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Publication Date
2021-03-01

DOI
10.1016/j.envdev.2021.100612

Peer reviewed

Environmental Development 37 (2021) 100612

Contents lists available at ScienceDirect

Environmental Development

journal homepage: www.elsevier.com/locate/envdev

Modeling adaptation policies to increase the synergies of the water-climate-agriculture nexus under climate change

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ARTICLE INFO

Keywords:
Water-climate-agriculture nexus
Optimization
LINGO 18 model
Time reliability

ABSTRACT

The water-climate-agriculture nexus quantifies synergies, trade-offs, advantages and disadvantages that arise between water management, food production, and climate change consequences taking into account the environmental impacts, economic conditions, and population growth. This work evaluates the water-climate-agriculture nexus in the Gharanghu basin, Iran, seeking to achieve sustainable management of its water system. An optimization model solves for water-release adaptive strategies corresponding to five nexus scenarios to cope with reduced water resources under climate change. The scenarios are as follows (Afshar et al., 2006): change in cropping pattern (Asadieh and Afshar, 2019), reduction of areas under cultivation (Asgari et al., 2015), reuse of agricultural wastewater in irrigated land (Ashofteh et al., 2017), combination of scenarios (Afshar et al., 2006) and (Asgari et al., 2015), namely change in cropping pattern and reuse of agricultural wastewater simultaneously, and (Bates et al., 2008) integration of scenarios (Asadieh and Afshar, 2019) and (Asgari et al., 2015) namely, reduction of areas under cultivation and reuse of agricultural wastewater simultaneously. The nexus scenarios are evaluated with the time reliability index (the ratio of the number of months in which water is supplied to the total months of reservoir operation) based on changes in water supply and agricultural water demand. Results show the time reliability index in the climate change interval (monthly time series for the period 2040–2069) without implementing any nexus scenario equals 28%, and it increases with the implementation of the water-climate-agriculture nexus scenarios. The time reliability of the system equals 85% implementing scenario (Bates et al., 2008) (reducing the area under cultivation and reusing agricultural wastewater in irrigated land). The authors' previous research projects that climate change impacts in the study region would be severe. This paper's findings provide water managers and planners with useful strategies for optimal reservoir operation that rely on decreasing water demand and increasing water supply. The approach introduced and applied in this study, which develops modeling adaptation policies to increase the synergies of the water-climate-agriculture nexus, is applicable to other basins.

1. Introduction

A key challenge concerning water supply in the coming years is population growth. The United Nations estimated the world's population at 7.3 billion in 2015 (United Nations, 2015), and is projected to be about 8.3 billion by 2030, meaning that about 6 million

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https://doi.org/10.1016/j.envdev.2021.100612
Received 7 May 2020; Received in revised form 15 January 2021; Accepted 6 February 2021
Available online 19 February 2021

people are added to the world's population every month. The growing world population will demand increased food production with concomitant rise in water and energy use, and altering land use for food supply. The Food and Agriculture Organization (FAO) (2012) predicts a large number of people will face water shortages by 2025. Also, water and food demand by 2030 will rise 40 and 35%, respectively [United States National Intelligence Council (US NIC), 2012]. This will increase the pressure for more food production, especially in water-scarce regions, requiring more water and energy use and improved protection of agricultural lands for food supply. Food securing requires protecting agricultural lands. Such protections involve preserving fertile soil, repelling pests, and adapting to and mitigating climate change impacts. Achieving food security requires policy and decision making and investment in the human, water, natural resource, agricultural research, and rural infrastructure sectors (Rosegrant and Cline, 2003). Water is a resource sensitive to climate change as it is a central determinant of the quality of life and ecosystems health (Sadoff and Muller, 2009). Climate change also affects the agricultural sector by increasing water demand, altering crop fertility, and by reducing the available water in areas that are in dire need of irrigation (FAO, 2011). The importance of securing water resources and protecting agricultural lands calls for mitigating the adverse effects of climate change. The nexus concept considers the reciprocal interactions between water and agriculture to achieve agricultural and water security exercising scientifically-based management.

Several studies have been reported concerning the effects of vital resources on human well-being. Many studies have been conducted about different aspects of the nexus, such as the water-food security nexus depending on water pricing, energy production, virtual water provision, and water quality (Gulati et al., 2013), adapting the energy-water-food security nexus in the Hindu Kush Himalayan region to assess the adaptive responses to climate change (Rasul and Sharma, 2015). Endo et al. (2017) stated that achievement of water-food security must rely on reducing water consumption and increasing the efficiency of water resources. Berardy and Chester (2017) simulated a food-energy-water model management in Arizona to evaluate the impacts of rising temperature on water and energy supplies. Ehteram et al. (2018) projected that water releases in the future (2011–2030) would be less than in the baseline (1981–2000) period under climate change in Dez basin, Iran. Mortada et al. (2018a,b) presented a model for optimal water resources allocation under nutritional, socio-economic, agricultural, environmental, and natural resources constraints. Zhang et al. (2018) optimized water-food-energy nexus for developing an effective agricultural drought management in Nebraska, USA. Li et al. (2019a) implemented the optimal Agricultural Water-Energy-Food Sustainable Management (AWEFSM) model to manage water-energy-food nexus in the Heihe river basin, China. Wicaksono et al. (2019) proposed an optimization module (WEFSiM-opt) linked to the WEF nexus simulation model (WEFSiM) to maximize the User reliability index (URI) for water, energy, and food in Korea. Zheng et al. (2019) modeled the water-energy-food nexus during 1996–2015 in the Yangtze River basin, China. Li et al. (2019) optimized water-energy-food nexus under uncertainty in Fujin city, China to maximize economic benefits and minimize environmental impacts. Laspidou et al. (2020) determined strong resource inter-linkages and nexus hotspots through the water-energy-food-climate nexus in Greece. Li et al. (2020) implemented the Environmental Input-Output (EIO) model to calculate sectoral embodied energy, CO_2 emissions, and Water (ECW). Embodied ECW, the proportion of direct ECW, and their changes were applied to unravel the ECW nexus.

