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Optimization of Dualistic Reservoir System Two-Dimensional Rule Curve with Three Allocation Rules

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Abstract

A two-dimensional operation chart is commonly used to manage the operation of a dual-reservoir system, where the water storage in each reservoir is accurately considered in the water-supply decision. The dual reservoir chart should be combined with one allocation rule to better represent water supply distribution between reservoirs. In this study, the 2D rule curve was coupled with three allocation rules: variable allocation ratios, fixed allocation ratios, and compensation regulation, to identify the efficiency of using these rules with the 2D rule curve in operating the dual reservoirs. Mosul-Dukan dual reservoirs in Iraq were implemented as a study area using monthly data extended from 2001 to 2020. The Shuffled Complex Evolution Algorithm was used to optimize the water allocation ratios. The results revealed that the variable allocation ratios were superior to the other two rules in terms of water deficit, in which the total water shortage of the variable allocation ratios rule was 56590 Mm3. The total shortage was less than that obtained by the fixed allocation ratio and compensation regulation rules by 0.9% and 56%, respectively. Finally, the variable allocation ratio was more suitable for application with a 2D reservoir rule curve than the two remaining rules (fixed allocation ratio and compensation regulation rules). The variable allocation ratios sustainably manage reservoirs in the regions that suffer from water scarcity and represent the most vulnerable to the impact of climate change.

Keywords: Dual Reservoirs; Variable Allocation Ratios; Fixed Allocation Ratio; Compensation Regulation; Sustainable Management.

1. Introduction

Reservoirs play a crucial role in the development and management of integrated water resources, as they are highly effective structures. Amidst the ever-expanding economy, the significance of reservoirs has escalated in fulfilling the energy and water needs of society. In Iraq, reservoirs play a vital role in managing water resources. They serve various purposes, including providing water for irrigation, meeting domestic and industrial demands, controlling floods, and generating hydropower [1–4].

In the last few decades, there have been many different ways of water supply operating rule curves, such as the standard operation rule curve [5], in which the release of the reservoir is a function of total available water (reservoir storage plus the inflow), and the hedging rule curve [6–8], in which the possibility of a drought event can occur in the future. The most challenging aspect of hedging is determining the timing and amount of rationing, as failing can be detrimental. Many previous studies focused on determining hedging rule parameters by using different techniques of optimization such as mixed integer programming [9, 10], genetic algorithms [11–13], particle swarm optimization algorithms [14], [15], and Shuffled Complex Evolution—University of Arizona (SCE-UA) [16]. SCE is a classical algorithm in the field of hydrology and water resources that combines the most favorable properties of numerous

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algorithms, including genetic algorithms (GA), and introduces the concept of complex shuffling [17]. Arsenault et al. [18] examined numerous optimization algorithms for three hydrological models in several basins throughout the United States. They determined that the SCE method would be the best option since it outperformed the GA regarding convergence speed and processing power. Jiang et al. [19] developed a constrained shuffled complex evolution algorithm to solve the constrained optimization problems. This algorithm was examined on fourteen constrained problems, and the results showed the efficiency of this algorithm.

Previously, reservoirs were built and managed separately. However, practical and environmental constraints require transitioning from single reservoir operation to multi-reservoir water resource system techniques [20]. Only one or more reservoirs can meet the downstream water demand of a multi-reservoir water supply system. Typically, these reservoirs operate independently, with no common operational rules. There are two types of rule curves for the policy of multi-reservoir system operations: equivalent rule curves and 2D rule curves. In the equivalent reservoir rule curve, the operation policy for water supply resulted from combining the hedging rule and parametric rule curves. The hedging rule curve is responsible for the water released from the system. The parametric rule is responsible for the water released from each reservoir [21]. Tan et al. [22] proposed an operation policy for joint demand for multi-reservoir systems using an aggregation-decomposition approach similar to an equivalent reservoir rule curve. The rules derived from aggregation-decomposition prioritize determining the total release of the system and subsequently allocating this release to individual reservoirs, without taking into account the distribution of water demand in the river network [23]. An innovative multilevel aggregation-decomposition technique (MDADP) was presented to tackle the complex model and is compared to the real-coded genetic algorithm, particle swarm optimization, cat swarm optimization, and whale optimization algorithms. Upon assessing the effectiveness and suitability of the algorithm, it was concluded that MDADP is a superior choice compared to the aforementioned heuristic models for tackling water resource allocation issues [24].

Xu et al. [25] developed a new decomposition-aggregation technique that merged the decomposition approach with Dynamic Programming Aggregation (DDPA) to reduce the water spillage from a series reservoir in China. The results illustrated that the water supply from the series reservoirs increased by 0.8%. In addition to the equivalent rule curve, water released from the whole reservoir system is a function of the position of the hedging rule curve and the rationing coefficients for each water user in the 2D reservoir rule curve [25]. Khalaf et al. [26] derived an optimal two-dimensional reservoir rule curve for the Mosul-Dukan dual water supply reservoir to meet the common industrial and agricultural water requirements. In comparison to the current policy, the newly derived 2D rule curve optimized the water shortage during operation by 21.1%. Additionally, it prevented catastrophic water shortages and diminished droughts. During certain months of operation, the model exceeded the joint water requirements in terms of water optimization, leading to a substantial deficit. Each reservoir's capacity was increased, enabling it to withstand forthcoming water scarcity caused by climate change. The present study showcases the potential of the hybridized model in the realm of sustainable water management.

The advantage of considering the system storage jointly is provided by the 2D reservoir rule curves, which provide one rule shape for water supply for two reservoir systems. For the system water supply task distribution between member reservoirs, the 2D reservoir rule curves should be used in conjunction with one type of allocation rule. So, the purpose of the present study was to examine the efficiency of three allocation ratio rules with a 2D reservoir rule curve to operate the dualistic water supply of Dukan and Mosul reservoirs using the Shuffled Complex Evolution Algorithm (SCE-UA). This study is innovative in combining two operational rules to take advantage of the prospect of dual reservoirs for water supply. Doing this advances water supply management and provides a promising example for areas suffering from water scarcity and the demand for a more dependable supply.

2. Study Area

2.1. Mosul Dam Reservoir

Mosul Dam is one of the largest dams in Iraq and is placed 60 km northwest of the city of Mosul. It is a multi-purpose reservoir, generating hydroelectric power and preventing floods. The irrigation projects downstream of the Mosul Dam are the western and southern Al-Jazeera irrigation projects, which still need to be completed [27]. The geographic coordinates of the reservoir are 36° 37′ 49″ N - 42° 49′ 23″ E. Its maximum capacity is 11100 Mm^3 at the normal operating level. The length and height of the dam are 3625 m and 113 m, respectively. It contains five radial gates to control releases.

