



# Assessment of the hedging policy on reservoir operation for future drought conditions under climate change

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## Abstract

Reservoirs play a fundamental role in enhancing sustainable development and economic circumstances, especially in areas with limited water resources. Recently, experts in water resources management have been faced with global warming and climate change as two critical issues that are causing serious problems in water resources. Accordingly, the current study attempts to evaluate the future climate change impacts on agricultural reservoir operation. The results indicated an increase in mean long-term temperature, decreased reservoir's inflow, and an increase in the agricultural water requirement for the Jarreh reservoir system in southwestern Iran, during the period of 2025–2054, under the RCP 8.5 scenario. The results also showed a decrease in reliability (37%) and an increase in vulnerability (9%) using standard operation policy (SOP) under future climate conditions. Due to the predicted drought conditions for the study area, a two-dimensional hedging policy is proposed to mitigate the negative effects of climate change. The results of the hedging model indicated an improvement in the performance of indices in comparison with the use of SOP under climate change impacts. Generally, by using the hedging policy, decreased vulnerability (24%) and reduced maximum deficiencies (14%) are expected for future climate changes.

**Keywords** Climate change · Reservoir operation · Hedging policy · Agricultural water requirement · Drought conditions

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## 1 Introduction

Recently, climate change and global warming have become two international issues that affect various aspects of human life (e.g., economic, social, and lifestyle). In addition, the impact of these phenomena on elements of the hydrologic cycle, temperature, and other related climatic parameters, put pressure on water resources and water supply systems. On the other hand, according to the United Nations, rapid population growth has led to an increase in global demand for water, food, and energy in recent years, which may cause more pressure on water resources security than what climate change has observed (Vörösmarty et al. 2000). Therefore, an increase in demand for water along with the attempts to industrialize, develop, and expand sustainable agriculture to meet the growing need for food worldwide, can create difficulties in the long-term and mid-term plans of governments and organizations.

According to the above-mentioned problems, reservoirs play an important role in sustaining water resources management and, as a result, ensuring the development of economic, social, and food security (i.e., Yasarer and Sturm 2016; Chen et al. 2016). Reservoirs also have remarkable impacts on reducing the flood risk, storing flood waters, and maintaining the surface water allocation for different water users (Yüksel 2010). Hence, evaluating the performance of reservoirs under future climate changes is of the utmost importance in order to increase the reliability of water resources systems with the aim of sustainable development and supplying water for different sector demands. Under climate change circumstances, a deeper understanding of a reservoir's performance can contribute to creating adaptation scenarios for planning and managing the consequences of the positive and negative aspects of this issue. Ashofteh et al. (2015) and Zamani et al. (2017) studied the impact of climate changes on reservoirs' vulnerability in recent years.

Karamouz et al. (2012) developed a probability scheme for reservoir operation during drought periods using the hedging rule under climate change. They showed that the proposed probabilistic framework led to less water shortage and mitigated the drought damage. Georgakakos et al. (2012) investigated the value of adaptation in reservoir management under climate change impacts in the water resources system of northern California. They stated that a reservoir managed with the present condition is not capable of presenting a satisfying performance under climate change conditions. Furthermore, it was suggested that the adaptive management of the reservoir can reduce the effects of climate changes. Alvarez et al. (2014) investigated adaptation scenarios to climate changes on three reservoir operations in Lièvre River basin, Quebec, Canada. They used adjustments of current reservoir operation rules as the adaptation strategies in order to reduce the flooding in the basin. The results for the future period (2041–2070) showed an increase in water storage in the Lièvre River basin as well as a reduced risk of flooding in the Montreal Archipelago basin. From their study, they concluded that there was a decrease in reliability and an increase in vulnerability for the reservoir under future climate change conditions. Moreover, the reduction of inter-annual variability of reservoir water level influenced by climate change has been reported as another result of applying adaptation in the study area.

Vonk et al. (2014) studied the adaptability of operating several reservoirs systems under climate change conditions by considering the changes of demand and supply for the future period (2011–2040) in the water resources system located in Xinanjiang-Fuchunjiang reservoir cascade, Hangzhou, China. In Vonk et al.'s (2014) investigation, the compatibility of scenarios was simulated using the water evaluation and planning (WEAP) system and were optimized by the non-dominated sorting genetic algorithm II (NSGA-II). The

results showed an increase of 6.4% in mean annual energy production index and a reduction of 84% in the shortage index due to applying adapted operating rules. Adeloye et al. (2016) appraised the impacts of the hedging rule on the performance of the Pong reservoir in India under climate change conditions. They showed that the hedging policy can effectively reduce the impacts of water deficit caused by climate change conditions. Furthermore, Mateus and Tullos (2017) evaluated the sensitivity, reliability, and vulnerability of reservoirs in the Santiam River basin in Oregon, USA, under climate change conditions. The results of their study indicated a reduction in the reliability of a summer stream entering the reservoir under the effects of climate change. Also, increased sensitivity in using groundwater and its impact on the operation of reservoirs has been reported. Ultimately, a modified rule curve was recommended to reduce the negative effects of climate change, especially in the reduction of summer reliability.

