Assessing the Impact of Multi-Reservoir Rationing on Downstream Drought Occurrence: A Case Study of Dez and Gotvand Reservoirs

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Received: 2025.07.04
Accepted: 2025.07.21
J. Hydraul. Struct., 2025; 12(2):34-50
DOI: 10.22055/jhs.2025.50084.1357

ABSTRACT

Water resource management in multi-reservoir systems is critical for meeting diverse demands while ensuring sustainability. In this study, we delve into optimizing the operating rule curve for such systems by integrating the Particle Swarm Optimization algorithm. Our overarching goal is to minimize relative deficiencies in water supply, considering both standard operating policies (SOP) and discrete two-level hedging policies. Our case study focuses on the Great Karun basin, a real-world scenario where water scarcity poses significant challenges. By coupling the PSO algorithm with a system simulation model, we search for optimal hedging levels across all reservoirs and months. Additionally, we rigorously compare the output results of our combined simulation-optimization model with those obtained from a SOP-based simulator. Furthermore, we analyze the flow drought index at key points throughout the basin under both rationing and SOP policies. Notably, while rationing generally reduces average drought severity, it may inadvertently exacerbate conditions in severely water-stressed areas like the Dez basin. The novelty of this study lies in coupling PSO-based optimization with detailed system simulation to develop dynamic hedging policies for multi-reservoir drought management. Our research contributes valuable insights into multi-reservoir system operation, shedding light on effective strategies for meeting water demands while mitigating the impact of droughts.

KEYWORDS

Reservoir operation, Hydrological drought, Simulation-optimization, Great Karun System, Water resource.

1. Introduction

The water resources crisis necessitates efficient utilization of water for various purposes, including municipal, drinking, agriculture, and industry. Structural facilities, such as large dam reservoirs, can play a crucial role in mitigating the effects of drought through their operational strategies [1, 2]. Reservoir operating policies directly impact the severity and duration of drought periods in watersheds that include storage reservoirs. While the Standard Operating Policy (SOP) ensures demand fulfillment, it requires adaptation during droughts [3, 4]. In this regard, hedging policy based on the optimum rationing strategy is recommended to minimize shortages and enhance reservoir system efficiency [5]. Although various optimization techniques have been proposed to achieve optimal operating rule curves [6], developing suitable operational strategies becomes more challenging when multiple purposes must be met across the entire basin. Real-world problems involving conflicting objectives—such as supplying agricultural demands, hydropower energy production,

and flood protection pose significant challenges [7, 8]. Meanwhile, effective drought mitigation measures have been proposed and investigated [9], extending beyond structural facilities. Given that drought, unlike other natural disasters, evolves over an extended period, effective cost reduction can be achieved by developing appropriate mitigation strategies, which should be planned meticulously, based on the suitable drought monitoring [10, 11, 12].

López-Moreno et al. [13] conducted research focusing on the impact of reservoirs on hydrological droughts downstream. Their study evaluated how a large reservoir affects hydrological droughts in a border river shared by two countries. Li et al. [14] quantitatively assessed the effects of reservoir outlets on hydrological droughts at downstream stations. Guo et al. [15] proposed an operation rule that combines parametric and rationing approaches to mitigate severe shortages during drought periods in multi-reservoir water management. Chang et al. [16] introduced a specialized reservoir policy based on rationing to minimize losses caused by water scarcity during droughts. To assess flow dynamics, calculating Indicators of Hydrologic Alteration (IHA) is common practice. Al-Faraj et al. [17] used these indicators to analyze temporal changes and the mutual influence of upstream human development on consecutive basin droughts. In a related study, Al-Faraj et al. [18] investigated the effects of successive droughts and human activities in the upstream region on a semi-arid border basin. Wu et al. [19] proposed a valuable method for assessing the impact of reservoir operating rules during droughts on multiscale correlations between hydrological and meteorological droughts at the basin level.

Men et al. [20] have made significant advancements in reservoir management by introducing the joint hedging rule as an improvement over the traditional rationing approach. They applied this novel rule to the Yuqiao Reservoir in Tianjin, China, and compared it with conventional hedging and standard operating policies. Meanwhile, Wu et al. [21] investigated the impact of anthropogenic regulations on hydrological drought development and recovery processes. Their findings highlight the reservoir operation's influence on short-term drought severity reduction and duration. Additionally, Ahmadianfar and Zamani [22] explored the effects of future climate change on agricultural reservoir utilization. Floods and droughts, as natural hazards linked to water resources, have caused significant harm to human societies. Proper management is crucial to prevent further disasters related to climate change risks [23, 24]. Meanwhile, evaluating the effects of climate change requires specialized methods to address related uncertainties [25, 26]. Obtaining a reliable projection of future runoff and streamflow across a watershed enables system managers to mitigate uncertainties and make informed decisions based on more accurate forecasts [27]. In a separate study, Ren et al. [28] emphasized that water and soil resource protection projects significantly alter river flow variability. These changes result from intricate interactions between natural processes and human activities, which remain incompletely understood. They investigated these interactions in a large river basin with multiple reservoirs to identify exploitation scenarios aimed at mitigating drought and flood effects [28].

In recent years, several studies have investigated the impact of regulating uncontrolled surface flows on hydrological drought occurrence [29, 30]. The primary objective of this research is to assess the influence of operating policies on hydrological drought characteristics within a regulated watershed. To achieve this, we employ hedging policies and standard operating policy models. Additionally, we extract optimal policies using the Particle Swarm Optimization (PSO) algorithm as an optimizer. The calculation of the surface flow drought index relies on reservoir

outputs from a multi-reservoir system, and we evaluate how operating policies affect this index. Given the significance of the Great Karun watershed's water resources system in the country [3], we conduct a case study within this system.

