Evaluation of the VIKOR and FOWA Multi-Criteria Decision Making Methods for Climate-Change Adaptation of Agricultural Water Supply

Parvin Golfam[1] · Parisa-Sadat Ashofteh[1] · Hugo A. Loáiciga[2]

Abstract

Confronting climate change is a daunting challenge that requires policies for climate adaptation in the field of water resources management. This paper proposes a method for reservoir operation associated with climate-change projections aimed at ensuring the sustainability of agricultural water supply. The method is applied to the Aidoghmoush reservoir in East Azerbaijan province (Iran) employing climate-change projections for 2040–2069, and compares the future-period results with those calculated for the baseline period (1971–2000). The water-supply system depending on the Aidoghmoush reservoir is simulated using the climate-change projections. The water-supply system simulations are ranked with two multi-criteria decision-making (MCDM) methods according to their suitability for satisfying agricultural water demands and sustain cropping patterns. These are the multi-criteria optimization and compromise resolution (VIKOR) and the Fuzzy Order Weighted Average (FOWA) MCDM methods. The MCDM methods identify the best water-supply management alternatives for climate-change adaptation.

Keywords Water evaluation and planning (WEAP) · Climate change adaptation strategies · Decision-making criteria · Multi-criteria decision making · VIKOR method · FOWA method

✉ Parisa-Sadat Ashofteh
ps.ashofteh@qom.ac.ir

Parvin Golfam
P.Golfam@stu.qom.ac.ir; golfam.parvin@gmail.com

Hugo A. Loáiciga
hloaiciga@ucsb.edu

1   Department of Civil Engineering, University of Qom, Qom, Iran

2   Department of Geography, University of California, Santa Barbara, CA 93016-4060, USA

1 Introduction

The topic of adaptation of water resources management to population growth and climate change has garnered widespread attention. Varanou et al. (2002) reported the regional impact of climate change on water quantity and quality issues in the Ali Efenti Basin in central Greece relying on the soil and water assessment tool (SWAT) model. Kundzewicz et al. (2006) analyzed future changes in precipitation and the duration of dry spells over the European continent. Krol et al. (2011) assessed the impacts of climate-change on the water availability in reservoirs of northeastern Brazil. Several studies have proposed water-resources adaptation strategies to climate change. Raskin et al. (1992) implemented the Water Evaluation and Planning (WEAP) model for simulating current water balances and evaluating water management strategies in the Aral Sea region. Farajzadeh et al. (2014) evaluated the impacts of climate change on water supply reliability and allocation in the Karkheh river basin, Iran. Choosing among alternative adaptation strategies is aided by multi-criteria decision-making (MCDM) methods. Tecle (1988) identified more than 70 decision-making methods. Denpontin et al. (1983) provided a list of decision-making methods and stated that creating a comprehensive framework for implementing these methods is challenging because decision making studies have broad diversity in terms of quality, quantity, and accuracy.

The use of MCDM methods for choosing optimal water management strategies has received in-depth attention in the field of water resources systems. Jaber and Mohsen (2001) proposed strategies and measures to alleviate and overcome water scarcity in Jordan. The latter authors implemented the Analytic Hierarchy Process (AHP) to conclude that water desalination was the most promising water resource, followed by water harvesting. Abrishamchi et al. (2005) managed the urban water system of the City of Zahidan, Iran, employing compromise programming. Their results revealed compromise programming identified suitable and comprehensive urban water management plans. Kim and Chung (2014) introduced an index-based robust decision-making framework for watershed management under climate change. Their framework considered the uncertainty inherent in climate models and climate change scenarios employing the minimax regret strategy. The latter authors applied their framework to an urban watershed in Korea. Studies show that so far, other research has not been conducted using two methods of decision making of VIKOR and FOWA in water resources management in order to prioritize and choose the best adaptation strategy for climate change. However, the VIKOR multi-criteria decision-making method has been used in other management fields, such as selection of material (Jahan et al. 2011), improving the quality of airline services in Taiwan (Liou et al. 2011), choosing the best fiber concentration in food systems (Ansarifar et al. 2019), selection of materials for the repair of concrete structures (Kiani et al. 2018), prioritizing strategic environmental assessment (SEA) alternatives in the long-term plan for building a dam in Korea (Kim et al. 2015), selection of renewable energy project (Cristóbal 2011), prioritization of land use conservation strategies in the reservoir basin (Chang and Hsu 2009).

In the present study, the aim is to find the best strategy to adapt to the phenomenon of climate change in the Aidoghmoush basin in East Azerbaijan province in Iran. Because the agricultural sector is the largest water user in the basin, climate change adaptation scenarios have been developed for this area. In order to rank and select the best strategy to adapt to the phenomenon of climate change, a powerful multi-criteria decision tool was used. In this study, two methods of decision making, VIKOR and FOWA were applied. This work introduces an approach for selecting sustainable cropping pattern under climate change conditions. The

approach is applied to the agricultural regions downstream of Aidoghmoush reservoir in East Azerbaijan province, Iran. Climate-change projections are made for the period 2040–2069. Cropping patterns are vetted using the WEAP model leading to the calculation of decision-making indexes. The VIKOR and FOWA MCDM methods are implemented to select the optimal agricultural management strategy under climate-change conditions.

2 Methodology

This paper presents a methodology for selecting the water-resources management policies in semi-arid regions to cope with climate change. Five climate-change adaptation scenarios are defined, and the WEAP model is implemented to simulate the scenarios in 2040–2069 and to calculate the values of seven decision-making criteria. The VIKOR and FOWA decision-making methods were implemented to vet the adaptation scenarios (the management alternatives) and the decision-making criteria. This paper's methodology is depicted in Fig. 1.

