Sustainability assessment of restoration plans under climate change by using system dynamics: application on Urmia Lake, Iran

Elham Ebrahimi Sarindizaj and Mahdi Zarghami

ABSTRACT

During the last decade, Urmia Lake has lost most of its surface area. As a result, finding management practices to restore the sustainable ecological status of Urmia Lake, the world's second largest hyper-saline lake, is imperative. In this study, the sustainability of different plans under climate change was assessed using system dynamics. The plans were evaluated with respect to sustainability criteria including reliability, resiliency, and vulnerability measures. According to the results due to different management practices, on average, water consumption should be reduced by at least 30% to restore the lake. The results revealed that only hybrid plans which incorporate multiple management practices, instead of focusing on just one approach, can be influential. Among the hybrid plans, that of increasing irrigation efficiency, reducing cultivated area, changing crop pattern, and inter-basin water transfer was identified as the most sustainable plan. About eight years after applying this plan, the lake will achieve its ecological level and will remain sustainable. Considering comprehensive factors, the proposed model can help watershed managers to take the necessary measures to restore this vital ecosystem. The results of this study can be applied to water resources systems with the same problem, especially those in semi-arid regions with multidisciplinary aspects.

Key words | climate change, environmental management, modeling, system dynamics, Urmia Lake

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INTRODUCTION

Despite global water resources limitations, increasing population growth and human activities have led to greater water demand. Among all natural resources, water is one of the most challenging issues. The main objective of sustainable environmental management is finding a proper balance between humans and their impact on the environment (Falkenmark 2003). Water management practices directly alter water availability and distribution, with feedbacks on land surface fluxes (Ferguson & Maxwell 2012).

Urmia Lake with a 5,200–6,000 km^2 area is the largest lake in the northwestern region of Iran (Fathian *et al.* 2014). In past decades, the lake's water level has significantly dropped. Furthermore, the decreasing trend of Urmia Lake's level in recent years has become a challenge and one of the most problematic issues in the region. This ongoing reduction of water level has had critical impacts on agriculture, environment, and the economy (Fathian *et al.* 2014).

In the current decade, saving Urmia Lake is one of the most important priorities. Nevertheless, the absence of comprehensive research to evaluate the effect of adaptation/mitigation strategies on the lake is evident (Zarghami & AmirRahmani 2017). Irrigation accounts for ~90% of water consumption in Iran (Iran Ministry of Energy 2012). Since the agricultural sector is known to be the main culprit of the basin's water shortage, it is vital to assess the impact of irrigation water consumption on the lake's restoration.

doi: 10.2166/wcc.2018.209

In this study, some effective variables such as water demand (in millimeters per month, calculated using NETWAT software), cultivated area (hectare per month), and irrigation efficiency were used in crop and horticultural cultivated land modeling.

System dynamics (SD) models are tools to facilitate understanding of the interactions between diverse but interconnected sub-systems that drive the dynamic behavior of the larger system (Forrester 1968). However, a model's ability to provide proper insights into potential consequences of system perturbation depends on efficient recognition of the main constituents and feedback loops between them (Gohari *et al.* 2013).

Finding management practices to achieve sustainable ecological status of the lake is vital due to the socio-environmental consequences of the current status of Urmia Lake. Sustainable water resources management is complex and climate change brings more complexity to the problem. Hence, managing water resources considering climate change is crucial for determining the possible future challenges. To progress in sustainability, quantifiable indicators are key tools for managers (Aydin 2014; Graziano & Rizzi 2016).

A new set of emission scenarios are consistent with the new Representative Concentration Pathways (RCPs) and are different from the emission scenarios described in the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) (Semenov & Stratonovitch 2015). The RCPs included mitigation measures to achieve specific emission targets. However, the Lars-WG model does not consider RCPs.

Hassanzadeh *et al.* (2012) assessed the dynamic status of Urmia Lake in the past. They showed that the effect of inflow variations were the result of climate change and overuse of surface water resources by 65%, which is the main factor behind the lake's shrinkage. Zarghami & AmirRahmani (2017) produced an SD model with hydrological demands and percolation sub-models. They assessed the contribution of some plans to increase Urmia Lake's level.

Here, the developed SD model for Urmia Lake is the integration of simpler models made earlier (Hassanzadeh *et al.* 2012; Zarghami & AmirRahmani 2017). This model represents the complex reactions among the variables while taking public participation into account. The goals of this study are to observe Urmia Lake's dynamic status up to 2030, apply various restoration plans and assess their sustainability. To reach this end, a new holistic SD model consisting of hydrological and agricultural sub-models with consideration of climate change has been developed to achieve sustainable status in the lake ecosystem. Sustainability of the plans is evaluated by a sustainability index (SI) based on reliability, vulnerability, and resiliency performances. According to the results of this model, the following can be understood: how much water is required for Urmia Lake to achieve its ecological level; how vulnerable, resistant, and reliable are the restoration plans; and generally, which plan is the most sustainable one.

