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Evaluation of Water Sustainability under a Changing Climate in Zarrineh River Basin, Iran

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Abstract

This paper presents the results of studies on water resources management strategies, under the influence of climate change, in the Zarrineh River basin, providing some 41% of the total inflow into the Lake Urmia. Climate change simulation over the period 1992–2050 was performed by downscaling of seven global circulation models. The best model was then selected for modelling the hydrological behavior of the basin using a rainfall-runoff model while an allocation model was used to evaluate future supply and demands. A system dynamics model was further utilized to investigate the sustainability of the dynamic behavior of the basin. Five suggested water resources management strategies for two future climate scenarios were investigated. Results indicated that implementation of the strategy of 40% reduction in agricultural water demand would provide higher degrees of sustainability. Based on this, the average annual inflow to Lake Urmia in the years 2021 to 2050 would be 1029.75 MCM, which is equal to 81.02% of the Lake Urmia's environmental requirement from the river's share.

1 Introduction

Water sustainability is a relatively new notion for the performance evaluation of water resources systems over long-term periods (Santikayasa et al. 2014; Srdjevic and Srdjevic 2017). Water sustainability is defined as the ability of a water resources system to meet all of its demands in various water consumption sectors. To preserve the sustainability of the system against climate change, understanding the climate change process and its threatening factors is

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necessary (Li et al. 2014; Zhai and Tao 2017). Climate change has led to changes in the magnitude and timing of runoff and, therefore, have serious consequences for present water resources as well as for management of future water resources systems (Arnell 1999; Dibike and Coulibaly 2005; Nkomozepi and Chung 2014; Torabi Haghighi and Klove 2017). In addition, several studies over the world indicate that tensions over water resources will intensify as a result of decreases in water availability due to climate change (MacDonald 2010; Siegfried et al. 2011; Gandure et al. 2013; Singh et al. 2014). Although the threatening factors in climate change may be out of control, they can be predicted to find adaptive solutions to these environmental changes (Adger et al. 2011).

Common points among most studies, assessing watershed sustainability against climate change, has been to analyze spatio-temporal impacts of climate change on hydro-climatological parameters, investigate uncertainties in future climate, and ultimately make efforts to present and compare the effectiveness of different management strategies (Prodanovic and Simonovic 2010; Hassanzadeh et al. 2012; Xiao-jun et al. 2014; Gohari et al. 2017). These common features of long-term water resources studies have led many researchers to spend considerable time and make efforts to investigate these constantly changing systems within the system dynamics modelling (Forrester 1961, 1969; Ford 1999; Sterman 2000; Winz et al. 2009; Mirchi et al. 2012). This framework can clear the interactions among disparate but interacting subsystems, driving the long-term system behavior (Simonovic and Li 2003, 2004; Langsdale et al. 2007). This approach shifts from simulation models that work based solely on 'if… then…' analyses (Gohari et al. 2017). To investigate the interactions between different water consumption sectors and available water resources in the basins, water supply and demand models are used (Blanco-Gutiérrez 2010; Yilmaz and Harmancioglu 2010). These models, providing integrated evaluation of climate, land use, hydrology, irrigation facilities, water allocations and water management priorities of the basin, enable analysts to present a comprehensive analysis of possible management strategies (Joyce et al. 2011; Santikayasa et al. 2014; Ahmadaali et al. 2018). In modelling these water management strategies, the evaluation of the existing water resources in the following years under the influences of climate change and the means of applying rainfall-runoff models with predicted hydrological parameters (e.g. precipitation and temperature) are necessary. The main inputs are usually derived from the General Circulation Models (GCMs) and downscaled, using statistical or dynamical methods (Fowler et al. 2007; Teutschbein and Seibert 2012; IPCC 2013; McSweeney et al. 2015). Therefore, evaluation of sustainability within a dynamic framework that couple climate change impacts with integrated water resources management, may address the spectrum of stakeholders' concerns comprehensively.

In this study, the sustainability of the Zarrineh River basin, the largest sub-basin of the Lake Urmia basin, is investigated as an integrated system dynamics model under a range of climate change strategies. Lake Urmia, located in northwestern Iran, is the second largest hypersaline lake of the world and has been shrinking rapidly over the last 25 years as the water level decreases about 40 cm a year on average (Jalili et al. 2016; Ahmadaali et al. 2018). This desiccation has led to many economic, social and environmental consequences (Boroughani et al. 2019). As a consequence, addressing food security given the limited water resources in the area, inevitable reduction of agricultural uses of water to meet the lake's environmental demands, reducing water consumption and reallocating the available water resources, and improving consumption efficiency are among the challenges in the region's environmental policy agenda (Urmia Lake Restoration National Committee 2015). Due to decreasing water supplies, as well as uncertainties in future climate and future demands in the Zarrineh River

basin (Yazdandoost and Moradian 2019), development of water sustainability analysis of the basin is deemed appropriate. The present study aims to evaluate the sustainability of different water resource management strategies, affected by climate change, and to determine their impacts on the Lake Urmia inflow by 2050. This study is divided into the following sections: Sec. 2 introduces the study area and the method. The method includes the following parts, providing a five-step toolbox: 1) evaluation of climate change impacts on hydro-climatological parameters, 2) future water supply and demands assessment, 3) analysis of sustainable strategies, 4) evaluation of sustainability in a system dynamics model, and 5) choosing the best strategy. Sec. 3 provides the results and discussion and Sec.4 presents the conclusions.

2 Materials and Methods

2.1 Study Area

The Zarrineh River basin, with a population of approximately 1,200,000 people (according to the latest national census in 2015), situated in the northwest of Iran, is enclosed between a longitude of 45°46′-47°22′ E and a latitude of 35°40′-37°26'N. Since it covers an area of about 11,841.2 km^2, it is one of the largest basins in the country and the largest sub-basin of the Lake Urmia basin. In recent years, the lake has faced severe water scarcity and is drying up (Fig. 1). Poor water resources management, climate change, low irrigation water use efficiency and population growth are among the main causes of the lake shrinkage (Ghaheri et al. 1999; Ahmadzadeh Kokya et al. 2011; Delju et al. 2013; Nikbakht et al. 2013; Gholampour et al. 2015; Ahmadi et al. 2016; Shadkam et al. 2016; Zarghami and AmirRahmani 2017; Ghale et al. 2018).