Along with studying the effects of climate change on the reservoirs performance, determining appropriate policy rules that are compatible with the future climate conditions is of great importance in water planning and management. In this regard, the standard operating policy (SOP) is introduced as a simple rule for reservoir operation systems (i.e., Maass et al. 1962; Loucks et al. 1981). One of the major disadvantages of this policy is the lack of saving water and extreme shortages when the reservoir experiences drought events. Hence, a suitable reservoir operating rule during drought periods has a substantial influence on mitigating drought impacts (Ahmadianfar et al. 2016). A widely used policy, applied to save water for the normal periods and use it in the drought periods, is introduced as the hedging rule. Shih and Revelle (1994) introduced a continuous hedging rule to minimize the maximum shortage by assuming a constant demand. Srinivasan and Philipose (1996) employed the parameters of hedging so as to develop the hedging rule and to verify its efficacy on the performance indices of the reservoir. Neelakantan and Pundarikanthan (2000) implemented an integrated numerical technique utilizing artificial neural networks (ANNs) and the hedging rule in order to efficiently evaluate performance of the reservoir systems. Tu et al. (Tu et al. 2003; Tu et al. 2008) presented a set of reservoir rule curves based on the current storage level in order to start hedging for a multi-reservoir operation system. Shiau (2009) suggested a different type of hedging rule with three parameters, namely, a hedging factor, starting water availability, and ending water availability.

Over the past decade, researchers have applied a type of hedging rule called the “two-point” hedging rule. Celeste and Billib (2009) presented a two-dimensional (2-D) hedging rule and compared its performance with the two-point hedging rule so as to operate a reservoir system in northeastern Brazil under 20 various inflow scenarios. Their results indicated a satisfying performance of the two-dimensional hedging rule. With respect to the reported effective performance of this type of hedging rule, it should be considered that to date, no research has been reported that explores the application of a two-dimensional hedging rule to optimize reservoir systems under climate change.

The main purpose of this research is to evaluate the effects of this type of hedging policy on the rule curve of a reservoir in order to allocate the agricultural water requirements under the impacts of climate change. In this study, Jarreh reservoir, located in southwestern Iran, has been selected as a case study.

The summary objectives of this study are: (i) studying the effect of climate change on inflow to the reservoir, (ii) investigating the effect of climate change on

agricultural water requirements, (iii) extracting a basic rule curve under climate change conditions, (iv) extracting the optimized basic rule curve by applying the hedging policy under climate change conditions, and finally, (v) extracting the indices for assessing the reservoir performance and investigating the effect of applying hedging under climate change impacts.

## 2 Methodology

The stages of conducting this study can be divided into two generalized parts, including (i) projection of climate change impacts on water resource systems and (ii) reservoir simulation and optimization. More details on each of these segment are described following.

### 2.1 Projection of climate change impacts on water resource systems

#### 2.1.1 Climate change projection

In the present study, in order to produce climate scenarios, three models, namely, CSIRO-Mk3.6.0 (Rotstayn et al. 2012), MIROC-ESM (Watanabe et al. 2011), and GFDL-ESM2M (Dunne et al. 2012) derived from the fifth assessment report (AR5) of the intergovernmental panel on climate change (IPCC), were used. Daily minimum and maximum temperature and precipitation data of these three models were obtained from the NASA earth exchange global daily downscaled projections (NEX-GDDP), and bias correction was conducted on them. More details about climatic data used in this study can be found in Thrasher and Nemani (Thrasher and Nemani 2012). In order to reduce the uncertainty caused by the usage of GCMs and to better understand the range of possible climate variations, the outputs of three climatic models have been combined under the RCP 8.5 scenario. This scenario, as one of the set of representative concentration pathways (RCPs), assumes a continuous increase in greenhouse gas emissions throughout the twenty-first century (Riahi et al. 2011).

In the first step, monthly climatic variables (temperature and precipitation) are extracted from GCM's output for the future period (2025–2054) and base period (1976–2005). Then, the difference of long-term monthly mean temperature and the ratio of long-term monthly mean precipitation are calculated based on:

$$\Delta T_i = \left( \bar{T}_{GCM, fut_i} - \bar{T}_{GCM, base_i} \right) \quad (1)$$

$$\Delta P_i = \left( \frac{\bar{P}_{GCM, fut_i}}{\bar{P}_{GCM, base_i}} \right). \quad (2)$$

In the following, to give weight to each of the three climatic models, Eq. (3) is employed. According to this, each model that is able to better simulate climatic variables in the base period (1976–2005), also has a higher weight. Afterward, the combined output made based on Eq. (4) is calculated using the weights and monthly climate variables' changes from three climatic models each month.