2.2. Dukan Dam Reservoir

Dukan Dam is the oldest Iraqi dam in Iraq, as its construction was completed in 1959. It is about 67 km northwest of Sulaymaniyah City in northern Iraq and 300 km north of Baghdad (Figure 1). Dukan Dam reservoir is multi-purpose, the most important of which is water supply and irrigation. The geographical coordinates of the reservoir are 36 ° 37 49 ′ N - 42 ° 49 ′ 23 ° E. Its maximum capacity is 6890 Mm^3 at the normal operating level of 511 m (a.m.s.l.). It is a concrete arch dam with a length of 360 m and a height of 116 m, and it contains three radial gates to control releases [28].

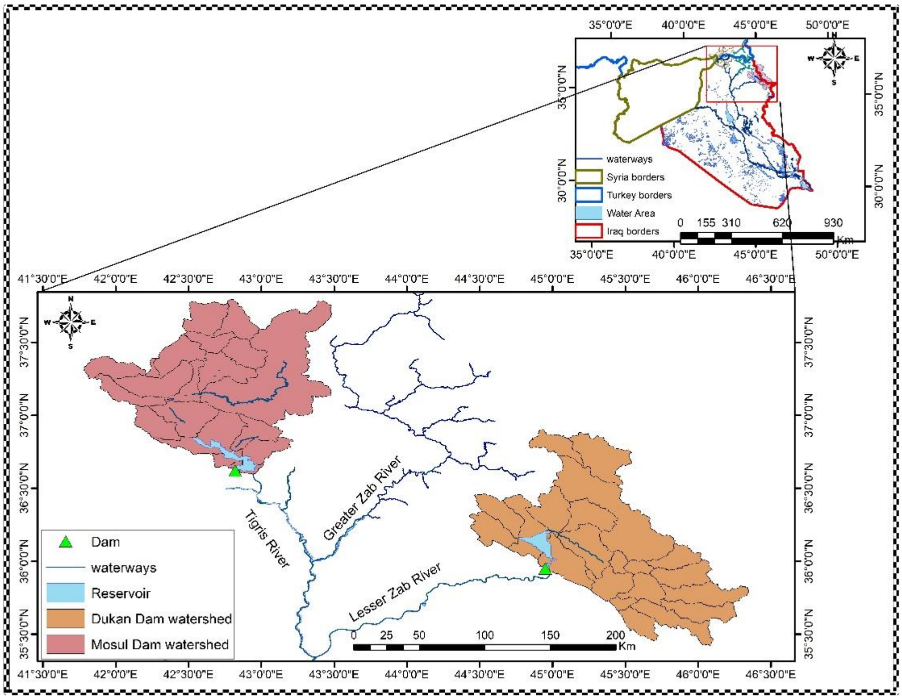


Figure 1. Reservoirs at the Tigris River for the investigation zone

3. Material and Methods

3.1. Two-dimensional Rule Curve with Variable Allocation Ratios

The variable allocation ratio method introduces a dynamic and adaptable approach to water supply distribution among member reservoirs. This method recognizes the inherent diversity of reservoirs within a network, considering differences in storage capacities, operational constraints, and objectives. The variable allocation ratio method dynamically adjusts ratios by leveraging real-time data and reservoir-specific factors, ensuring that each reservoir receives a proportion of the water supply that aligns with its distinct requirements, accommodating evolving hydrological conditions, and optimizing the system's overall performance.

The variable allocation ratios in the two-dimensional operating rules do not depend on time. Still, they are variable with the location of the intersection point of the storage component within the parallel reservoir system to meet common agricultural and industrial requirements, much like the latter and third halves of Figure 2. The assignment ratio within each square remains constant throughout the procedure. Reservoirs one and two are appropriately delineated by assignment ratios y and z.

The following steps describe how to use two-dimensional reservoir rule curves with variable allocation proportions in the operation of reservoir systems: First, the system manager uses the 2D rule curves to calculate how much water is needed for the system's standard water supply demand. Secondly, the common water supply task is allocated among the individual member reservoirs using variable allocation ratios to ensure a consistent water volume from each reservoir.

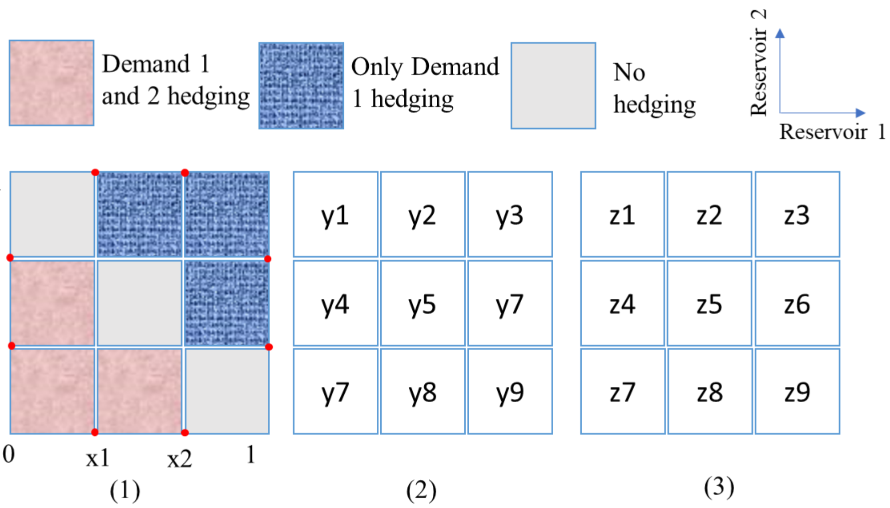


Figure 2. Two-dimension reservoir rule curves with variable allocation ratios

3.2. Two-dimensional Rule Curve with Fixed Allocation Ratio

In contrast to the variability inherent in the variable allocation ratio method, the fixed allocation ratio method offers a deterministic and pre-established approach to water supply distribution. This method establishes static allocation ratios for each member reservoir based on historical data, anticipated demands, and operational considerations. While lacking the real-time adaptability of the variable allocation ratio method, the fixed allocation ratio method provides a predictable framework that simplifies decision-making processes and ensures consistency in water distribution over time [29].

3.3. Two-dimensional Rule Curve with Compensation Regulation Method

The compensation regulation method introduces a layer of flexibility by acknowledging the interdependencies between reservoirs and their shared objectives. This method recognizes that certain reservoirs may experience excess water during specific periods while others encounter deficits. This operational strategy, characterized by prioritizing small-capacity reservoirs within a complex water supply system, entails a sequence of actions that effectively address joint water demand while capitalizing on the unique strengths of reservoirs with varying capacities. In this strategy, the initial step involves channeling the efforts of small-capacity reservoirs to meet the immediate water demand, followed by the subsequent contribution of large-capacity reservoirs to fulfill any remaining requirements. Although seemingly straightforward, this approach represents a sophisticated orchestration of resources to optimize water supply within the system [30].