According to the studies, Lake Urmia needs about 3100 MCM (million cubic meters) of water inlet per annum to have a sustainable ecosystem, which is equivalent to the ecological level of the lake's water level (1274.1 m above sea level) (Abbaspour and Nazaridoust 2007;
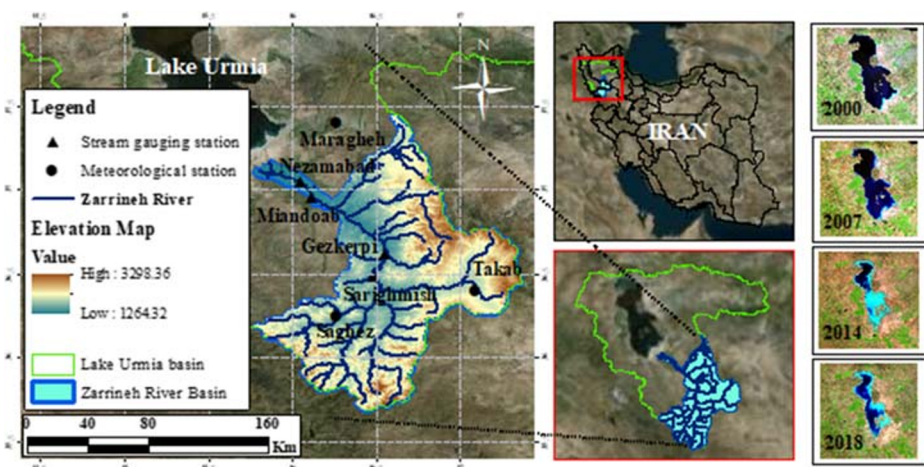

Fig. 1 The location of the study area and the Lake Urmia over time (https://earthshots.usgs.gov/earthshots/node/72#ad-image-0-7). The images were acquired by Land Remote-Sensing Satellite (LANDSAT)

Alborzi et al. 2018). Considering that Zarrineh River provides about 41% of the environmental flow requirements of Lake Urmia, the share of the environmental requirements of the lake from the river is estimated as 1271 MCM annually (Ahmadaali et al. 2018).

Statistics show that in 2015, the cultivated area in the Zarrineh River basin was about 111,000 ha and most of the crops, planted in the basin, were high-yield crops such as alfalfa, wheat, barley, sugar beet, apples and grapes (Ahmadaali et al. 2018). The average irrigation efficiency in the basin was reported to be about 40.2% in the year and percentage of cultivated area under surface irrigation system was 86.6% and the number changes to 12.3% and 1.1% for sprinkler irrigation system (about 75% efficiency) and drip irrigation system (about 95% efficiency), respectively (Ahmadaali et al. 2018). This information indicates the need for different management strategies, especially in the agricultural sector (see Fig. 2).

2.2 Methodology

This study was carried out in a five-step toolbox as shown in Fig. 3 and each of the steps is discussed in more details below.

2.2.1 Evaluation of Climate Change Impacts on Hydro-Climatological Parameters

Here, daily precipitation and temperature data of seven GCMs (BCC-CSM1–1, BNU-ESM, CSIRO-Mk3–6-0, GFDL-ESM2G, IPSL-CM5A-LR, MIROC-ESM, MIROC-ESM-CHEM), based on two global scenarios for emissions concentration namely RCP2.6 and RCP8.5 (Representative Concentration Pathways) from the Fifth Assessment Report (AR5), were applied
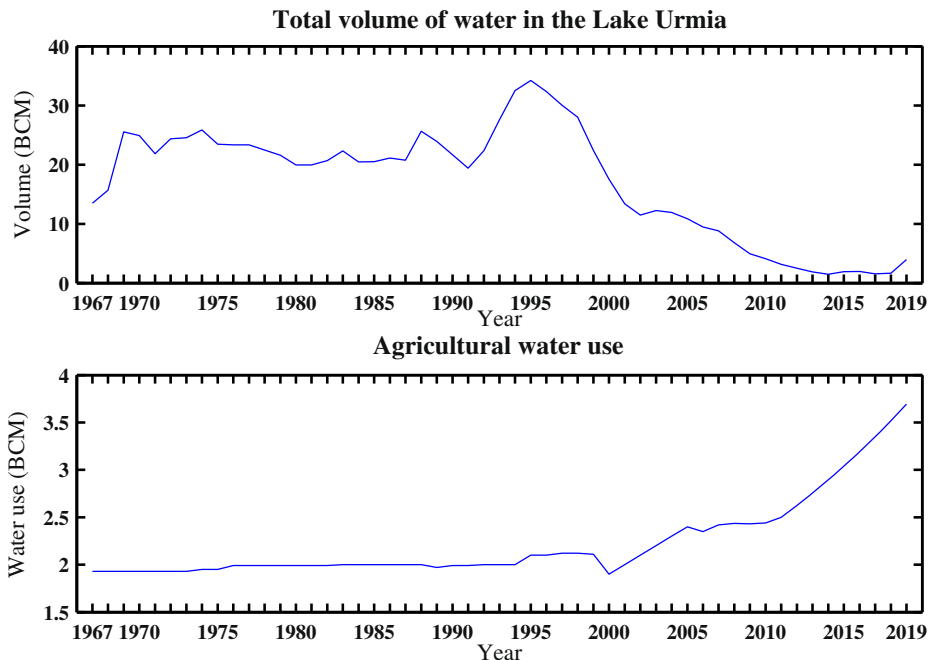

Fig. 2 **a** Lake Urmia volume changes and (**b**) changes in agricultural water use in the Lake Urmia basin in 1967–2019 (Gohari et al. 2017)

and downscaled using an ANN (Artificial Neural Network) technique in twelve 0.5-degree cells in the Zarrineh River basin. ANNs are able to find confirmable relationships between a set of inputs (GCMs data) and the corresponding outputs (observational data). As the downscaled precipitation and temperature by ANNs are often characterized by considerable biases, a bias correction method was further applied. The best model was then chosen based on statistical indices and the results were utilized in a rainfall-runoff model, namely the Hydrologiska Byråns Vattenavdelning (HBV-Light) model (Seibert 2003). HBV-Light, a conceptual, continuous and semi-distributed streamflow model, includes some different routines and it can simulate snow, soil water, evaporation, groundwater and channel routing. Therefore, the impacts of climate change on the streamflow of Zarrineh River, operated under RCPs, were investigated. The detailed performance assessment of this section is fully covered in Yazdandoost and Moradian (2019).

2.2.2 Future Water Supply and Demands Assessment

At this stage, all sources of water supply in the target area were quantitatively identified. In this regard, the hydrological cycle was studied. In addition, demands and consumptions, stakeholder objectives, the allocation of priorities, water conflicts and challenges, and water policies were identified at the regional level. In the present study, to do an integrated assessment of climate, hydrology, water use and water management priorities in the study area, WEAP software (Water Evaluation And Planning system) was used (Yates et al. 2005a, 2005b). WEAP represents the system by its various components, including supply-side issues (surface water, underground water, reservoirs, water transfers, etc.) and demand-side topics (water use patterns, equipment efficiencies, costs, reuse strategies, water allocations, etc.). It is distinguished by its integrated approach to simulate both the engineered and natural components of a water system. This allows the planners access to a comprehensive view of the broad range of factors which must be considered in managing water resources for future uses. For the sake of integrity of modelling, the model was constructed by considering all the sub-basins of the Lake Urmia basin and the leading rivers; then the impacts of climate change on the Zarrineh River basin were investigated (Fig. 4).
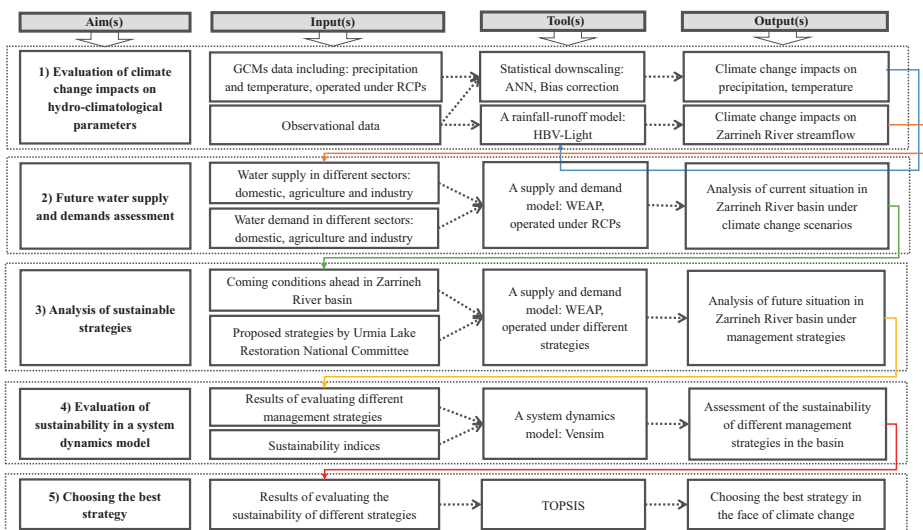