$$w_{ij} = \frac{\left(\frac{1}{\Delta d_{ij}}\right)}{\sum_{j=1}^3 \left(\frac{1}{\Delta d_{ij}}\right)} \quad (3)$$

$$\overline{\Delta X}_i = \sum_{j=1}^3 (w_{ij} \times \Delta x_{ij}) \quad (4)$$

where  $w_{ij}$  is the weight of GCM  $j$  in month  $i$ ,  $\Delta d_{ij}$  is the difference among mean climate variables (temperature or precipitation) simulated by GCM  $j$  in month  $i$ ,  $\Delta x$  is the monthly climate variables' changes (temperature or precipitation) given by GCM  $j$  in month  $t$ , and  $\overline{\Delta X}_i$  is the combined mean monthly climate variables' changes (temperature or precipitation) in month  $i$ . Finally, combined monthly values entered into the LARS-WG model (Barrow and Semenov 1995) as climate scenarios and a 30-year series of climatic variables have been obtained for the period of 2025–2054.

### 2.1.2 Rainfall runoff processing

HACRES (Jakeman and Hornberger Jakeman and dan Hornberger 1993), as a lumped conceptual model, is used to simulate the rainfall-runoff process. This model is based on unit hydrograph principles and composed of a nonlinear loss module followed by a linear module. The nonlinear module converts rainfall into effective rainfall and following the linear module routes the effective rainfall to streamflow. In this study, after calibrating and validating the model, the reservoir's inflow was generated for the future period (2025–2054) based on generated temperature and precipitation time series.

### 2.1.3 Calculation of agricultural water demand

The main purpose of the construction of the Jarreh reservoir is to provide the agricultural water requirements of the Ramhormuz plain; thus, it is necessary to assess the climate change impacts on crop water requirements. For this purpose, the Food and Agriculture Organization (FAO) Penman–Monteith method (Allen et al. 1998) and the FAO-24 methodology (Doorenboos and Pruitt Doorenboos and Pruitt 1977) have been used to calculate the reference and crop evapotranspiration. Also, the soil conservations (SCS) method by CROPWAT (Smith 1992) was employed to compute the effective precipitation. In the following, the net water requirement (NWR) and water demand volume (WDV) were obtained based on:

$$NWR_{t,j} = \max(ET_{c,t,j} - PE_{eff,t}, 0) \quad (5)$$

$$WDV_{t,j} = \left(\frac{NWR_{t,j} \times A_j}{100000}\right). \quad (6)$$

## 2.2 Reservoir simulation and optimization

### 2.2.1 Reservoir operation model

First, to assess the climate change impacts on the performance of the Jarreh reservoir, the SOP rule approach is applied to operate the reservoir in the baseline and future periods. In the following, a 2-D hedging rule is used for future periods to assess the performance of the reservoir operation under climate change conditions. For this purpose, in order to minimize the sum of squared shortages of agricultural water supply, an objective function has been used as follows:

$$Z = \sum_{t=1}^T \left( \frac{D_t - R_t}{D_{\max}} \right)^2 \quad \text{for } t = 1, 2, \dots, T \tag{7}$$

where  $Z$  is the objective function,  $t$  is the number of operation periods,  $R_t$  is the reservoir release at period  $t$ ,  $D_t$  is the agricultural water demand,  $D_{\max}$  is the maximum agricultural demand, and  $T$  is the total number of operation periods.

Moreover, the continuity equation is applied to evaluate the operation of reservoir systems. In fact, this equation implements the water balance during each operation period based on:

$$S_{t+1} = S_t + Q_t - R_t - Sp_t - E_t \quad \text{for } t = 1, 2, \dots, T \tag{8}$$

where  $S_t$  and  $S_{t+1}$  are the storage volumes at period  $t$  and  $t + 1$ , respectively.  $Q_t$  is the inflow to reservoir,  $E_t$  is the evaporation volume, and  $Sp_t$  is the volume of overflow water from reservoir. In order to calculate the  $Sp_t$  and  $E_t$ , the following equations are considered:

$$Sp_t = \begin{cases} S_{t+1} - S_{\max} & \text{if } S_{t+1} > S_{\max} \\ 0 & \text{otherwise} \end{cases} \quad \text{for } t = 1, 2, \dots, T \tag{9}$$

$$E_t = e_t \times \bar{A}_t \quad \text{for } t = 1, 2, \dots, T \tag{10}$$

$$\bar{A}_t = \frac{A_t + A_{t+1}}{2} \quad \text{for } t = 1, 2, \dots, T \tag{11}$$

$$A_t = -1.74 \times 10^{-5} \times S_t^2 + 3.29 \times 10^{-2} \times S_t + 0.366 \tag{12}$$

where  $S_{\max}$  is the maximum volume of storage,  $S_{\min}$  is the minimum volume of storage,  $e_t$  is the depth of evaporation at time period  $t$ , and  $\bar{A}_t$  is the average area of reservoir.  $A_t$  and  $A_{t+1}$  are area of reservoir at period  $t$  and  $t + 1$ , respectively.

