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Research Article

Economic Model for Optimal Allocation of Water Resources with an Emphasis on Risk and Consistency Index in the Sistan Region: The Application of Interval Two-Stage Stochastic Programming Method

Zahra Ghaffari Moghadam [a,*], Mahmoud HashemiTabar [b], Ali Sardar Shahraki [b]

[a] Department of Agricultural Economics, Agricultural Institute, Research Institute of Zabol, Zabol, Iran
[b] Department of Agricultural Economics, Management and Economic Faculty, University of Sistan and Baluchestan, Zahedan, Iran

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Abstract
The issue of water resource management in the Sistan region has been complicated by water fluctuations of the Hirmand River in recent years and the competition of the drinking, agricultural, and environmental sectors on water use. The present study applies the economic model including interval two-stage stochastic programming (TSP) method under uncertainty conditions to study agricultural water allocation and the assessment of risk and consistency including stochastic simulation of the existing water, an optimization model of agricultural water, and the risk assessment of the water shortage under three scenarios of high, average, and low inflow levels in three regions of Zahak, Zabol, and Miankangi as the three main agricultural areas in Sistan for the time horizon of 2019-2020. The results show that there will be no water shortage for agricultural users in the Zahak region at the high and average inflow levels. But, this area will need 122 million m^3 more water at the low inflow level. Also, the water shortage in the Zabol area will be inadequate by 149.69 million m^3 at the average inflow level and by 185.65 million m^3 at the low inflow level. Also the results of the TSP model for Miankangi County indicate that no water will be allocated to this sector. The risk assessment of agricultural water shortage by the results of optimization will help decision-makers better understand the risk of water shortage under different scenarios. It is found that the Zabol region will have higher risk of agricultural water shortage than the Zahak region, so efficient risk management should be initiated from this region.
Keywords: Economic model, Two-Stage Stochastic Programming, Risk Assessment, Optimal Water Allocation, Uncertainty

Introduction

About 30% of the world's land resources are located in arid and semi-arid regions. Water scarcity is a major obstacle to social and economic development in these areas (Farrokhzadeh et al., 2020). Based on the amount of water resources and per capita consumption, Iran is one of the countries that will face physical water scarcity by 2025 (International Water Management

* Corresponding author E-mail: zahraghafari@uoz.ac.ir

Institute, 2000). If no change is made in the pattern of water consumption, Iran will have problem in meeting water demands of different sectors, especially the agricultural sector, even if water is used as highly efficiently and productively as possible. Therefore, attention has been drawn to the management of water resources and their optimal allocation for agricultural development at the national and regional levels.

There are various uncertainties in the components of the water resources system, which challenges the optimal allocation of agricultural water in the real-world conditions. So, the consideration of uncertainty in optimization methods is an effective method for actualizing agricultural water allocation system (Singh, 2015; Li et al., 2014).

This complexity and uncertainty of water resources management have made it more difficult to solve water issues. Chance-constrained programming (CCP), fuzzy programming, and interval-parameter programming (IPP) are the methods commonly used to model such problems (Wu et al., 2021; Zhang et al., 2021; Acharya et al., 2021; Ma et al., 2020; Wang et al., 2020). Stochastic programming is used in optimization problems in which some or all parameters are stochastic and the constraints are very unlikely to be violated (Nasseri & Bavandi, 2017). CCP was developed by Charnes and Cooper (1959). The CCP and FP methods cannot correctly express the economic significance of violating predetermined factors. In addition, these methods can express the right-hand side stochastic aspects of the model correctly, but they are unable to express the uncertainty of the left-hand side parameters (Maqsood et al., 2005). The two-stage programming technique was first introduced by Dantzig to solve stochastic programming problems (Kambo, 1984). The technique converts stochastic problems into crisp problems, and unlike CCP, two-stage programming does not allow the violation of the constraints.