2.1 Climate Projections and Impacts on Water Resources and Agricultural Water Consumption

Projections of surface air temperature and precipitation in the study area were made with the HadCM3 climatic model employing the A2 scenario of greenhouse gases emissions (International Panel on Climate Change, IPCC 2007). The temperature and precipitation projections were downscaled to the basin scale with the method of temperature differences and precipitation ratios of Wilby and Harris (2006) aided by measurements of temperature and precipitation made during the baseline interval (1971–2000) (see also, IPCC-TGCIA 1999). The downscaled temperature and precipitation projections were input to the IHACRES hydrologic model to simulate runoff, and to calculate crops consumptive use (of water) with the CROPWAT model. The results of the climate projections and agricultural consumptive use in the study area were reported by Ashofteh (2015). Those projections indicate the temperature in the Aidoghmoush basin would increase in the future period (2040–2069) from 1.7 to 3.9 °C in comparison with the baseline period (See Table 1). Also, the range of rainfall variations in the future period would be between −39 and 28% relative to the baseline period (Table 1). This means the
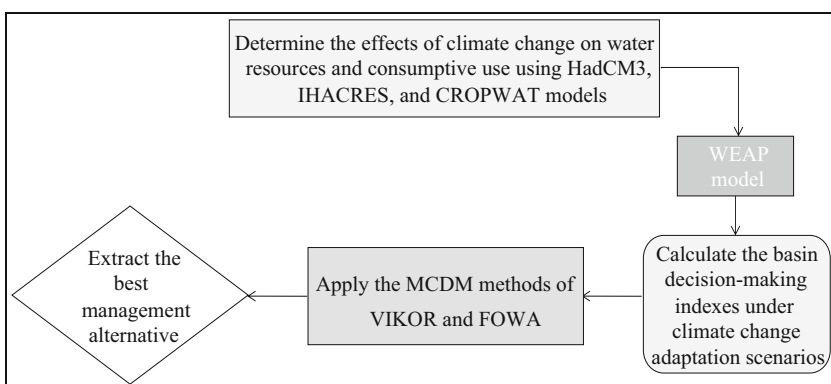

Fig. 1 The flowchart of the proposed methodology

Table 1 Climate change scenario for temperature and rainfall from HadCM3 model under A2

Month	$\Delta T(°C)$	ΔP (%)
Jan	2.4	13.0
Feb	1.8	−1.3
Mar	1.9	21.2
Apr	2.5	−2.9
May	2.3	−18.3
Jun	3.0	−37.0
Jul	3.6	−21.4
Aug	3.9	−39.4
Sep	3.1	−29.5
Oct	2.9	3.8
Nov	1.7	28.7
Dec	1.8	14.5

average monthly long-term temperature in the future period is about 23% higher than in the baseline period. The average monthly long-term precipitation in the future period would be about 12% lower than in the baseline period. The average monthly long-term inflow into the reservoir during the future period would be reduced by about 25% relative to the baseline period (See Fig. 2). The average annual volume of water demand in the future period would increase by about 20% compared to the baseline period (Fig. 2). The increasing future water demand calls for reservoir operation adaptive to a changing climate.
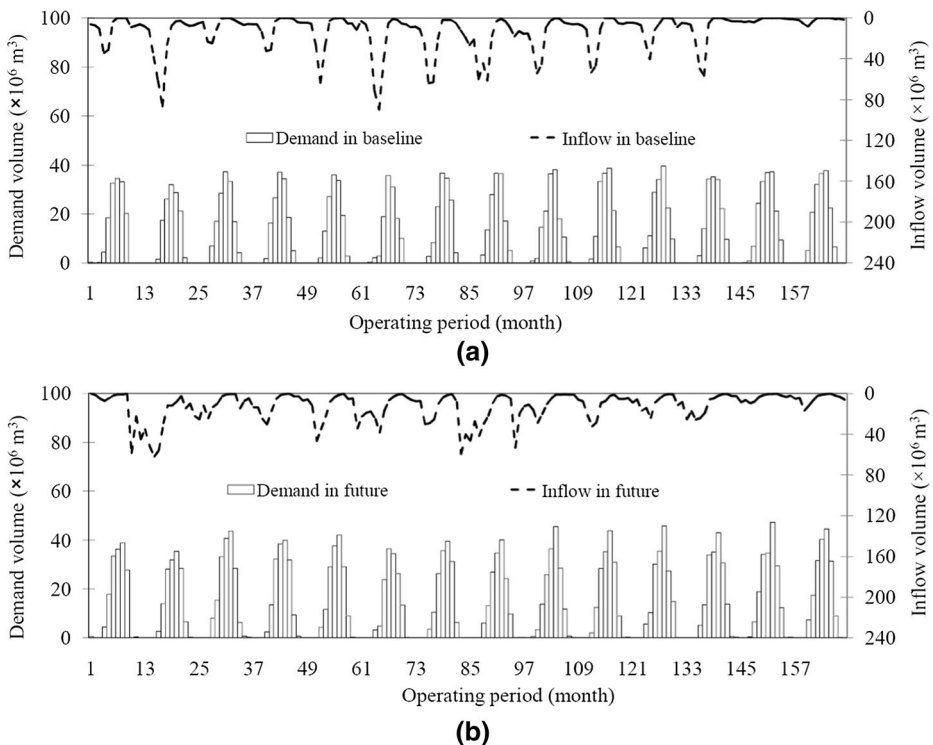

Fig. 2 Comparison of inflow and demand for period of **a** baseline and **b** futures

2.2 Integrated Water Resources Management with the WEAP Model

The WEAP simulation model (Sieber et al. 2005) is implemented to assess the performance of the water supply system under current conditions and in the future period of analysis influenced by climate change. The WEAP model is an integrated water resources planning and management tool with which to evaluate water policies. The features of this model are comprehensiveness, capability to evaluate policies based on cost, benefit, and environmental indexes, capability for data exchange with other software, and capability to create water plans tailored to the needs of the user. The WEAP model operates based on the equations of water balance. The WEAP model is a type of decision support system (DSS) that can implement standard operating policies (SOPs) to reservoir operation.

2.3 Decision-Making Criteria

The long-term planning results obtained with the WEAP model are quantified in the form of decision-making criteria. These criteria vary according to the type of problem being solved. The vulnerability, time reliability, resilience and sustainability of the water-supply system are frequently used criteria in reservoir operation studies. In addition to the four cited criteria this work quantifies the volume reliability, index of supply to demand, and availability criteria. The Appendix presents the equations for the decision-making criteria expressed in terms of quantitative indexes.

2.4 MCDM Models

Decision-making methods are classified as Multi Objective Decision-Making (MODM) and Multi Attribute Decision-Making (MADM) methods. The MODM methods select Pareto fronts to satisfy multiple objectives. MADM methods select the best alternative among proposed alternatives and are commonly used in management studies. There are numerous MCDM methods. This work implements the VIKOR and FOWA methods to determine the best alternative for managing water supply systems under climate-change conditions.