This paper's objective is modeling the nexus scenarios for water use. The model is implemented and demonstrated in the Gharanghu basin of East Azerbaijan province, Iran. The authors' previous research on the status of water resources in the study region

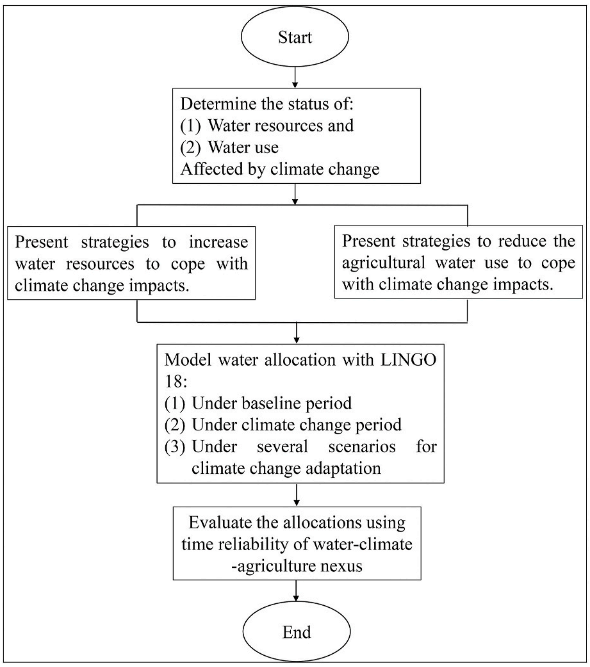


Fig. 1. The flowchart of this paper's methodology.

affected by climate change serves as background for an optimization model that minimizes the water-supply deficits under baseline (monthly time series of 1971–2000) and climate-change (2040–2069) periods. Water supply and use are assessed in 1971–2000 [based on the recommendation of the national meteorological organization (WMO) (IPCC-TGCIA, 1999)], and 2040–2069. Five water-climate-agriculture nexus scenarios are evaluated, namely (Afshar et al., 2006): changing crop pattern (Asadieh and Afshar, 2019), reduction of cultivation area (Asgari et al., 2015), reuse of agricultural wastewater for irrigation of the cultivation area (Ashofteh et al., 2017), combination of the changing crop pattern and reuse of agricultural wastewater (Bates et al., 2008), combination of the reduction of area under cultivation and reuse of agricultural wastewater. The time reliability index of water supply-agricultural water demand of the Gharanghu basin is calculated and analyzed for each scenario.

The nexus scenarios applicability varies depending on basin conditions, and on how well they would be managed in the context of climate change. The main objective in the Gharanghu basin is to supply agricultural water with the Gharanghu reservoir. This objective is imperiled by climate change due to increased water demand. It would be possible to change the cultivation pattern and reduce the crops' areas under cultivation in the study basin to cope with the increase in water demand under climate change. It is also possible to reuse agricultural wastewater as a suitable strategy to cope with the reduction in water resources under climate change in the study region. The choice of a pertinent scenario depends on specific regional conditions, social, and technical characteristics.

2. Methods and materials

The optimized allocation of water resources to agriculture under climate change and baseline conditions was herein assessed in the study area with the LINGO 18 optimization model. Adaptation policies to cope with the water-climate-agriculture nexus were modeled with LINGO 18. Lastly, each adaptation scenario was evaluated by means of the time reliability index of the water-climate-agriculture nexus. Fig. 1 shows the flowchart of this paper's methodology.

The study area.

2.1. Data and information of study area

The Gharanghu basin in the East Azerbaijan province in Iran constitutes the case study (Fig. 2). The geographical area of this region is placed within northern latitudes from 37° and 18′ to 37° and 45′, and eastern longitude from 46° and 26′ to 47° and 44′, adjacent to the Caspian Sea basin. The Gharanghu basin's area equals 3950 km^2. The main river of this basin is the Gharanghu River with an