2. Case study:

In pursuit of our research objectives, we have selected the Great Karun multi-reservoir system, consists of the Karun and Dez rivers in Khuzestan province, as our study area. The Great Karun watershed covers an extensive area of 67,257 square kilometers in the southwest of Iran and ranks among the most significant watersheds of the Persian Gulf. Approximately 67% of this basin comprises mountainous terrain, while the remaining 33% consists of high plains. Our investigation centers around a water resources system that includes six reservoir dams and their associated power plants, strategically positioned along the Dez and

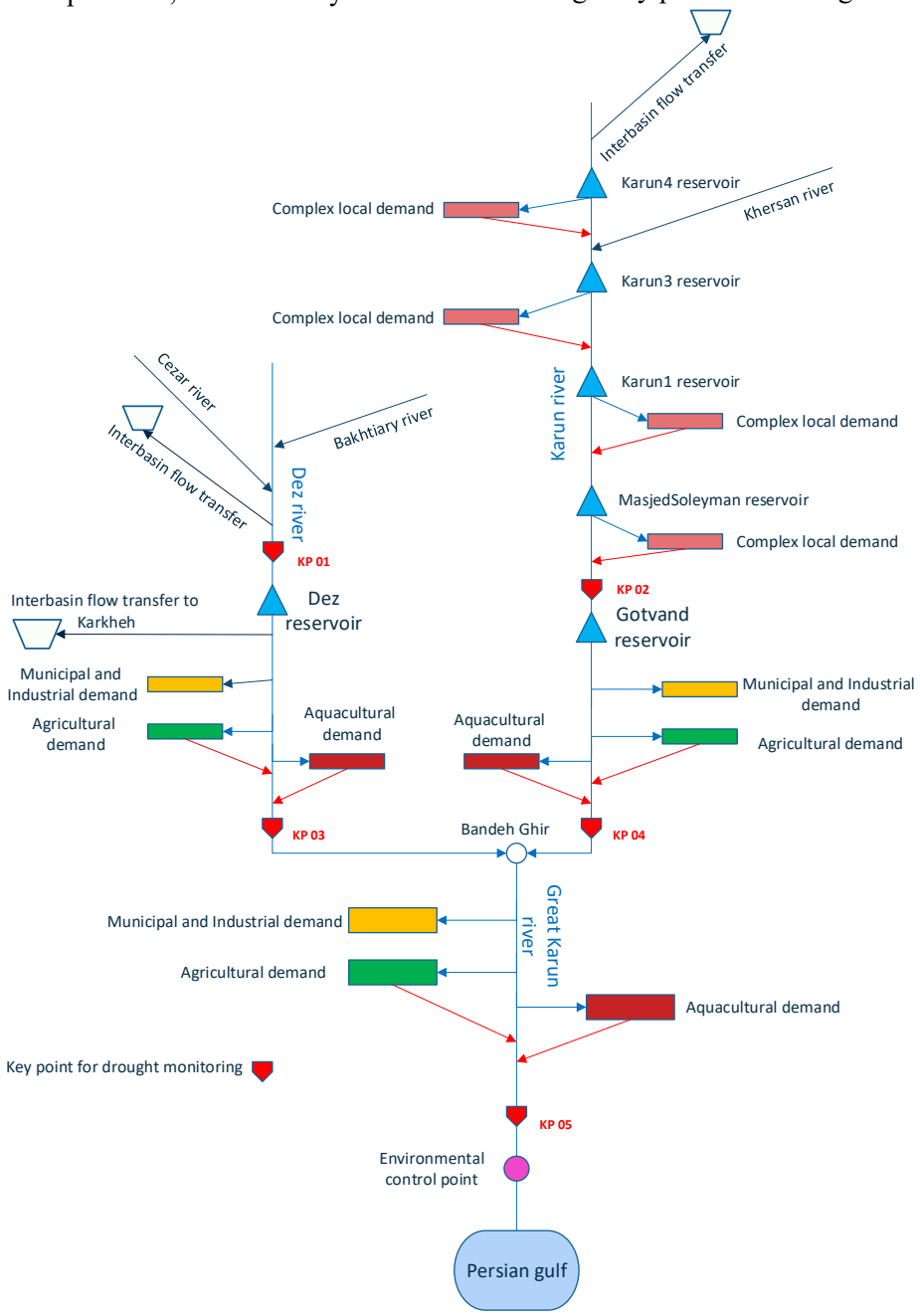


Figure 1. Schematic diagram of the investigated system

Karun rivers. Additionally, tributary rivers such as Khersan, Cesar, and Bakhtiari contribute to the flow into these two main rivers. The system serves various purposes, including drinking-urban supply, agriculture-industry, aquaculture, environmental conservation, and water transfer [3]. The average annual water discharge in the Great Karun basin amounts to 20.4 billion cubic meters, representing approximately 20% of Iran's total surface water resources. However, the current annual water demand in the region exceeds this, reaching 24.9 billion cubic meters. The vast irrigated agricultural area—spanning more than 755,500 hectares—makes the Great Karun basin a crucial food producer for Iran. Presently, the multi-reservoir system has a total storage capacity of 18.5 billion cubic meters. Figure 1, shows the investigated Schematic diagram of the Great Karun water resources system in our study.

3. The proposed methodology

In this research, we utilize the Particle Swarm Optimization (PSO) algorithm to optimize the operating rule curves in a multi-reservoir system. PSO algorithm and the simulation models were implemented in the Visual Basic for Applications (VBA) programming environment. Leveraging various operating strategies can lead to mitigating drought effects based on basin characteristics [31]. Our objective is to minimize the square of relative deficiencies. In this context, various indices have been recently proposed and evaluated [32]. While more complex indices offer greater capabilities, they require additional information for accurate calculation and introduce increased uncertainty, especially when data is scarce. In our research, we have chosen a well-known water shortage index, WSI [33, 34], as the objective function to determine the optimal rule curves. To achieve the optimum performance of the system, we connect the PSO algorithm to a system simulator based on standard operating policies (SOP) and discrete two-level hedging policies. Under the discrete hedging policy, the reservoir volume is divided into three regions using two different rule curves [35]. When the reservoir volume is in the first area (above the two hedging levels), all demands are met. In the second area (between the two levels), mild hedging begins for lower-priority demands. For instance, upstream reservoirs (such as Karun 4, Karun 3, Karun 1, and Masjed Soleyman) experience slight shortages in meeting hydropower generation demand. Downstream of Gotvand Dam, agriculture, industry, aquaculture, and transfer to Karkheh are also hedged. Finally, when the reservoir volume plus inflow falls below the two rationing levels (the lowest area), severe rationing is applied. All demands except Drinking demand, are significantly limited, and four fixed rationing coefficients (two for hydropower generation and two for downstream demands) are defined.