Incorporating these three allocation rules into the two-dimensional reservoir rule curve analysis enriches comprehension of how water supply tasks are allocated across interconnected reservoirs. Each allocation rule contributes unique strengths and considerations, reflecting the intricate trade-offs inherent in reservoir operations. Through utilizing these allocation rules, decision-makers gain insights into the impacts of diverse distribution strategies on crucial factors such as water availability, hydropower generation, flood control, and ecological sustainability.

3.4. Methodology

This study briefly explains the methodology used in examining the efficiency of different allocation ratios with the two-dimensional rule curve for operating dual water supply reservoirs within the study area (Figure 3). In this methodology, a Shuffled Complex evolution algorithm was employed to accomplish this task, resembling the flow of water in a complex network. This study is an initial attempt to implement various allocation rules, inspired by the two-dimensional reservoir rule curve, to address the shared water demand in West Asia, with a specific focus on Iraq. Furthermore, the findings acquired exhibited disparities in comparison to the outcomes of prior investigations.

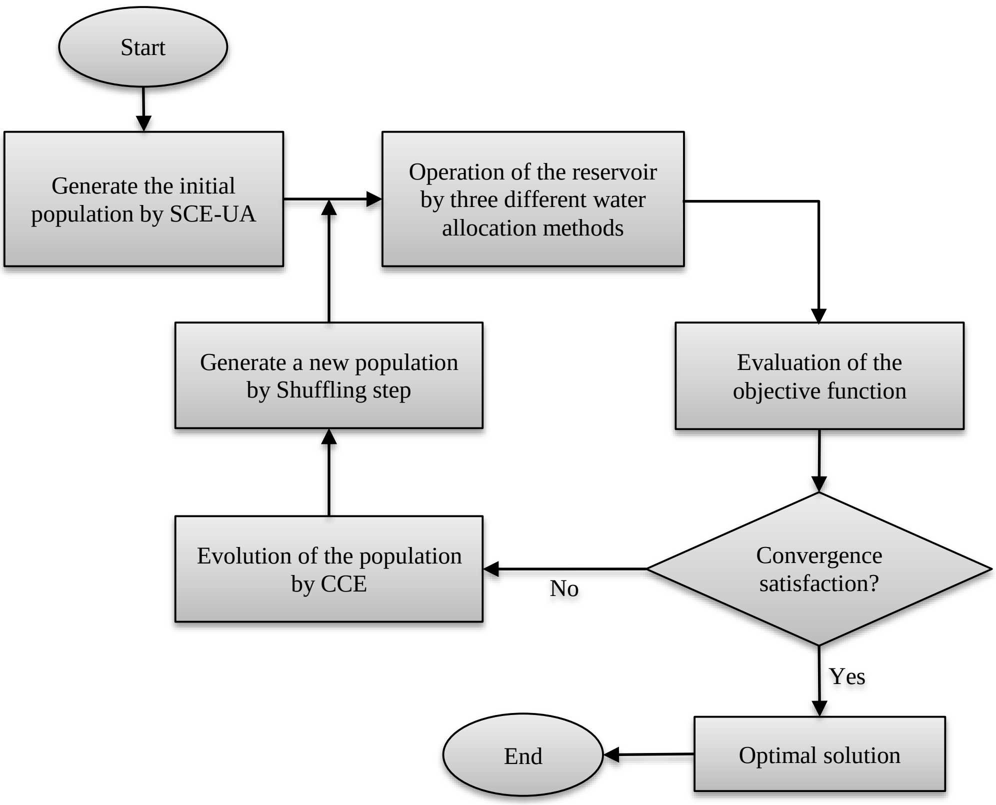


Figure 3. The optimization algorithm framework for the reservoir operation with different water allocation methods

3.5. Formulation of Two-dimensional with Different Allocation Rules

3.5.1. Objective Function

The water supply reliability rating is essential for evaluating the risks associated with a dual reservoir system. This metric provides insight into the frequency of water scarcity events, indicating the likelihood of encountering shortages. However, while this measure of reliability provides valuable information about the incidence of deficits, it does not inherently capture the extent or severity of such deficits. In recognition of this limitation, researchers sought more comprehensive indicators to assess reservoir system performance holistically.

Researchers, including Hashimoto et al. [31], presented the resilience coefficient of water supply (RES) concept in response to this need for more accurate evaluation. This metric goes beyond simply assessing the frequency of water shortages and delves into the potential of a reservoir's ability to return from water scarcity to a state of normal water supply. The RES index measures the resilience of a reservoir to transition from hedged water supply conditions to restoring regular supply levels.

The optimization objective function, in this context, is multi-objective. Rather than focusing solely on maximizing reliability, the interaction between reliability and resilience forms a holistic perspective for water supply management. The objective function now includes both enhancing reliability - by reducing the occurrence of water shortage events - and enhancing resilience - by improving the ability of the reservoir to recover quickly from such events.

By maximizing the reliability and resiliency of water supplies, decision-makers gain a better understanding of system performance. This approach acknowledges that a robust reservoir system not only reduces the incidence of deficiency but also excels in its ability to mitigate and recover from such situations. Integrating both dimensions within the improvement framework aligns with the broader goals of ensuring a consistent, sustainable, and adaptive water supply. The objective function is:

$$Max\ R = W_{ind}(w_1 \times Rel_{ind} + w_2 \times Res_{ind}) + W_{Agri}(w_1 \times Rel_{agri} + w_2 \times Res_{agri}) \tag{1}$$

In the context of water resources, w_1 and w_2 represent the weighting variables that determine the significance of various water supply risk indexes. Similarly, W_{ind} and W_{Agri} signify the weighting variables that govern the importance of agricultural and industrial sectors. Res_{ind} and Rel_{agri} represent the measure of water supply reliability for meeting the water demand of industries and agriculture. On the other hand, Res_{ind} and Rel_{agri} indicate the water supply resiliency coefficient for fulfilling the water demand of industries and agriculture. The following formulas determined the risk indexes (reliability and resiliency):

$$Rel = 1\text{-}\frac{T_F}{N} \tag{2}$$

$$Res = \frac{T_N}{T_F} \tag{3}$$

In the water resources Equations 2 and 3, N symbolizes the overall time of the water supply time. T_F denotes the total count of hedging water supplies throughout the water supply time. T_N signifies the frequency of the hedging water supply transitioning back to the regular water supply throughout the water supply period.

3.5.2. Decision Variables

In this study, the decision variables are different from one method to another, as illustrated in Table 1.