The case study is the Urmia Lake basin which is a closed drainage basin with an approximate area of 52,000 km^2 in the northwest of Iran (Figure 1). Urmia Lake is the second largest hyper saline lake and has a unique ecosystem and important socio-economic and ecological role in the region (Ebrahimi & Zarghami 2018). Due to its unique ecological features, the lake has been designated as a UNESCO Biosphere Reserve (CIWP 2008). The lake basin has experienced extreme water shortages in recent years due to the dry climate (Alipour 2006). Inflow to the lake includes rainfall, surface water, and groundwater and the only outflow from the lake is evaporation (Hassanzadeh *et al.* 2012).

The required ecological water level for Urmia Lake is 1,274.1 m above sea level (Abbaspour & Nazaridoust 2007). This water level is calculated using ecological and water quality (NaCl concentration) indices. The ecological water level of Urmia Lake is evaluated considering the required ecological concentration of NaCl (i.e., 240 ppt). If the water level in Urmia Lake rises more than 1,274.1 m, Artemia (a species of brine shrimp) can tolerate the water quality index concentration (Abbaspour & Nazaridoust 2007). As shown in Figure 2, the lake's annual water level dropped below the ecological level from 2001. One of the socio-economic aspects of Urmia Lake is the use of Artemia fish and shrimp aquaculture which is commercially important, but which recently has been restricted and is becoming extinct. In addition, windblown salty dusts from dry areas of the lakebed can threaten the health of the resident population in the basin (Zarghami & AmirRahmani 2017).

According to the reports of the Iran Ministry of Energy (2012), approximately 70% of the Urmia Lake basin's

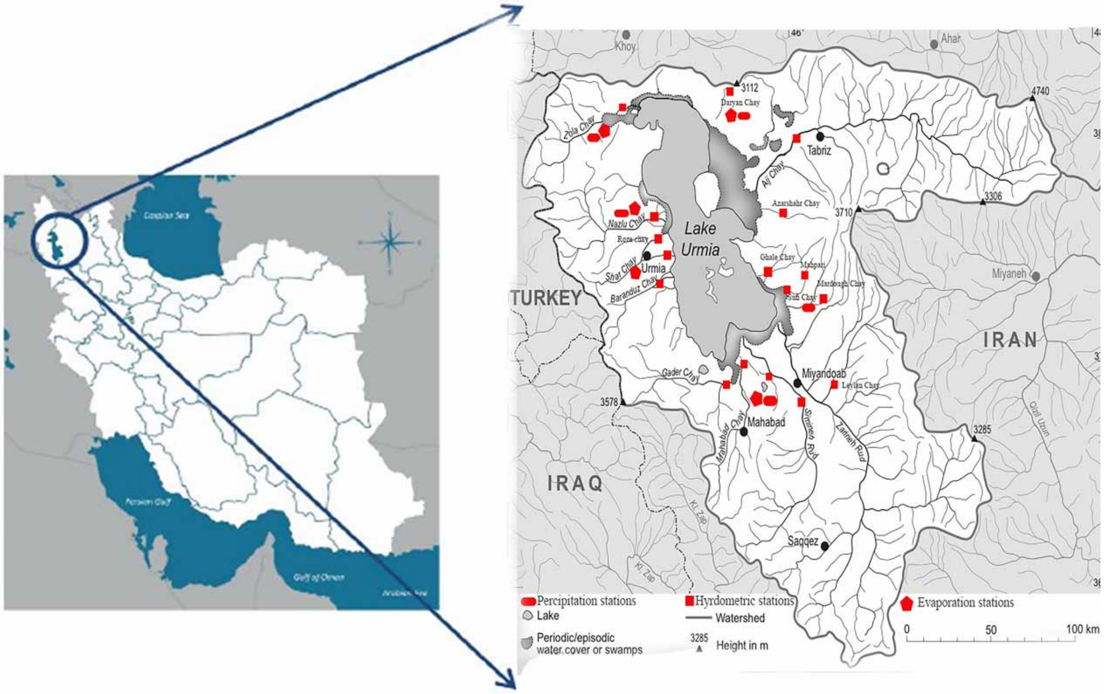

Figure 1 | Geographic location of the stations used for assessing Urmia Lake in Iran.

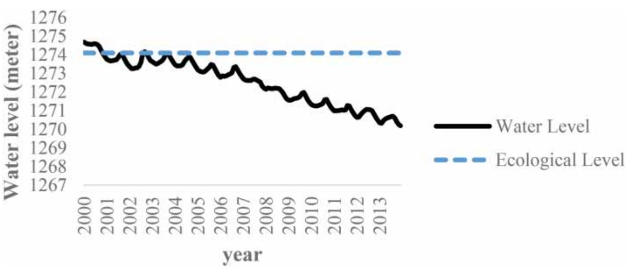

Figure 2 | Water level and ecological level of Urmia Lake (2000–2014).

cultivated lands are crop lands (Figure 3) and 30% of the area is dedicated to horticultural lands. The average irrigation efficiency of crop lands and horticultural lands were equal to 37% and 45%, respectively.