Aim(s)	Input(s)	Tool(s)	Output(s)
1) Evaluation of climate change impacts on hydro-climatological parameters	GCMs data including: precipitation and temperature, operated under RCPs	Statistical downscaling: ANN, Bias correction	Climate change impacts on precipitation, temperature
	Observational data	A rainfall-runoff model: HBV-Light	Climate change impacts on Zarrineh River streamflow
2) Future water supply and demands assessment	Water supply in different sectors: domestic, agriculture and industry	A supply and demand model: WEAP, operated under RCPs	Analysis of current situation in Zarrineh River basin under climate change scenarios
	Water demand in different sectors: domestic, agriculture and industry		
3) Analysis of sustainable strategies	Coming conditions ahead in Zarrineh River basin	A supply and demand model: WEAP, operated under different strategies	Analysis of future situation in Zarrineh River basin under management strategies
	Proposed strategies by Urmia Lake Restoration National Committee		
4) Evaluation of sustainability in a system dynamics model	Results of evaluating different management strategies	A system dynamics model: Vensim	Assessment of the sustainability of different management strategies in the basin
	Sustainability indices		
5) Choosing the best strategy	Results of evaluating the sustainability of different strategies	TOPSIS	Choosing the best strategy in the face of climate change

Fig. 3 The dominant perspective of the proposed toolbox

In this step, using simulated streamflow data for the period 1992 to 2050 under the influence of climate change from the results of the previous step, as well as the consumption data of the three main water users i.e. domestic, industrial and agricultural sectors in 2010 were considered. The model was validated for the period of 2011 to 2018 and then the amount of supply and demand in the basin were modeled to the end of 2050. The required data were obtained from the Agricultural Statistics and Information Center of the Ministry of Agriculture of Iran.

2.2.3 Analysis of Sustainable Strategies

After examining the future conditions of the target region and identifying threatening factors related to climate change, adaptive strategies to address these changes were identified. Strategies are constructed in the current situation and they can be used to investigate the impacts of different assumptions or policies on the future available water resources. These strategies are the answers to 'if… then…'
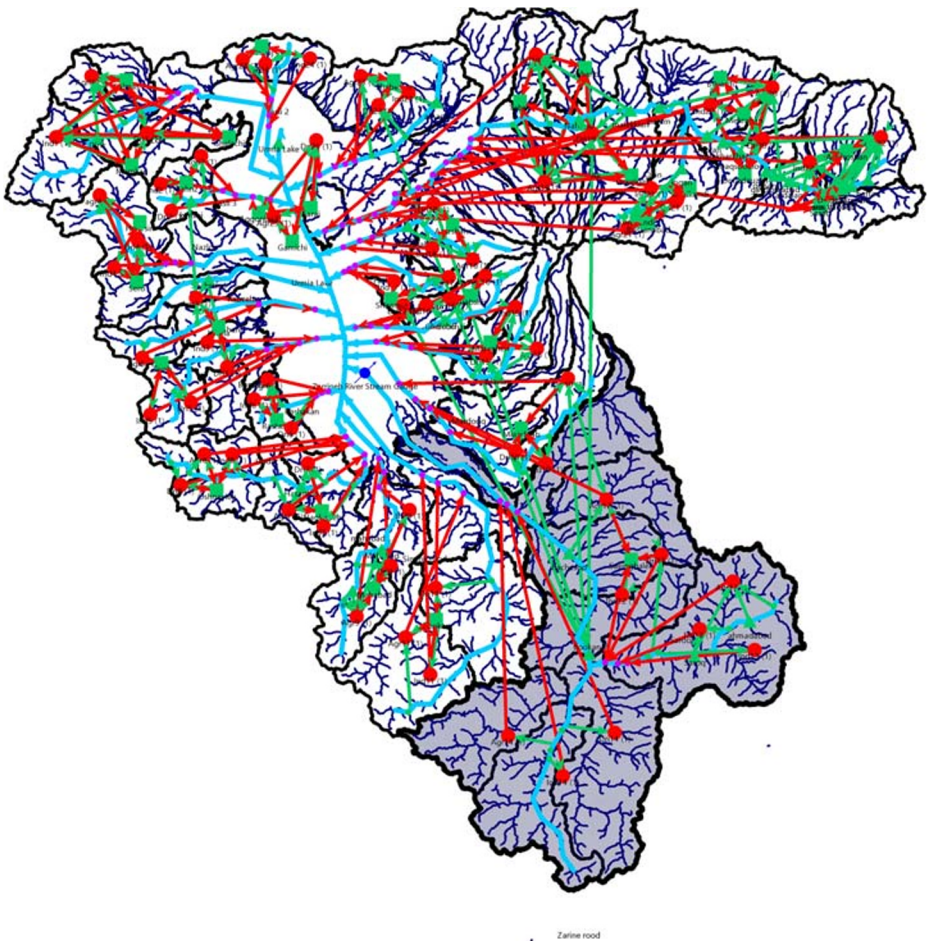

Fig. 4 Schematic of the WEAP model for the Lake Urmia and the Zarrineh River basins

questions (Mugatsia 2010) and are evaluated based on several parameters such as water consumption, adaptability to environmental goals and sensitivity to uncertainty in the key variables. In order to evaluate the performance and sustainability of the Zarrineh River basin against climate change under various possible conditions, several climate change strategies were evaluated in the region. These strategies include the following (Urmia Lake Restoration National Committee 2015): 1) Base strategy (S0): this strategy is based on the future climate predictions (RCP2.6 and RCP8.5) and it attempts to predict the conditions of the basin in various horizons in the future in case no actions are taken to improve the current conditions. However, water demands in different sectors vary according to the predicted growth rates and will be applied to the other strategies. 2) 30% increase in irrigation efficiency (S1): with regard to the irrigation efficiency, this strategy reduces water losses by the improvement of conveyance and distribution efficiency by 30% of the present condition. 3) 25% decrease in domestic and industrial water demands (S2): the strategy is implemented to alleviate water shortage in domestic and industrial sectors. 4) 130% increase in irrigation efficiency and 25% decrease in domestic and industrial water demands (S3): this strategy combines S2 and improvement of irrigation efficiency by 30%; and 5) 40% decrease in agricultural water demand (S4): as high-consumption agriculture is a major limiting factor in the Zarrineh River basin, changes in agricultural water demand can be considered as a management strategy. These management strategies were primarily adopted based on proposals by local mangers and practitioners without particular knowledge of their effective magnitude or rank and purely based on intuitions and best judgements. Their main goals were sought to increase water supply, increase efficiency and reduce water demand, so that the saved water can be re-allocated to the Lake Urmia and promote its sustainability.