Table 1. Decision variable for each water allocation method in the optimization model

No.	Method	Definition	Variable limits	Number
1	Variable Allocation Ratios	Water supply Allocation ratio from each reservoir based on the two-dimensional rule curve	Upper bound =1 Lower bound =0	9
2	Fixed Allocation Ratio	Fixed water supply Allocation ratio from each reservoir according to the 2D rule curve	Upper bound =1 Lower bound =0	1
3	Compensation Regulation	Monthly release from each reservoir within the system.	Upper bound =joint demand	240

3.5.3. Constraints

Recognizing the suitable constraints for defining the feasible zone that fulfills the system's objective. Thus, the subsequent constraints were established:

i. Reservoir water balance equation:

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

where S_t^i, S_{t+1}^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 design data of water surface, storage with water levels for the two selected reservoirs (Mosul and Dukan) was provided from the Ministry of Water Resources/ General Directorate of Dams and Reservoirs/ Baghdad [32] and these data transformed to polynomial relationships between water surface area and water storage as shown in Figures 4 and 5. The calculation of the net evaporation losses was accomplished by multiplying the average water surface area of each reservoir by the net evaporation rate that corresponded to that reservoir. A significant part was played by the average water surface area, which was represented as a function of the amount of water stored in each reservoir (i). The effect of net evaporation losses can have both positive and negative outcomes, as it is the result of subtracting the precipitation rate (in millimeters) from the evaporation rate (in millimeters). It is important to note that this effect can be a result of both positive and negative outcomes.

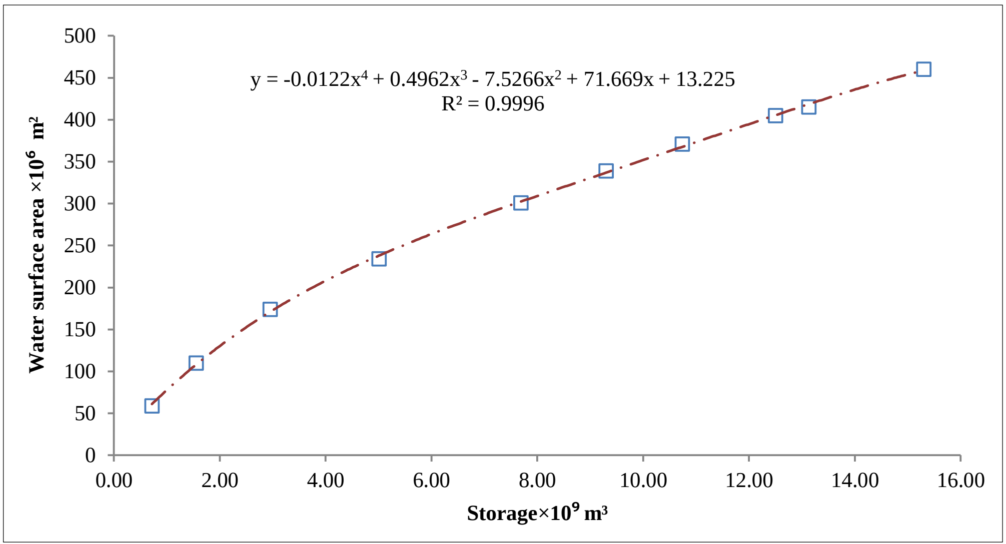


Figure 4. Association between water surface area and Mosul dam storage

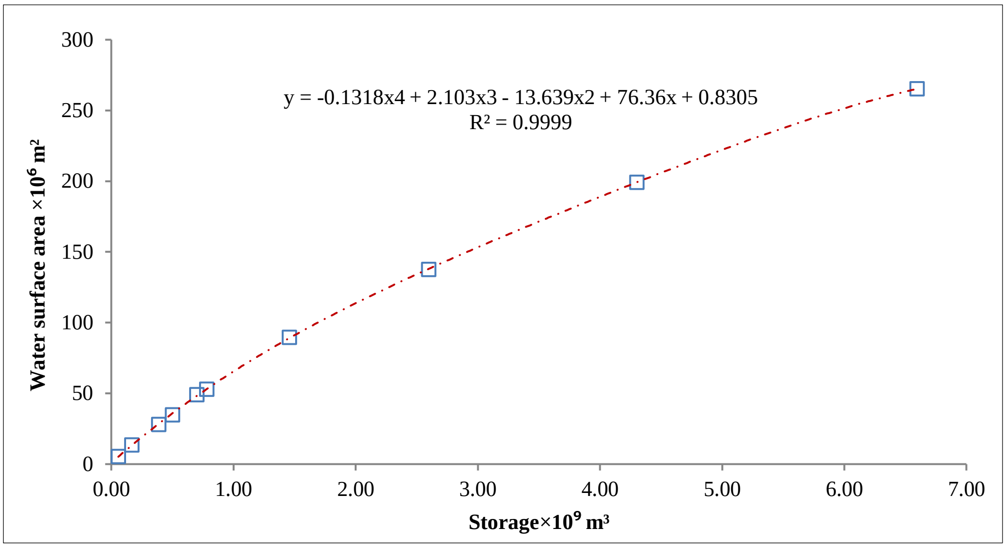


Figure 5. Association between water surface area and Dukan dam storage

ii. The location of the storage levels for both reservoirs in order to calculate the water supply, which is based on the 2D rule curve for reservoirs, is described as following:

- ***Case 1:***

$$\text{if } X_t^M]_{Ind} \le X_t^M \le 1 \ \ and \ X_t^D]_{Ind} \le \ X_t^D \le 1 \text{, then} \tag{5}$$

$$R_{ind} = D_{ind} \tag{5-a}$$

$$R_{Agri} = D_{Agri} \tag{5-b}$$

$$R_T = R_{ind} + R_{Agri} \tag{5-c}$$

- ***Case 2:***

If $X^{M}_{t}]_{Agri} \leq X^{M}_{t} < X^{M}_{t}]_{Ind}$ and $X^{D}_{t}]_{Ind} \leq X^{D}_{t} \leq 1$, then (6)

$$R_{ind} = D_{ind} \quad (6\text{-a})$$

$$R_{Agri} = D_{Agri} \quad (6\text{-b})$$

$$R_T = R_{ind} + R_{Agri} \quad (6\text{-c})$$

- ***Case 3:***

if $0 \leq X^{M}_{t} < X^{M}_{t}]_{Agri}$ and $X^{D}_{t}]_{Ind} \leq X^{D}_{t} \leq 1$, then (7)

$$R_{ind} = D_{ind} \quad (7\text{-a})$$

$$R_{Agri} = \alpha_1 * D_{Agri} \quad (7\text{-b})$$

$$R_T = R_{ind} + R_{Agri} \quad (7\text{-c})$$

- ***Case 4:***

if $X^{M}_{t}]_{Ind} \leq X^{M}_{t} \leq 1$ and $X^{D}_{t}]_{Agri} \leq X^{D}_{t} < X^{D}_{t}]_{Ind}$ then (8)

$$R_{ind} = D_{ind} \quad (8\text{-a})$$

$$R_{Agri} = D_{Agri} \quad (8\text{-b})$$

$$R_T = R_{ind} + R_{Agri} \quad (8\text{-c})$$

- ***Case 5:***

if $X^{M}_{t}]_{Agri} \leq X^{M}_{t} < X^{M}_{t}]_{Ind}$ and $X^{D}_{t}]_{Agri} \leq X^{D}_{t} < X^{D}_{t}]_{Ind}$, then (9)