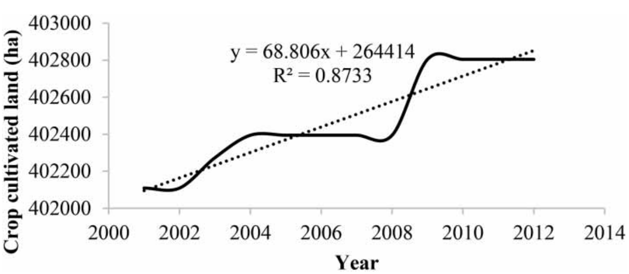

Figure 3 | Curve fitting of crop cultivated lands in the Urmia Lake basin (2001–2012).

METHODOLOGY

In order to plan for sustainable water resource development, the SD model of Urmia Lake was developed. Consideration of hydrological factors, population, and water demand sectors was proposed to improve the previous Urmia Lake SD models. To achieve this, the first step was assessing the climate of the lake basin using LARS-WG (version 5.0) model. Then, effective factors about the basin were recognized and partitioned into the SD model incorporating climate change considerations. In order to investigate the impact of various restoration plans on Urmia Lake, VENSIM software was utilized.

Meteorological forcing

Rainfall

Data and statistics on monthly rainfall were collected from five stations (Figure 4) close to the lake. The average amount of these stations was considered as rainfall on the lake (Table 1).

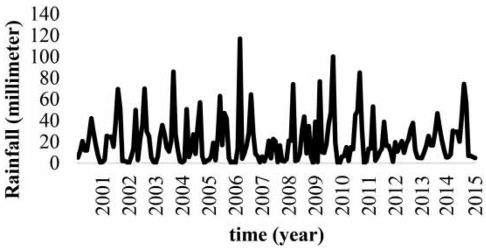

Figure 4 | Monthly rainfall using five stations in the Urmia Lake basin (2001–2015).

Table 1 | Rainfall stations used to model Urmia Lake

Location	Longitude	Latitude
Urmia Lake	45-39-43	37-68-22
Bonab	46-03-00	37-19-00
Sharfkhaneh	45-28-00	38-11-00
Dashkhaneh	45-41-00	37-01-00
Abajalu Sofla	45-08-00	37-43-00
Yalghuz Aghaj	44-56-00	38-14-00

Evaporation

Evaporation intensity was calculated by collecting data and statistics on monthly pan evaporation from five stations (Figure 1) close to the lake (Figure 5).

Evaporation volume was calculated using a volume–area relationship, a pan coefficient, and a salt coefficient. Studies suggest that the pan coefficient could be considered from 0.6 (Nimmo 1964) to 0.94 (Garrett & Hoy 1978). Salt coefficient was calibrated to 0.93 (the range was 0.72 to 0.96) (Quants 2014). It is assumed that the evaporation will also keep this increasing trend in the future.

Climate change

The obtained data from eight synoptic stations of Urmia, Tabriz, Takab, Sarab, Salmas, Sardasht, Maragheh, and Mahabad (Figure 1) were downscaled by the LARS-WG model in order to study the climate change of the basin. A 25-year baseline of weather data (1991–2014) was used to generate the long-term weather series from 2014 to 2030.

The LARS-WG model uses predictions of 15 GCMs (general circulation models) approved by the IPCC (AR4) under three scenarios of SRES storylines of A1B, A2, and B1 (Arnell *et al.* 2004). These scenarios cover a range of future

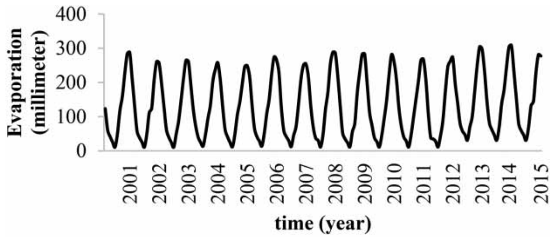

Figure 5 | Monthly evaporation using five stations in the Urmia Lake basin (2001–2015).

socio-economic, demographic, and technological storylines. LARS-WG uses a semi-empirical distribution (SED) to provide approximate probability distributions of precipitation, minimum and maximum temperatures, and solar radiation. The number of intervals (n) used in SED is 23. For each climatic variable v, a value of a climatic variable v_i corresponding to the probability p_i is calculated as Equation (1):

$$v_i = \min\{v{:}P\ (v_{obs} \leq v) \geq p_i\}\ i = 0,\ \ldots,\ n \quad (1)$$

where $P()$ denotes probability based on observed data $\{v_{obs}\}$. For each climatic variable, two values, p_0 and p_n, are fixed as $p_0 = 0$ and $p_n = 1$, with corresponding values of $v_0 = \min\{v_{obs}\}$ and $v_n = \max\{v_{obs}\}$. To approximate the extreme values of a climatic variable accurately, some p_i are assigned close to 0 for extremely low values of the variable and close to 1 for extremely high values; the remaining values of p_i are distributed evenly on the probability scale (Semenov & Stratonovitch 2010).