2.2.4 Evaluation of Sustainability in a System Dynamics Model

An appropriate framework for climate sustainability assessment focuses on understanding the process of climate change and assessing the threats to water sustainability. Evaluating the sustainability of a water resources system against climate change, using an indicator-based approach, enables analysts to compare the effectiveness of different management strategies under different climate change scenarios (Juwana et al. 2012). For this purpose, in this study, four indices of Reliability, Vulnerability, Maximum Deficit and Integrated System Performance were used which are defined as follows:

Reliability (Rel) The index is defined as the probability that the system can sufficiently meet all water demands during the simulation period (Klemes et al. 1981; Hashimoto et al. 1982; McMahon et al. 2006; Gohari et al. 2017; Ahmadaali et al. 2018):

$$Rel = \frac{Number\ of\ months\ with\ satisfactory\ values}{Total\ number\ of\ months\ in\ the\ simulation\ period} \tag{1}$$

Vulnerability (Vul) The index illustrates the average probability of failure to meet water demand (Sandoval-Solis et al. 2011; Gohari et al. 2017). In other words, it is a statistical measure of magnitude of failures in the simulation period (Ahmadaali et al. 2018):

$$Vul = \frac{\sum Unsatisfactory\ value / Number\ of\ months\ with\ unsatisfactory\ values}{Total\ water\ demand\ in\ the\ simulation\ period} \tag{2}$$

Maximum Deficit (MaxDef) The index shows the maximum monthly deficit for each sector (Gohari et al. 2017):

$$MaxDef = \frac{\text{Max}(unsatisfactory\ value)}{\text{Total water demand in the simulation period}} \tag{3}$$

Integrated System Performance (ISP) The index is a combination of essential performance measures, providing information about the sustainability of the water resources system over long periods. The index changes from 0 for the worst possible value up to 1 for the best possible value (Loucks 1997; Yilmaz and Harmancioglu 2010; Gohari et al. 2017):

$$ISP = \sqrt[3]{Rel \times (1-Vul) \times (1-MaxDef)} \tag{4}$$

In this study, system dynamics modelling was applied using Vensim (Ventana Systems 2010) to model the actual behavior of the system and estimate the indicators. Dynamic simulation models include equations that represent changes dynamically. If the initial conditions of the system are specified, then the status of the system could be calculated in the next time steps. So, the future of the system can be predicted. In this way, the decisions can be made in a virtual environment and the system's response to changes could be examined (Eberlein and Peterson 1992; Abadi et al. 2015). Modelling in Vensim is started by presenting a graphic representation of the system, continued with establishing the time frame and the base year (current account) data. Finally, the situations of the base year are simulated and the model is calibrated. Here, the developed model comprises hydro-climatological (i.e. precipitation, temperature, surface water and groundwater interaction), social (water demands in domestic usages), industrial and agricultural sub-systems. A schematic of the system dynamics model is shown in Fig. 5.'
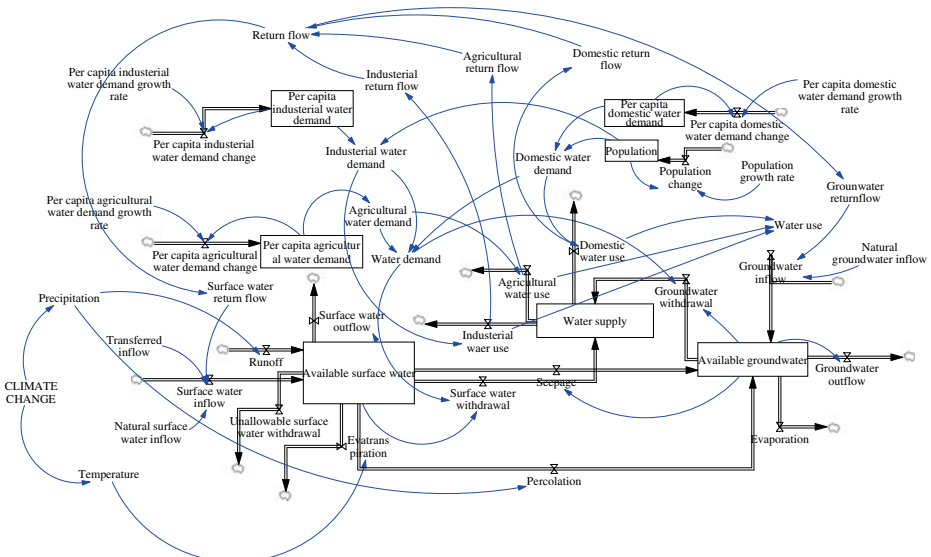

Fig. 5 Stock and flow diagram of the system dynamics model

2.2.5 Choosing the Best Strategy

When there are a number of strategies and a number of criteria for evaluating the strategies, one of the most important challenges is choosing the best strategy or prioritizing them according to the defined criteria. In such these cases, multi criteria decision making methods 1or decision support systems can be employed. In this study, TOPSIS method (Technique for Order of Preference by Similarity to Ideal Solution) was used to rank strategies and select the best strategy (Hwang and Yoon 1981). In this method 'm' strategies are evaluated by 'n' criteria. The technique is based on the notion that the decision alternatives must have the least distance with the positive ideal solution (best possible) and the maximum distance with the negative ideal solution (worst possible). Detailed information about the method is provided in Hwang and Yoon (1981) and García-Cascales and Lamata (2012).

3 Results and Discussion

In the first step of the proposed toolbox, the results of the study by Yazdandoost and Moradian (2019) on hydro-climatological changes in the Zarrineh River basin, based on the CSIRO-Mk3–6-0 data as the best GCM model in the area, showed that the daily mean precipitation is expected to decrease from 0.94 and 0.96 mm in 2015 to 0.65 and 0.68 mm in 2050 based on RCP2.6 and RCP8.5, respectively. In the case of temperature, the numbers change from 12.33 and 12.37 °C in 2015 to 14.28 and 14.32 °C in 2050. These results are in line with previous studies in the target region (e.g. Alborzi et al. 2018; Emami and Koch 2018). Corresponding to these scenarios, the results of these changes will lead to a decrease in the annual streamflow of Zarrineh River from 59.49 m^3/s in 2015 to 22.61 and 23.19 m^3/s in 2050 (Fig. 6). These results imply that, RCP8.5 is more pessimistic than RCP2.6 in the case of radiative forcing values and its annual temperature increase was estimated to be greater. However, since the rainfall-runoff models are more sensitive to changes in precipitation (Fang et al. 2015), the runoff from this scenario was estimated to be greater.