In recent years, many studies have focused on the allocation of agricultural water resources that encompass uncertainty (Li et al., 2020;Yue et al., 2020; Gong et al., 2020; Ren et al., 2019; Ahmadi et al., 2017; Li et al., 2016) among which inexact two-stage stochastic programming model has been more effective in expressing uncertainty conditions with certain probability distribution (Wang and Zhu, 2021; Ren et al., 2021; Chen et al., 2021; Ji et al., 2017; Guo, et al., 2009). Also, a good deal of research has addressed water quality using inexact two-stage programming method. For example, Zhang (2021) developed an A risk-averse stochastic quadratic model with recourse for supporting irrigation water management in uncertain and nonlinear environments. Hung and Loucks (2000) applied an inexact two-stage stochastic programming model for water reservoirs in Canada. The concept of inexact optimization was provided in its method in the context of the two-stage stochastic model. The drawback of this model is that it oversimplifies the assumptions of the fuzzy membership functions. The results revealed that this model provided more realistic results for water resources management than the single-stage model.

Li et al. (2008) applied multi-stage programming with interval parameters for the management of water resources in Canada under different scenarios. The results were provided for 81 scenarios for urban, agricultural, and industrial users and three future periods. Sethi et al. (2006) addressed the simultaneous optimization of water resources allocation and cropping pattern in the Balasore region, India. They employed chance-constrained linear programming (CCLP) and deterministic stochastic programming to adopt long-term policies for the sustainable management of agricultural lands and water resources in the region. The results of the sensitivity analysis showed that 20% of the available surface water and 30% of the available groundwater constituted the optimal levels of water allocation. Also, a 40% deviation from the current cropping pattern would suffice to supply the minimum food requirement. In a study using multi-objective programming under uncertain conditions, Li and Guo (2014) addressed optimal water allocation in China. The results are valuable for supporting the adoption of existing irrigation patterns and identifying an optimal multi-objective water allocation program under uncertain conditions. Li et al. (2016) employed an interval two-stage stochastic programming model for the allocation of water resources and land and used the results of the model to assess the risk of irrigation water shortage in the studied region under uncertain conditions within the Heihe river basin. Their proposed model can be a guideline for developing comprehensive irrigation models for determining cropping patterns for the target time horizon under uncertain conditions.

Chen et al., (2021) used an interval two-stage fuzzy credibility constraint programming (ITSFCCP) method for optimize the allocation of water resources in Lincang. This model proposed to deal with multiple uncertainties that can be expressed as fuzzy sets, discrete intervals and probability distributions.

Ren et al., (2021) applied an improved interval multi-objectives programming method. to the optimization allocation of irrigation water resources in Jinghuiqu irrigation district, Shaanxi Province, China. Ling et al. (2017) used an inexact two-stage stochastic programming model for the management of water resource allocation under uncertainty conditions. The model that they proposed included interval-parameter programming and two-stage stochastic programming that expresses the uncertainty of the parameters by interval values with probability distribution. They reported that the scenarios influenced water distribution pattern, water shortage, total profit, and system cost. Kalbali et al. (2017) determined cropping pattern, water allocation among competing users, and net profit of the system under different scenarios using two-stage stochastic programming method. The results showed that with the water allocation using the two-stage stochastic programming model, the water demand of the aquaculture and environmental sectors would be met and there would be no shortage in these sectors under the studied scenarios. However, the water demand of the agricultural sector would not be met under dry year conditions.

The review of the literature shows that the water crisis will be inevitable in the future and the agricultural sector is extremely susceptible to the water crisis. The increased demand for food, climate change, and severe constraints of water resources will indeed create critical conditions for water resources in Iran, and the Sistan region is no exception. The objectives of the present study were to explore optimal allocation of water and maximum benefits of the agricultural sector by using an interval two-stage stochastic programming model under uncertainty conditions, to determine allocative water inflow to different agricultural regions, to find out the extent of water shortage for each sector under high, normal, or low inflow rates, and to assess the risk of agricultural water shortage. The model was solved by the GAMS (ver. 23.5) software package. In addition to determining optimal water allocation between different agricultural sectors in the Sistan region and the extent of water shortage of each sector, the risk of water shortage of individual sectors was modeled and estimated under uncertainty conditions with an emphasis on sustainability indices at different inflow rates.