In order to assess the performance of the LARS-WG model, proper statistical tests were done to compare the observed and synthetic time series. Each test produces a p-value for measuring the probability that both sets of data come from the same distribution. The results of the t and F tests at 1% probability showed that the monthly rainfall predicted model means and standard deviations are in agreement with the observed series. A similar process was done for the maximum and minimum temperatures in the region.

Rainfall–runoff model

Seventeen hydrometric stations, which are located around the lake (Figure 1), were used to determine the surface water flow (Figure 6).

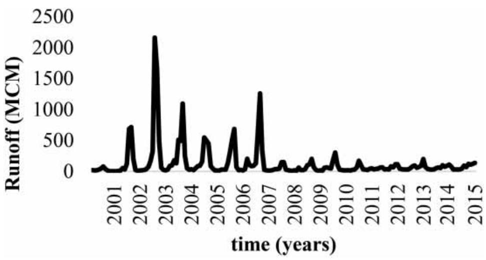

Figure 6 | Monthly runoff using 17 hydrometric stations in the Urmia Lake basin (2001–2015).

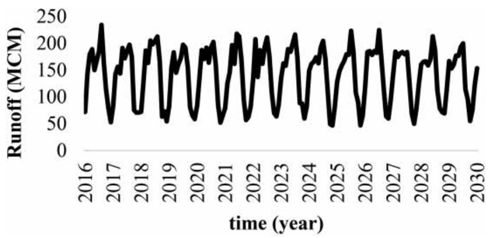

Figure 8 | Monthly runoff prediction of the Urmia Lake basin using a linear regression model between rainfall and runoff of the basin (2015–2030).

Average change of the different emission scenarios effect was in the range of 2 to 5%. To get more conservative results, the most pessimistic emission scenario (A2) was used to predict runoff. The runoff was calculated using rainfall (Figure 7) and runoff (Figure 8) of the basin. To do this, a linear regression model was developed relating rainfall and basin runoff. Runoff predictions were then calculated using predicted rainfall by the LARS-WG model. Most rainfall occurs between March and June and it is expected that the average lake runoff from 2015 to 2030 will be reduced by 15% compared with the period of 1996 to 2014.

System dynamics

System dynamics model

In the context of SD, variables are either stocks, flows, auxiliaries or constants. Stocks are state variables and start from an initial value and change by changing their inflows or outflows. Flow variables are used to define rates to change the stock variables. Information between levels (state variables) and flows are integrated with auxiliary variables; however, there are a few parameters with values that can be assumed as constant over the simulation horizon. The stock value at any time (t) when it has one inlet and one outlet is calculated using Equation (2):

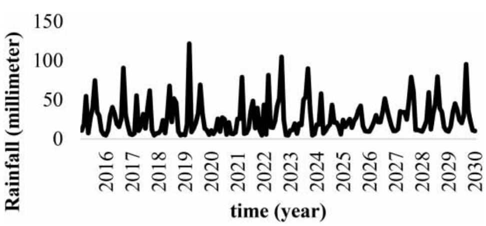

Figure 7 | Monthly rainfall prediction of the Urmia Lake basin (2015–2030).

$$Stock(t) = \int_{t_0}^{t_n} [Inflow(t) - Outflow(t)]dt + Stock(t_0) \quad (2)$$

where *Stock(t)* is stock at time t; *Inflow(t)* is inflow at time t; *Outflow(t)* is outflow at time t; and $Stock(t_0)$ is stock at time t_0.

Key variables to develop SD model

In the agriculture sector, water demand (millimeters per month), cultivated area (hectare per month), and irrigation efficiency were used in crop and horticultural land modeling. Water demand was calculated using NETWAT software. This software uses the FAO–Penman–Monteith method on a 10-day and monthly basis. Water demand in the Urmia Lake basin is evaluated by considering a period of planting, harvesting, and growth and the required meteorological data were obtained from synoptic stations over a 30-year period.

Furthermore, lake water balance analysis showed that the amount of groundwater inflow to the lake is negligible (Hassanzadeh *et al.* 2012) and is considered equal to 1% of available surface water.