In the second step, for WEAP modelling, based on the results obtained from the previous step as well as the consumption data (with various characteristics) of the three of domestic, industrial and agricultural sectors in 2010, the model was validated for the period of 2011 to 2018. In addition, the proposed strategies were assumed to be operational from 2020. As mentioned earlier, in this study the WEAP model was first calibrated and validated for the Lake Urmia basin and then, the effects of climate change on the Zarrineh River basin were investigated. Model validation results (Table 1) indicated that the constructed model is capable of estimating regional water supply and consumption, well.

In the third step, the proposed management strategies were evaluated. Evaluation of the sustainability of these strategies in the fourth step was performed by modelling the system dynamics in Vensim, using the WEAP model outputs. The results of the sustainability indices for the different consumption segments for the both climate scenarios, obtained from the system dynamics model for the total basin average between 2020 and 2050, are presented in Table 2.

The table shows that the maximum water shortage will occur if S0 occurs, which is not unexpected. However, the important point to consider in implementing this strategy is that the corresponding values of Rel for this scenario are always greater than or equal to those for S1 and S2 scenarios across various usages. This is because Rel calculates the number of times that
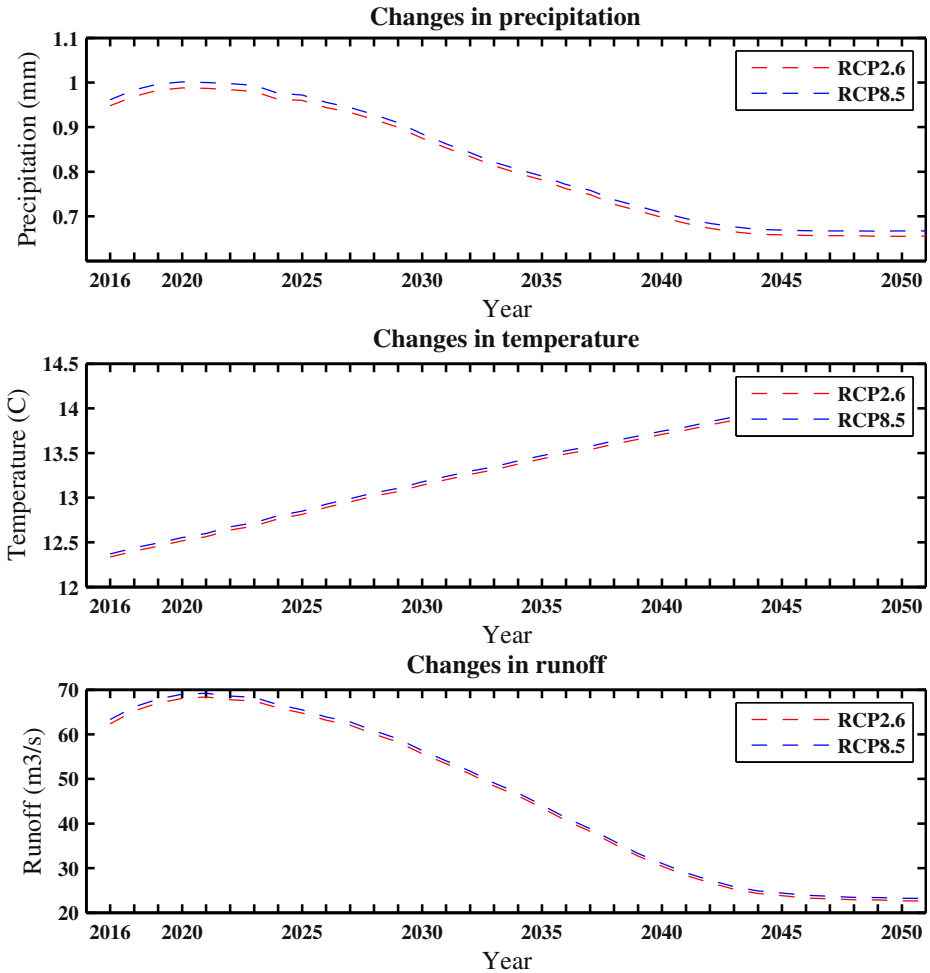
Fig. 6 The annual mean precipitation, temperature and streamflow of the Zarrineh River operated under RCP2.6 and RCP8.5 from 2016 to 2050

water demand is not met and does not consider the amount of unmet demand. On the other hand, the values of Vul in all the strategies were obtained to be the same for each specific usage, which is due to the presence of a large figure in the denominator of the fraction in the calculation formula, during the study period. This in turn implies the necessity of considering

Table 1 Comparing the results of the WEAP model and the observations for volume of water in the Lake Urmia in the verification period and water demand in different sectors in 2018

	Volume of Lake Urmia (BCM)								Water demand (MCM)		
Year	2011	2012	2013	2014	2015	2016	2017	2018	Domestic demand	Agricultural demand	Industrial demand
WEAP	3.66	3.20	2.49	2.09	1.84	1.72	1.71	1.65	189.9	3236.3	69.95
Observation	3.16	2.49	1.87	1.48	1.90	1.95	1.54	1.66	175.9	3351.1	97.1

Table 2 Performance criteria of reliability, vulnerability, maximum deficit and ISPI for the Zarrineh River basin for the applied RCPs

Strategy	Domestic usage				Agricultural usage				Industrial usage			
	Rel	Vul	MaxDef	ISPI	Rel	Vul	MaxDef	ISPI	Rel	Vul	MaxDef	ISPI
S0-RCP2.6	0.288	0.001	0.004	0.096	0.459	0.003	0.015	0.767	0.285	0.001	0.002	0.657
S1-RCP2.6	0.286	0.001	0.001	0.095	0.458	0.003	0.009	0.768	0.283	0.001	0.002	0.656
S2-RCP2.6	0.288	0.001	0.001	0.096	0.459	0.003	0.009	0.768	0.281	0.001	0.002	0.654
S3-RCP2.6	0.289	0.001	0.001	0.096	0.461	0.003	0.009	0.769	0.283	0.001	0.002	0.656
S4-RCP2.6	0.327	0.001	0.001	0.109	0.472	0.003	0.009	0.775	0.325	0.001	0.002	0.687
S0-RCP8.5	0.288	0.001	0.004	0.096	0.459	0.003	0.015	0.767	0.284	0.001	0.002	0.657
S1-RCP8.5	0.286	0.001	0.001	0.095	0.458	0.003	0.009	0.768	0.283	0.001	0.002	0.656
S2-RCP8.5	0.288	0.001	0.001	0.096	0.459	0.003	0.009	0.768	0.281	0.001	0.002	0.654
S3-RCP8.5	0.289	0.001	0.001	0.096	0.460	0.003	0.009	0.769	0.283	0.001	0.002	0.656
S4-RCP8.5	0.327	0.001	0.001	0.109	0.473	0.003	0.009	0.776	0.325	0.001	0.002	0.687

all the indices in choosing the best strategy. In this regard, in the final step, TOPSIS method was used to select the best strategy. The inputs of this method were obtained from Table 2 as the decision matrix, and the aim was to select an option that had the highest Rel and ISPI, and the least Vul and MaxDef. The ranking of these strategies for each of the climate scenarios are presented in Table 3. In this table, strategies were ranked according to the closeness (CL) to the ideal solution.