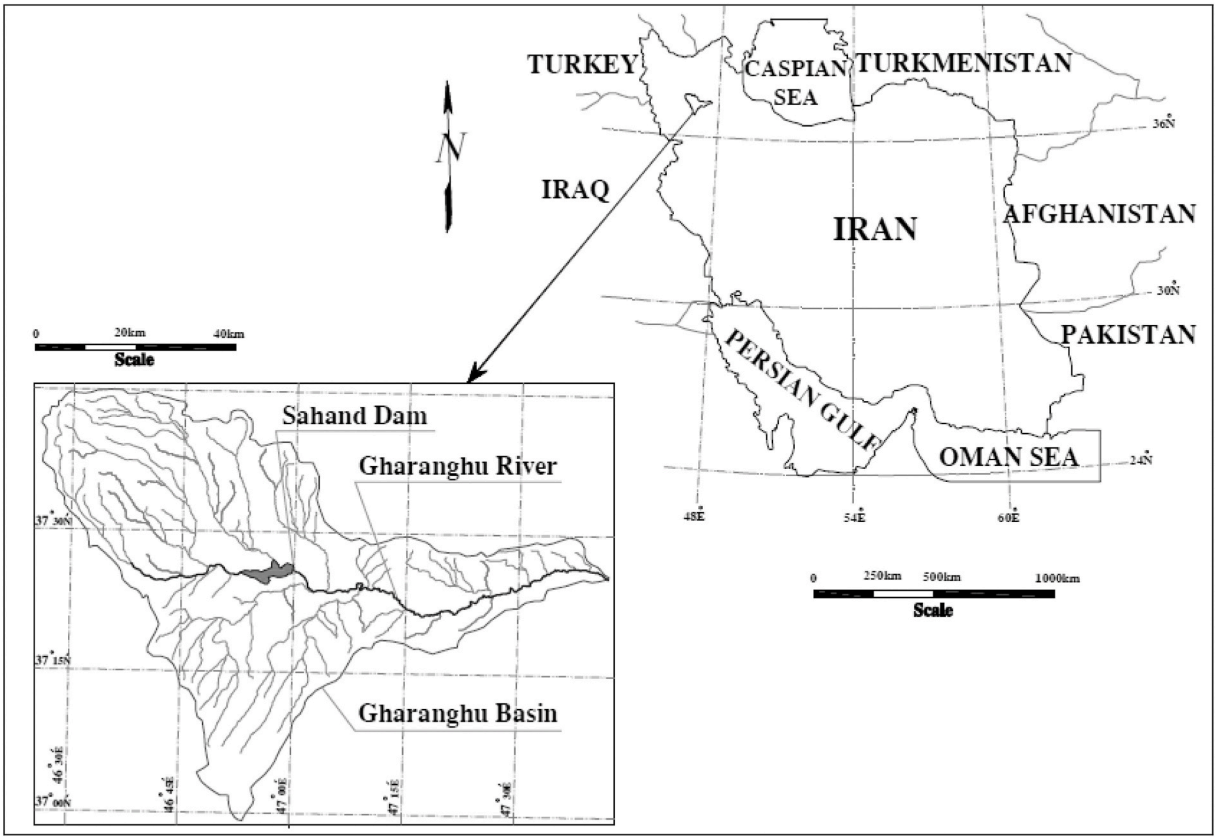


Fig. 2. Location of the Gharanghu basin.

approximate length of 120 km aligned in an east to west direction (Ashofteh et al., 2017).

The water supply system centers around the Sahand multi-purpose reservoir which provides irrigation water for 14,500 ha (1 ha = 1 ha = 10^4 m^2) of land cultivated downstream the reservoir, and water supplies for domestic, industrial, and environmental sectors equaling respectively 3, 3, and 5 × 10^6 m^3 annually. The total capacity of the Sahand reservoir equals 165 × 10^6 m^3, including 135 × 10^6 m^3 and 17 × 10^6 m^3, useful and dead capacities, respectively.

Crops cultivated in the Gharanghu basin are Wheat, Barley, Alfalfa, Soya, Forage corn, Feed corn, Potato, and Walnut. These crops occupy 12, 8, 12, 8, 5, 8, 12, and 35%, respectively of the cultivated area. .

The authors' previous research on the changes in surface temperature and rainfall within the study basin have shown the average monthly long-term temperature and rainfall under climate change would increase and decrease about 23 and 12% relative to the baseline interval, respectively (Ashofteh et al., 2017). Simulations of climatic variables were previously done by Ashofteh et al. (2017) employing the HadCM3 model (under greenhouse gases concentration pathway A2). The maximum average temperature would occur in August, and the minimum average rainfall would be in July. Also, these authors' previous research on the status of resources and consumers of water in the study region affected by climate change projected the river inflow to the Sahand reservoir and downstream water demand would decrease and increase about 25 and 20%, respectively, relative to the baseline interval due to climate change effects (Ashofteh et al., 2017) (Fig. 3). Simulations of the status of water resources and water uses in this study region were previously reported by Ashofteh et al. (2017) with the IHACRES hydrologic model and the CROPWAT model for crop water use, respectively. The cited projections indicate the Gharanghu basin would face heightened water stress in the summer season, and the agricultural sector as the largest water consumer must adapt to achieve higher water productivity and agricultural production. The water-climate-agriculture nexus employed in this study evaluates the adaptation scenarios for the best water-management strategy to cope with climate change.

2.2. Trade-offs and synergies

This work evaluates the water-climate-agriculture nexus to reduce the trade-offs between water resources and agriculture demand resulting from climate change, and to increase the mutual benefits from them through nexus scenarios in future years in the Gharanghu basin.

A schematic of the water-climate-agriculture nexus scenarios created in this work is presented in Fig. 4. The optimization model attempts to reduce water stress caused by the mismatch between water supply and water use under climate change. The nexus

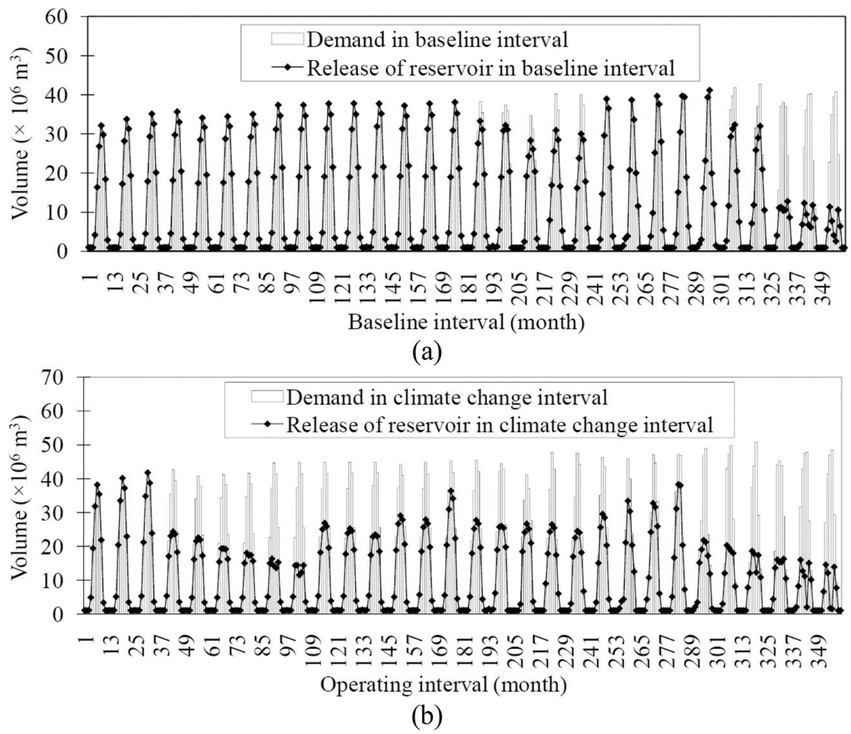


Fig. 3. Reservoir release and water demand corresponding to the (a) baseline interval (1971–2000) and (b) climate-change interval (2040–2069) without implementation of nexus scenarios.

scenarios shown in Fig. 4 pose alternative strategies taken in the agricultural sector to achieve water security and to decrease water demand.