The causal loop diagrams (CLDs) of water resources system including the lake and its sub-systems are identified in Figure 9. Sub-systems include population, socio-economic, hydrologic, and agricultural parts. In these diagrams, elements of the system are connected by arrows with positive and negative polarities. A positive link indicates the parallel behavior of variables: in the case of an increase in the 'cause' variable, the variable that is affected also increases, while a decrease in the 'cause' variable implies

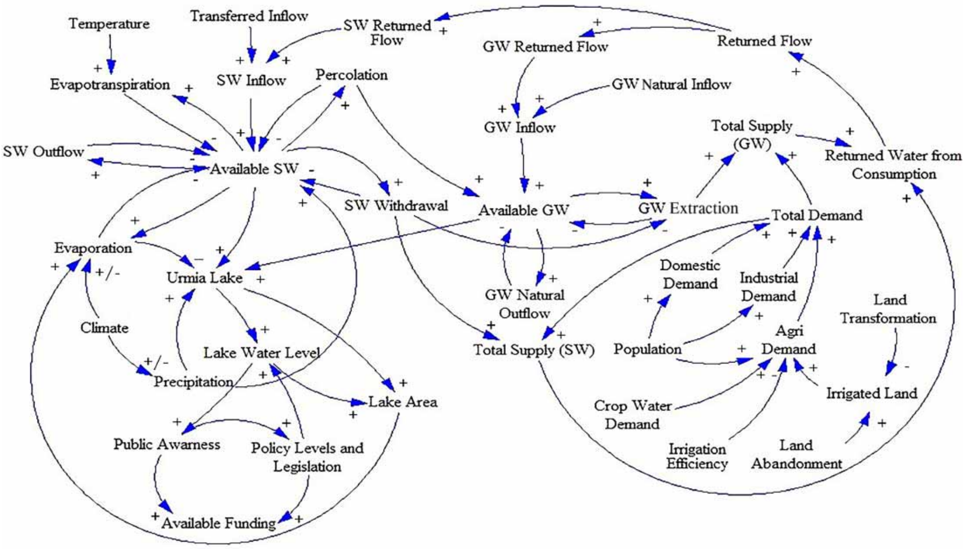

Figure 9 | Causal loop diagram for Urmia Lake.

a decrease in the affected one. A negative link indicates an inverse linkage between variables (Halbe *et al.* 2013).

The CLDs consist of various variables (lake balance, surface flow, the agriculture demand, population, and groundwater). The causal loops which have been added compared to the last publication of the Urmia SD model are displayed in Figure 10, however some parts of Figure 11 were published earlier (Hassanzadeh *et al.* 2012; Gohari *et al.* 2013). As mentioned in the Introduction, the agricultural sector is the main culprit causing shrinkage of Urmia Lake, and thus, assessing the agriculture in the basin in detail and considering the consequences of applying the related restoration plans is essential.

Using the CLDs, the stock flow diagram was developed in Vensim software, as shown in Figure 11, to characterize the system processes. In order to simulate the model, monthly data were entered and the required hydrologic equations were defined in the Vensim environment.

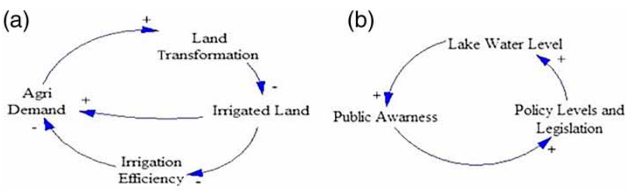

Figure 10 | New key loops affecting the sustainability of the restoration plan for the Urmia Lake.

The variables used in the SD model, their sources and units, are listed in Table 2.

To assess the model's performance, statistical measures such as coefficient of determination (R^2) by Equation (3) and root mean square error (RMSE) by Equation (4) were used:

$$R^2 = \left\{ \frac{\sum_{i=1}^{n} (Q_i - \bar{Q})\left(\ddot{Q}_i - \tilde{Q}\right)}{\sqrt{\sum_{i=1}^{n} (Q_i - \bar{Q})^2 \sum_{i=1}^{n} \left(\ddot{Q}_i - \tilde{Q}\right)^2}} \right\}^2 \quad (3)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} \left(Q_i - \ddot{Q}_i\right)^2}{n}} \quad (4)$$

where Q_i is estimated water level; $\bar{Q}$ is average of estimated water levels; $\ddot{Q}_i$ is observed water level; $\tilde{Q}$ is average of observed water levels; and n is number of the months between 2001 until 2014.

Sensitivity analysis using Monte Carlo simulation

The Monte Carlo method is used to sample a set of numbers between bounded domains (distribution for each particular parameters is specified) (Kasperska *et al.* 2014). Vensim provides an infrastructure to apply Monte Carlo simulation on the model to examine its behavior under uncertainty.