The combined simulation-optimization model searches for optimal hedging levels across all reservoirs and months. We separately code a simulation model based on standard operating policies (SOP). By comparing the output results of this simulator with those of the combined simulation-optimization model, we assess the impact of the hedging policy. Within the hedging model, three constraints elucidate the operational rules of the model:

$$R_t = S_t + In_t \quad \text{if} \quad S_t + In_t \le D_t \tag{1}$$

$$R_t = D_t \quad \text{if} \quad D_t \le S_t + In_t \le D_t + S_{max} \tag{2}$$

$$R_t = S_t + In_t - S_{max} \quad \text{if} \quad S_t + In_t \ge D_t + S_{max} \tag{3}$$

Here, R_t represents the reservoir outflow in time step t, In_t denotes the reservoir inflow in period t, (S_t) represents the storage volume at the beginning of period t, D_t corresponds to the demand amount in period t, and S_{max} represents the maximum

capacity of the reservoir storage volume. Under the standard operation policy, the frequency of water shortages in the water resources system is typically lower during this period. However, this approach does not provide control over the severity of the shortages. This method is approximately optimal whenever there is sufficient water to meet the planned demands [36].

The objective function in this research is accounted for by the following equation. In fact, the optimization model seeks the minimum of the sum-of-squares values of relative deficiencies of all system demands:

$$Objective\ Function = \sum_{i=1}^{N}\sum_{j=1}^{J}\sum_{t=1}^{T}\left(\frac{R_{j,i,t} - D_{j,i,t}}{D_{j,i,t}}\right)^2 \quad (4)$$

Where, $D_{j,i,t}$ represents the amount of the *j*th demand downstream of the *i*th reservoir during the period *t*, $R_{j,i,t}$ denotes the released flow for supplying the *j*th demand from the *i*th reservoir during the period *t*, The indices *T*, *J*, and *N* correspond, respectively, to the total number of demand sites downstream of each reservoir, the total length of the time steps, and the number of reservoirs throughout the multi-reservoir system. The decision variables in this research are the threshold volumes in all reservoirs and the different phases of rationing for each month.

The constraints in the reservoir operation problem are divided into primary and secondary constraints [7]. The primary constraints must be applied in all models, while the secondary constraints are defined according to the type of problem and the handling of the system. The first and most important constraint in reservoir operation is the mass balance equation. Other primary constraints include the upper and lower limits for the variables of reservoir storage volume and release. The secondary constraints, which depend on the type of problem, can include factors such as the average long-term shortage and the maximum and minimum values of production in hydropower plants. The main equations for reservoir simulation models are as follows:

$$S_{i,t+1} = S_{i,t} + Q_{i,t} - R_{i,t} - Spill_{i,t} - loss_{i,t} \quad (5)$$

$$S_{i,min} \leq S_{i,t+1} \leq S_{i,max} \quad (6)$$

$$S_1 = S_{T+1} \quad (7)$$

$$R_{i,min} \leq R_{i,t} \leq R_{i,max} \quad (8)$$

$$S_{i,t}, Q_{i,t}, R_{i,t}, Spill_{i,t} \geq 0 \quad (9)$$

In the above equations, $S_{i,t}$ represents the storage volume of the *i*th reservoir in month *t*, $Q_{i,t}$ is the volume of water entering the *i*th reservoir in month *t*, $R_{i,t}$ is the release flow from the *i*th reservoir in month t, $Spill_{i,t}$ is the amount of spilled water from the *i*th reservoir in month t, and $loss_{i,t}$ includes evaporation, drainage, and leakage from the *i*th reservoir in month *t*. In this study, to reduce the volume of calculations and accept a certain error margin, evaporation and other reservoir losses are omitted. Additionally, $S_{i,min}$ is the minimum storage volume of the *i*th reservoir, $S_{i,max}$ is the maximum storage volume of the *i*th reservoir, S_1 is the storage volume of the reservoir at the beginning of the simulation period, and S_{T+1} is the storage volume of the reservoir at the end of the simulation period (where *T* being the length of the simulation period). For the reservoir release, limits must be set to ensure the minimum amount of water entering the downstream area to control water quality, maintain the survival of living organisms and fish, and protect the downstream area from flooding risks [7]. Here, $R_{i,max}$ is the maximum release flow from the *i*th reservoir, and $S_{i,min}$ is the minimum release flow from the *i*th reservoir. The upper and lower limits of the reservoir storage volume must ensure the maximum volume for flood control and the minimum level for dead storage and power plant operation. Additionally, the

reservoir's storage volume at the beginning and end of the operation period should be the same. To ensure feasible solutions, the values of the reservoir storage volume, release flow, inlet, and overflow should always be greater than or equal to zero.

In this research, a simulation model has been coded separately based on the Standard Operating Policy (SOP) in the VBA (Visual Basic for Applications) environment. The studied system is simulated using this policy as a baseline to investigate the performance of other policies. The results of the combined simulation-hedging optimization model are compared with the output of this SOP policy simulator as a baseline. According to the SOP, the release from the reservoir is based solely on the demand of the same period. If there is enough water to meet the demand, the reservoir output is adjusted to satisfy the total demand. If there is insufficient water to meet the demand, the entire available water is released. Additionally, if the available water exceeds the demand, the reservoir starts to fill, and if necessary, the excess water is overflowed [37]. The mathematical representation of this operating policy is as follows:

$$R_t = S_t + In_t \quad \text{if} \quad S_t + In_t \le D_t \tag{10}$$

$$R_t = D_t \quad \text{if} \quad D_t \le S_t + In_t \le D_t + S_{max} \tag{11}$$

$$R_t = S_t + In_t - S_{max} \quad \text{if} \quad S_t + In_t \ge D_t + S_{max} \tag{12}$$

Finally, the flow series passing through key points throughout the basin, based on both hedging and Standard Operating Policies (SOP), is introduced into the drought model. The model calculates the flow drought index for each of these points. Subsequently, we investigate the impact of the operation policy under each of these two policies on the index results at different key points.