Table 3 shows that the greatest sustainability of system would occur with 40% reduction in agricultural water consumption (S4). Practicing S4 would be best performed as follows: a) reducing the cultivated area in the region, b) decreasing cultivation of water-intensive crops, c) increasing irrigation efficiency by changing surface irrigation systems to sprinkler and drip irrigation systems, and d) increasing total irrigation efficiency by increasing conveyance, distribution, and application efficiency through rehabilitating the Zarrineh River irrigation network, river dredging, water conveyance by pipes, and training and technical supports of the farmers (Gohari et al. 2017; Richter et al. 2017; Ahmadaali et al. 2018; Emami and Koch 2018).

With the aim of assessing the Lake Urmia's environmental requirement from Zarrineh River, the average annual inflow to the lake from the river was evaluated under different management strategies. As mentioned earlier, the share of the environmental flow requirements of the lake from the river is estimated at 1271 MCM annually. Table 4 illustrates the average annual inflow to the lake, taking into account the water consumption from the river by different consumption segments from 2021 to 2050. Based on the table, the largest amount of inflow to the lake belongs to S4-RCP8.5. In this strategy, the average annual inflow to the

Table 3 The result of priorities of the strategies for different RCPs based on TOPSIS method

Strategy	RCP2.6		RCP8.5	
	CL	Rank	CL	Rank
S0	0.0116	5	0.0102	5
S1	0.8646	4	0.8644	4
S2	0.8668	3	0.8667	3
S3	0.8702	2	0.8699	2
S4	1.0000	1	1.0000	1

Table 4 Mean annual streamflow of Zarrineh River under different strategies between 2021 and 2050

Strategy	RCP2.6		RCP8.5	
	Supply delivered (MCM/year)	Supply delivered (%)	Supply delivered (MCM/year)	Supply delivered (%)
S0	922.59	72.59	941.22	74.05
S1	927.05	72.94	945.70	74.41
S2	921.90	72.53	940.36	73.99
S3	954.48	75.10	972.53	76.52
S4	1010.83	79.53	1029.75	81.02

Lake Urmia between 2021 and 2050 will be 1029.75 MCM, which is equal to 81.02% of the Lake Urmia's environmental requirement of the river (Fig. 7).

The scenarios, used in the study were presented by practitioners in the Urmia Lake Restoration National Committee and it is recommended to review more diverse strategies. Investigation of results from these scenarios is very helpful; however, considering relatively little attention has been paid to the integrated water resources management aspects such as social, economic, political etc., the reliability of such analyses is questionable (e.g. Mizanur Rahaman and Varis 2005). So, the important barriers, policy and otherwise, will affect the application of these strategies and will need to be better understood and addressed. Going forward, additional considerations may need to be considered and the criteria mentioned in this toolbox can be changed. Investigating a variety of scenarios in the proposed toolbox, decision makers use an automate tool to look at management strategies as well as a wide range of criteria. This gives the policy makers a higher degree of confidence that the selected option is going to serve societies well over time across the climate scenarios, still being affordable and feasible to implement.
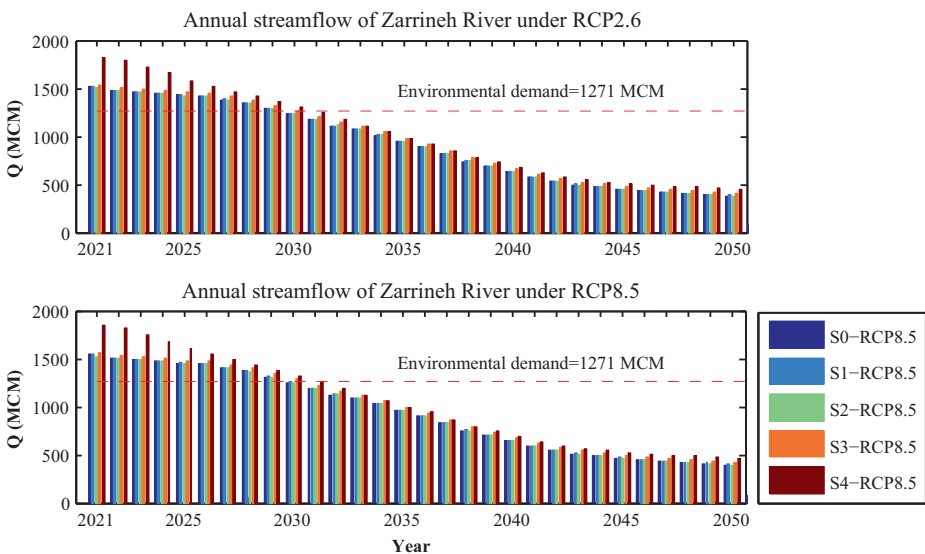
Fig. 7 Changes in Lake Urmia's inflows from Zarrineh River based on different strategies, operated under RCPs between 2021 and 2050

4 Conclusions

Sustainable climate change strategies must be based on a holistic view of the dynamic processes and interactions between the different components of a water resources system that take into account the various aspects of system sustainability along with its hydrological features. The applied approach in this study was to use the system dynamics modelling to model the actual behavior of the Zarrineh River basin under a changing climate. In this study, the precipitation and temperature data of seven GCMs (BCC-CSM1–1, BNU-ESM, CSIRO-Mk3–6-0, GFDL-ESM2G, IPSL-CM5A-LR, MIROC-ESM, and MIROC-ESM-CHEM) were downscaled using statistical downscaling methods and then the best model was chosen based on statistical indices. Then, the effects of climate change on the future streamflow of the river were investigated, using a rainfall-runoff model. A WEAP model was then used to evaluate the system response to climate change in various domestic, industry and agricultural sectors, providing an insight into the study of the sustainability of five management strategies. Finally, four sustainability indices were evaluated in a system dynamics model and then the TOPSIS method was utilized to select the best strategy.

Results showed that the changing climate is expected to increase daily mean temperature from 12.33 and 12.37 °C in 2015 to 14.28 and 14.32 °C in 2050 based on RCP2.6 and RCP8.5, respectively. The amounts of precipitation will also change as temperatures rise. In the case of precipitation, there is a decrease from 0.94 and 0.96 mm in 2015 to 0.65 and 0.68 mm in 2050 respectively based on the applied climate scenarios. The projected increase in temperature and reduction in precipitation, lead to a decrease of the annual streamflow of Zarrineh River from 59.49 m^3/s in 2015 to 22.61 and 23.19 m^3/s in 2050. Reduction in basin resources and increasing water demand will intensify water conflicts. To adapt to these environmental changes, the strategy of 40% agricultural water use reduction was selected. Based on this strategy, the average annual inflow to Lake Urmia between 2021 and 2050 will be 1029.75 MCM, which is equal to 81.02% of the lake's environmental requirement from the river.