The optimization model.

The optimization model developed determines the optimal reservoir release in the baseline and future operation intervals based on the constraints and objective function. The optimization model is solved for the various adaptive scenarios with the software LINGO 18. The time reliability index is calculated for each scenario and the best scenario is selected based on the index values.

The LINGO 18 software was implemented to optimize the water supply system's performance in the study basin. LINGO 18 is well-known optimization software with proven efficient computational capability featuring various mathematical, statistical, and probabilistic functions. LINGO features an extensive set of fast solvers for linear, nonlinear (convex & non-convex), quadratic, quadratically constrained, and integer optimization (LINGO users manual, 2019). Many previous works have employed LINGO's non-linear programing (NLP) to solve reservoir problems (see, e.g., Asadia et al., 2019; Asgari et al., 2015; and Afshar et al., 2006). Some appealing traits of LINGO are its flexibility, user friendliness, connectivity to other software, and being free access. It is noteworthy that the Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Ant Colony Optimization (ACO) algorithms, among other evolutionary and meta-heuristic algorithms (Bozorg-Haddad et al., 2017; Solgi et al., 2017) are feasible alternatives for water resources modeling. The type of applied optimization chosen for specific water resources modeling may affect the accuracy of the final results and the convergence time to the optimal solution.

This work's objective function is minimizing the deficits of the water supply system having as decision variables the reservoir releases:

$$MinimizeDeficit = \sum_{t=1}^{T} \left(\frac{D_t - R_t}{D_t} \right)^2 \tag{1}$$

in which, *MinimizeDeficit* = the objective function (minimization of deficit of the water-supply system), D_t= volume of water demand downstream of the reservoir in month t, T = the total operating intervals (months), R_t= the reservoir release in month t.

The constraints of the optimization model cover reservoir storage, reservoir release, and spillway flows that are defined according

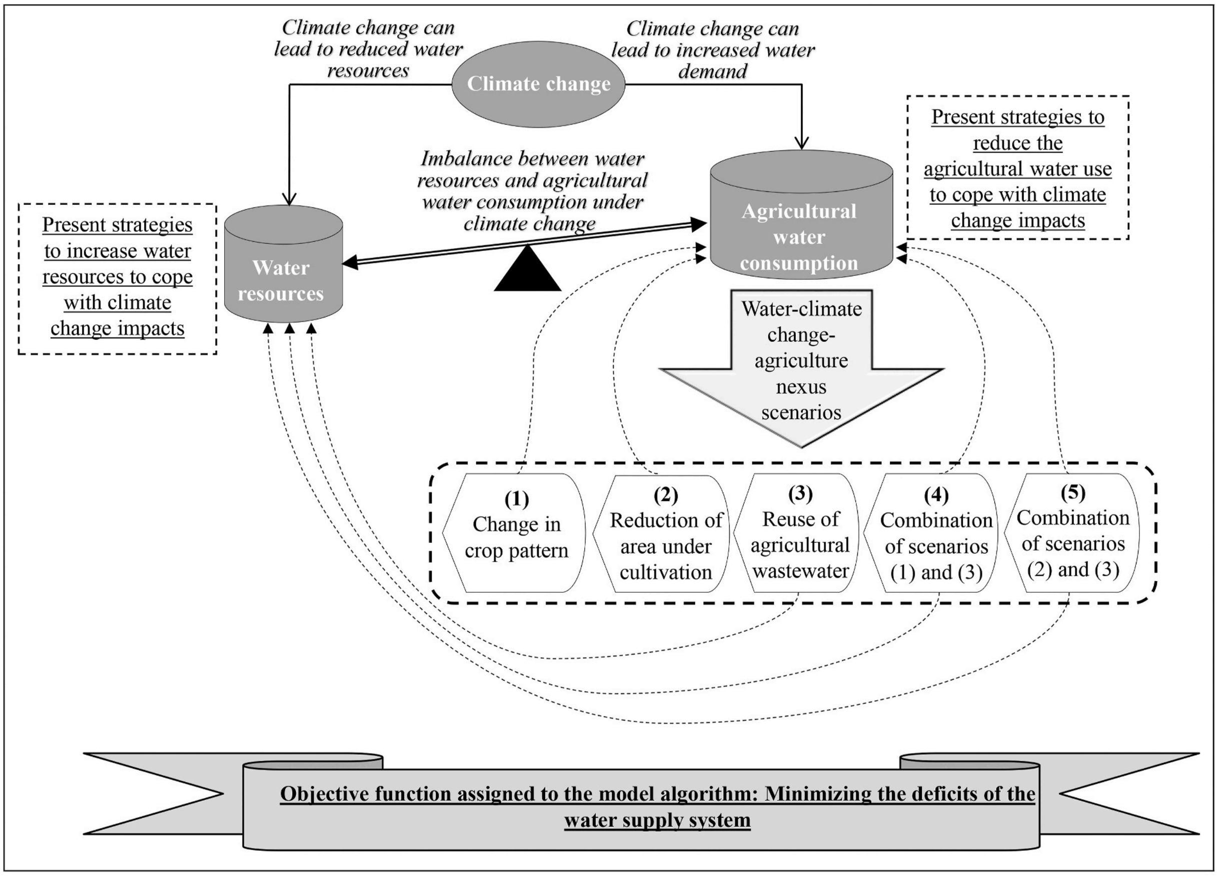


Fig. 4. The schematic of the water-climate-agriculture nexus scenarios.

to the Equations (Asadieh and Afshar, 2019) through (Ashofteh et al., 2017):

Constraints on reservoir storage:

$$S_{t+1} = S_t + Q_t - R_t - SP_t - \frac{EV_t \times (aS_t + b)}{1000}$$
$$S_{\min} \le S_t \le S_{\max} \quad (2)$$