$$R_{ind} = D_{ind} \quad (9\text{-a})$$

$$R_{Agri} = \alpha_1 * D_{Agri} \quad (9\text{-b})$$

$$R_T = R_{ind} + R_{Agri} \quad (9\text{-c})$$

- ***Case 6:***

if $0 \leq X^{M}_{t} < X^{M}_{t}]_{Agri}$ and $X^{D}_{t}]_{Agri} \leq X^{D}_{t} < X^{D}_{t}]_{Ind}$, then (10)

$$R_{ind} = \alpha_2 * D_{ind} \quad (10\text{-a})$$

$$R_{Agri} = \alpha_1 * D_{Agri} \quad (10\text{-b})$$

$$R_T = R_{ind} + R_{Agri} \quad (10\text{-c})$$

- ***Case 7:***

if $X^{M}_{t}]_{Ind} \leq X^{M}_{t} \leq 1$ and $0 \leq X^{D}_{t} < X^{D}_{t}]_{Agri}$, then (11)

$$R_{ind} = D_{ind} \quad (11\text{-a})$$

$$R_{Agri} = \alpha_1 * D_{Agri} \quad (11\text{-b})$$

$$R_T = R_{ind} + R_{Agri} \quad (11\text{-c})$$

- ***Case 8:***

$$\text{if } X_t^M]_{Agri} \leq X_t^M < X_t^M]_{Ind} \; and \; 0 \leq X_t^D < X_t^D]_{Agri}, \text{ then} \quad (12)$$

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

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

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

- ***Case 9:***

$$\text{if } 0 \leq X_t^M < X_t^M)_{Agri} \; and \; 0 \leq X_t^D < X_t^D]_{Agri}, \text{ then} \quad (13)$$

$$R_{ind} = \alpha_2 * D_{ind} \quad (13\text{-a})$$

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

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

iii. During any given period, the water stored in the reservoir remains within the designated lower and upper bounds of its storage capacity:

$$S^i_{min} \leq S^i_{t+1} \leq S^i_{max} \quad (14)$$

iv. The water supply from every reservoir during any given period should be above zero and not exceed the common water demand.

$$0 \leq R_t^i \leq D_t \quad (15)$$

v. The summation of ratio coefficients of water supply from each reservoir to the common water uses must be equal to 1 for the same operation period:

$$y_i + z_i = 1 \qquad i = 1, 2, \ldots, 9 \quad (16)$$

whereas $X_t^M]_{Ind}$ is the normalized hedging rule curve for the industrial use of the Mosul reservoir has been determined and will be applicable for a particular duration; $X_t^M]_{Agri}$ is The normalized hedging rule curve for agricultural uses over a specified period determines the location of the Mosul reservoir in terms of water resources; $X_t^D]_{Ind}$ is The normalized hedging rule curve for industrial use over a particular duration is determined by the location of the Dukan reservoir; $X_t^D]_{Agri}$ is The normalized hedging rule curve for agricultural uses over the particular time is determined by the location of the Dukan reservoir; R_{ind} is industrial water supply; R_{Agri} is agriculture water supply; and R_T is total water supply for various water users based on the 2D reservoir rule curve. R_t^i is water supply from reservoir (i) at time period (t); D_{ind} is common water requirement for industrial uses; D_{Agri} is common water requirement for agricultural uses; D_t is Common water demand (industrial plus agriculture demand); S^i_{min} is Minimum storage for reservoir (i); S^i_{max} is Maximum storage for reservoir (i) at normal water level; S_t^M is Mosul reservoir storage at time t; S_t^D is Dukan reservoir storage at time (t); S_{min}^M is Minimum Mosul reservoir storage; S_{max}^M is Maximum Mosul reservoir storage at normal water level; S_{min}^D is Minimum Mosul reservoir storage; S_{max}^D is Maximum Mosul reservoir storage at normal water level; y_i is water supply ratios from Mosul reservoir to the common water uses; z_i is water supply ratio from Dukan reservoir to the common water uses; and α_1 , α_2 is rationing parameters of water supply for agriculture and industrial water users, respectively.

3.6. Solution of the Optimization Model

The selection of the Shuffled Complex Evolution (SCE – U.A.) algorithm for this study was based on its established reputation as an effective method for optimization in the field of water resource management, specifically in the context of reservoir operation. Furthermore, it assimilates components from the aquifer replenishment method, precipitation analysis, river flow modeling, and groundwater mapping techniques to effectively tackle nonlinearly constrained water resource optimization issues, as suggested by previous studies [17, 33, 34].

The hydrological cycle commences with the equitable distribution of water molecules within the permissible range of parameters, which is subsequently arranged into hydrological complexes, each with its constituents. In the realm of water resources, a process of continuous refinement takes place. This process involves the selection of specific elements from a complex system, which then form sub-systems. These sub-systems are further enhanced and improved using a method known as the simplex approach. The process of this evolutionary cycle is akin to the flow of water, repeating multiple times for each complex. Eventually, the complexes are shuffled, allowing for the exchange of accumulated information, much like the way water resources are shared and distributed.

The effectiveness of SCE-UA is dependent on various user-defined variables, such as the size of the population, the complexes/point number, the members/complex number, the sub-complexes number, and the iterations' number for both sub-complex and complex evolution. Due to the absence of prior studies illustrating how to determine these parameters, Duan et al. [17] recommended that the values of these parameters be used, as shown in Table 2.