The research methodology of this study is outlined in a general flowchart, as depicted in Figure 2.

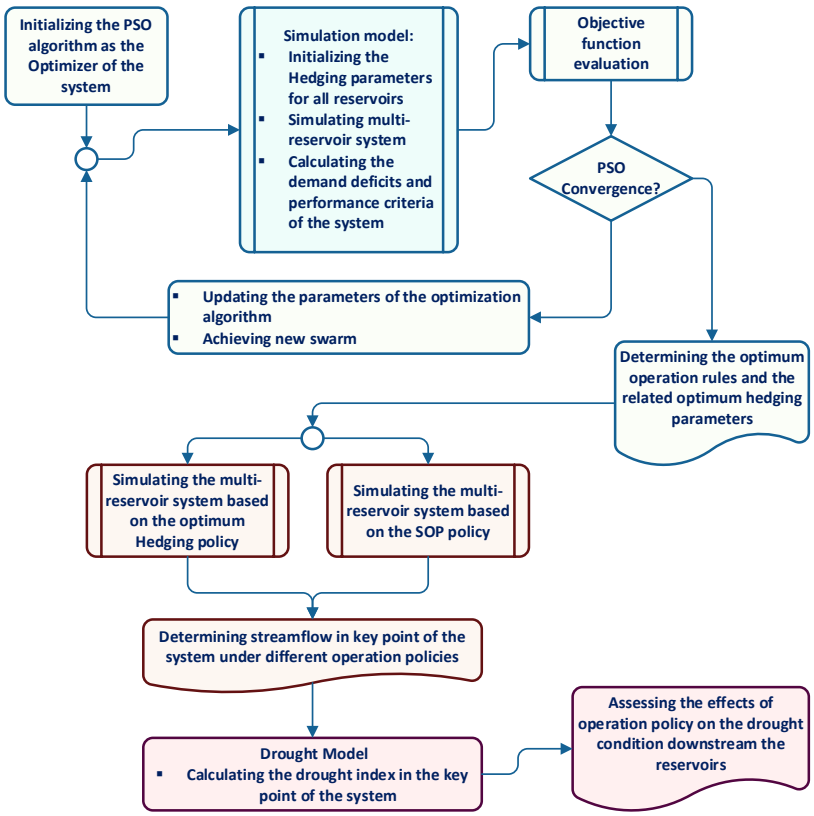


Figure 2. Flowchart of the proposed methodology

Many drought indices have been developed to describe and evaluate drought characteristics such as severity, duration, and temporal extent for each type of drought [19]. Based on the desired drought criteria, the intensity and duration of drought are expressed with an index. An index consolidates various meteorological and hydrological parameters, such as rainfall, temperature, evapotranspiration, runoff, and other indicators of water supply, into a single format or formula, providing a comprehensive tool for decision-making. These indicators are usually expressed as a single number to maximize the use of raw data, enhance comprehensibility, and empower designers and planners in their decision-making processes [38].

Hydrological drought indices such as the Palmer PHDSI index [39], SWSI surface water storage index [40], SDI surface flow drought index [41, 42], SRI standard runoff index [43], and SSI standard surface flow index [44] are among the most common tools for determining the characteristics of hydrological drought. The Palmer index and surface water storage index have received less attention due to their complexity and the extensive calculations they require. Therefore, an index similar to the SPI standardized precipitation index, called the SDI surface flow drought index, can be used. This index, based on the average monthly flow, was first proposed by Benzoy [41]. The calculation principles of the SDI index are the same as those of the SPI index. In this research, the SDI index has been used to investigate hydrological drought. The drought control points are specified in Figure 1 as the *control points for drought monitoring*. The predetermined Control points, such as KP05, were chosen based on their strategic locations downstream of key reservoirs and major river confluences, allowing for effective monitoring of cumulative hydrological impacts and drought propagation throughout the basin. These points represent critical nodes for water allocation, operational decision-making, and assessing downstream drought severity, ensuring the results directly inform practical management and policy interventions.

To calculate the drought index of the streamflow, the drought index calculation software such as DrinC can be applied, but due to the impossibility of connecting this software to the programming code and also the slowing down of the simulation and optimization process, the calculations related to the SDI index was coded in the VBA programming environment as a drought model. After simulating and optimizing the system, the output results are given to the drought model to calculate the drought index according to these flow outputs. After extracting the outflow data on a monthly scale during a statistical period (preferably 30 years or more), it is necessary to form a time series on a desired scale. Then a suitable statistical distribution is fitted to the time series of flow values. Log normal distribution is considered to fit the time series.

If the monthly time series of flow volumes $Q_{i,j}$ are available, the cumulative flow volume $V_{i,\mathrm{k}}$ can be obtained. Here, i and j stands for the water year and month respectively.

$$V_{i,\mathrm{k}} = \sum_{j=1}^{3k} Q_{i,j} \quad i = 1,2,\dots \quad j = 1,2,\dots,12 \quad k = 1,2,3,4 \tag{13}$$

The SDI data for analysis should ideally follow a normal or log-normal distribution. In small watersheds, flows may exhibit a probability distribution with skewness, similar to the gamma distribution. To address this, the distribution is transformed to a normal distribution [42]. Consequently, the surface flow drought index is calculated for the reference period k of the ith year, based on the log-normal distribution.

In the following formulas, the two-parameter lognormal distribution is utilized

for transformation. The natural logarithms of the cumulative flow data, with mean $\overline{y_K}$ and standard deviation $S_{y,k}$, are taken into account.

$$SDI_{i,k} = \frac{y_{i,k} - \overline{y_K}}{S_{y,k}} \qquad i = 1,2,\dots \qquad k = 1,2,3,4 \tag{14}$$

$$y_{i,k} = \ln(V_{i,k}) \qquad i = 1,2,\dots \qquad k = 1,2,3,4 \tag{15}$$

The drought status of a region is determined by comparing the calculated value of this index with the classification presented in Table 1.