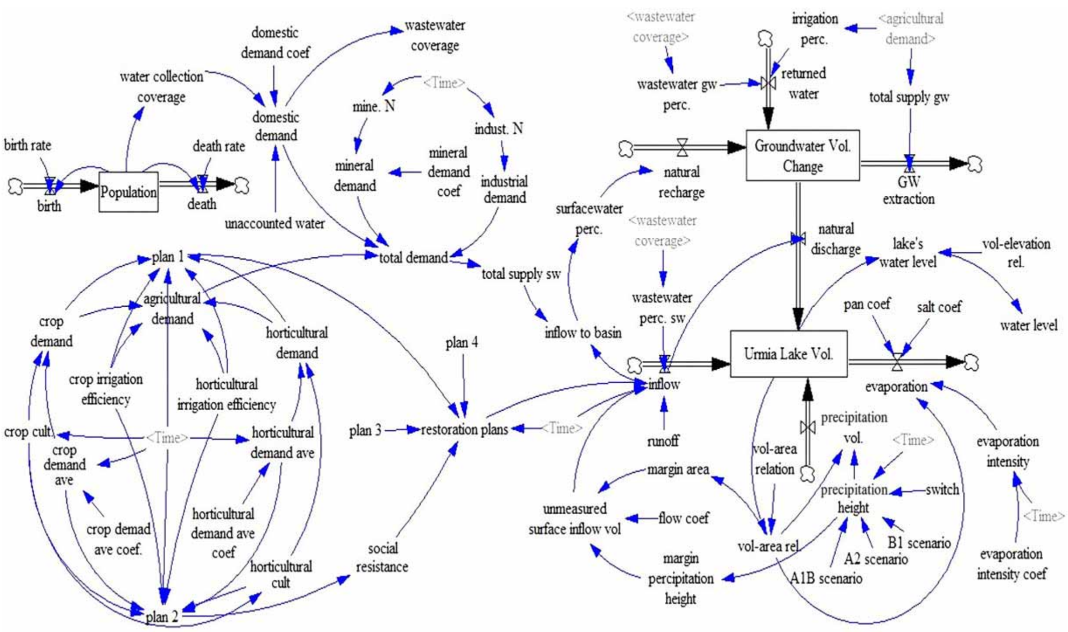

Figure 11 | Stock and flow diagram for the Urmia Lake SD model.

There were few sensitive parameters in this model. Among all variables, '*pan coef.*' and '*salt coef.*' did not have a certain value. The effect of changing these parameters on the lake's water level was assessed using Monte Carlo simulation in Vensim software. As previously mentioned, pan coefficient could have the value from 0.6 to 0.94 and this range for salt coefficient varies from 0.72 to 0.96. The result of sensitivity analysis is shown in Figure 12.

A notable point is that changes in the pan coefficient had a considerable influence over Urmia Lake's water level. The sensitivity of the lake's water level to the pan coefficient grows throughout the test simulation, such that, by the end of the simulation, its influence on the lake's water level was considerably greater than the initial change made to the parameter. The effect of changing the pan coefficient is different from the effect of changing the salt coefficient on the lake's water level. The effect of changing the salt coefficient is greater in the median time and negligible in the initial time and at the end of the simulation. Furthermore, changes in the salt coefficient had less effect on the Urmia Lake level compared with changes in the pan coefficient. Pan coefficient and evaporation depend on various parameters, thus in order to valid prediction, it should have a wider range.

Simulation plans

Among the various plans to change the lake's level, five restoration plans were considered. These policies, strategies, and projects were selected among the suggestions of ULRP, which is responsible for saving the lake in Iran (ULRP 2014). The chosen plans as shown below are the most applicable and efficient ones.

Plan 1: impact of increasing the irrigation efficiency on the lake level

As the agriculture sector is a high water demand sector, managing water in this sector is crucial. Therefore, using an efficient irrigation plan is important to achieve sustainable agriculture, as from the farmers' point of view irrigation could be an economic concern (Faramarzi 2012). The irrigation efficiency for crop cultivated lands and horticultural cultivated lands is about 0.37 and 0.45, respectively, in the Urmia Lake basin. Efficiency could be increased up to about 0.90 by using mechanized or drip irrigation. Hence, changing the irrigation method in some of the cultivated lands will greatly reduce agricultural water consumption. It is

Table 2 | Variables of the Urmia Lake SD model

Data	Source(s)	Units	Data source type
Total supply GW	Iran Ministry of Energy	MCM/month	Modeled
Natural recharge	Survey data	MCM/month	Modeled
Returned water	Survey data	MCM/month	Modeled
Groundwater extraction	Iran Ministry of Energy	MCM/month	Modeled
Natural discharge	Hassanzadeh *et al.* (2012)	MCM/month	Statistical
Groundwater volume change	Survey data	MCM/month	Modeled
Wastewater percolation SW	Iran Ministry of Energy	MCM/month	Statistical
Precipitation volume	Survey data	MCM/month	Modeled
Perception height	Iran Ministry of Energy	Millimeter/month	Statistical
Margin area	Survey data	km^2/month	Modeled
Margin precipitation height	Survey data	Millimeter/month	Modeled
Unmeasured surface inflow volume	Survey data	MCM/month	Modeled
Evaporation	Survey data	MCM/month	Modeled
Urmia Lake volume	Survey data	MCM	Statistical/Modeled
Population	Statistical Center of Iran	Dimensionless	Statistical
Domestic demand	Iran Ministry of Energy	MCM/month	Modeled
Mineral demand	Iran Ministry of Energy	MCM/month	Modeled
Industrial demand	Iran Ministry of Energy	MCM/month	Modeled
Horticultural demand	Survey data	MCM/month	Modeled
Crop demand	Survey data	MCM/month	Modeled
Agricultural demand	Survey data	MCM/month	Modeled
Total demand	Survey data	MCM/month	Modeled
Total supply SW	Iran Ministry of Energy	MCM/month	Modeled
Inflow to basin	Survey data	MCM/month	Modeled
Inflow	Survey data	MCM/month	Modeled
Surface water percolation	Iran Ministry of Energy	MCM/month	Modeled
Wastewater GW percolation	Iran Ministry of Energy	MCM/month	Statistical
Irrigation percolation	Iran Ministry of Energy	MCM/month	Statistical
Crop cultivated land	Iran Ministry of Agriculture; ULRP[a]	Ha/month	Statistical
Horticultural cultivated land	Iran Ministry of Agriculture; ULRP	Ha/month	Statistical
Crop demand average	NETWAT software	Millimeter/month	Statistical
Horticultural demand average	NETWAT software	Millimeter/month	Statistical
Runoff	Iran Ministry of Energy	MCM/month	Statistical
Evaporation intensity	Iran Ministry of Energy	Millimeter/month	Statistical
Lake's water level	Survey data	Meters/month	Modeled
Pan coef.	Survey data	Dimensionless	Personal intuition
Salt coef.	Survey data	Dimensionless	Personal intuition