Case Study

The Sistan region stretches over an area of 2545.512 km^2 (Long. 61°31' E., Lat. 30°55' N.) in the north of Sistan and Baluchestan province, east of Iran. It has an elevation of 478 meters from sea level and has a hot and arid climate. This region with an area of over 8000 km^2 has been made of the sediments of the Hirmand River over thousands of years. Figure 1 shows the location of the Sistan region (Ghaffari Moghaddam, 2021).

The Sistan region has gained unique characteristics due to frequent droughts and its specific hydrological and spatial conditions. The specific conditions of this region are rooted in its placement at the end of a closed watershed, a complex hydrological system of the Hirmand River, and the supply of the environmental needs of the Hamoon in severe conditions, the blow of 120-day winds, slight annual precipitation, the high temperature and low infiltration of the soil, the constraints of groundwater resources, shared surface water resources with the neighboring countries, and lack of control over the origins of the Hirmand River (Nouri et al., 2020).

The only source of water in Sistan Plain is the Hirmand River whose water shortage and large fluctuations are the main issues challenging water management in the Sistan region. Frequent droughts and floods of recent years have adversely influenced the water use of the drinking, agricultural, and environmental sectors.

The water fluctuations of this river by human intervention in Afghanistan and climate change have created many problems for water management in this area. Additionally, the international Hamoon wetland and the impact of this river on this wetland are other issues complicating the management of the water resources in Sistan (Mozaffari, 2014). Given the fluctuations of the Hirmand River water, the limitations of water resources, the increase in water requirements, and the occurrence of intermittent droughts that impose heavy damages, it is clear that sustainable agricultural development needs comprehensive studies and more targeted measures in the context of water management and close consideration of the sustainability of water resources.

This research aims to address optimal water allocation, specify maximum profit of the agricultural sector using a two-stage stochastic programming method under uncertain conditions, and determine allocative water inflow of different agricultural regions and the water shortage of each sector under high, normal, and low inflow rates of the river. If the water promised to the users is released in the desired time frame, the system's net profit will increase; otherwise, the consumer should supply its water requirement from more expensive sources and/or reduce his/her activities, which would both lead to a loss. The data on the prices, production, and cultivation area of the selected crops was provided by the Agriculture Jahad Organization and the related institutions. Data on the water inflow rate of the Sistan region was provided by the Regional Water Organization for the 1985-2021 period.

Figure 1. Sistan geographical location

Methodology

The two-stage stochastic programming model is a technique that is used for water resource management. In this model, the first-stage decision refers to the allocation of water among users with respect to their needs and ignoring the uncertainty of water flow. In the second stage, water allocation among the users is based on the uncertainty of the river flow rate. This decision-making process yields a two-stage stochastic programming model whose general model can be shown as below (Li et al., 2016):

$$Max\ f = \sum_{i=1}^{m} NB_i T_i - \sum_{i=1}^{m}\sum_{j=1}^{n} P_j C_i D_{ij} \tag{1}$$

$Subject\ to$:

$$\sum_{i=1}^{m}\left(T_i - D_{ij}\right) \leq q_j \quad \forall j \tag{2}$$

$$T_{imax} \geq T_i \geq D_{ij} \quad \forall i،j \tag{3}$$

$$T_i،D_{ij} \geq 0 \tag{4}$$

In which f denotes the net system benefit, NB_i is user i's benefit per unit of allocated water, T_i is the water demand of user i (a variable of the first-stage decision), C_i is the loss of user i per unit of unreleased water, D_{ij} is the water shortage of user i under the inflow rate of j (a part of T_i that is not released with the inflow q_j occurs; a variable of the second-stage decision), q_j represents the random variable of water supply, T_{imax} denotes the maximum water allocated to user i, P_j represents the probability of the occurrence of inflow level j, m is the number of water users, and n shows the number of inflow levels. We used the model proposed by Li et al. (2016). The objective function is to maximize the system's benefit with minimum loss caused by water shortage through optimal allocation of limited agricultural water resources to different irrigation sectors. The general form of the model is as below:

$$f^{\pm} = max\ (\sum_{i=1}^{I}\sum_{t=1}^{T} B_i^{\pm} D_{it} - \sum_{i=1}^{I}\sum_{t=1}^{T}\sum_{h=1}^{H} P_h BP_i^{\pm} S_{ith}) \tag{5}$$

In which $\sum_{i=1}^{I}\sum_{t=1}^{T} B_i^{\pm} D_{it}$ shows the system benefit and $\sum_{i=1}^{I}\sum_{t=1}^{T}\sum_{h=1}^{H} P_h BP_i^{\pm} S_{ith}$ represents the system loss in case of the shortage of agricultural water.

Water inflow constraint:

$$\sum_{i=1}^{I}(D_{it} - S_{ith})\,/\theta_i^{\pm} \leq Q_{th} \quad \forall t،h \tag{6}$$

Maximum and minimum water demand constraints:

$$(D_{it} - S_{ith})/\theta_i^{\pm} \leq Q_{max،it} \quad \forall i،t،h \tag{7}$$

$$D_{it} \leq S_{ith} \quad \forall i،t،h \tag{8}$$

Non-negative constraint:

$$S_{ith} \geq 0 \quad \forall i،t،h \tag{9}$$

in which f denotes the net system benefit of agricultural water allocation, i shows irrigation areas, t shows time, and h represents the present water level in that h=1, h=2, and $h=3$ show high, average, and low inflow levels, respectively. Also, B_i^+ and B_i^- represent the irrigation benefit for irrigation area i (IRR/m^3) at high and low levels, D_{it} is the demand for agricultural water in region i, P_h shows the probability of the occurrence of inflow h, BP_i^+ and BP_i^- indicate the loss of net benefit in irrigation area i when water demand of the sector I is not completely met (IRR/m^3) at high and low levels, respectively. In addition, S_{ith} indicates agricultural water shortage of region i at time t under scenario h, Q_{th} represents random water supply at time t under scenario h, $Q_{max,it}$ indicates maximum water demand in region i at time t (m^3), and $\theta_i^{\pm}$ is irrigation efficiency at high and low levels. The optimal solutions of the model are $F^{\pm}$ and $S_{ith}^{\pm}$ and the optimal agricultural water allocation is $WA_{ith}^{\pm\pm}$ estimated by:

$$S_{ith}^{\pm} = [S_{ith}^{+}, S_{ith}^{-}] \tag{10}$$

$$W_{ith}^{\pm} = [W_{ith}^{+}, W_{ith}^{-}] = [D_{it} - S_{ith}^{+}, D_{it} - S_{ith}^{-}] \tag{11}$$

Data preparation

Here, to determine the probability of water inflow type (low, average, or high water inflow level), it is necessary to follow three steps: (i) categorization of different inflow levels, (ii) determination of the occurrence of probability for different inflow levels, and (iii) determination of available monthly irrigation water for different levels (Li et al., 2016).

To classify different inflow levels, we used the frequency analysis method. P is defined as the frequency to determine different inflow categories. $P < 0.25\%$ is equivalent to the high inflow level, $0.25\% < P < 0.75\%$ corresponds to the average inflow level, and $P > 0.75\%$ is equivalent to the low inflow level. To this end, monthly water inflow data are arranged in a descending order expressed as $\{x_1, x_2, \ldots, x_m, \ldots, x_n\}$. Frequency is calculated by $P = (m/(n+1)) \times 100\%$ in that m is the number of 'greater than' or 'equal to' x_m. Then, different inflow levels are divided by P to yield the number of years corresponding to different inflow levels. The occurrence probability of individual inflow level is obtained by dividing the number of years of each inflow by the total number of years (Li et al., 2016).