In addition, there are constraints on reservoir release and reservoir storage based on:

$$S_{\min} \leq S_t \leq S_{\max} \quad \text{for } t = 1, 2, \dots, T \tag{13}$$

$$R_{\min} \leq R_t \leq R_{\max} \quad \text{for } t = 1, 2, \dots, T \tag{14}$$

### 2.2.2 Hedging policy

Hedging rule policy helps the reservoir systems to accept a small amount of water shortage in the current period and to decrease the water-shortage risk for future consumptions (Draper and Lund 2004). Various types of hedging rules have been successfully employed to appraise the operation of reservoir systems. Shih and Reville (1994, 1995) introduced a continuous hedging rule and afterward a discrete hedging rule. Later, Shiau and Lee (2005) presented two types of hedging rules. The first type of hedging rule employs water availability (storage plus inflow) and the second hedging rule relies on the potential deficit conditions during a particular future lead-time period. Celeste and Billib (2009) introduced a two-dimensional hedging rule for reservoir operation systems and showed this hedging rule has a better performance compared with the two-point hedging rule.

In the current research, the 2-D hedging rule is applied to improve the reservoir operation policy. This model employs a policy which is capable of generating a two-dimensional correlation of storage, release, and inflow as shown in Fig. (1) (Celeste and Billib 2009). According to this rule, the hedging policy applies when the combination of active storage and inflow ( $\sqrt{(S_t - S_{\min})^2 + Q_t^2}$ ) stands at the lower value of the hedging parameter ( $hdg_\tau$ ). To put it another way, the volume of water released from the reservoir is lower than what actually can be released from the reservoir. The rule implements hedging base on:

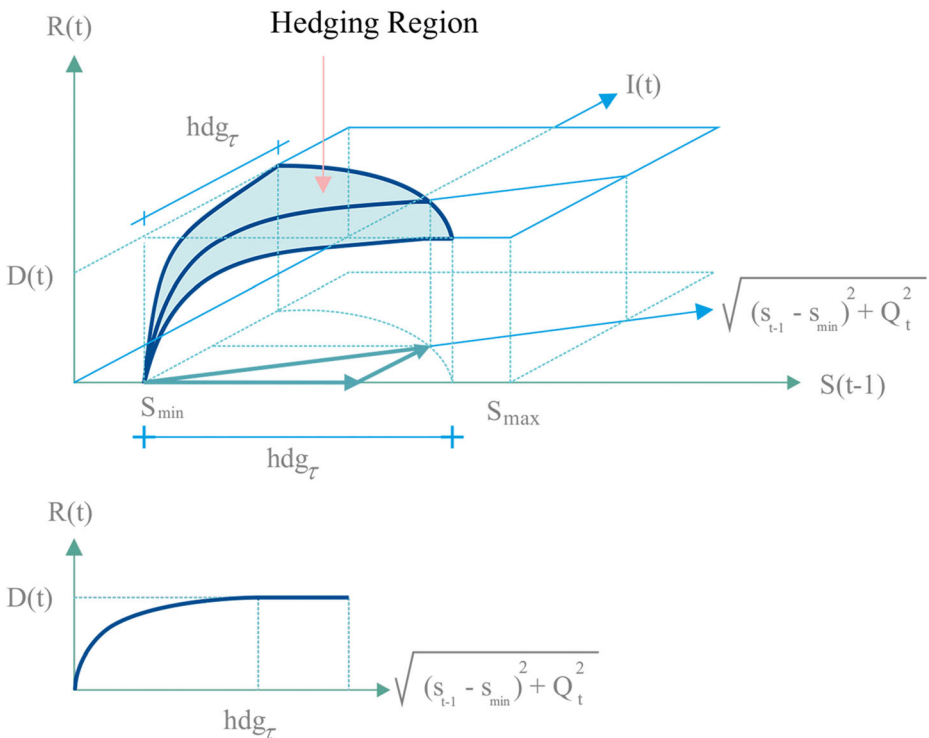


Fig. 1 Schematic of 2-D hedging model

(i) Apply hedging:

$$R_t = D_t \left[ \frac{\sqrt{(S_t - S_{\min})^2 + Q_t^2}}{hdg_\tau} \right]^{m_\tau}, \quad \text{if } \sqrt{(S_t - S_{\min})^2 + Q_t^2} \leq hdg_\tau \quad \text{for } t = 1, 2, \dots, T \tag{15}$$

(ii) Release demand:

$$R_t = D_t, \quad \text{if } \sqrt{(S_t - S_{\min})^2 + Q_t^2} > hdg_\tau \quad \text{for } t = 1, 2, \dots, T \tag{16}$$

where  $hdg_\tau$  is the determinant parameter of hedging for each month ( $\tau = 1, 2, \dots, 12$ ) and  $m_\tau$  is a regression parameter. For more details refer to Celeste and Billib (2009).