[a]Urmia Lake Restoration Program.

assumed that the irrigation method in 50% of cultivated lands of the basin will be changed to mechanized irrigation from traditional ones like furrow and flood irrigation.

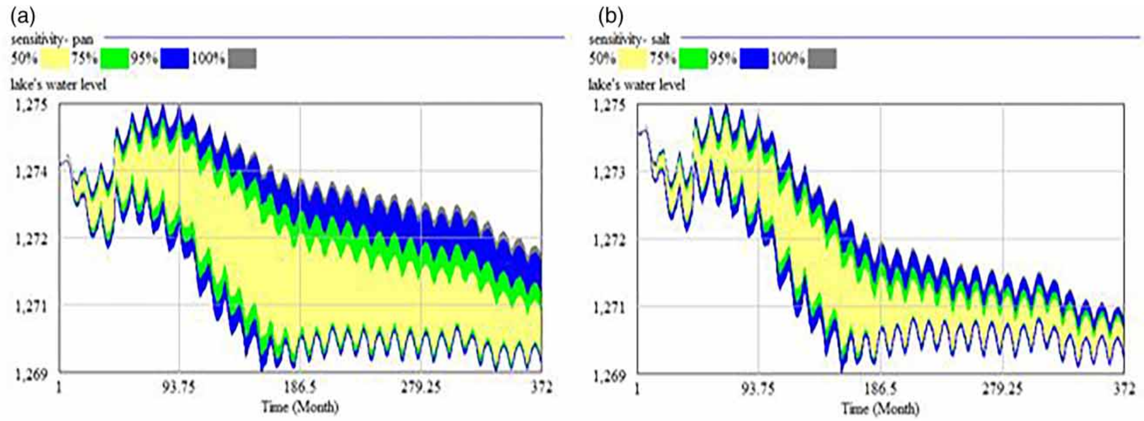

Figure 12 | Sensitivity analysis on the effect of uncertain parameters on the lake level: (a) pan coefficient and (b) salt coefficient.

Plan 2: impact of reducing cultivated area on the lake level

According to Warren *et al.* (2016), it seems that the changes in farming systems are going to be an important policy option for assessing environmental sustainability. Rapid growth in farmland in the basin is known to be one of the main factors behind the Urmia Lake disaster. Therefore, stopping its growth and decreasing the area are followed in Plan 2. It is assumed to have a maximum reduction of about 10% considering social resistance (changing 10% of irrigated land into dry farming).

Overall, by increasing the agricultural yields, the prices drop and cultivated areas decrease. Canada, China, and the United States are examples of countries that have experienced a decline in cultivated areas (Rudel *et al.* 2009). It is crucial to motivate farmers to adopt restoration policies. As reduction of cultivated areas imposes significant social costs on small farmers, increasing farmers' participation is very important (Rudel *et al.* 2009).

Iran's government has paid attention to this plan. Some subsidies were considered to reduce the financial burden and damage to cultivated lands. In this way, farmers would tend to accept the changes of water allocation in the Urmia Lake basin (ULRP 2014). Changing 10% of irrigated cultivated land to dry farming lands is suggested; however, due to social resistance it is considered that this plan will take at least three years to affect the Urmia Lake basin.

Plan 3: impact of changing crop pattern on the Urmia Lake level

According to the local authorities and experts, farmers are not aware of the impacts of their practices on water consumption. For instance, if in one year, one of the crops, such as sugar beet, is economically profitable in West Azerbaijan, most farmers in the next harvesting year are willing to cultivate sugar beet. Due to the different water demands of crops, replacing crops with less water demand and more economic crops can be considered as a solution for conserving the water. In this study, it was assumed that planting alfalfa, watermelon, clover, sugar beet, and sainfoin in crop cultivated land and also planting apple, pear, walnut, and almond in the horticultural cultivated land section would be stopped or reduced significantly. Applying this plan may influence farmers' income, and thus, compensations for the damage caused by the crop pattern change were considered as subsidies.