Risk assessment of agricultural water scarcity

The risk of irrigation water shortage was assessed by the results of stochastic simulation and optimization. Many indices can be used for water shortage risk assessment. Reliability, vulnerability, risk degree, and consistency index are the indices commonly used to describe the behavior of a water resource system, which were used in the present work (Li et al., 2016). The performance criteria of water resource systems are defined in terms of the parameters of water requirement and the amount of water supplied for ith water user and/or for a water resource that can include agricultural, industrial, drinking, and environmental uses and/or dams or underground water reserves (Loucks et al., 1981).

Reliability

Reliability is defined as the probability by which water allocated to a user can meet his/her demand (Guo et al., 2012; Hashimoto et al., 1982), or to what extent a system will be able to operate reliably and without failure. It is expressed as below:

$$\alpha = \frac{1}{T}\sum_{t=1}^{T}(1 - Z_t) \tag{12}$$

Risk is equal to:

$$\beta = 1 - \alpha \tag{13}$$

In which α denotes the reliability of a water resource system and β represents the risk. Z_t is a zero-one variable that takes value 1 when the system is unable to meet a user's demand; otherwise, it takes value zero. The total number of steps is shown as t.

Vulnerability

Vulnerability is a measure to determine the damages of a system due to a failure event (Hashimoto et al., 1982). It is defined for a water resource system as below:

$$x = \frac{1}{T_s}\sum_{t=1}^{T}\frac{Z_t(D_t - WA_t)}{D_t} \tag{14}$$

In which T_s denotes the total number of failures over time, and D_t and WA_t represent agricultural water demand and the allocated water at time t, respectively.

Risk degree

Risk degree refers to the stochastic system parameters because of uncertainty. It is expressed by:

$$C_v = \sigma/\mu \tag{15}$$

In which σ denotes the standard deviation of the sample and μ represents the mean of the sample.

Consistency index

The consistency index has been proposed to measure the dynamics of a system. The higher the value of this index is, the more dynamic the system will be. The index is expressed as:

$$\lambda = \frac{\sum_{t=1}^{T}(\Delta max - \Delta(t))}{T(\Delta max - \Delta min)} \tag{16}$$

$$\Delta(t) = |WA_t^* - D_t^*| \tag{17}$$

$$WA_t^* = T.WA_t \Big/ \sum_{t=1}^{T} WA_t \tag{18}$$

$$D_t^* = T.D_t \Big/ \sum_{t=1}^{T} D_t \tag{19}$$

$$\Delta max = max\{\Delta(1)، \Delta(2)، \ldots ، \Delta(T)\} \tag{20}$$

$$\Delta min = min\{\Delta(1)، \Delta(2)، \ldots ، \Delta(T)\} \tag{21}$$

Then, the uncertainty in risk assessment of agricultural water shortage is examined by the concept of membership functions in the fuzzy theory (Ruan et al., 2005). In the fuzzy logic, which was first presented by Zadeh (1965), the correctness of a proposition can vary over a range of 0-1. As such, it is possible to provide approximate reasoning. The membership function reflects the extent of fuzziness of a set. Research can use diverse membership functions, such as triangular, trapezoidal, Gaussian, sigmoid, and bell-shaped membership functions, as per the objective (Safavi and Golmohammadi, 2016).

This study assessed these four indices and estimated the risk level of agricultural water shortage. Table 1 presents the categorization of the factors of these assessment indices (Ruan et al., 2005).