2.5 The VIKOR Method

Opricovic (1998) introduced the VIKOR method for solving problems in discrete spaces with conflicting and sometimes contradictory criteria. VIKOR is the Serbian acronym for multi-criteria optimization and compromise resolution. This method focuses on grouping and selecting management alternatives from a set of alternatives, and it finds compromise solutions for a problem with diverse criteria. The compromise solution is the closest solution to the ideal solution (see Fig. 3 for depiction of ideal and compromise solutions). The steps of the VIKOR method are described below.

2.6 Calculation of the Decision Matrix Based on Criteria and Alternatives

A decision matrix is formed taking into account n criteria and m management alternatives. The decision-making matrix is calculated in normalized form with Eq. (1):

$$f_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \quad i = 1, 2, \cdots, m; \; j = 1, 2, \cdots, n \tag{1}$$
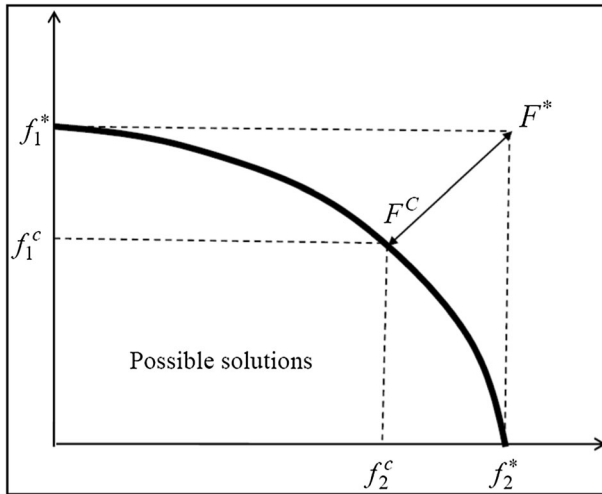
Fig. 3 The difference between the ideal (F^*) and the compromise (F^C) solutions (VIKOR method)

in which, x_{ij} = performance of alternative i according to criterion j; and f_{ij} = ith, jth element of the normalized decision matrix.

2.7 Determination of the Best and Worst Criteria Values

The best (worst) value of a criterion that represents a benefit (say, agricultural revenue) is its largest (smallest) value. The opposite holds true for a criterion that reduces benefit, such as a production cost, i.e., its best (worst) value is its smallest (largest) value. The best and worst values of a criterion representing a benefit are calculated with the following equations:

$$f_j^* = maximum\left(f_{ij}, i = 1, 2, \cdots, m\right) \quad j = 1, 2, \cdots, n \tag{2}$$

$$f_j^- = minimum\left(f_{ij}, i = 1, 2, \cdots, m\right) \quad j = 1, 2, \cdots, n \tag{3}$$

in which, f_{ij} = the ith, jth element of the weighted normalized matrix; f_j^* = the best value of criterion j; and f_j^- = the worst value of criterion j.

2.8 Determination of Two Normalized Distances

The VIKOR method defines a normalized (group utility) distance as follows:

$$S_i = \sum_{j=1}^{n} W_j \cdot \frac{f_j^* - f_{ij}}{f_j^* - f_j^-} \quad i = 1, 2, \cdots, m \tag{4}$$

in which W_j = weights of criteria expressing the decision makers' preferences in terms of the relative importance of the criteria that can be assigned with the analytic hierarchy process (AHP) or using Shannon's entropy. The minimum and maximum values of the normalized

distances defined by Eq. (4) are denoted by S^* and S^-, respectively. The minimum S_i represents the maximum utility for the majority of decision makers.

The VIKOR method defines a normalized individual (regret) distance as follows:

$$R_i = maximum \left[W_j \cdot \frac{f_j^* - f_{ij}}{f_j^* - f_j^-} \right] \quad i = 1, 2, \cdots, m \tag{5}$$

The minimum and maximum values of the normalized distance defined by Eq. (5) are denoted by R^* and R^-, respectively. The minimum R_i expresses the smallest individual regret of an opponent to the water management alternatives.

2.9 Calculation of the VIKOR Index

The VIKOR index is calculated with the following equation:

$$Q_i = J \cdot \left[\frac{S_i - S^*}{S^- - S^*} \right] + (1 - J) \cdot \left[\frac{R_i - R^*}{R^- - R^*} \right] \quad i = 1, 2, \cdots, m \tag{6}$$

in which J = weight representing maximum group utility (in the range [0, 1]).

2.10 Determination of the Best Management Alternative

The management alternatives are ranked sorting by the values S [group utility given by Eq. (4)], R [individual regret given by Eq. (5)], and Q [VIKOR index given by Eq. (6)] in ascending order. These produce three ranking lists. Propose as a compromise solution the alternative A_1 which is the best ranked by the measure Q (minimum) if the following two conditions are satisfied:

(a) Acceptable advantage: If alternatives A_1 and A_2 are respectively ranked first and second bests according to the VIKOR index the following equation must hold:

$$Q(A_2) - Q(A_1) \geq \frac{1}{m-1} \tag{7}$$

in which $Q(A_1)$ and $Q(A_2)$ = the VIKOR indexes of alternatives A_1 and A_2, respectively.

(b) Acceptable stability: alternative A_1 must also be the best ranked according to the measures of utility (S) and regret (Q).Alternatives A_1 and A_2 are both chosen as best if one or both of conditions (a) and (b) are not met.

2.11 The Fuzzy Ordered Weighted Averaging (FOWA) Method

This method was introduced by Yager (1993). The FOWA is applied in group decision-making to reach consensus among expert opinion makers. The FOWA calculates weights for management alternatives as follows (Yager 1993):

$$w_j = F \cdot \left(\frac{j}{n} \right) - F \cdot \left(\frac{j-1}{n} \right) \quad j = 1, 2, \cdots, n \tag{8}$$

in which, j = index (decision-making criterion) number; n = number of indexes; w_j = weight of index j; and F = linguistic quantifier. The linguistic quantifier measures fuzzy majority. It is computed as follows:

$$F(r) = \begin{cases} 0 & r < a \\ \frac{r-a}{b-a} & a \le r \le b \\ 1 & r > a \end{cases} \tag{9}$$

in which, (a, b) = quantifier domain. The (fuzzy) linguistic quantifier F may be "at least half", "maximum", or "as far as possible", which correspond to the ranges (0, 0.5), (0.3, 0.8), and (0.5, 1), respectively, and indicate respectively decision-makers who are optimistic, have neutral opinion, or are pessimistic about a management alternative. The argument r is supplied by decision makers. The weights in Eq. (8) are calculated and they multiply the elements of the normalized criteria matrix [see Eq. (1)]. The cumulative values are calculated for each management alternative. The quality of alternatives increases with increasing cumulative value. This procedure is illustrated in the Section 4.