### 2.2.3 Optimization method

In this study, the enhanced differential evolution (EDE) algorithm, newly developed by Ahmadianfar et al. (2017), is applied to extract the optimal operation policies of the reservoir under climate change conditions. The EDE mechanism is described as follows:

**Initialization** The proposed optimization algorithm begins to create the initial population with  $Np$  size. This population is selected with uniform distribution based on:

$$X_{ij}^g = L + (U - L) \times rand \quad \text{for } i = 1, 2, \dots, Np, \quad j = 1, 2, \dots, D \tag{17}$$

where  $X_{ij}^g$  is the  $j$ th variable of the  $i$ th vector of the initial population and  $U$  and  $L$  are the upper and lower bounds of decision variables, respectively.  $g$  is the generation number, and  $D$  is the dimension of each vector. Furthermore,  $rand \in [0, 1]$  is a random number.

**Mutation operator** In the proposed algorithm, a new mutation mechanism is combined with the mutation presented by Storn and Price (1997) as follows:

$$\text{if } rand < \left( C_{\max} + (C_{\max} - C_{\min}) \times e^{(-it/Max\_it)} \right) \tag{18}$$

$$y^g = X_{r_1}^g + \beta(X_{r_2}^g - X_{r_3}^g) + \beta(X_{r_4}^g - X_{r_5}^g) \tag{19}$$

else

$$y^g = X_{avg}^g + \beta_1(X_{best}^g - X_{better}^g) + \beta_2(X_{best}^g - X_{worst}^g) + \left( \frac{\beta_1 + \beta_2}{2} \right) (X_{better}^g - X_{worst}^g) \tag{20}$$

end if.

where  $C_{\max}$  and  $C_{\min}$  are two constant parameters between 0 and 1,  $it$  is the generation number, and  $Max\_it$  is the maximum of generation number.  $y^g$  is the mutant vector,  $r_1 \neq r_2 \neq r_3 \neq r_4 \neq r_5$  are randomly selected indices of vectors, and  $\beta, \beta_1, \beta_2 \in [0, 1]$  are the three random



numbers.  $X_{best}^g$  is the best vector of the current population,  $X_{avg}^g$  is average of three vectors, namely,  $X_{lbest}^g$ ,  $X_{better}^g$  and  $X_{worst}^g$ .  $X_{lbest}^g$ ,  $X_{better}^g$ , and  $X_{worst}^g$ , are the best, better, and worst five randomly chosen vectors of the current population, respectively.

**Crossover operator** The crossover operator combines the target vector ( $X_i^g$ ) with the mutated vector ( $y^g$ ) to produce the trail vector ( $Z_i^g$ ) based on:

$$Z_{ij}^g = \begin{cases} y_{ij}^g & \text{if } rand < pC \text{ or } j = j_{rand} \\ X_{ij}^g & \text{otherwise} \end{cases} \tag{21}$$

where  $pC \in [0, 1]$  is the probability crossover rate, and  $j_{rand} \in [0, 1]$  is a randomly chosen index.

**Selection operator** The selection operator implements a competition between the target vector ( $X_i^g$ ) and the trail vector ( $Z_i^g$ ) based on its objective function values. The scheme of this operator is defined as follows:

$$X_i^{g+1} = \begin{cases} Z_i^g & \text{if } f(Z_i^g) \leq f(X_i^g) \\ X_i^g & \text{otherwise} \end{cases} \tag{22}$$

### 2.2.4 Evaluation of operation policies performance

In the present study, four evaluation indices, namely, reliability, resilience, vulnerability, and sustainability, were used to verify reservoir operation policies and to assess the efficiency of various types of policies. The descriptions of under study indices were detailed as follows:

**Reliability index** This index is the probability that the available water of the reservoir system can meet the water demand during the given simulation period (*Rel*). Furthermore, this can be presented by the proportion of the total actual water release to the total water demand (*Rel*) as follows:

$$Rel = \frac{m}{T} \tag{23}$$

$$Rel^t = \frac{\sum_{t=1}^T R_t}{\sum_{t=1}^T D_t} \quad \text{for } t = 1, 2, \dots, T \tag{24}$$

where  $m$  is the number of periods (months) that the water demand was met.

**Resilience index** The resilience index is a measure of the probability that a reservoir system can be recovered from a period of defeat as follows:

$$Res = \frac{N_s}{N_t}, \quad 0 < Res \leq 1. \tag{25}$$

**Vulnerability index** The vulnerability index shows the severity of defeat. This index indicates the proportion of average total shortages to the total water demand as follows:

$$Vul = \frac{\frac{1}{N_t} \sum_{t=1}^{N_t} (D_t - R_t)}{\sum_{t=1}^T (D_t)} \quad \text{for } t = 1, 2, \dots, T \quad (26)$$

where  $Vul$  is vulnerability, and the other parameters have been previously defined (Hashimoto et al. 1982).