Table 1. Drought classification according to the SDI values [45]

SDI value	Drought status
$SDI > 0$	Non-drought
$-1 < SDI < 0$	Mild drought
$-1.5 < SDI < -1$	Moderate drought
$-2 < SDI \leq -1.5$	Severe drought
$SDI \leq -2$	Extreme drought

4. Results

In the optimization process, the monthly hedging levels in the reservoirs serve as decision variables for the problem. Modeling occurs on a monthly basis, considering two levels of rationing in each reservoir. All simulation and optimization codes were developed and executed in VBA within the Microsoft Excel environment. In this study, rationing coefficients, based on the common operational standards, are fixed for meeting demands at each level. Consequently, the total number of decision variables equals 144—representing the thresholds for monthly rationing across all system reservoirs. Repeated model executions revealed that achieving better results requires a particle count in the algorithm at least twice the number of decision variables. In this study, the model employed 576 particles. Initially, a larger population significantly improved convergence speed. Given the problem's complexity and variable count, the algorithm was iterated 5000 times to reach convergence. Optimal levels are determined as upper (target level) and lower limits (firm level) based on the maximum and minimum volumes of Dez, Gotvand, Karun 4, Karun 3, Karun 1, and Masjed Soleyman reservoirs.

4.1. System simulation results based on SOP and optimal hedging policies

In order to evaluate the system's performance under the two policies of optimal hedging and SOP policies, we use the objective function of the relative shortage index and performance criteria such as reliability, quantitative reliability, maximum vulnerability, and average vulnerability. These results demonstrate the long-term system performance from 1955-56 to 2014-15, as well as its behavior during the last 10-year drought period from 2005-06 to 2014-15.

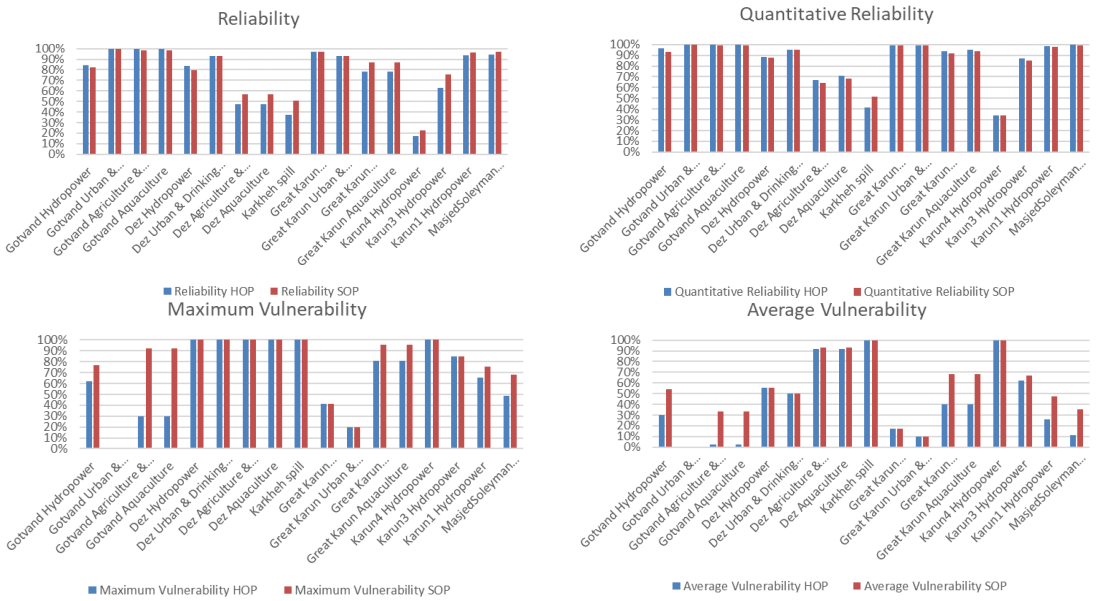


Figure 3. Comparison of reservoir performance under different exploitation policies: Left Side: Dez Reservoir, Right Side: Gotvand Reservoir, First Row:

Figure 3, represents the comparative chart bars for performance criteria of SOP, and optimum HOP. The analysis of the Dez and Gotvand reservoirs reveals critical insights into the impact of multi-reservoir rationing on downstream water management. Gotvand exhibited high reliability across all sectors, consistently achieving near or full satisfaction of water demands under both HOP and SOP scenarios. Conversely, Dez experienced lower reliability, particularly in agriculture and aquaculture, where demand satisfaction rates fell below 70%. Quantitative reliability reinforced these trends, with Gotvand maintaining strong performance across sectors, while Dez struggled, especially in agriculture and aquaculture. Vulnerability analysis highlighted significant challenges for Dez, with maximum and average vulnerabilities in agricultural and aquaculture sectors exceeding 91% in both scenarios, underscoring the high risk of unmet demands. In contrast, Gotvand showed relatively low vulnerabilities, particularly in urban and drinking water supplies, which remained stable and minimally impacted. Overall, the findings emphasize the differential performance of these reservoirs under rationing scenarios, highlighting the need for targeted strategies to address vulnerabilities, especially for the more affected sectors like agriculture and aquaculture in the Dez system. As illustrated in Figure 3, the Gotvand Reservoir consistently achieves high reliability in meeting water demands across all sectors under both SOP and hedging policies, whereas the Dez Reservoir struggles particularly in agricultural and aquaculture sectors, with demand satisfaction rates falling below 70%. This underscores the greater vulnerability of Dez to shortages even under optimized operation.

Comparative results for all reservoirs within the system are presented, with a focus on the Dez and Gotvand reservoirs (see Figure 4). Notably, both hedging and SOP models exhibit similar effects on the storage volume of the Dez reservoir. However, in specific months, the hedging policy leads to higher storage volumes than SOP. This difference is particularly evident in 1988 and 1990. Interestingly, the hydropower production remains nearly the same between the two models. The output flow from the Dez reservoir also reflects similar behavior under optimum hedging and SOP policies. In the Gotvand Reservoir, except for the early years of the last 10-year period, where both policies yield similar storage volumes, the years 2007 to 2014 reveal a clear difference.