The FOWA operator is a developed OWA operator that uses fuzzy numbers to consider the uncertainty of the data. If Ψ is a set of fuzzy numbers the mapping of the FOWA operator with the dimension n is as follows:

$$FOWA : \ \psi^n \rightarrow \psi \tag{10}$$

The weighted vector related to w has dimension n [see Eqs. (11) and (12)]:

$$w_j \in [0, 1], \quad \sum_{j=1}^{n} w_j = 1 \tag{11}$$

$$FOWA\left(\tilde{a}_1, \tilde{a}_2, ..., \tilde{a}_n\right) = \sum_{j=1}^{n} w_j b_j \tag{12}$$

in which, $\tilde{a}_i$ = Fuzzy numbers, and b_j = the j-th largest value of the $\tilde{a}_i$.

3 Study Area, Creation of Adaptation Scenarios

The section describes the study area and climate scenarios.

3.1 The Study Area

Figure 4 show the study area (the Aidoghmoush basin) in East Azerbaijan province in northwestern Iran (Ashofteh et al. 2015, 2017). The Aidoghmoush River flows into the Ghezelozan River. Characteristics of the basin, reservoir, and its downstream irrigation network are listed in Table 2.

3.2 Adaptation Policies to Climate Change

The agricultural sector is the main water user in the study area. The effects of climate change on the agricultural sector are not limited to water supply. They impact crops
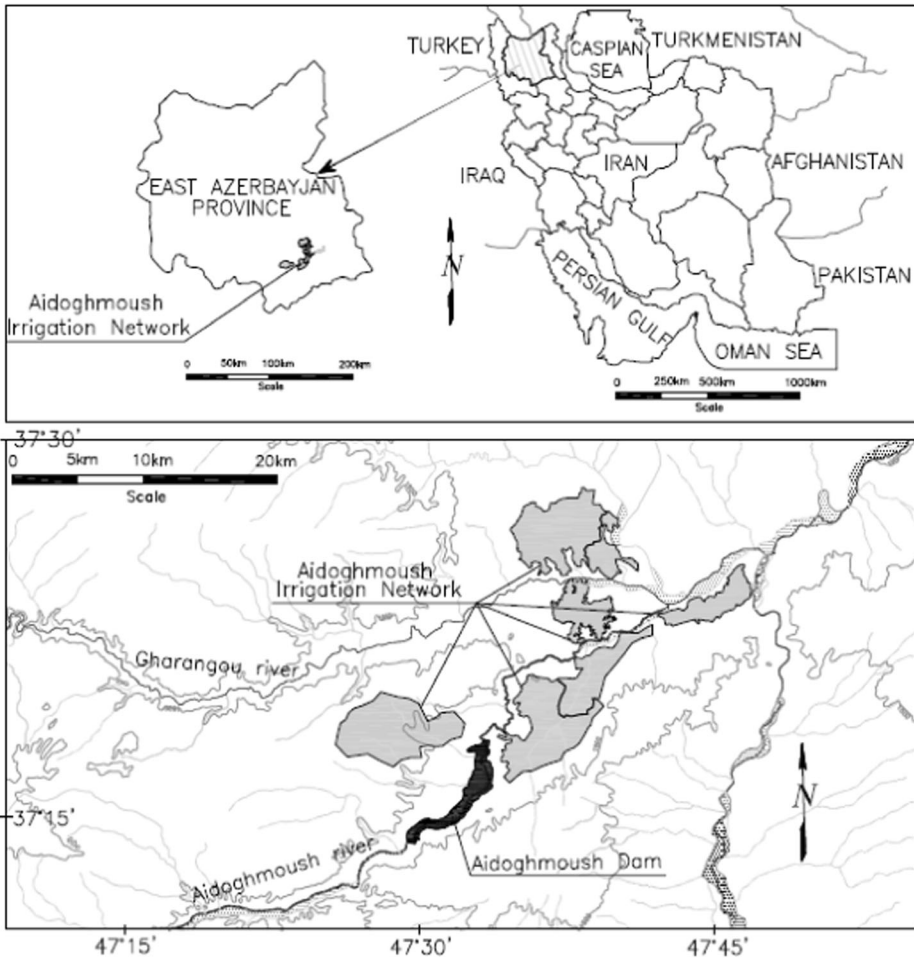
Fig. 4 Study area

Table 2 Basin, reservoir, and downstream irrigation network characteristics

Basin characteristic	Information
Geographic profile and area	Longitude = 46º 52′ to 47º 45′ (east)
	Latitude = 36º 43′ to 37º 26′ (north)
	Basin area = 1802 km^2
Ruggedness index	Maximum elevation = 3605 m
	Minimum elevation = 1043
	Maximum slope = 36.5%
	Minimum slope = 0.2%
Aidoghmoush reservoir	Normal level = 1341.5 m
	Useful volume = 137 (10^6 m^3)
	Dead volume = 7.8 (10^6 m^3)
	Total Capacity = 145.7 (10^6 m^3)
	Annual discharge = 190 (10^6 m^3)
Downstream reservoir network	Area under cultivation = 13,500 ha
Number of meteorology stations	Rain gauges = 11
	Climatology = 1
	Synoptic = 1

under cultivation insofar as growth and yield are concerned. The agricultural sector is one of the main contributors to economic productivity in the study area. This work assessed adaptation strategies corresponding to five scenarios of agricultural water use modification. The first, second, third, fourth, and fifth scenarios correspond to reducing water use by 4, 9, 13, 18, and 23% relative to the baseline condition, which consider climate-change adaptation. The five water-reduction scenarios and their corresponding cropping patterns are displayed in Fig. 5. This study does not address the economic value of crops. Rather, this paper focuses on matching of irrigation water requirement with available water resources. The values of the criteria at the baseline time interval (without climate change) are listed in Table 3.