**Sustainability index** The sustainability index recognizes policies that keep the desired characteristics of the water reservoir management system. This index is based on the combination of the three previously presented indices:

$$\gamma_1 = (ReI \times Res \times (1 - Vul))^{\frac{1}{3}} \quad (27)$$

where  $\gamma_1$  is the sustainability index (Sandoval-Solis et al. 2010). Also, according to the Adeloye et al. (2016) investigation, another definition of this index can be obtained using  $ReI'$  instead of  $ReI$  as follows:

$$\gamma_2 = \left( ReI' \times Res \times (1 - Vul) \right)^{\frac{1}{3}}. \quad (28)$$

### 2.3 Data and study area

In this study, the water supply system of the Jarreh reservoir, located in Khuzestan province, in southwestern Iran, was chosen as a case study. The daily minimum and maximum temperature and precipitation data were used to project the effects of future climate changes on the rainfall-runoff process and the agricultural water demands. Additionally, these climatic data were accumulated from eight hydrometric stations, located in the basin of the Zard River basin (ZRB) and Ramhormoz plain. At the outlet of the basin under study, the Jarreh reservoir, with a volume of 261 MCM, has been constructed in order to meet the agricultural water demands of the Ramhormoz plain. This plain, with an area of 22,470 ha, as one of the most important agricultural plains in Khuzestan province, plays an important role in enhancing the living and economic circumstances of the inhabitants. In fact, the vast majority of settlers in this region are involved in agricultural activities. The most cultivated plants in this plain include wheat, barley, and corn. The geographical location of the study area is characterized in Fig. 2. More details on the district under study can be found in Zamani et al. (2016).

### 3 Results and discussion

According to the results of weighting the models based on their performance in the simulation of climate variables, the MIROC-ESM model has a better performance in simulating the temperature and precipitation than the two other models. After computing the weights for three

climatic models in each month, the simulated temperature and precipitation changes obtained from the combination of the three climatic models' output have been calculated.

After extracting the combined values, by using LARS-WG, the expected monthly changes of climate variables are downscaled for the study area. Based on the results, the highest expected increase for the mean long-term temperature is in Nov, Oct, and Aug. The results indicated an increase in average annual temperature of 2.1°C using the RCP 8.5 scenario. Moreover, the decrease in average annual precipitation is expected within a range of 15%.

In the following, the effect of climate change on reservoir inflow has been assessed by statistical evaluation of the IHACRES model's performance. The results of IHACRES indicated a satisfactory performance during the calibration period ( $R^2 = 0.92$  and  $RMSE = 2.73 \text{ m}^3/\text{s}$ ) and verification period ( $R^2 = 0.73$  and  $RMSE = 3.72 \text{ m}^3/\text{s}$ ) for the simulation of the rainfall-runoff process. According to Fig. (3), a regular decrease is expected in the monthly inflow of the reservoir for future climate conditions. The highest decrease in the amount of reservoir inflow is expected in autumn and spring seasons. In general, the decrease in mean annual reservoir inflow would be 39.4% under RCP 8.5. Since the main purpose of the construction of the Jarreh reservoir is to meet the agricultural water supply needs for the Ramhormuz plain, this downward trend in reservoir inflow would cause serious problems in water allocation and system operation in the future conditions.

The results also indicated an increase in the net water requirement and water demand volume. The expected increase in NWD is 10.24. Also, an 18% increase in WVD is expected under climate change conditions in the future period compared with the baseline.

Due to the existing increase in temperature values, a decrease in the reservoir inflow, and following an increase in agricultural water requirements under future climate conditions, the Jarreh water resources system will face the major problem of providing an adequate water supply. In the present study, the SOP was used to simulate the reservoir operation for the base