Table 1. Categorization of risk assessment indices (Ruan et al., 2005)

Risk of water shortage	Reliability	Vulnerability	Consistency index	Risk degree
Low risk level (I)	≤0.200	≤0.200	≥0.800	≤0.200
Average low risk level (II)	0.201-0.400	0.201-0.400	0.601-0.800	0.201-0.400
Average risk level (III)	0.401-0.600	0.401-0.600	0.401-0.600	0.401-0.600
Average high risk level (IV)	0.601-0.800	0.601-0.800	0.201-0.400	0.601-0.800
High risk level (V)	≥0.800	≥0.800	≤0.200	≥0.800

Result and Discussion

The volume of inflow water into the irrigation network cannot be calculated by fixed and deterministic values because of the random nature of the river inflow into the dam. So, the future behavior of a system can be forecasted by simulation methods. Assuming the adequacy of past data to build future data, we used historical data and Monte Carlo simulation. For each individual year of the studied period, the random values were selected 100 times by past data. It should be noted that 100 times of random selection for supply rate were performed for the low, average, and high inflow levels, too. Table 2 presents probability levels and water inflow using a normal distribution function for the specified period.

Table 3 presents information on the crop species with the highest acreages in the studied areas, as well as their mean price, mean yield, and net water requirement in Sistan

Table 2. Data on water inflow levels and the probability of different inflow levels (million m^3)

Inflow level	Probability of occurrence	Water inflow rate
Low	25%	282.3
Average	50%	582.13
High	25%	927.16

Table 3. Data on main crops grown in Sistan

Crop	Mean yield (kg)	Mean price (IRR)	Net water requirement (m^3/ha)	Acreage (ha)
Wheat	1893.89	13000.00	5360.00	10317.44
Barley	1610.67	9817.00	5000.00	1607.44
Melon	19300.00	6597.00	4500.00	1246.11
Watermelon	23788.89	3113.00	7330.00	1066.78
Sorghum	44491.22	7108.00	22440.00	1628.44
Alfalfa	19416.67	2000.00	3462.00	308.84

Irrigation benefit for the irrigation area B_i is estimated as follows: yield per unit water is multiplied by crop price; then, the results are summed up for all the crops of an individual irrigation area, and the corresponding benefit is obtained for that region. The coefficient of penalty (loss or reduction of net profit BP_i) should be greater than irrigation benefit in region B_i because if the promised water is not realized, farmers will have to use more expensive resources or limit their activity to cope with the water shortage. We assume that the penalty coefficient is (1.30, 1.35) that is multiplied in the irrigation benefit of each individual irrigation area (Li et al., 2016).

Tables 4 and 5 present optimal water allocation among various irrigation areas at different inflow levels.

Table 4. Optimal water allocation to the Zahak irrigation area under different scenarios (million m^3)

Month	Water demand	At high inflow level 25% probable		At average inflow level 55% probable		At low inflow level 25% probable	
		Water shortage	Allocated water	Water shortage	Allocated water	Water shortage	Allocated water
1	(13.52,11.83)	0	(13.52,11.83)	0	(13.52,11.83)	(8.84, 7.74)	(4.68, 4.09)
2	(11.36,9.94)	0	(11.36,9.94)	0	(11.36,9.94)	(7.92, 6.93)	(3.44, 3.01)
3	(11.76,10.3)	0	(11.76,10.3)	0	(11.76, 10.3)	(7.08, 6.2)	(4.68, 4.1)
4	(9.2,8.1)	0	(9.2,8.1)	0	(9.2, 8.1)	(3.64, 3.2)	(5.56, 4.9)
5	(9.45,9.45)	0	(9.45,9.45)	0	(9.45, 9.45)	(2.84, 3.7)	(6.612, 5.75)
6	(16.07,16.1)	0	(16.07,16.1)	0	(16.07, 16.1)	(6.27, 7.5)	(9.8, 8.6)
7	(27.88,27.9)	0	(27.88,27.9)	0	(27.88, 27.9)	(15.68, 17.2)	(12.2, 10.7)
8	(42.53,42.53)	0	(42.53,42.53)	0	(42.53, 42.53)	(27.25, 29.2)	(15.28, 13.33)
9	(34.88,30.52)	0	(34.88,30.52)	0	(34.88, 30.52)	(22.58, 19.75)	(12.3, 10.8)
10	(16.12,14.1)	0	(16.12,14.1)	0	(16.12,14.1)	(9.62, 8.42)	(6.5, 5.68)
11	(10.94,9.6)	0	(10.94,9.6)	0	(10.94, 9.6)	(4.62, 4.04)	(6.32, 5.56)
12	(12.16,10.64)	0	(12.16,10.64)	0	(12.16, 10.64)	(5.72, 5)	(6.44, 5.64)