4 Results and Discussion

4.1 Results of the WEAP Model

The average annual volume of water consumption in the climate change period was calculated to be 19% larger than in the baseline period downstream of the Aidoghmoush reservoir. At the same time the water resources under climate change would decrease by 23% compared to the baseline period. This suggests future water resources would be inadequate, and the basins water system would face water shortages. Adaptation must be made to confront the impending water scarcity. Figure 6 shows the long-term monthly water demand in the climate change period corresponding to the five water-use scenarios. Figure 6 also displays the agricultural water use without applying adaptive strategies. Figure 5 indicates the volume of agricultural water consumption associated with climate change without applying adaptation strategies would be the largest. The long-term average monthly water consumption in the climate change period would be 15.5 ($\times10^6$ m³) without adaptation. This compares with long-term average monthly water consumption in the baseline period equal to 13.1 ($\times10^6$ m³). Declining reservoir inflow

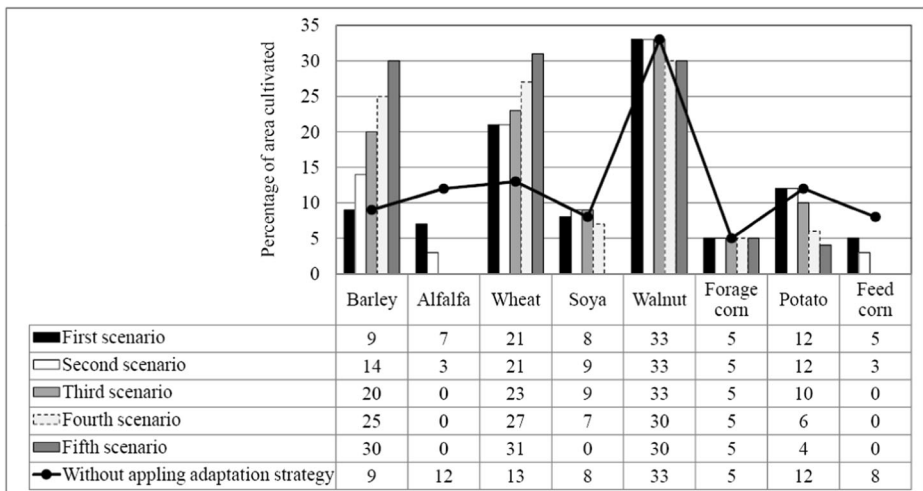|	Barley	Alfalfa	Wheat	Soya	Walnut	Forage corn	Potato	Feed corn
■ First scenario	9	7	21	8	33	5	12	5
☐ Second scenario	14	3	21	9	33	5	12	3
▦ Third scenario	20	0	23	9	33	5	10	0
▨ Fourth scenario	25	0	27	7	30	5	6	0
▦ Fifth scenario	30	0	31	0	30	5	4	0
●— Without appling adaptation strategy	9	12	13	8	33	5	12	8

Fig. 5 Water-reduction scenarios and corresponding cropping patterns

Table 3 Comparison of calculated decision-making criteria corresponding to water-use scenarios

Scenario	Criterion (%)						
	Time reliability	Vulnerability	Resiliency	Sustainability	Volume reliability	Availability	Supply to demand
At the baseline	92	4	43	38	86	89.2	86
Without adaptation strategy	76	11	29	19	64.6	72.5	64.6
Applying the first adaptation scenario	79	10	33	23	65.1	75.8	65.1
Applying the second adaptation scenario	80	9	34	25	68	77.5	68
Applying the third adaptation scenario	82	8	35	26	71.2	78.6	71.2
Applying the fourth adaptation scenario	83	7	35	27	74.4	80.3	74.4
Applying the fifth adaptation scenario	86	6	33	28	77.8	84	77.8

necessitates adaptation by reducing long-term average monthly demand by 14.8, 14.1, 13.3, 12.6 and 11.9 ($\times 10^6$ m^3) according to scenarios 1, 2, 3, 4, and 5, respectively. These volumes of water correspond to 4, 9, 13, 18, and 23% reduction of baseline crop water consumption, respectively.

4.2 Comparison of Decision-Making Criteria

Values of the decision-making criteria were calculated with the WEAP model and are listed in Table 3. Figure 7 shows the calculated changes in decision-making criteria during 2040–2069 without and with adaptation scenarios. Table 3 and Fig. 4 indicate
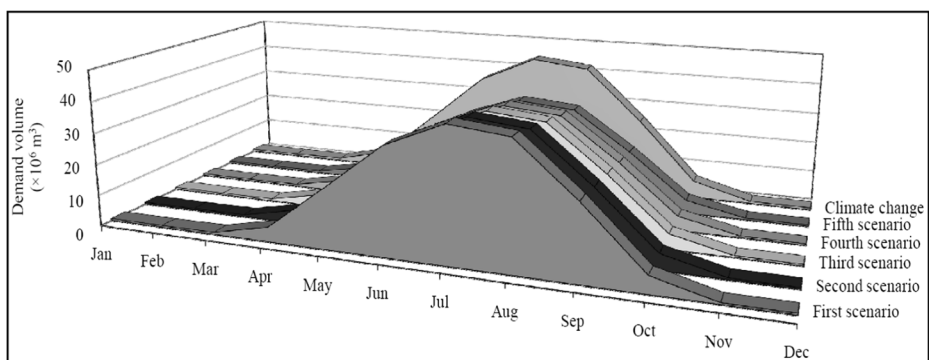