Constrains on reservoir releases:

$$0 \le R_t \le D_t \quad (3)$$

Constraints on spillway flows:

$$\begin{cases} if\ S_t + Q_t - \frac{EV_t \times (aS_t + b)}{1000} \ge S_{\max}\ Then\quad SP_t = S_t + Q_t - \frac{EV_t \times (aS_t + b)}{1000} - S_{\max} \\ \qquad\qquad Otherwise\ SP_t = 0 \end{cases} \quad (4)$$

in which, S_{t+1}= the storage volume of reservoir at the beginning of month t+1, S_t= the storage volume of reservoir at the beginning of month t, Q_t= the reservoir inflow in month t, SP_t = the volume of spillway in month t, EV_t = the evaporation rate in month t (mm), $S_{\min}$ = the minimum storage volume of reservoir (dead volume), $S_{\max}$ = the maximum storage volume of reservoir. The constants a and b equal 0.0581 and 0.8808, respectively, according to the storage vs. water elevation function. The optimization model defined by equations (Afshar et al., 2006) through (Ashofteh et al., 2017) is solved with the software LINGO 18. It is noted that due to the lack of information on future evaporation from the reservoir its value was assumed to be of the same magnitude as that of the baseline interval.

Water-climate-agriculture nexus scenarios.

The following water-climate-agriculture nexus scenarios are here considered for Gharanghu river basin, Iran. The scenarios constitute adaptive strategies to cope with reduced water resources under climate change. The optimized water allocations are determined with the scenarios and under baseline climate and climate change by means of the optimization model.

(1) Change of cropping pattern

Change of cropping patterns constitutes a viable adaptation with climate change (Batts et al., 2008). The cropping pattern changes such that crops with high-consumptive use of water are replaced by low-consumptive use ones adapted to the area's climate while maintain the nutritional value of food production. For example, the percentage of crops with high-consumptive use such as alfalfa was reduced, and, instead the percentage of crops with low-consumptive use such as wheat and barley was increased. This would reduce agricultural water use while preserving a nutritious and desirable diet.

(2) Reduction of the area under cultivation

Reducing the area under cultivation is another adaptive strategy to cope with effects of climate change in the agricultural sector. In the implementation of this scenario one must ensure an adequate and nutritious diet is maintained in the area under consideration. Reduction of the area under cultivation may diminish the agricultural water consumption significantly.

(3) Reuse of agricultural wastewater

Agricultural wastewater reuse is an adaptation strategy to cope with climate change. Wastewater reuse reduces the adverse environmental effects from wastewater discharge and increases the economic gains and cost saving arising from increased water supply (see, e.g., Loáiciga, 2015). Wastewater reuse may be effective in regions threatened with water shortage due to climate change. Diminished water resources impact food security directly and adversely (Corcoran et al., 2010). Agricultural water reuse has many advantages such as supplying reliable water for farmers, increasing food production, and providing nutrients that reduce the use of fertilizers reducing pollution of rivers and surface water resources, and reducing the withdrawal of groundwater resources (Toze, 2006).

(4) Combining the change in cropping pattern and reuse of agricultural wastewater

Combing the reduction of water consumption in "agricultural sector" with the surplus water in "water resources sector" may be effective in adapting to reduced water resources by climate change. Changing the cropping pattern reduces water consumption on the one hand, and wastewater reuse increases the volume of available water resources on the other hand.

(5) Combining reduction of area under cultivation and reuse of agricultural wastewater

Combining the reduction of area under cultivation and reuse of agricultural wastewater constitutes an attractive adaptive strategy to cope with climate change impacts. Reduction of area under cultivation means less agricultural water consumption, and agricultural wastewater reuse augments the water supply.

Evaluation of allocations using time reliability index of nexus.

The time reliability index of a water supply system measures its capacity to meet water demands (Hashimoto et al., 1982). The reliability is computed as follows:

$$\chi = \frac{n}{T}$$
$$n = \sum_{t=1}^{T} count(R_t \geq D_t) \tag{5}$$

in which, χ = the time reliability index of the water supply system, n = number of months in which the reservoir release is equal or greater than water demand in month t, *count* = count function of the months in which water demand is supplied, and T = the total operating intervals (months).

3. Results

3.1. The optimization model

The total volume of reservoir release was calculated for the baseline and future intervals and is listed in Table 1. The reservoir release is as a function of inflow to reservoir, the evaporation rate, and water demand. Therefore, the storage of reservoir is reduced by increasing water demand and by decreased reservoir inflow in the climate-change (future) interval. The total reservoir release in the climate-change interval is decreased about 12% related to the baseline interval. The deficit in the water supply system according to the objective function for each time interval is listed in Table 1, where it is seen the objective function' value in the climate change interval is increased about 182% relative to the baseline interval.

The best releases corresponding to each nexus scenario were determined. The results are listed in Table 2. According to Table 2 the scenario (Afshar et al., 2006), i.e., changing the agricultural water demand caused by modification of the cropping pattern, had a water release equal to 3451.25 × 10^6 m^3, which is 6.37% less compared to the reservoir released calculated under climate-change without adaptation scenarios. Reduction of the agricultural volume demand would increase the number of months with full water supply from 100 months to 147, which amounts to an improvement in performance of the system of water-supply. The number of months with fully satisfied water demand equals 129, 180, 299, and 307 under scenarios 2, 3, 4, and 5, respectively.

3.2. Implementation of the nexus scenarios

The changes in water use and reservoir release corresponding to the baseline and climate-change intervals with implementation of the nexus scenarios are depicted in Fig. 5, which shows that changes in water use and reservoir release corresponding to the baseline and climate-change intervals are significant without implementation of nexus scenarios.

