20] Guo, X., Hu, T., Zeng, X., & Li, X. (2013). Extension of Parametric Rule with the Hedging Rule for Managing Multireservoir System during Droughts. Journal of Water Resources Planning and Management, 139(2), 139–148. doi:10.1061/(asce)wr.1943-5452.0000241.

[21] Tan, Q. feng, Wang, X., Wang, H., Wang, C., Lei, X. hui, Xiong, Y. song, & Zhang, W. (2017). Derivation of optimal joint operating rules for multi-purpose multi-reservoir water-supply system. Journal of Hydrology, 551, 253–264. doi:10.1016/j.jhydrol.2017.06.009.

[22] Kosasaeng, S., Yamoat, N., Ashrafi, S. M., & Kangrang, A. (2022). Extracting Optimal Operation Rule Curves of Multi-Reservoir System Using Atom Search Optimization, Genetic Programming and Wind Driven Optimization. Sustainability (Switzerland), 14(23), 16205. doi:10.3390/su142316205.

[23] Kangrang, A., & Chaleeraktrakoon, C. (2008). Suitable conditions of reservoir simulation for searching rule curves. Journal of Applied Sciences, 8(7), 1274–1279. doi:10.3923/jas.2008.1274.1279.

[24] Adeloye, A. J., Soundharajan, B. S., Ojha, C. S. P., & Remesan, R. (2016). Effect of hedging-integrated rule curves on the performance of the pong reservoir (India) during scenario-neutral climate change perturbations. Water Resources Management, 30(2), 445–470. doi:10.1007/s11269-015-1171-z.

[25] Mohanavelu, A., Soundharajan, B. S., & Kisi, O. (2022). Modeling Multi-objective Pareto-optimal Reservoir Operation Policies Using State-of-the-art Modeling Techniques. Water Resources Management, 36(9), 3107–3128. doi:10.1007/s11269-022-03191-4.

[26] Chang, F. J., Chen, L., & Chang, L. C. (2005). Optimizing the reservoir operating rule curves by genetic algorithms. Hydrological Processes, 19(11), 2277–2289. doi:10.1002/hyp.5674.

[27] Kangrang, A., Prasanchum, H., & Hormwichian, R. (2018). Development of Future Rule Curves for Multipurpose Reservoir Operation Using Conditional Genetic and Tabu Search Algorithms. Advances in Civil Engineering, 2018, 1–10. doi:10.1155/2018/6474870.

[28] Marchand, A., Gendreau, M., Blais, M., & Guidi, J. (2019). Optimized operating rules for short-term hydropower planning in a stochastic environment. Computational Management Science, 16(3), 501–519. doi:10.1007/s10287-019-00348-2.

[29] Haddad, O. B., Afshar, A., & Mariño, M. A. (2008). Honey-bee mating optimization (HBMO) algorithm in deriving optimal operation rules for reservoirs. Journal of Hydroinformatics, 10(3), 257–264. doi:10.2166/hydro.2008.018.

[30] Techarungruengsakul, R., & Kangrang, A. (2022). Application of Harris Hawks Optimization with Reservoir Simulation Model Considering Hedging Rule for Network Reservoir System. Sustainability (Switzerland), 14(9), 4913. doi:10.3390/su14094913.

[31] Ahmadianfar, I., Kheyrandish, A., Jamei, M., & Gharabaghi, B. (2021). Optimizing operating rules for multi-reservoir hydropower generation systems: An adaptive hybrid differential evolution algorithm. Renewable Energy, 167, 774–790. doi:10.1016/j.renene.2020.11.152.

[32] Ahmadianfar, I., Khajeh, Z., Asghari-Pari, S. A., & Chu, X. (2019). Developing optimal policies for reservoir systems using a multi-strategy optimization algorithm. Applied Soft Computing, 80, 888–903. doi:10.1016/j.asoc.2019.04.004.

[33] Yaseen, Z. M., Karami, H., Ehteram, M., Mohd, N. S., Mousavi, S. F., Hin, L. S., Kisi, O., Farzin, S., Kim, S., & El-Shafie, A. (2018). Optimization of Reservoir Operation using New Hybrid Algorithm. KSCE Journal of Civil Engineering, 22(11), 4668–4680. doi:10.1007/s12205-018-2095-y.

[34] Masoumi, F., Masoumzadeh, S., Zafari, N., & Emami-Skardi, M. J. (2022). Optimal operation of single and multi-reservoir systems via hybrid shuffled grey wolf optimization algorithm (SGWO). Water Supply, 22(2), 1663–1675. doi:10.2166/ws.2021.326.

[35] Nezhad, O. B., Najarchi, M., NajafiZadeh, M. M., & Hezaveh, S. M. M. (2018). Developing a shuffled complex evolution algorithm using a differential evolution algorithm for optimizing hydropower reservoir systems. Water Science and Technology: Water Supply, 18(3), 1081-1092. doi:10.2166/ws.2017.179 .

[36] Ministry of Water Resources (2022). General Directorate of Dams and Reservoirs in Iraq, Baghdad. Iraq.

[37] Al-Ansari, N., Adamo, N., Al-Hamdani, M. R., Sahar, K., & Al-Naemi, R. E. A. (2021). Mosul Dam Problem and Stability. Engineering, 13(03), 105–124. doi:10.4236/eng.2021.133009.

[38] Othman, L., & Ibrahim, H. (2014). Simulation-Optimization Model for Dokan Reservoir System Operation. Sulaimani Journal for Engineering Sciences, 1(1). doi:10.17656/sjes.10053.

[39] You, J. Y., & Cai, X. (2008). Hedging rule for reservoir operations: 2. A numerical model. Water Resources Research, 44(1). doi:10.1029/2006WR005482.

[40] You, J. Y., & Cai, X. (2008). Hedging rule for reservoir operations: 1. A theoretical analysis. Water Resources Research, 44(1). doi:10.1029/2006WR005481.

[41] Hashimoto, T., Stedinger, J. R., & Loucks, D. P. (1982). Reliability, resiliency, and vulnerability criteria for water resource system performance evaluation. Water Resources Research, 18(1), 14–20. doi:10.1029/WR018i001p00014.

[42] Sandoval-Solis, S., McKinney, D. C., & Loucks, D. P. (2011). Sustainability Index for Water Resources Planning and Management. Journal of Water Resources Planning and Management, 137(5), 381–390. doi:10.1061/(asce)wr.1943-5452.0000134.

[43] Boyle, D. P., Gupta, H. V., & Sorooshian, S. (2000). Toward improved calibration of hydrologic models: Combining the strengths of manual and automatic methods. Water Resources Research, 36(12), 3663–3674. doi:10.1029/2000WR900207.

[44] Naeini, M. R., Analui, B., Gupta, H. V., Duan, Q., & Sorooslíian, S. (2019). Three decades of the shuffled complex evolution (sce-ua) optimization algorithm: Review and applications. Scientia Iranica, 26(4A), 2015–2031. doi:10.24200/sci.2019.21500.

[45] Duan, Q., Sorooshian, S., & Gupta, V. K. (1994). Optimal use of the SCE-UA global optimization method for calibrating watershed models. Journal of Hydrology, 158(3–4), 265–284. doi:10.1016/0022-1694(94)90057-4.