Fig. 6 Comparison of the volume of water demand with and without adaptation strategies under five scenarios under climate change
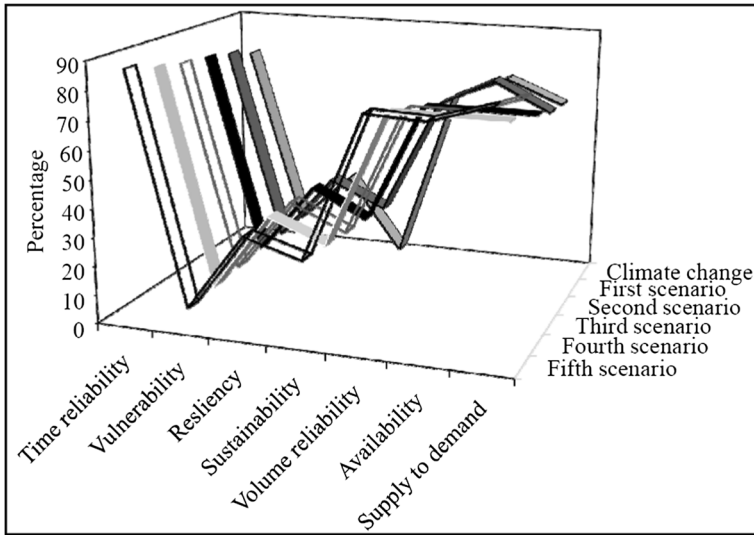
Fig. 7 Changes in decision-making criteria with and without adaptation strategy under climate change

the decision-making criteria feature the worst values without adaptation strategy, and they improve as the amount of water demand decreases with increasing scenario number. It is evident the decision-making criteria would improve during the climate change period by applying adaptation scenarios to climate change, which reduce the agricultural demand. Table 4 lists the change in the values of the decision-making criteria caused by the adaptation strategies corresponding to the five water-reduction scenarios. The changes shown in Table 4 reaffirm the gains that would be produced by the adaptation scenarios relative to the "do nothing" policy.

4.3 Results of the VIKOR Method

Table 5 list the results for the VIKOR method for each adaptation scenario. It is seen in Table 6 the VIKOR values (group utility, individual regret, and VIKOR index) improve, that is, become smaller, as the reduction of agricultural water demand increases with increasing with scenario number. The values of the VIKOR index listed in Table 5 were

Table 4 Criteria change with application of adaptation strategies and without application of adaptation strategies

Scenarios	Criterion (%)						
	Time reliability	Vulnerability	Resiliency	Sustainability	Volume reliability	Availability	Supply to demand
First	+4	−2	+13	+19	+1	+4	+1
Second	+6	−10	+18	+27	+5	+6	+5
Third	+8	−19	+19	+32	+10	+8	+10
Fourth	+10	−28	+20	+37	+15	+10	+15
Fifth	+14	−37	+15	+39	+20	+15	+20

Positive and negative signs indicate an increase and decrease of the decision-making criteria, respectively

Table 5 Regret and utility index value calculated with the VIKOR method

Scenarios	Regret index (R)	Utility index (S)	Combination of indexes of utility and regret (Q)
First	0.66	1.54	1
Second	0.495	1.24	0.77
Third	0.33	0.87	0.52
Fourth	0.165	0.48	0.26
Fifth	0.026	0.026	0

calculated with $J = 0.5$in Eq. (7). The VIKOR index constitutes the overall ranking of scenarios. It is seen in Table 5 the fifth scenario (i.e., reduction of water consumption by 23%) has the lowest index Q and it is therefore, the best strategy for climate-change adaptation.

Figure 8 displays the values of the group utility (S), individual regret (R), and VIKOR index (Q) corresponding to the five scenarios of water reduction. Figure 8 affirms the findings listed in Table 5: the quality of the alternatives or scenarios increases with increasing number of scenario. Scenario 5 being the best alternative in this case with $Q = 0$.

4.4 Results of the FOWA Method

The weights of the decision-making criteria or indexes were calculated with Eqs. (8) and (9) and are listed in Table 6. The weights multiplied the elements of the normalized criteria matrix and the cumulative values for the five scenarios or management alternatives were calculated. They are listed in Table 7. These results show improving quality of the scenarios with increasing scenario number.

The results of the FOWA method are displayed in Fig. 9. The cumulative value obtained corresponding to optimistic ("at least half"), neutral ("maximum"), and pessimistic ("as far as possible") decision makers were obtained. The fifth scenario (23% reduction in water consumption) achieved the highest cumulative value among all scenarios, thus being the best adaptation strategy to cope with climate change.

5 Concluding Remarks

Adaptation to climate change is essential to sustain agriculture in semiarid countries, Iran being a case in point. The HadCM3 climatic model was applied with the A2 GHG

Table 6 Weights of criteria corresponding to linguistic quantifiers

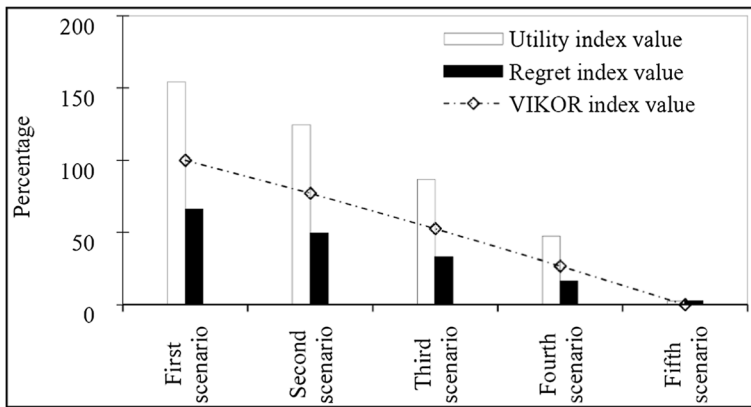| Criteria	At least half (0 and 0.5)	Maximum (0.3 and 0.8)	As far as possible (0.5 and 1)
Sustainability	0.25	0	0
Vulnerability	0.25	0	0
Resiliency	0.25	0.15	0
Time reliability	0.25	0.25	0
Volume reliability	1	0.25	0.25
Availability	0	0.25	0.25
Supply to demand	0	0.1	0.15

Fig. 8 Changes in group utility (S), individual regret (R), and VIKOR index (Q)

Table 7 Cumulative value of scenarios corresponding to linguistic quantifiers

Scenarios	At least half (0 and 0.5)	Maximum (0.3 and 0.8)	As far as possible (0.5 and 1)
First	0.34	0.13	0.09
Second	0.31	0.12	0.07
Third	0.40	0.16	0.14
Fourth	0.42	0.18	0.15
Fifth	0.67	0.28	0.17