Nexus scenarios were considered and implemented to minimize the deficit in the water supply system. Each of the scenarios has the objectives of mitigating climate-change effects, reducing agricultural water consumption, and to augmenting water resources through reuse of agricultural wastewater. The objective function's values obtained from model outputs corresponding to the nexus scenarios are listed in Table 3, where it is seen the maximum and minimum objective function values correspond respectively to scenarios (Asadieh and Afshar, 2019) and (Bates et al., 2008).

3.3. Time reliability index of water supply associated with the nexus scenarios

The time reliability index was calculated for the baseline and climate-change intervals with and without implementation of nexus scenarios and is displayed in Fig. 6.

The time reliability index is equal to 72% in the baseline interval, while it is reduced to 28% in the climate-change interval without nexus scenarios. The time reliability index calculated for the baseline period with nexus scenarios, namely, change in cropping pattern, reduction of area under cultivation, reuse of agricultural wastewater, combination of scenarios (Afshar et al., 2006) and (Asgari et al.,

Table 1
The total optimal reservoir release and value of the objective function in the baseline and the climate change periods without nexus scenarios.

Operating interval	The total optimal reservoir release (× 10^6 m^3)	Value of the objective function (× 10^6 m^3)
Baseline	4185.4	8.3
Climate change	3686.2	23.4

Table 2
The values of the total optimal reservoir release corresponding to the nexus scenarios under climate change.

Characteristics of scenarios	Reservoir release ($\times 10^6$ m^3)	Water demand ($\times 10^6$ m^3)	Reservoir inflow ($\times 10^6$ m^3)	Shortage of water supply ($\times 10^6$ m^3)	number of months with full water supply
Baseline	4185.4	4706.6	2207.7	521	271
Climate change (without scenarios)	3686.2	5583.2	1704.0	1897	100
Change in the cropping pattern	3451.3	4021.2	1704.0	570	147
Reduction of the area under cultivation	3606.8	4802.2	1704.0	1195	129
Reuse of agricultural wastewater	4446.6	5583.2	7676.5	1137	180
Combination of scenarios (Afshar et al., 2006) and (Asgari et al., 2015)	3733.3	4021.2	7676.5	288	299
Combination of scenarios (Asadieh and Afshar, 2019) and (Asgari et al., 2015)	4460.1	4803.7	7676.5	344	307

2015), and combination of scenarios (Asadieh and Afshar, 2019) and (Asgari et al., 2015) equaled 41, 36, 50, 83, and 85%, respectively.

The water-climate-agriculture nexus scenarios call for reducing the water system deficits and increasing the balance between water supply and demand. Specifically, the change in time reliability index calculated under the climate-change interval with nexus scenarios relative to the time reliability index in the same interval without implementation of the nexus scenarios is listed in Table 4.

The results listed in Table 4 establish the maximum increase in the time reliability index corresponds to scenario (Bates et al., 2008), that is, the combination of scenarios (Asadieh and Afshar, 2019) and (Asgari et al., 2015), or the reduction of the area under cultivation and reuse of agricultural wastewater. This means that a combination of demand management that reduces water consumption as well as wastewater reuse which compensates water resources available would be the best nexus scenario concerning water supply.

A comparison of our findings with others who have studied the same region and other regions in Iran and the world with characteristics similar to this paper's study region reveals that choosing the right strategies to cope with climate change requires in-depth knowledge of the study area and its capacity to adapt. Also, this work has shown the uncertainties related to climate change adaptation, such as uncertainties in climate projections, affect water and reservoir management.

4. Discussion

This work's results indicate that reservoir inflow (the only water-supply resource in the case study region) will be reduced in the future due to the climate change. This work considered the evaporation rate to be the same in the future period as in the baseline period due to the lack of data. The Surface Energy Balance Algorithm for Land (SEBAL) can be applied to improve evaporation projections at regional scales employing remote sensing data (Bastiaanssen et al., 2005).

Milly et al. (2005) assessed the results of 12 climate models to project the variation in runoff for different regions. The results projected 10–40% increasing in runoff in eastern equatorial Africa, the La Plata basin, and high-latitude North America and Eurasia, and 10–30% decreasing in runoff in southern Africa, southern Europe, the Middle East, and the mid-latitude western North America by the year 2050. Gohari et al. (2014) indicated average monthly temperature in the Zayandeh-Rud basin of Iran would increase 0.46–0.76 °C, and annual precipitation would decrease 14–38% in the time interval (2015–2044). Also, the annual runoff would decrease 8–43% under climate change. Shadkam et al. (2016) indicated annual inflow to Urmia Lake, Iran, decreased by 48% due to climate change effects in the period (1960–2010). Based on such reports one must anticipate that water scarcity in the coming years may be heightened in many regions, and planning to cope with scarcity must be done in several sectors, especially in the agricultural sector, because of its high vulnerability and its role in food security and economy. Madani (2014) argued that an inefficient agricultural sector is one the reasons of the current water crisis in Iran. Gohari et al. (2014) showed adaptation strategies in the Zayandeh-Rud basin would meet non-agricultural demands but would not meet the agricultural demand; thus, the agricultural sector must be the main focus of regional management planning under climate change. This paper developed scenarios which focus on the agricultural sector. Designing and measuring nexus scenarios with the reliability time index are useful and timely because it allows policymakers to build the necessary infrastructure to cope with the water crisis.

This study findings show that the components of the regional water/food system interact through complex feedbacks, which call for a multi-sectorial approach to water management to ensure food security. Other studies, e.g., Khan and Hanjra (2009) indicate that global food production generates environmental footprints, and investments are needed to boost water productivity and improve energy-use efficiency in crop production to reduce the environmental footprint. Gulati et al. (2011) investigated the connection level between water, energy, and food products to evaluate the cost of energy and water on food price and food security level in Africa. Their results showed that sustainable solutions for food security require integrated thinking in strategic planning for water-energy-food production, in agreement with this work's findings.

Several studies with distinct approaches have been reported on the nexus concept, some of which are cited below.