In order to enhance evaluate possible strategies, it is recommended to define strategies, focusing on water consumption management and water conservation management, simultaneously. This study considers the technical aspects of systems sustainability; while many parameters including social, economic, environmental, and political factors could influence the sustainability of water resources systems. So, it is recommended to define and evaluate indices that clarify the system's response to these parameters.

Compliance with Ethical Standards

Conflicts of Interest   The authors declare that they have no conflict of interest.

References

Abadi LSK, Shamsai A, Goharnejad H (2015) An analysis of the sustainability of basin water resources using Vensim model. KSCE J Civ Eng 19:1941–1949. https://doi.org/10.1007/s12205-014-0570-7

Abbaspour M, Nazaridoust A (2007) Determination of environmental water requirements of Lake Urmia, Iran: an ecological approach. Int. J. Environ. Stud. 64:161–169

Adger N, Brown K, Nelson D, Berkes F, Eakin H, Folke C, Galvin K, Gunderson L, Goulden M, O'Brien K, Jack Ruitenbeek J, Tompkins E (2011) Resilience implications of policy responses to climate change. WIREs CLIMATE CHANGE 2(5):757–766. https://doi.org/10.1002/wcc.133

Ahmadaali J, Barani G, Qaderi K, Hessari B (2018) Analysis of the effects of water management strategies and climate change on the environmental and agricultural sustainability of Urmia Lake basin, Iran. Journal of Water 10(2):1–21. https://doi.org/10.3390/w10020160

Ahmadi A, Abbaspour M, Arjmandi R, Abedi Z (2016) Resilient approach toward urban development in Lake catchments; case of Lake Urmia. Scientia Iranica 23(4):1627–1632

Ahmadzadeh Kokya T, Pejman A, Mahin Abdollahzadeh E, Ahmadzadeh Kokya B, Nazariha M (2011) Evaluation of salt effects on some thermodynamic properties of Urmia Lake water. Int J EnvironRes 5343–8

Alborzi A, Mirchi A, Moftakhari H, Mallakpour I, Alian S, Nazemi A, Hassanzadeh E, Mazdiyasni O, Ashraf S, Madani K, Norouzi H, Azarderakhsh M, Mehran A, Sadegh M, Castelletti A, AghaKouchak A (2018) Climate-informed environmental inflows to revive a drying lake facing meteorological and anthropogenic droughts. Environ Res Lett 13(2018):084010. https://doi.org/10.1088/1748-9326/aad246

Arnell N (1999) Climate change and global water resources. Glob Environ Chang 9(1):S31–S49. https://doi.org/10.1016/S0959-3780(99)00017-5

Blanco-Gutiérrez I (2010) Economic-hydrologic analysis of water management strategies for balancing water for nature and water for food: implications for the Guadiana River basin. Spain. Doctoral Thesis. Polytechnical University of Madrid

Boroughani M, Hashemi H, Hosseini SH, Pourhashemi S, Berndtsson R (2019) Desiccating Lake Urmia: a new dust source of regional importance. IEEE Geosci Remote Sens Lett 17:1483–1487. https://doi.org/10.1109/LGRS.2019.2949132

Delju A, Ceylan A, Piguet E, Rebetez M (2013) Observed climate variability and change in Urmia Lake Basin, Iran. Theor Appl Climatol 111:285–296

Dibike YB, Coulibaly P (2005) Hydrologic impact of climate change in the Saguenay watershed: comparison of downscaling methods and hydrologic models. Journal of Hydrology, 9 June 307(1–4):145–163

Eberlein RL, Peterson DW (1992) Understanding models with Vensim. Eur J Oper Res 59(1):216–219. https://doi.org/10.1016/0377-2217(92)90018-5

Emami F, Koch M (2018) Agricultural water productivity-based hydro-economic modeling for optimal crop pattern and water resources planning in the Zarrineh River basin, Iran, in the wake of climate change. Sustainability. 10:3953. https://doi.org/10.3390/su10113953

Fang GH, Yang J, Chen YN, Zammit C (2015) Comparing bias correction methods in downscaling meteorological variable for a hydrologic impact study in an arid area in China. Hydrol Earth Syst Sci 19:2547–2559. https://doi.org/10.5194/hess-19-2547-2015

Fowler HJ, Ekström M, Blenkinsop S, Smith AP (2007) Estimating change in extreme European precipitation using a multimodel ensemble. J Geophys Res 112:D18104. https://doi.org/10.1029/2007JD008619

Ford A (1999) Modeling the environment: an introduction to system dynamics modeling of environmental systems. Island Press, Washington DC

Forrester JW (1961) Industrial dynamics. MIT Press, Cambridge

Forrester JW (1969) Urban dynamics. MIT Press, Cambridge

Gandure S, Walker S, Botha JJ (2013) Farmers' perceptions of adaptation to climate change and water stress in a south African rural community. Environmental Development 5:39–53. https://doi.org/10.1016/j.envdev.2012.11.004

García-Cascales MS, Lamata MT (2012) On rank reversal and TOPSIS method. Math Comput Model 56:123–132. https://doi.org/10.1016/j.mcm.2011.12.022

Ghale YAG, Altunkaynak A, Unal A (2018) Investigation an anthropogenic impacts and climate factors on drying up of Urmia Lake using water budget and drought analysis. Water Resour. Manage. 32:325–337

Ghaheri M, Baghal-Vayjooee M, Naziri J (1999) Lake Urmia, Iran: a summary review. Int. J. Salt Lake Res. 8: 19–22

Gohari A, Mirchi A, Madani K (2017) System dynamics evaluation of climate change adaptation strategies for water resources Management in Central Iran. Water Resour Manag 31:1413–1434. https://doi.org/10.1007/s11269-017-1575-z

Gholampour A, Nabizadeh R, Hassanvand MS, Taghipour H, Nazmara S, Mahvi AH (2015) Characterization of saline dust emission resulted from Urmia Lake drying. J. Environ. HealthSci. Eng. 13 82

Hashimoto T, Stedinger JR, Loucks DP (1982) Reliability, resiliency and vulnerability criteria for water resource system performance evaluation. Water Resour Res 18(1):14–20. https://doi.org/10.1029/WR018i001p00014

Hassanzadeh E, Zarghami M, Hassanzadeh Y (2012) Determining the main factors in declining the Lake Urmia level by using system dynamics modeling. Water Resour Manage. 26:129–124

Hwang C L, Yoon K (1981) Multiple attribute decision making: methods and applications: a state of the art survey, springer-Verlag, Berlin; Heidelberg; New York

IPCC (2013) Climate change 2013: the physical science basis, contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University press, Cambridge, UK; New York, USA

Jalili S, Hamidi SA, Namdar Ghanbari R (2016) Climate variability and anthropogenic effects on Lake Urmia water level fluctuations, northwestern Iran. Hydrol Sci J 61(10):1759–1769

Joyce BA, Mehta VK, Purkey DR, Dale LL, Hanemann M (2011) Modifying agricultural water management to adapt to climate change in California's central valley. Clim Chang 109(1):299–316