The underline entries show improving quality of the fifth scenario

emission scenario to make climate projections of temperature and precipitation in the (future) period 2040–2069 within the Aidoghmoush basin, Iran. The IHACRES rainfall-runoff hydrologic model was implemented to calculate the runoff volume in the future interval (2040–2069) relying on temperature and rainfall projections. The results of IHACRES model indicate the average monthly reservoir inflow in the future period
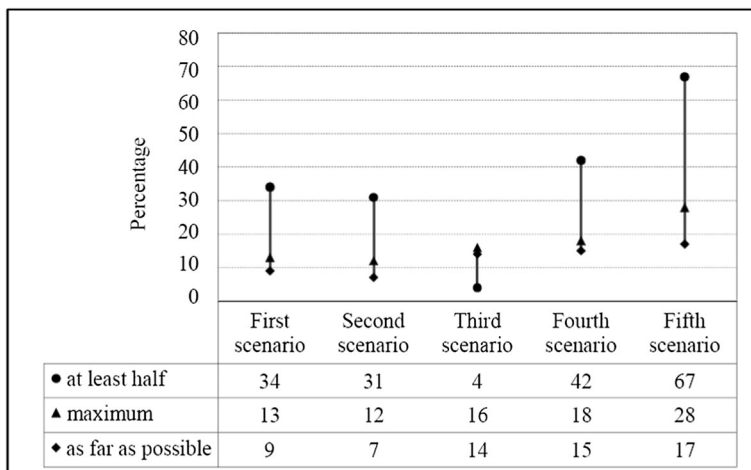

	First scenario	Second scenario	Third scenario	Fourth scenario	Fifth scenario
● at least half	34	31	4	42	67
▲ maximum	13	12	16	18	28
◆ as far as possible	9	7	14	15	17

Fig. 9 Results of the FOWA method

would decrease by 25% relative to the baseline time period. The CROPWAT model was applied with the climatic projections for the study area to calculate likely crop consumptive use in the future period. The CROPWAT results indicate the average annual water demand would increase by 20% compared to the baseline period.

Simulations with the WEAP model established the decision-making criteria in the future period without applying adaptation strategy would lead to substantially inferior performance compared with strategies for water demand reductions under climate change. Changing the crop pattern is one of the low-cost and effective adaptation strategies in counteracting the adverse effects of climate change. Five scenarios of future agricultural water demand reductions were entertained in this study. Each scenario is associated with a specific crop pattern. The VIKOR and FOWA decision-making were implemented and both provided similar rankings for the quality of climate-change management alternatives. The alternatives' qualities improve with declining future demand of agricultural water. This means scenario 5, which prescribes a 23% reduction in agricultural water demand, was found to be the best adaptation scenario while supporting a viable crop pattern.

The results of these two methods of decision-making show that despite the same conditions in weighting the criteria, the best alternative is different in two methods, which shows different approaches in each method; and decision makers according to the problem and characteristic of decision-making, can choose the most suitable method.

Compliance with Ethical Standards

Conflict of Interest None.

Appendix

Seven indexes, each corresponding to a decision criterion, are employed in this study. Their equations and intervening variables are presented in this section.

Time Reliability Criteria

This index measures the capacity of a reservoir system to satisfy downstream water demands (Hashimoto et al. 1982):

$$\alpha = \frac{N}{T} \tag{13}$$

$$N = \sum_{t=1}^{T} count(R_t \geq D_t) \tag{14}$$

where: α = time reliability index; N = the number of periods (months) in which the reservoir release is equal or greater than the downstream water demand (the number of satisfactory states); $count$ = a counting function (it counts periods when releases are equal to or larger than water demand during the operational period); D_t = the volume of downstream water demand in period t; R_t = the reservoir release in period t; T = the number of operational periods (number of months).

Vulnerability Index

This index measures the average volumetric severity of failure to meet downstream water demands by reservoir system releases (Hashimoto et al. 1982):

$$\nu = \frac{\sum_{t=1}^{N_D} |R_t - D_t|}{T \cdot D_{\max}} \tag{15}$$

in which ν = vulnerability index; $D_{\max}$ = the maximum water demand among all the monthly water demands in the operational period; N_D = the number of months in which the reservoir release is less than the downstream water demand, i.e., the summation on the right-hand side of Eq. (15) applies to reservoir releases and water demands in months such that $R_t < D_t$.

Resiliency Index

Measures how quickly a reservoir system recovers from a water-supply deficit (water-supply deficit is an unsatisfactory state whereby the monthly reservoir release is less than the downstream monthly water demand) to a situation whereby the monthly water release satisfies the monthly water demand (a satisfactory state) (this is a modified definition of resiliency of that by Hashimoto et al. 1982):

$$\beta = \frac{N^{'}}{N_D} \tag{16}$$

where β = resiliency index; $N^{'}$ = the number of months in which a satisfactory state occurs immediately after an unsatisfactory state; N_D = the number of months in which the reservoir release is less than the downstream water demand (this is the number of unsatisfactory states).

Sustainability Index

The sustainability index combines the reliability, vulnerability, and resiliency indexes and is defined by the following equation (Loucks 1997):

$$\gamma = \alpha\beta(1-\nu) \tag{17}$$

in which γ = sustainability index.

Supply to Demand Index

This index is a ratio of the actual water supply to the total water demand and is expressed as follows (ASCE 1998):

$$S = \frac{\sum_{t=1}^{T} Su_t}{\lambda} \tag{18}$$

$$Su_t = \begin{cases} D_t & if \ R_t > D_t \\ R_t - D_t & if \ R_t < D_t \end{cases} \tag{19}$$

$$\lambda = \sum_{t=1}^{T} D_t \tag{20}$$

where S = supply to demand index; Su_t = equals the water demand if the reservoir release exceeds the water demand in period t, otherwise it equals the reservoir release minus the water demand in period t; λ = the total volume of downstream water demand.

Volumetric Reliability

This index measures the volume of water supplied divided by the total water demand (McMahon et al. 2006):

$$R_V = 1 - \frac{\sum_{t=1}^{T}(D_t - R_t)}{\sum_{t=1}^{T} D_t} \qquad 0 \leq R_v \leq 1 \tag{21}$$

where R_V = volume reliability index.

Availability Index

This index estimates the probability of a reservoir system supplying the downstream water demand (Jiménez-Cisneros 1996):

$$\xi = prob[R_t \geq D_t | D_t > 0] \cong \frac{N}{N_0} \tag{22}$$

in which ξ = availability index; $prob$ = probability of release is more than demand, provided that demand is greater than zero; N = the number of periods in which the reservoir release equals or exceeds the water demand, given that the water demand is nonzero; N_0 = the number of months in which the water demand is nonzero.