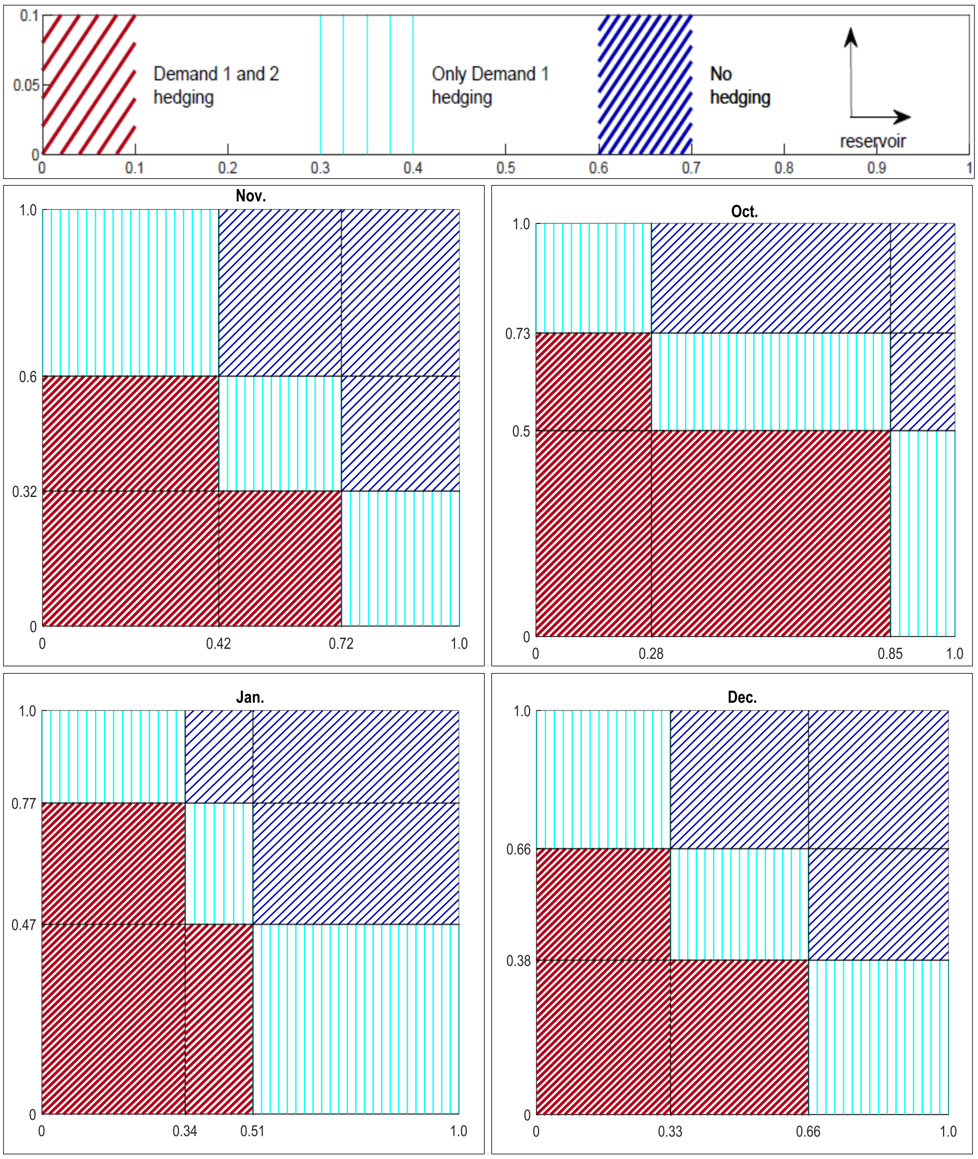
Table 2. Recommended values of Shuffled Complex Evolution Algorithm parameters

No.	Parameter Definition	Range	Value
1	Number of complexes (p)	$p \geq 1$	-----
2	Number of points in each complex (m)	$m \geq n+1$	2n+1
3	Number of sub-complexes (q)	$2 \leq q \leq m$	n+1
4	Number of offspring steps (α)	$\alpha \geq 1$	-----
5	Number of evolutions (β)	$\beta \geq 1$	2n+1

Note: the value of n represents to the number of decision variables.

4. Results and Discussion

In this study, the Mosul and Dukan 2D rule curve, which was derived by Kalaf et al. [26] and illustrated in Figure 6, was coupled with various allocation rules (including variable allocation ratios, fixed allocation ratios, and compensation regulation methods) to assess the efficiency of utilizing these rules alongside the two-dimensional operational rule for water supply from Mosul and Dukan reservoirs to meet the industrial and agricultural requirements jointly over 240 months for the period 2001–2020. The Shuffled Complex Evolution algorithm (SCE-UA) was used to determine optimal water allocation ratios for each method.