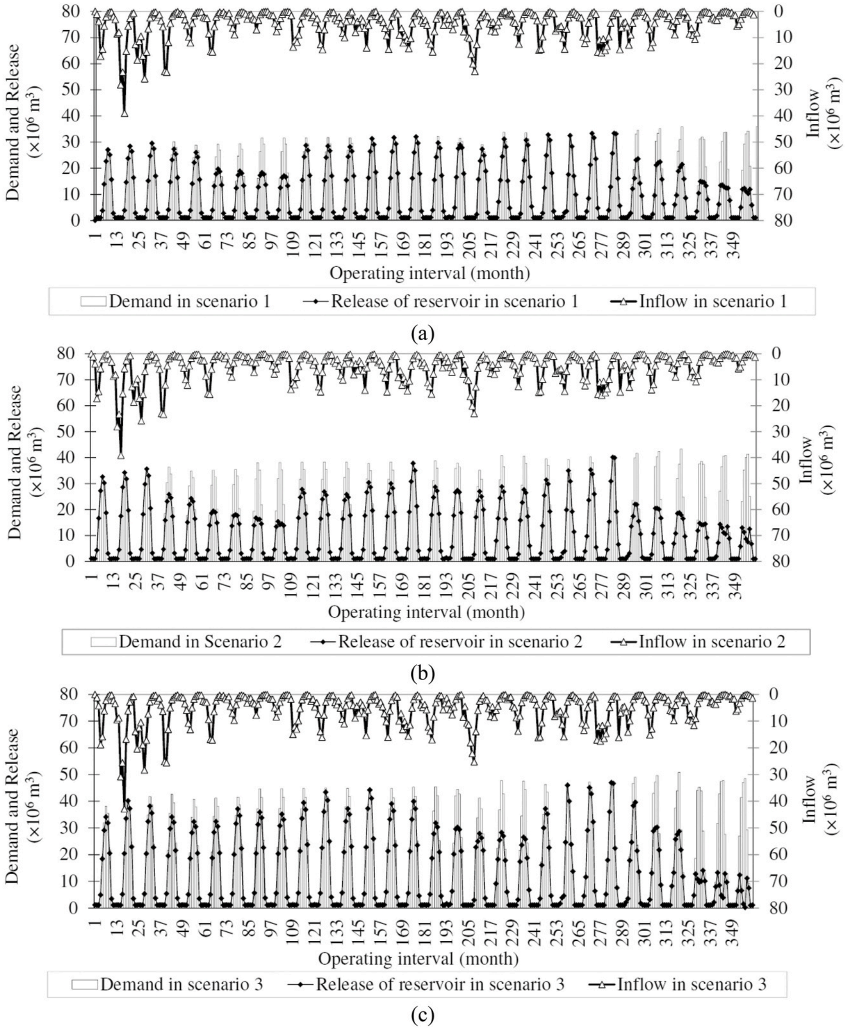
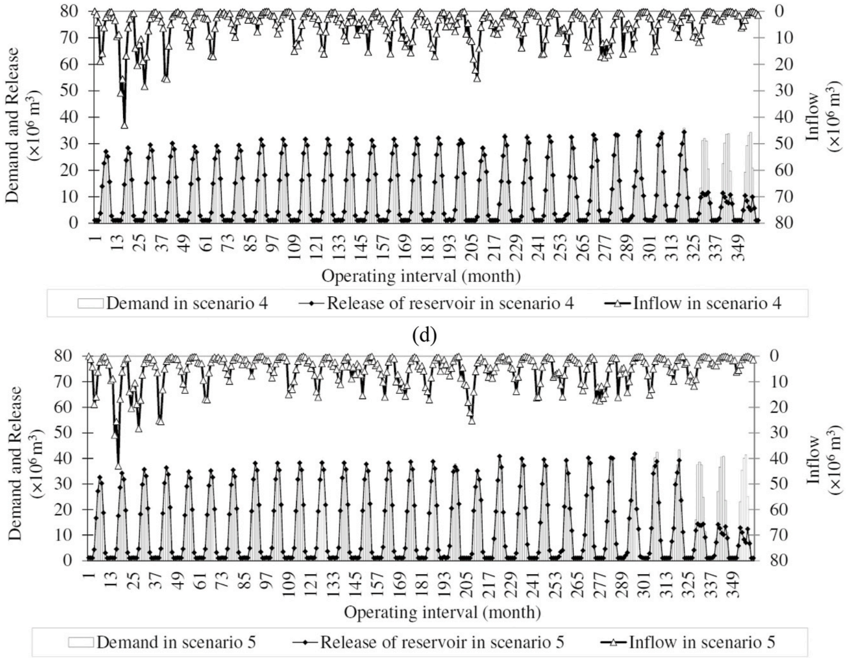


Fig. 5. Reservoir release and water demand corresponding to the (a) change in cropping pattern scenario, (b) reduction of the area under cultivation, (c) reuse of agricultural wastewater scenario, (d) combination of change in cropping pattern and reuse of wastewater scenarios, (e) combination of reduction of the area under cultivation and reuse of agricultural wastewater scenarios.

Li et al. (2019b) developed an optimization model for the allocation of resources toward sustainable management of the agricultural water, food and energy nexus under uncertainties to obtain maximum economic benefits and minimize environmental impacts in Fujin city, China. Zhang and Vesselinov (2017) developed a multi-period socioeconomic model called WEFO. This model was applied to quantitatively analyze the interrelationships and trade-offs between energy supply, electricity generation, water supply-demand, food production and mitigation of environmental impacts. Their results showed this model could be helpful for making cost-effective decisions for optimal WEF management. Mortada et al. (2018a,b) presented an optimization model that maximizes the composite water-food security status by means of optimal water and agricultural policies. It is concluded that there have not been previous reported studies about the water-climate-agriculture nexus as herein reported; yet, previous works have the common objective of highlighting that the nexus concept provides the framework for simultaneously deliver multiple sustainable development goals linked to food, agriculture, energy, water, and combating climate change.