References

Abrishamchi A, Ebrahimian A, Tajrishi M, Mariño MA (2005) Case study: application of multicriteria decision making to urban water supply. J Water Resour Plan Manag 131(4):326–335. https://doi.org/10.1061/(ASCE)0733-9496(2005)131:4(326)

American Society of Civil Engineers (ASCE) (1998) Sustainability criteria for water resources systems. (task committee on sustainability criteria, water resources planning and management division, ASCE and working group, UNESCO/IHP IV project M-4.3). ASCE, Reston

Ansarifar E, Shahidi F, Mohebbi M, Ramezanian N, Koocheki A, Mohamadian A (2019) Optimization of limonene microencapsulation based on native and fibril soy protein isolate by VIKOR method. LWT. https://doi.org/10.1016/j.lwt.2019.02.071

Ashofteh P-S (2015) Developing flexible strategies in water resources and consumption management for adaptation with climate change. Ph.D. dissertation, Dept. of Irrigation and Reclamation Engineering, University of Tehran, Karaj, Iran

Ashofteh P-S, Bozorg-Haddad O, Mariño MA (2015) Risk analysis of water demand for agricultural crops under climate change. J Hydrol Eng 20(4). https://doi.org/10.1061/(ASCE)HE.1943-5584.0001053

Ashofteh P-S, Bozorg-Haddad O, Loáiciga HA (2017) Development of adaptive strategies for irrigation water demand management under climate change. J Irrig Drain Eng 143(2):04016077. https://doi.org/10.1061/(ASCE)IR.1943-4774.0001123

Chang C-L, Hsu C-H (2009) Multi-criteria analysis via the VIKOR method for prioritizing land-use restraint strategies in the Tseng-Wen reservoir watershed. J Environ Manag 90(11):3226–3230. https://doi.org/10.1016/j.jenvman.2009.04.020

Cristóbal JRS (2011) Multi-criteria decision-making in the selection of a renewable energy project in Spain: the VIKOR method. Renew Energy 36(2):498–502. https://doi.org/10.1016/j.renene.2010.07.031

Denpontin M, Mascarola H, Spronk J (1983) A user oriented listing of MCDM. Revue Beige de Research Operationelle 23:3–11

Farajzadeh M, Madani K, Massah A, Davtalab R (2014) Climate change on reliability of water delivery in downstream Karkheh River basin and its adaptation strategies. Journal of Soil and Water Resources Conservation 3(3):49–63 (In Persian)

Hashimoto T, Stedinger JR, Loucks DP (1982) Reliability, resiliency and vulnerability criteria for water resources system performance evaluation. Water Resour Res 18(1):14–20

IPCC (2007) Climate change 2007 : mitigation. In: Davidson O, Swart R (eds) Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, p 881

IPCC-TGCIA (1999) Guidelines on the use of scenario data for climate impact and adaptation assessment. Version 1. Prepared by Carter, T. R., Hulme, M. and Lal, M. intergovernmental panel on climate change. Task Group on Scenarios for Climate Impact Assessment, 69 p

Jaber JO, Mohsen MS (2001) Evaluation of non-conventional water resources supply in Jordan. Desalination 136(1-3):83–92

Jahan A, Mustapha F, Yusof Ismail M, Sapuan SM, Bahraminasab M (2011) A comprehensive VIKOR method for material selection. Mater Des 32(3):1215–1221. https://doi.org/10.1016/j.matdes.2010.10.015

Jiménez-Cisneros B (1996) Water availability index based on quality and quantity: its application in Mexico. Water Sci Technol 34(12):165–172

Kiani B, Liang RY, Gross J (2018) Material selection for repair of structural concrete using VIKOR method. Case Studies in Construction Materials 8:489–497. https://doi.org/10.1016/j.cscm.2018.03.008

Kim Y, Chung E-S (2014) An index-based robust decision making framework for watershed management in a changing climate. Sci Total Environ 473-474:88–102

Kim Y, Park D, Um M-J, Lee H (2015) Prioritizing alternatives in strategic environmental assessment (SEA) using VIKOR method with random sampling for data gaps. Expert Syst Appl 42(22):8550–8556. https://doi.org/10.1016/j.eswa.2015.07.010

Krol MS, de Vries MJ, van Oel PR, de Araújo JC (2011) Sustainability of small reservoirs and large scale water availability under current conditions and climate change. Water Resour Manag 25(12):3017–3026

Kundzewicz ZW, Radziejewski M, Pinskwar I (2006) Precipitation extremes in the changing climate of Europe. Clim Res 31(1):51–58

Liou JJH, Tsai C-Y, Lin R-H, Tzeng G-H (2011) A modified VIKOR multiple-criteria decision method for improving domestic airlines service quality. J Air Transp Manag 17(2):57–61. https://doi.org/10.1016/j.jairtraman.2010.03.004

Loucks DP (1997) Quantifying trends in system sustainability. Hydrol Sci J 42(4):513–530

McMahon TA, Adeloye AJ, Zhou S-L (2006) Understanding performance measures of reservoirs. J Hydrol 324(1-4):359–382

Opricovic S (1998) Multi criteria optimization of civil engineering systems. Faculty of Civil Engineering, Belgrad, 2(1), 5-21

Raskin P, Hansen E, Zhu Z, Stavisky D (1992) Simulation of water supply and demand in the Aral Sea Region. Water Int 17(2):55–67

Sieber J, Swartz C, Huber-Lee A (2005) User guide for WEAP21. Stockholm Environment Institute Tellus Institute, Stockholm

Tecle A (1988) Choice of multi criterion decision making techniques for watershed management. Ph.D. Dissertation, University of Arizona

Varanou E, Gkouvatson E, Baltas E, Mimikou M (2002) Quantity and quality integrated catchment modeling under climate change with use of soil and water assessment tool model. J Hydrol Eng 7(3):228–244

Wilby RL, Harris I (2006) A framework for assessing uncertainties in climate change impacts: low flow scenarios for the riverThomes, U.K. Water Resour Res 42(2):W02419

Yager RR (1993) Families of OWA operators. Fuzzy Sets Syst 59(2):125–148. https://doi.org/10.1016/0165-0114(93)90194M