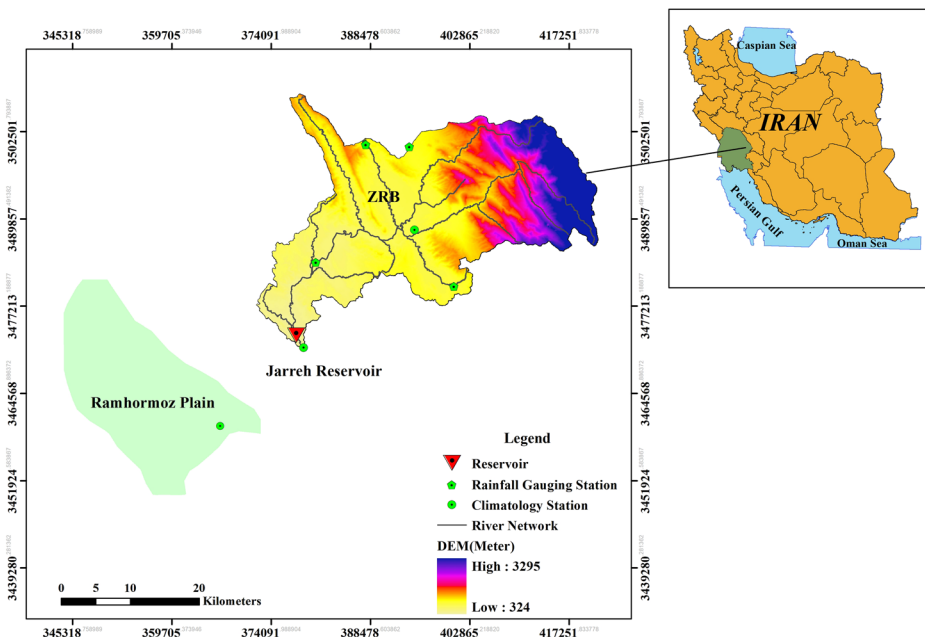


Fig. 2 The location of study area in Iran

and future periods. The results of this operation rule are listed in Table 1. Based on the results, applying SOP under the future conditions of climate change leads to a reduced reliability index (37%) and to an increased vulnerability index (9%) compared with the baseline. Sandoval-Solis et al. (2010) proposed that an increase in the sustainability index is more appropriate from the current period to the next period. In this study, the calculation of the sustainability index showed a reduction of 24% in the climate change conditions compared with the baseline. Also, the objective function values are equal to 3.02 and 14.26 for the base and future periods, respectively.

Based on these results, the current rule operation (SOP) is not suitable for the future periods, and formulating and implementing effective policy in the future is essential. In accordance with the results obtained from the simulation of reservoir inflow, it can be clearly seen that there is a severe drought period in the future. Moreover, hedging, as one of the most effective policies for encountering drought conditions, has been used to mitigate the negative effects of climate change on the operation of the Jarreh reservoir.

Optimal rule curves of the hedging policy for the Jarreh reservoir have been computed under climate change impacts by using the EDE. Additionally, the optimal parameters of the hedging rule for the future period are presented in Table 2. It is noteworthy that the SOP method is considered a common method for the reservoir operation systems to evaluate the performance of the proposed policy (Karamouz et al. 2012; Adeloey et al. 2016).

The results of the 2-D hedging rule performance for the future period are presented in Table 3. The comparison between the results of the hedging rule and the SOP showed that the reliability index ( $Rel$ ) obtained by the two methods is approximately the same. Another reliability index ( $Rel$ ) obtained by the hedging rule is about 31% less than the SOP (the values of reliability for the hedging rule and the SOP are 0.6 and 0.41, respectively); of course, this result is expected due to the nature of the SOP method. The vulnerability index ( $Vul$ ) for the hedging ( $Vul = 0.56$ ) is 24% better than that obtained by the SOP ( $Vul = 0.74$ ). This situation indicates the advantage of rationing during normal periods of reservoir operation that can lead to an appropriate reduction in the vulnerability value of the water deficit.

Furthermore, the reservoir system suffered from large single period deficits obtained by the SOP ( $=40$ ), while the corresponding value calculated by the hedging rule is 34.4. Also, the results revealed that the proposed method has improved the maximum of shortages by 14% in comparison with the SOP. Significant changes were not observed for the sustainability index. The objective function value computed by the hedging rule is 31% less than the value obtained by the SOP method.

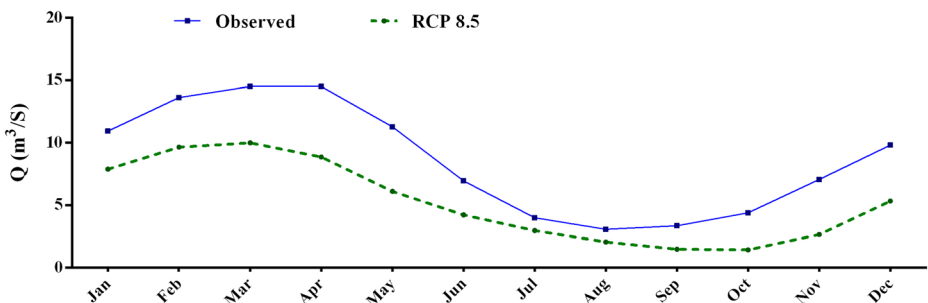


Fig. 3 Comparison of simulated long-term mean monthly runoff in baseline and future (2025–2054)

**Table 1** Comparison of reservoir performance indices for the SOP in baseline and future

Indexes	Baseline	Future (RCP 8.5)
Rel'	0.97	0.65
Rel	0.95	0.60
Res	0.25	0.20
Vul	0.68	0.74
$\gamma_1$	0.42	0.31
$\gamma_2$	0.42	0.32
Objective function	3.02	14.26

As mentioned earlier, one of the purposes of the hedging application is to reduce the severity of the deficiencies; therefore, to show the impact of the hedging rule, the deficit maximum in each year has been calculated and depicted in Fig. (4). It is clearly seen that the hedging rule has reduced the deficit maximum compared with the SOP in each year.