Table 5. Optimal water allocation to the Zabol irrigation area under different scenarios (million m^3)

Month	Water demand	At high inflow level 25% probable		At average inflow level 55% probable		At low inflow level 25% probable	
		Water shortage	Allocated water	Water shortage	Allocated water	Water shortage	Allocated water
1	(20.06, 17.55)	0	(20.06, 17.55)	(20.06, 17.55)	(0, 0)	(20.06, 17.55)	(0, 0)
2	(15.84, 13.86)	0	(15.84,13.86)	(15.84, 13.86)	(0, 0)	(15.84, 13.86)	(0, 0)
3	(5.04, 4.41)	0	(5.04, 4.41)	(5.04, 4.41)	(0, 0)	(5.04, 4.41)	(0, 0)
4	(1.24, 1.1)	0	(1.24, 1.1)	(1.24, 1.1)	(0, 0)	(1.24, 1.08)	(0, 0.02)
5	(7.35, 5.25)	0	(7.35, 5.25)	(1.48, 1.3)	(5.87, 3.95)	(7.35, 5.25)	(0, 0)
6	(11.73, 8.25)	0	(11.73, 8.25)	(5, 4.4)	(6.73, 3.85)	(11.73, 8.25)	(0, 0)
7	(14.72, 9.4)	0	(14.72, 9.4)	(3, 2.62)	(11.72,6.78)	(14.72, 9.39)	(0, 0.01)
8	(18.67, 11.02)	0	(18.67, 11.02)	(6.8, 5.95)	(11.87,5.07)	(18.67, 11.02)	(0, 0)
9	(38.8, 33.95)	0	(38.8, 33.95)	(38.8, 33.95)	(0, 0)	(38.8, 33.95)	(0, 0)
10	(15.54, 13.6)	0	(15.54, 13.6)	(15.54, 13.59)	(0, 0.01)	(15.54, 13.59)	(0, 0.01)
11	(16.66, 14.6)	0	(16.66, 14.6)	(16.66, 14.57)	(0, 0.03)	(16.66, 14.6)	(0, 0)
12	(20, 17.5)	0	(20, 17.5)	(20, 17.5)	(0, 0)	(20, 17.5)	(0, 0)

Table 4 shows optimal water allocation over a cropping year at irrigation efficiencies of 40% and 35% using the ITSP model. As the results show, farmers will face no water shortage at the high and average inflow levels, and water demand and allocation do not change in these scenarios and all water demand will be satisfied. Given the water allocation and target water demand at the low inflow level, there will be 122 million m^3 of water shortage, which is a huge number. The greatest water shortage will happen in Month 8. Final water allocation values will be estimated by subtracting water shortage from target water demand.

The results on allocation in Zabol County show that there will be no water shortage for farmers at the high inflow level, but 36.19 million m^3 of water is allocated at the average inflow level, which is a high value. This water is allocated from Month 5 to Month 8 resulting in a shortage of 149.46 million m^3. At the low inflow level, no water is allocated to this sector causing a shortage of 185.65 million m^3. The results of the TSP model for Miankangi County indicate that no water will be allocated to this sector. The results on allocation by the proposed model are consistent with Sardar Shahraki (2018), Hosseinzad and Raei (2021), Kalbali et al. (2017), and Meng et al. (2021).