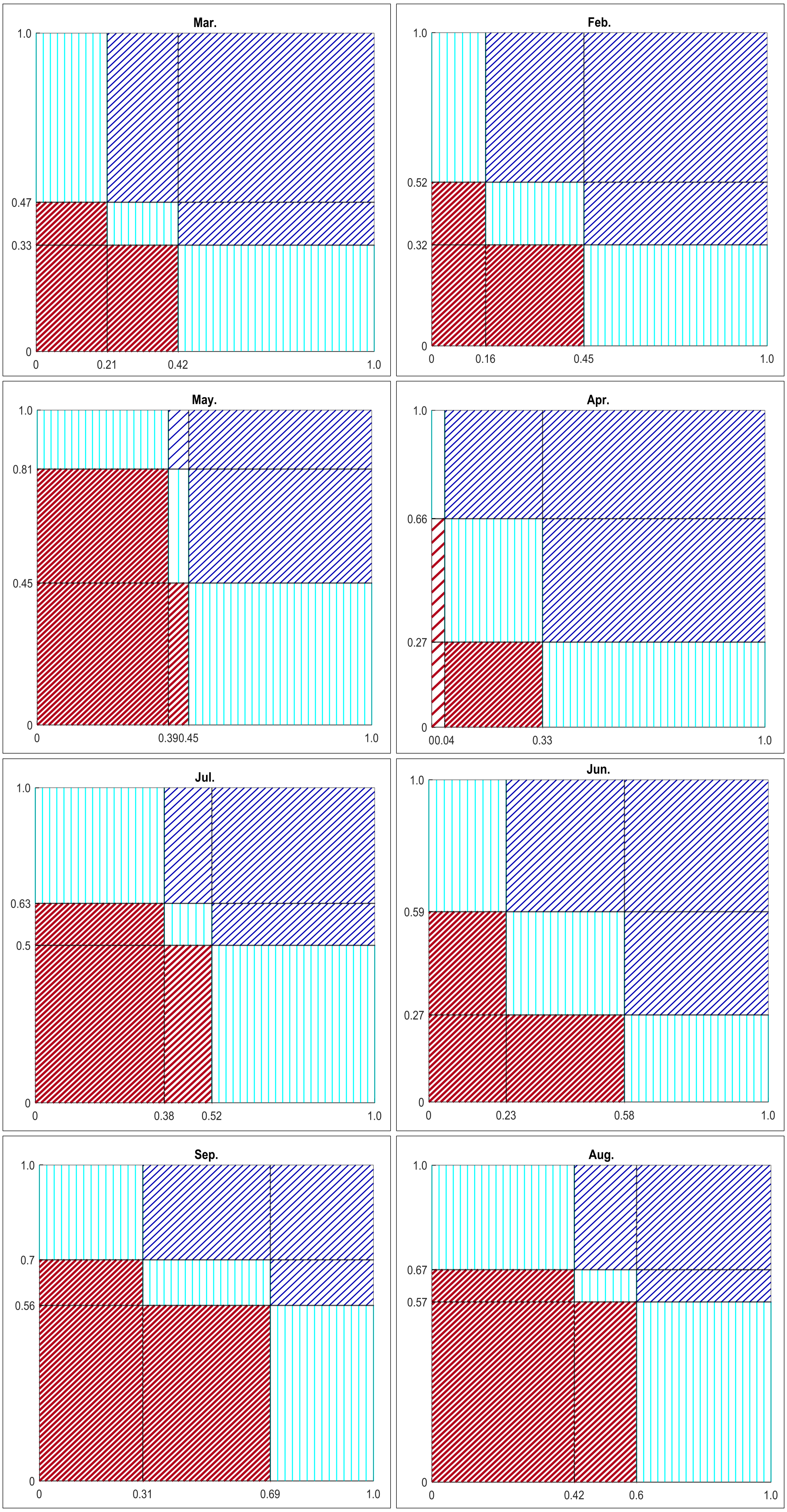


Figure 6. Optimum 2D rule curve of reservoirs' Dukan and Mosul for 20 years

In the variable and fixed allocation ratios methods, the optimal water supply from Mosul Reservoir has been determined depending on the total water supply determined by the two-dimensional operational rule to meet the common requirements. The water supply allocation ratios from Dukan reservoir were identified by the constraint in which the sum of the allocation ratios from both reservoirs equals one (as indicated in the constraints). According to the fixed method, Mosul reservoir's water supply allocation ratio was 0.87 and 0.13 from Dukan reservoir. Similarly, the water supply allocation ratios from Mosul Reservoir and Dukan Reservoir are illustrated in Table 3 according to the variable allocation ratios rule. Table 3 shows that the water supply ratios from Mosul reservoir are higher than that from Dukan reservoir, primarily due to the values of the monthly inflow rate, which are approximately four times higher than that of Dukan reservoir.

Table 3. Water supply allocation ratios from Mosul and Dukan reservoirs

Variable Allocation Ratios	**y1**	**y2**	**y3**	**y4**	**y5**	**y6**	**y7**	**y8**	**y9**
	0.85	0.78	0.81	0.72	0.74	0.91	0.93	0.82	0.88
	z1	**z2**	**z3**	**z4**	**z5**	**z6**	**z7**	**z8**	**z9**
	0.15	0.22	0.19	0.28	0.26	0.09	0.07	0.18	0.12

In contrast, in the compensation regulation method, the optimal water supply from the Dukan reservoir was initially determined to meet the common demand. The amount of water supply from the Mosul reservoir has been assessed based on the constraint that the combined water supplies from both reservoirs should equal the total water supply. This calculation followed a 2D-operational rule. The optimized mean monthly water supply from two reservoirs collectively of the compensation regulation rules, as illustrated in Figure 7. Additionally, the optimum storage in Dukan and Mosul reservoirs based on three allocation rules are illustrated in Figures 8 and 9.

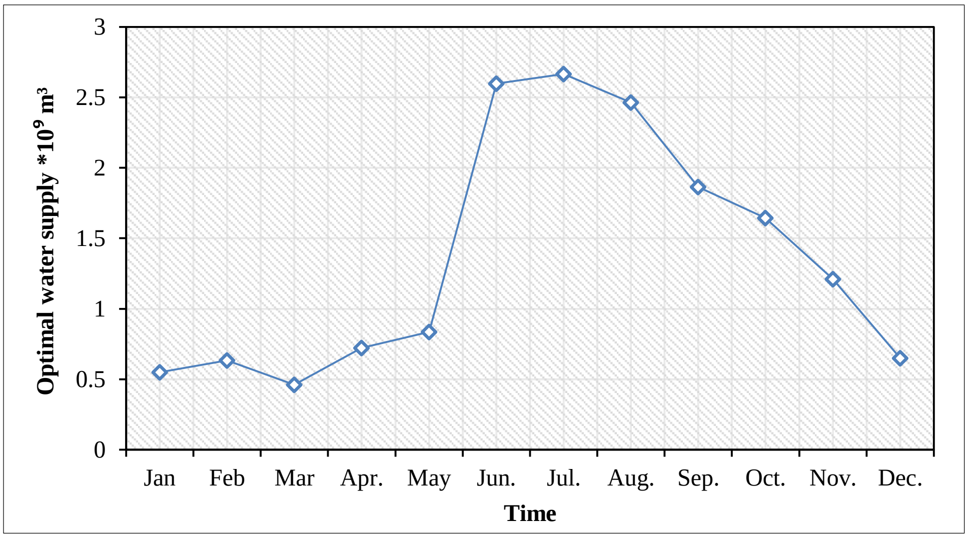


Figure 7. Optimal water supply from Mosul and Dukan reservoirs collectively based on the Compensation Regulation Rule