The hedging policy conserves more water during these years, resulting in increased hydropower generation compared to SOP. Furthermore, when comparing the output flow from the Gotvand reservoir, the hedging policy consistently outperforms SOP in meeting water demands. This performance disparity extends to other reservoirs within the Karun cascade.

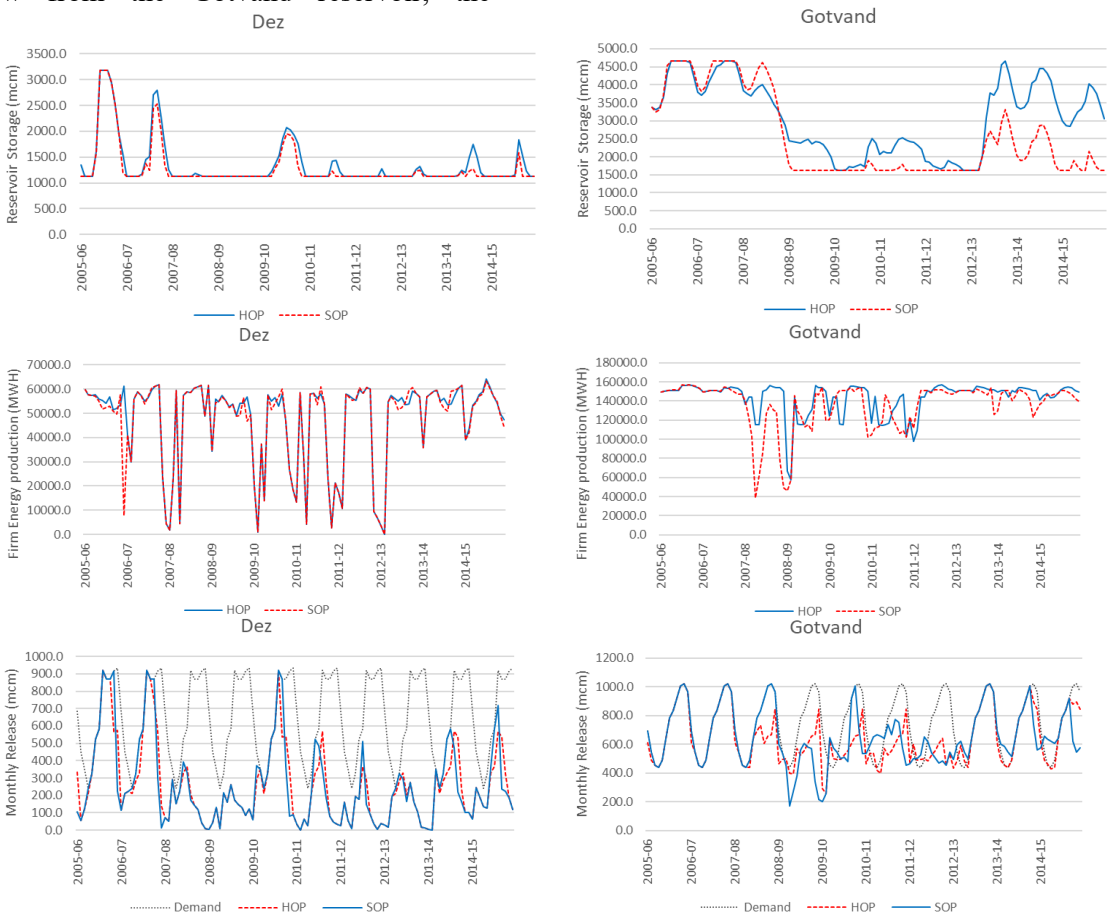


Figure 4. Comparison of reservoir performance under different exploitation policies: Left Side: Dez Reservoir, Right Side: Gotvand Reservoir, First Row: Storage volume of reservoirs, Second Row: Produced hydropower energy, Third Row: Output flow to meet demands

Figure 4 reveals that while storage volumes and outflows for the Dez Reservoir remain similar under both policies, the hedging policy occasionally maintains higher storage in critical months. For Gotvand, the hedging approach provides notably improved storage and outflows during drought years, resulting in increased hydropower production relative to SOP.

4.2. Results of drought assessment model

A comprehensive comparative study was conducted for all control points within the system. To succinctly summarize the results, we focus on the last control point in the system (*KP05*, in figure 1). We calculated the SDI (Streamflow Drought Index) series for the monthly flow passing through the *KP05* control point. Subsequently, we investigated the impact of reservoir management under both SOP policies and optimal hedging policy on the drought index series. The statistical characteristics of hydrological droughts at *KP05* over a 60-year period (1955-2015) were extracted and are presented in details in Table 2.

Table 2. Drought status for KP05, based on SOP and hedging policies

	SOP (months)	Hedging Policy (months)
Mild drought	196	123
Moderate drought	34	31
Severe drought	39	90
Extreme drought	34	22

Table 2 demonstrates that the number of extreme and severe drought months at KP05 is reduced under the hedging policy, even though the duration of severe droughts may be longer, indicating a trade-off between drought intensity and frequency. Based on the results from Table 2, we observe that under the SOP policy, a very severe drought persisted for 34 months. However, this duration decreased to 22 months when implementing the optimal hedging policy. Specifically, the SOP policy resulted in more months falling within the severe drought category compared to the optimal hedging policy. Additionally, when considering mild droughts, there were 196 months classified as mild droughts under the SOP policy, whereas the optimal rationing policy had 123 months falling into this category. Table 3, summarizes the drought characteristics for *KP05* control point, under both SOP and hedging (HOP) policies.