Juwana I, Muttil N, Perera BJ (2012) Indicator-based water sustainability assessment - a review. Sci Total Environ 1(438):357–371. https://doi.org/10.1016/j.scitotenv.2012.08.093

Klemes V, Srikanthan R, McMahon TA (1981) Long-memory flow models in reservoir analysis: what is their practical value? Water Resour Res 17(3):737–751. https://doi.org/10.1029/WR017i003p00737

Langsdale S, Beall A, Carmichael J, Cohen S, Forster C (2007) An exploration of water resources futures under climate change using system dynamics modeling. Integr Asses J 7(1):51–79

Li F, Zhang G, Xu YJ (2014) Separating the impacts of climate variation and human activities on runoff in the Songhua River Basin, Northeast China. Water. 6(11):3320–3238

Loucks DP (1997) Quantifying trends in system sustainability. Hydrolog Sci J 42(4):513–530. https://doi.org/10.1080/02626669709492051

MacDonald GM (2010) Water, climate change, and sustainability in the southwest. PNAS 107(50):21256–21262. https://doi.org/10.1073/pnas.0909651107

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

McSweeney CF, Jones RG, Lee RW, Rowell DP (2015) Selecting CMIP5 GCMs for downscaling over multiple regions. Clim Dyn 44(Issue 11–12):3237–3232

Mirchi A, Madani K, Watkins D, Ahmad S (2012) Synthesis of system dynamics tools for holistic conceptualization of water resources problems. Water Resour Manag 26(9):2421–2442. https://doi.org/10.1007/s11269-012-0024-2

Mizanur Rahaman M, Varis O (2005) Integrated water resources management: evolution, prospects and future challenges, sustainability: science. Practice and Policy 1(1):15–21. https://doi.org/10.1080/15487733.2005.11907961

Mugatsia EA (2010) Simulation and scenario analysis of water resources management in Perkerra catchment using WEAP model. Master Thesis, Department of Civil and Structural Engineering, School of Engineering, Moi University, Kenya

Nikbakht J, Tabari H, Talaee PH (2013) Streamflow drought severity analysis by percent of normal index PNIin Northwest Iran. Theor. Appl. Climatol 112:565–573

Nkomozepi T, Chung SO (2014) The effects of climate change on the water resources of the Geumho River basin, Republic of Korea. Journal of Hydroenvironment Research, December 8(4):358–366

Prodanovic P, Simonovic SP (2010) An operational model for support of integrated watershed management. Water Resour Manag 24(6):1161–1194. https://doi.org/10.1007/s11269-009-9490-6

Richter BD, Brown JD, DiBenedetto R, Gorsky A, Keenan E, Madray C, Morris M, Rowell D, Ryu S (2017) Opportunities for saving and reallocating agricultural water to alleviate water scarcity. Water Policy 19(5):886–907

Sandoval-Solis S, McKinney DC, Loucks DP (2011) Sustainability index for water resources planning and management. J Water Resour Plan Manage 137(5):381–390. https://doi.org/10.1061/(ASCE)WR.19435452.0000134

Santikayasa IP, Babel MS, Shrestha S, Jourdain D, Clemente RS (2014) Evaluation of water use sustainability under future climate and irrigation management scenarios in Citarum River basin, Indonesia. International Journal of Sustainable Development & World Ecology 21(2):181–194

Seibert J (2003) Reliability of model predictions outside calibration conditions. Nord Hydrol 34(5):477–492. https://doi.org/10.2166/nh.2003.028

Shadkam S, Ludwig F, van Oel P, Kirmit Ç, Kabat P (2016) Impacts of climate change and water resources development on the declining inflow into Iran's Urmia Lake. Great Lakes Res 42:942–952

Siegfried T, Bernauer T, Guiennet R, Sellars S, Robertson AW, Mankin J, Bauer-Gottwein P, Yakovlev A (2011) Will climate change exacerbate water stress in Central Asia? Clim Chang 112:881–899. https://doi.org/10.1007/s10584-011-0253-z

Simonovic SP, Li L (2003) Methodology for assessment of climate change impacts on large-scale flood protection system. J Water Resour Plan Manage 129(5):361–371. https://doi.org/10.1061/(ASCE)0733-9496(2003)129:5(361)

Simonovic SP, Li L (2004) Sensitivity of the Red River basin flood protection system to climate variability and change. Water Resour Manag 18(2):89–110

Singh VP, Prakash Khedun C, Mishra AK (2014) Water, environment, energy, and population growth: implications for water sustainability under climate change. J Hydrol Eng 19(4):667–673

Srdjevic Z, Srdjevic B (2017) An extension of the sustainability index definition in water resources planning and management. Water Resour Manag 2017(31):1695–1712

Sterman JD (2000) Business dynamics, systems thinking and modeling for a complex world. McGraw-Hill, Boston

Teutschbein C, Seibert J (2012) Bias correction of regional climate model simulations for hydrological climate-change impact studies: review and evaluation of different methods. J Hydrol 456-457:12–29. https://doi.org/10.1016/j.jhydrol.2012.05.052

Torabi Haghighi A, Klove B (2017) Design of environmental flow regimes to maintain lakes and wetlands in regions with high seasonal irrigation demand. Ecol Eng 100:120–129

Urmia Lake Restoration National Committee (2015) Necessity of Lake Urmia Resuscitation, Causes of Drought and Threats; Report No: ULRP-6-43-Rep 1. [in Persian]

Ventana Systems (2010) User's guide version 5, Ventana Systems, Inc. Retrieved from http://www.vensim.com

Winz I, Brierley G, Trowsdale S (2009) The use of system dynamics simulation in water resources management. Water Resour Manag 23(7):1301–1323. https://doi.org/10.1007/s11269-008-9328-7

Xiao-jun W, Jian-yun Z, Jian-hua W, Rui-min H, ElMahdi A, Jin-hua L, Xin-gong W, Shahid S (2014) Climate change and water resources management in Tuwei river basin of Northwest China. Mitigation Adapt Strateg Glob Chang 19(1):107–120. https://doi.org/10.1007/s11027-012-9430-2

Yates D, Purkey D, Sieber J, Huber-Lee A, Galbraith H (2005a) WEAP21—a demand-, priority-, and preference-driven water planning model: part 2: aiding freshwater ecosystem service evaluation. Water Int 30(4):501512

Yates D, Sieber J, Purkey D, Huber-Lee A (2005b) WEAP21-a demand-, priority-, and preference-driven water planning model: part 1: model characteristics. Water Int 30(4):487–500

Yazdandoost F, Moradian S (2019) Climate change impacts on the streamflow of Zarrineh River. Iran Journal of Arid Land. https://doi.org/10.1007/s40333-020-0124-4

Yilmaz B, Harmancioglu NB (2010) An indicator-based assessment for water resources management in Gediz river basin, Turkey. Water Resour Manag 24(15):4359–4379

Zarghami M, AmirRahmani M (2017) A system dynamics approach to simulate the restoration plans for Urmia Lake, Iran. Optimization and dynamics with their applications. A Matsumoto (Singapore: springer) pp 309–26

Zhai R, Tao F (2017) Contributions of climate change and human activities to runoff change in seven typical catchments across China. Sci Total Environ 605:219–212