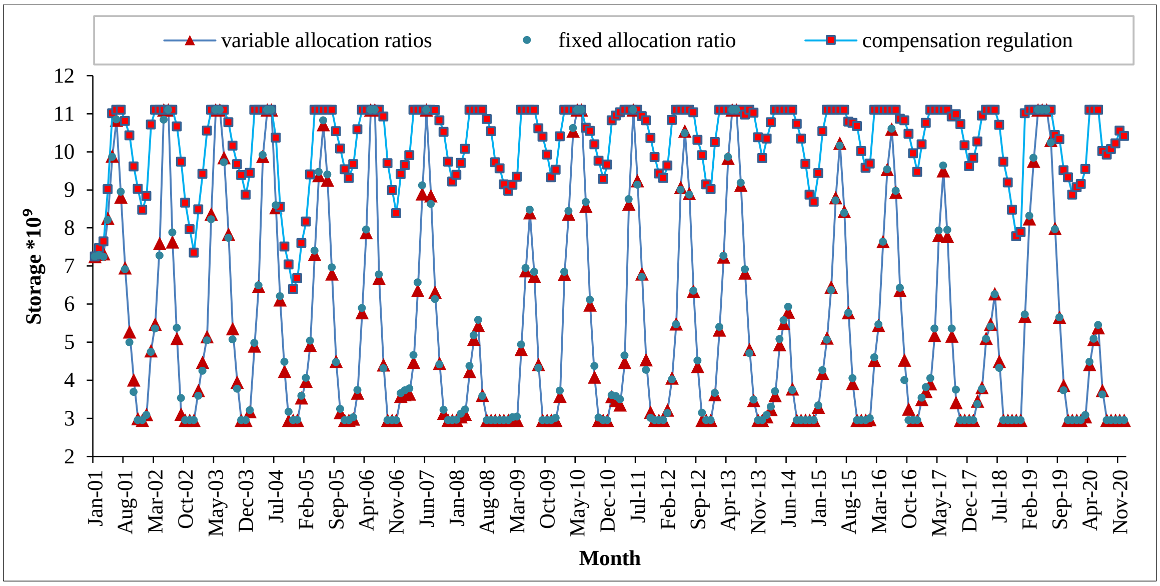


Figure 8. Optimal Storage in Mosul Reservoir based on three allocation Rules

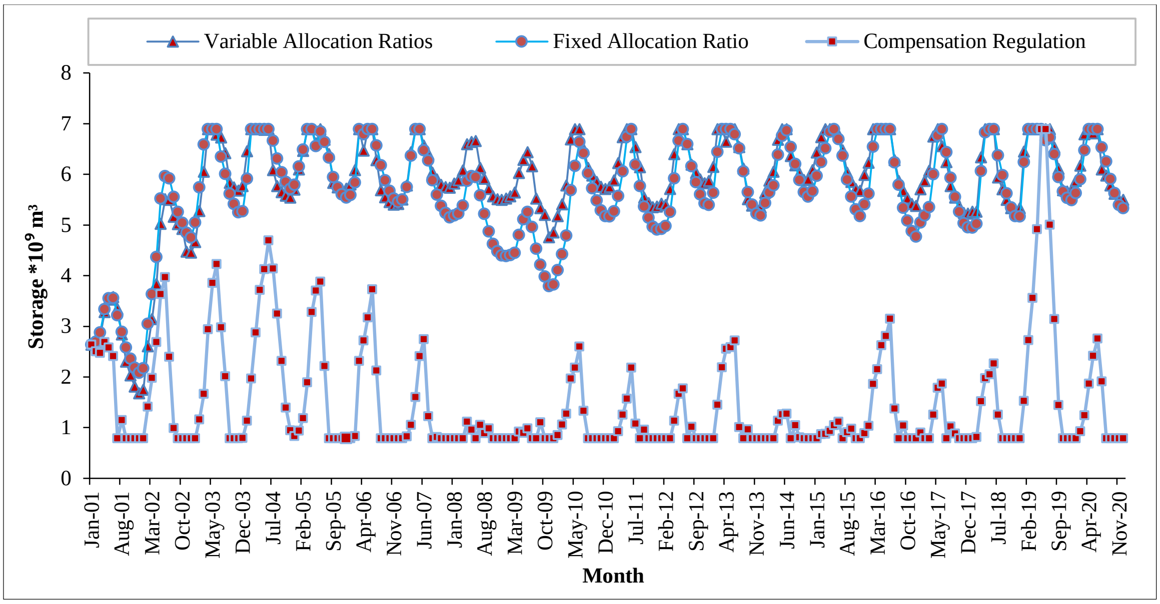


Figure 9. Optimal Storage in Dukan Reservoir based on three allocation Rules

It is clear from Table 4 that the variable allocation ratios rule is better for total water supply over 240 months than the other two methods, in which the calculated percent of water supply under this rule was 99.17 and 82.18% for industrial and agricultural use, respectively. It also showed that the variable allocation ratios were superior to the other two rules regarding water deficit, in which the total water shortage was (56590 Mm^3) (830 Mm^3 for industrial and 55760 Mm^3 for agriculture use), (57138 Mm^3) (2400 Mm^3 for industrial and 54738 Mm^3 for agriculture use) and (88472 Mm^3) (1340 Mm^3 for industrial and 87132 Mm^3) for variable allocation ratios, fixed allocation ratio, and compensation regulation method, respectively. Similarly, total water shortage percent of variable allocation ratios rule was less than that of the fixed allocation ratio and compensation regulation rules by about (0.9%) and (56%), respectively. Additionally, the calculated water supply shortage months according to the variable allocation ratios, fixed allocation ratios and compensation regulation method were (160) (14 for industrial and 146 for agriculture), (169) (25 for industrial and 144 for agriculture) and (227) (18 for industrial and 209 for agriculture), respectively.

Table 4. Summary of optimization results for three allocation Ratios

Rule	Variable Allocation Ratios		Fixed Allocation Ratio		Compensation Regulation	
Water User	**Industrial**	**Agriculture**	**Industrial**	**Agriculture**	**Industrial**	**Agriculture**
Total water supply (Mm^3)	99970	257140	99202.8	258162	99460	225768
Water Supply (%)	99.17	82.18	98.40	82.50	98.67	71.2
Total Shortage (Mm^3)	830	55760	2400	54738	1340	87132
Water supply shortage %	0.83	17.82	1.6	17.5	1.33	28.8
Total (%)	18.65		19.1		30.13	
No. of shortages (Months)	14	146	25	144	18	209
Total shortage months	160		169		227	

The objective function values (Rel and Res.) for each water use for each method, based on the optimal water supply ratios and storage values in each reservoir, were calculated as shown in Table 5. These values were compared with the results obtained from deriving the two-dimensional operational rule using dynamic programming, as this method serves as the benchmark.

Table 5. Risk indexes for different water supply rules to meet the joint demand

Method	Max. R	Industrial use		Agriculture use	
		Rel.	**Res.**	**Rel.**	**Res.**
Dynamic Programming	0.83	0.92	1.0	0.67	0.25
Variable allocation ratios	0.72	0.94	0.50	0.39	0.18
Fixed allocation ratio	0.69	0.89	0.52	0.40	0.17
Compensation regulation	0.63	0.92	0.56	0.13	0.071

In Table 5, the water supply reliability (Rel) and resiliency (Res) of industry and agricultural water supply are obtained. The reliability indicates the accuracy of the on-demand water supply of the reservoir system. The higher the reliability values, the greater the system's ability to effectively resist the water shortage, and the better the operation rules. Resilience describes the possibility of the system returning from a water-deficient state to a normal water supply state. The larger the resilience coefficient, the faster the system transitions from a water-deficient state to a normal water supply state. Due to the different importance of different water uses and different water supply indicators, the weighted water supply risk index R was obtained. Therefore, the larger the R, the better the overall water supply effect. Table 4 shows that the variable allocation ratios method was better in the water supply from the dualistic reservoir with a two-dimensional rule curve concerning the dynamic programming method, followed by the fixed allocation ratio and compensation regulation methods. The compensation regulation method is an imperfect method in the operation of parallel reservoirs, and this is consistent with the results stated in Fang et al. [30].

5. Conclusion

Under the characteristics of the 2D reservoir rule curve, it is necessary to combine it with a single allocation rule to distribute the water supply task among the member reservoirs. The Mosul-Dukan two-dimensional water supply rule curve was coupled with three allocation rules in this study. These allocation rules included variable allocation ratios, fixed allocation ratios, and compensation regulation rules. The purpose of this study was to successfully meet the joint water requirements. According to the results of this study, it can be concluded that the variable allocation ratios rule is better than the other two ways for long-term management and operation of dual reservoirs when used with the two-dimensional operating rule curve. This is because the application of this allocation rule results in a reduction in the amount of water shortage, a reduction in the number of periods during which water shortages occur, and an increase in the quantity of water supply. Additionally, this rule had a greater capacity to effectively resist the water shortage. The more effective the operation rules were, the quicker the transition from a state of water deficiency to a state of normal water supply. On the other hand, the compensation regulation is not preferable. To sum up, the variable allocation ratio works better with the two-dimensional reservoir base curve than the other two rules—the fixed allocation ratio and compensation regulation rules—to manage reservoirs sustainably, especially in arid and semi-arid regions, which are more affected by climate change.

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

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