Table 3. Calculated drought characteristics for *KP05*, based on SOP and hedging policies

Policy	ND	NE	Max DD	Mean DD	P	S_{ave}	S_{Max}
SOP	303	39	34	7	5.13	0.9	46.92
Hedging	266	27	39	9	3.64	1.08	56.52

As summarized in Table 3, the total number of drought months and the number of drought events decrease when the hedging policy is applied, but the average duration and severity of individual drought events increase slightly. This suggests that the hedging policy consolidates drought occurrences, resulting in fewer yet longer events. In this table ND is the number of total months of drought, DE is the number of observed drought events, Max DD is the maximum duration of the observed drought events (months), Mean DD is the average of the observed drought events (months). The peak of drought (P) is another studied characteristic that is considered to be the maximum absolute value of the SDI below the threshold level for the occurrence of drought. Another characteristic estimated in this study for drought is the drought severity (S), which is by definition the cumulative absolute value of the dimensionless SDI during a continuous drought event. The average value (S_{ave}) and the maximum value (S_{Max}) of this parameter have been reported under two compared operating strategies. Based on the characteristics' values, the average intensity of drought periods at this point is nearly 20% higher under the optimal hedging policy compared to the SOP policy. When comparing drought intensities across the entire period and both policies, we find that the peak intensity occurs in the SOP policy. Rationing has extended the maximum duration of droughts to 39 months, whereas the SOP policy had a criterion of 34 months. The application of the hedging policy has led to greater intensity between drought periods than the SOP policy due to the increased duration of droughts. During the statistical period, there were 303 months of drought based on the SOP policy and 266 months based on the optimal rationing. These findings align with similar research conducted by Guo et al. [15]. Their findings indicated that implementing an optimal rule of operation for a multi-reservoir system in North China can effectively prevent severe shortages during drought periods. In contrast, another study conducted by Li et al. [14] concluded that the way reservoirs are utilized has minimal impact on exacerbating droughts downstream. Instead, the general trend of

hydrological droughts in downstream stations is primarily influenced by water conditions and natural weather changes, which are determined by variations in precipitation. The discrepancies in results may arise from differences in climatical and hydrological conditions across the studied areas. Additionally, Li et al. [14] investigated the impact of the presence or absence of a large single-reservoir system in the region but did not derive an optimal operating policy.

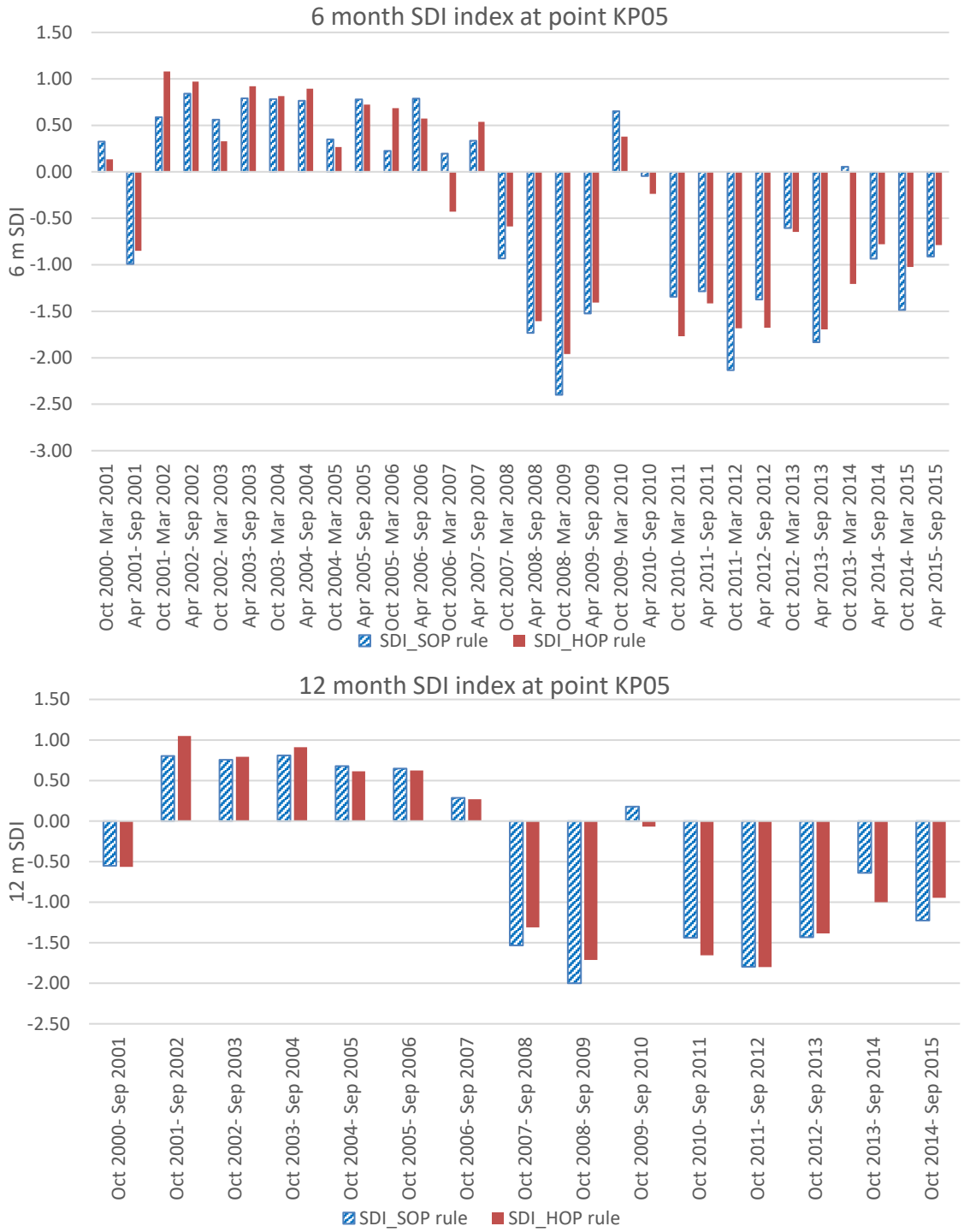


Figure 5. The impacts of operating policies on the SDI drought index downstream of the reservoirs across 6-, and 12-month scales

The graphs in Figure 5 illustrate the differences in the impacts of two policies—SOP and optimal rationing—on the SDI drought index at point KP05 (downstream of the reservoirs) across 6-, and 12-month scales. This distinction is particularly pronounced during the 2001-2015 period. The KP05, located downstream of Karun-e-Bozorg and after major tributary confluences, was chosen as it reflects the integrated effect of all upstream reservoir operations and basin inflows, making it an ideal reference for evaluating overall system performance under different management policies. The varying scales of the SDI time series at control point *KP05* reveal that, in wet years, the SOP policy lacked foresight for impending droughts. Consequently, the index under this policy often reflected normal conditions even in the years leading up to a drought. In contrast, during drought years, the index values under the SOP policy would abruptly turn negative, plunging the basin into a severe drought. On the other hand, the optimal rationing policy mitigated this effect by transitioning into the drought phase more gradually, thereby preventing acute shortages in the basin and averting severe drought conditions. Figure 5 clearly shows that SOP policy results in abrupt transitions to severe drought phases, as indicated by sharp drops in the SDI index, while the hedging policy cushions these impacts by enabling a more gradual entry into drought conditions, thus reducing the frequency of extreme events.