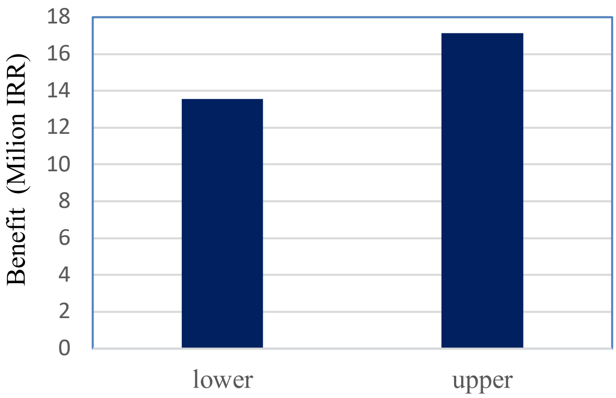

Figure 2. System benefits (Million IRR)

Risk assessment of agricultural water scarcity

The study assessed the risk of water shortage in each individual irrigation area under different inflow levels to better understand the conditions of water shortage at the high level, the amounts of water shortage, and the allocated water. Table 6 presents the results of the final assessment.

Table 6. Performance criteria for Zahak and Zabol under different inflow levels

		Reliability		Vulnerability		Risk degree		Consistency index	
Zahak	High inflow	0	(I)	0	(I)	0	(I)	-	-
	Average inflow	0	(I)	0	(I)	0	(I)	-	-
	Low inflow	1	(V)	0.53	(III)	0.76	(IV)	0.46	(III)
Zabol	High inflow	0	(I)	0	(I)	0	(I)	-	-
	Average inflow	0.67	(IV)	0.012	(I)	0.88	(V)	0.54	(III)
	Low inflow	1	(V)	1	(V)	0.61	(IV)	0.38	(IV)

The lower the risk of agricultural water shortage is, the better the system can tolerate the risk of water shortage. Agricultural water shortage depends on the existing water and the demand for it. The results indicate that no water shortage will happen and the risk will be zero in Zahak at the high and average inflow levels and in Zabol at the high inflow level. The study used the fuzzy method to measure the four risk indices in order to assess the efficiency of the water resource system from different aspects. According to the results, the high and average inflow levels are accompanied by a low-risk level for three indices of reliability, vulnerability, and risk degree. Risk levels III, IV, and V often happen at the low inflow level. The risk of irrigation water shortage is increased with the decrease in water availability (from the high to low inflow levels). In Zahak, when the inflow level is high or average, there is no risk of water shortage. Likewise, the risk of water shortage is zero in Zabol at the high inflow level. As is evident, the risk level is inconsistent at the low inflow level whereas it is consistent at the high inflow level. As the risk degree increases, this means that water shortage fluctuates in a wider range and this can happen at the higher inflow levels. In this categorization, the Zabol area has a higher risk of irrigation shortage than the Zahak region. So, efficient risk management should be initiated from this area. The consistency index indicates that in Zabol, the system is more dynamic at the average inflow level than at the low inflow level.

Conclusions and recommendations

The present study addressed water resource management in the Sistan region using the interval two-stage stochastic programming method under uncertainty conditions with an emphasis on consistency indices. Then, the results were used to assess the risk of agricultural water shortage in three regions. The results show that there is no water shortage in the Zahak region at the high and average inflow levels and all demand water will be allocated, but at the low inflow level, there will be a water shortage in all studied months. In the Zabol region, there will not be a water shortage at the high inflow level, but there will be a water shortage at the average inflow level in some months. At the low inflow level, water will not suffice in all months, and no water will be allocated to this sector. In Miankangi County, no water will be allocated at all inflow levels and the system benefit will be (13.55, 17.14) million IRR. Information dissemination about water allocation can help decision-makers decide on how water amount changes under uncertainty conditions and develop a comprehensive irrigation scheme for the planned period. In addition, risk assessment of irrigation water shortage by the results of the optimization model can help decision-makers understand the risk of water shortage in different scenarios.

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