This paper proposes nexus scenarios to increase the synergies and successfully exploit the trade-offs between the water-climate change-agriculture sectors, and to select the best scenario judged by the time-reliability index. The nexus scenarios were designed for implementation under climate change to take advantage of the trade-offs arising in the use of land and water resources. The values of the objective function and time-reliability index were calculated for each nexus scenario. Regarding the objective function in this paper, which is minimizing the water deficit in the system, Scenario 5 was the best scenario because it would cause the smallest water



(e)

Fig. 5. (*continued*).

deficit among the other nexus scenarios. The water supply system would achieve the highest maximum reliability index. The best scenario consists of a combination of the reduction of the area under cultivation and the reuse of agricultural wastewater.

5. Conclusions

The implementation of each proposed scenarios, has advantages and disadvantages. For example, the reduction in the cultivation area causes farmers to fallow their crops, which can be compensated by higher crop prices. The reuse of wastewater requires the creation of appropriate infrastructure for treatment, which requires investment. The combination of these two management options would result in conserving available water resources in the long-term significantly.

The High Level Panel of Experts (HLPE) (2016) recommended sustainable agricultural development to achieve food security by improving resources efficiency, strengthening resilience, and securing social equity/responsibility of agriculture and food systems. This study has developed and evaluated practical strategies for integrated water management and sustainable agricultural sector management under several scenarios.

In future research, considering the reuse of treated wastewater in the region, the nexus between water-agriculture-environment-climate can also be examined. The stability of nexus scenarios can be assessed with the Loucks stability index.

Author statement

All authors have seen and approved the final version of the manuscript being submitted. They warrant that the article is the authors' original work, hasn't received prior publication and isn't under consideration for publication elsewhere.

Table 3
The values of the objective function corresponding to nexus scenarios under climate change.

Nexus scenarios	Characteristics of scenarios	Value of the objective function (minimization)
Afshar et al. (2006)	Change in the cropping pattern	7.5
Asadieh and Afshar (2019)	Reduction of the area under cultivation	14.8
Asgari et al. (2015)	Reuse of agricultural wastewater	12.8
Ashofteh et al. (2017)	Combination of scenarios (Afshar et al., 2006) and (Asgari et al., 2015)	6.2
Bates et al. (2008)	Combination of scenarios (Asadieh and Afshar, 2019) and (Asgari et al., 2015)	5.9

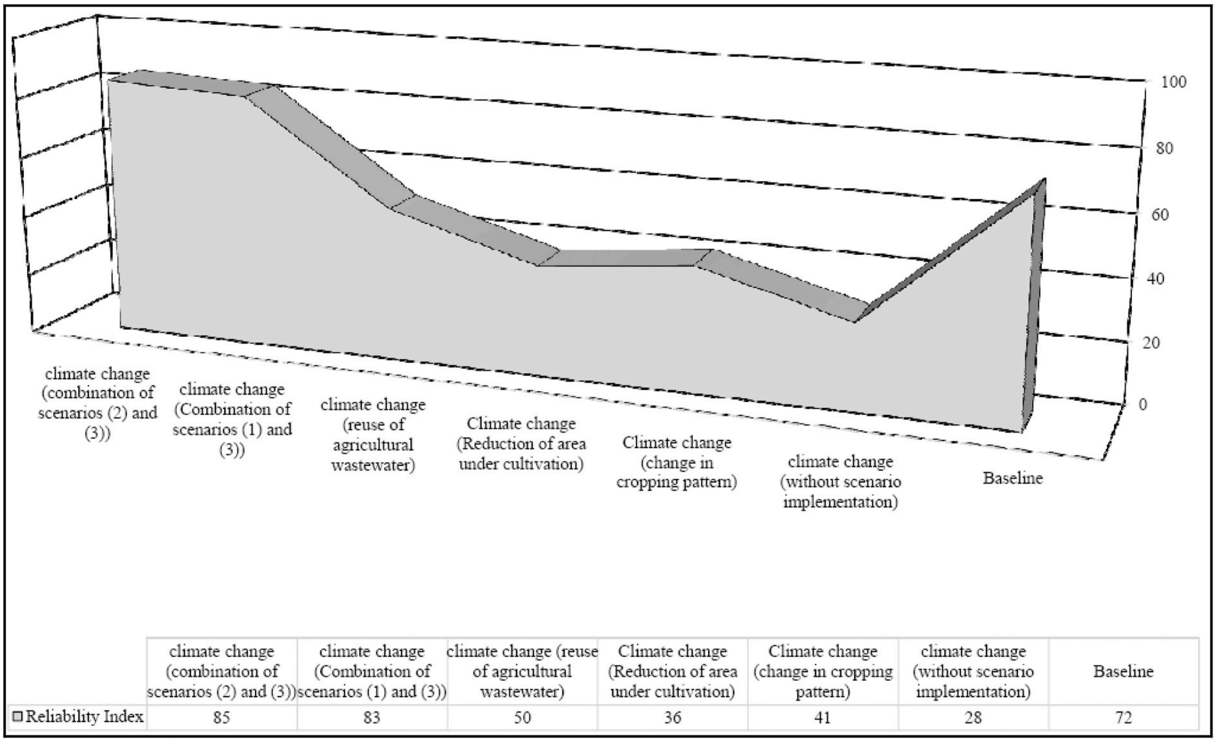


Fig. 6. The time reliability index (percentage).

Table 4
The percentage changes in the reliability index in the climate-change interval compared to the same interval without implementing nexus scenarios.

Nexus scenarios	Characteristics of scenarios	Amount of the change (%)
Afshar et al. (2006)	Change in the cropping pattern	46
Asadieh and Afshar (2019)	Reduction of the area under cultivation	28
Asgari et al. (2015)	Reuse of agricultural wastewater	78
Ashofteh et al. (2017)	Combination of scenarios (Afshar et al., 2006) and (Asgari et al., 2015)	196
Bates et al. (2008)	Combination of scenarios (Asadieh and Afshar, 2019) and (Asgari et al., 2015)	203

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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