By comparing the results across all control points, it becomes clear that during severe water shortages in the basin, the application of the rationing policy not only fails to improve the system's condition but may even exacerbate the basin's challenges. This is particularly evident at *KP05*, located downstream of Karun-e-Bozorg. At this location, a comparison of the impacts of the two policies on drought conditions and an analysis of the calculated drought criteria indicate that, for most metrics, rationing has not alleviated drought conditions in the basin. In fact, it has worsened the situation during certain months. Conversely, at *KP04*, downstream of Gotvand, the differences in the effects of applying the two policies—rationing and SOP—on the system are striking. The impact of rationing on alleviating drought conditions downstream of Gotvand is particularly noteworthy.

Based on the series of SDI indices at different scales, the large fluctuations in this index values at shorter-term scales (1, 3, and 6 months) suggest that the impact of reservoir operations is limited. These fluctuations appear to be more strongly influenced by intra-annual rainfall. Although in certain months the differences between the two policies' effects on the basin are marginal, it can be inferred that, likely due to rainfall variability and its impact on streamflow, the basin exited the drought phase in some months, while experiencing very severe droughts in others. Consequently, the indices at these scales exhibit significant month-to-month variability. However, when considering the 12-month SDI scale, the influence of reservoir operations on hydrological drought becomes more evident.

The results of this study are generally consistent with recent research on multi-reservoir drought management. For example, Guo et al. [15] and Chang et al. [16] demonstrated the effectiveness of optimized hedging policies in reducing the risk of severe shortages during droughts in complex reservoir systems. Similarly, Khorshidi et al. [8] and Ahmadianfar & Zamani [22] found that employing advanced optimization and risk-based approaches can enhance the performance and resilience of water systems under drought conditions. However, some studies, such as Li et al. [14] and Wu et al. [21], emphasize that while reservoir operation policies can mitigate certain impacts, the underlying hydrological regime and precipitation variability remain dominant factors influencing downstream drought (see also [28, 33]). Notably, our finding that hedging policies can sometimes increase drought severity or duration at specific downstream locations—such as the

Dez basin—aligns with these broader insights, highlighting the need for context-specific strategies. Overall, this study adds nuance to the literature by demonstrating both the potential benefits and trade-offs associated with optimized reservoir operations in semi-arid basins.

It is worth noting that the presented modeling approach is subject to several limitations. First, the simulation and optimization framework assume perfect knowledge of reservoir inflows and does not explicitly incorporate hydrological or demand forecast uncertainties, which may affect real-world applicability. In addition, secondary processes such as evaporation losses and operational constraints related to water quality and ecosystem needs were simplified or omitted. The use of a two-level hedging policy, while practical, might not capture all the flexibility required for complex, multi-purpose water systems. Calibration of the PSO algorithm and choice of control points may also influence the generalizability of results across different basin configurations.

Future research could address these issues by integrating stochastic inflow forecasting, expanding the model to account for evaporation and ecological constraints, exploring multi-objective optimization with additional system performance metrics, and applying advanced or adaptive hedging strategies. Furthermore, extending the analysis to include socio-economic impacts or stakeholder-driven scenarios would enhance the practical value of reservoir operation policies in real-world water management contexts.

5. Summary and conclusion

In our research, the operating rule curves for a multi-reservoir system is optimized using the PSO algorithm. The primary objective is to minimize relative deficiencies in water supply. Two strategies are compared: SOP and discrete two-level hedging policy. The proposed approach is applied to a real-world case study, focusing on the Great Karun basin. By integrating the PSO algorithm with a system simulator, optimal hedging levels are searched across all reservoirs and months. Additionally, the impact of the hedging policy is assessed by comparing the output results of our combined simulation-optimization model with those of a SOP-based simulation. Furthermore, the flow drought index at key points throughout the basin is analyzed under both rationing and SOP policies. The results indicate that applying the hedging policy improves the system's ability to meet demands compared to the SOP policy. By accepting more shortage periods and storing water in reservoirs, the rationing policy reduces vulnerabilities and prevents severe shortages and system failures during water scarcity. Investigating the impact of SOP policies and rationing at downstream points of Dez and Gotvand reservoirs on the flow drought index reveals that hedging prevents high-intensity drought periods by increasing less severe drought occurrences. Moreover, while rationing reduces the average severity of droughts compared to the SOP policy, the SDI index results for the downstream of Dez reveal no improvement under the rationing policy. Considering the severe water shortage in the Dez basin, applying the rationing policy actually exacerbates drought conditions rather than improving them. This insight is crucial for system managers. These findings offer practical guidance for water resource managers and policymakers in semi-arid regions, highlighting the value of optimization-based reservoir operation strategies to enhance drought resilience and support more informed, adaptive decision-making for sustainable water allocation.

Funding Statement

This research was funded by Shahid Chamran University of Ahvaz, under the grant number **SCU.C1402.31254**. The authors are grateful for the financial support provided.

Conflict of Interest declaration

The authors declare that they have no conflict of interest.

AI using declaration

During the preparation of this manuscript the authors used Chat GPT for paraphrasing some sentences and enhancing the readability of the text. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Author contributions declaration:

The first idea of the research was proposed and polished by Seyed Mohammad Ashrafi, and Arash Adib. Data collection was done by Sama Banitamim, and Seyed Mohammad Ashrafi. Material preparation, model development, and result analysis were performed by Sama Banitamim under the supervision of Seyed Mohammad Ashrafi. The first draft of the manuscript was written by Sama Banitamim and has been edited by Seyed Mohammad Ashrafi, and Arash Adib, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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