Considering the importance of providing agricultural water requirements during the periods in which the crops require irrigation water, and due to the expected drought conditions over southwestern Iran under future climate conditions, reviewing and modifying the allocation policies is vital. As an example and according to the results of the current study, the use of hedging can ameliorate the severity of deficiencies in the amount of required water. Obviously, less severe deficiencies could lead to less system damage. Thus, it is incumbent upon managers and stakeholders to consider the future drought conditions resulting from the climate variations.

## 4 Conclusion

Evaluation of the impacts of global warming and climate change on the hydrological cycle and water resources systems is vital for reservoir performance. In arid and semi-arid areas such as Iran, there is a ferocious demand for water resources due to the increase in temperature, population growth, and industrial development. These concerns have drawn remarkable attention from experts and stakeholders for the management of reservoirs and water resources during the future climate changes. Due to the importance of water and agriculture on the living

**Table 2** The optimal parameters of the 2-D hedging rule

Month	hdg <sub><math>\tau</math></sub>	m <sub><math>\tau</math></sub>
Jan	55.10	0.04
Feb	51.83	0.49
Mar	60.18	1.00
Apr	72.61	1.00
May	72.88	1.00
Jun	72.88	1.00
Jul	58.59	0.95
Aug	35.77	0.98
Sep	17.18	1.00
Oct	51.41	1.00
Nov	18.44	1.00
Dec	72.88	1.00

**Table 3** Comparison of the performance indices for the 2-D hedging rule and SOP in baseline and future

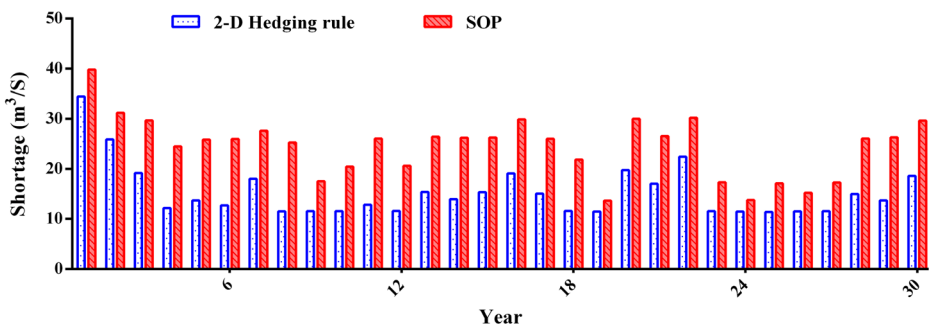
Indices	SOP	2-D hedging rule
Rel'	0.65	0.66
Rel	0.60	0.41
Res	0.20	0.14
Vul	0.74	0.56
$\gamma_1$	0.31	0.31
$\gamma_2$	0.32	0.35
Max. single period deficit (MCM)	40	34.40
Objective function	14.26	9.78

conditions of the inhabitants in southwestern Iran, the performance of the Jarreh reservoir in supplying the agricultural water requirement as well as the evaluation of the 2-D hedging policy on the reservoir operation, have been assessed under climate change conditions.

In general, the results indicated an increase in the mean monthly temperature during a 30-year period beginning in 2025. Also, an increase equivalent to 2.1°C and a decrease of about 15% are expected for mean annual temperature and precipitation, respectively. According to the expected increase in temperature and decrease in precipitation, a decrease of about 39% is expected for the annual reservoir inflow. Furthermore, an increase in the net water requirement and annual water demand volume is simulated for the Ramhormuz plain located downstream of the reservoir.

Considering the climate variations and drought conditions that are expected in the future over the study area and southwestern Iran, and due to the importance of water allocation concerning water shortage, optimal reservoir management as the main source of water supply is essential. For this reason and based on the simulated climate condition in the future, operating policies should be flexible and adaptable to mitigate the negative effects of climate change.

The results showed that two-dimensional hedging could be an appropriate policy for the assessment of the Jarreh reservoir operation during the drought conditions under future climate changes. Furthermore, the results indicated an improvement in the performance of evaluation indices in comparison with the use of standard operation policy under the impacts of climate change conditions. The application of the hedging method demonstrated a 24% decrease in vulnerability index, a 14% improvement in the maximum of shortages, and an increase in sustainability index during the future period (2025–2054) under the RCP 8.5 scenario.

**Fig. 4** Comparison of the deficit maximums obtained by the 2-D hedging rule and the SOP in each year

In addition to the assessment of climate change effects on the water resource systems and corresponding with the simulation of climate change, experts suggested that a reduction in the repercussions of climate change and the study of potential impacts of this phenomenon is beneficial. In this way, adaptation strategies and satisfactory improvement in the operation rules of reservoirs due to climate change conditions can lead to achieving an efficient water management system and to an increase in the reliability of the system. Furthermore, due to the semi-arid climate and water scarcity in Iran, it is of the utmost importance for the relevant decision-makers to consider updating the climate change investigations and inter-basin water transfer-supply project in southwestern Iran based on global warming and climate change issues over the future period.

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