Plan 4: impact of inter-basin water transfer on the Urmia Lake level

Another way of increasing water supply in a basin is water transferring. There are two major suggested water transfer projects for the Urmia Lake basin including Zaab and Aras. The Zaab basin was intended to transfer 700 MCM annually to the Urmia Lake basin to help with restoring the lake by supplying the demands partially. Also, 300 MCM is planned to be transferred annually from Aras basin into the lake.

Plan 5: impact of increasing irrigation efficiency and changing crop pattern on the Urmia Lake level

Simultaneously, increasing irrigation efficiency and changing crop pattern in the Urmia Lake basin was considered as a fifth plan.

Plan 6: impact of increasing irrigation efficiency, changing crop pattern, and inter-basin water transfer on the Urmia Lake level

The sixth plan involves increasing irrigation efficiency, changing crop pattern, and inter-basin water transfer in the Urmia Lake basin simultaneously.

Plan 7: impact of increasing irrigation efficiency, reducing cultivated area, and changing crop pattern on the Urmia Lake level

This plan is the accumulation of increasing irrigation efficiency, reducing the cultivated area, and changing crop pattern in the Urmia Lake basin.

Plan 8: impact of increasing irrigation efficiency, reducing cultivated area, changing crop pattern, and inter-basin water transfer on the Urmia Lake level

The simultaneous application of increasing irrigation efficiency, reducing the cultivated area, changing crop pattern, and inter-basin water transfer in the Urmia Lake basin is considered as an eighth plan.

Sustainability indices

Loucks *et al.* (2005) recommended the SI, including reliability, resiliency, and vulnerability performance criteria for quantifying and monitoring sustainability over time. In this study, SI is measured by these three indices. Reliability (*Rel*) is the probability that Urmia Lake's water level, X, is in a satisfactory state at time t, defined as Equation (5) (Aydin 2014):

$$Rel(x) = number\ of\ time\ periods\ t\ such\ X_t \geq X^T/n \tag{5}$$

Resiliency (*Res*) represents how fast the system recovers from a failure, defined as Equation (6) (Aydin 2014):

$$Res(x) = \frac{number\ of\ times\ a\ satisfactory\ value\ follows\ an\ unsatisfactory\ value}{number\ of\ times\ an\ unsatisfactory\ value\ occured} \tag{6}$$

Vulnerability (*Vul*) is the magnitude or duration of an unacceptable state of the lake's water level in a certain time scale characterizing the average probability of failure of the water level to meet the ecological level, defined in Equation (7) (Aydin 2014):

$$Vul(x) = \frac{sum\ of\ positive\ values\ of\ (X^T - X_t)}{number\ of\ times\ an\ unsatisfactory\ value\ occured} \tag{7}$$

where X^T is the ecological water level of the lake and X_t is the lake's level at time t. The definitions of the SI proposed by Sood & Ritter (2011) are used to calculate the SI (Equation (8)):

$$\mathrm{SI} = \mathrm{R}el(x) \times Res(x) \times [1 - Vul(x)/maximum\ Vul\ among\ all\ Scenarios] \tag{8}$$

RESULTS AND DISCUSSION

According to the results of the LARS-WG model, the average temperature and precipitation changes of the watershed under the A1B, A2, and B1 scenarios are presented in Figures 13 and 14, respectively.

In developing the SD model, the calibrated pan coefficient was found to be 0.925. The SD model was simulated considering different plans and then the outcomes discussed. First, the model should be verified.

Verification and validation

Boundary-adequacy test

This test verifies whether the model structure is appropriate for the model purpose. In SD modeling, this test is done by evaluating the endogenous and exogenous variables of the model. As given in Table 3, the variables have been evaluated according to the model's purpose.

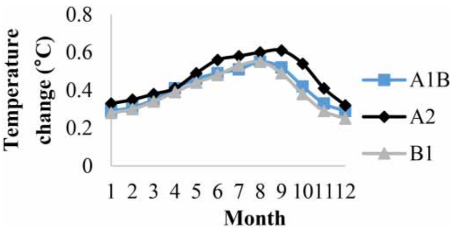

Figure 13 | Temperature changes of the watershed under A1B, A2, and B1 scenarios (2011–2030).

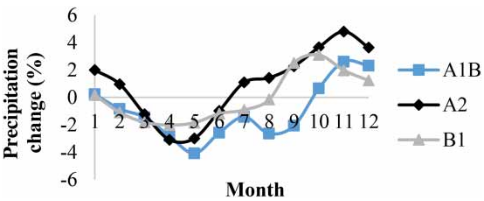

Figure 14 | Precipitation changes of the watershed under A1B, A2, and B1 scenarios (2011–2030).

Table 3 | Endogenous and exogenous variables of the Urmia Lake SD model

Endogenous variables		**Exogenous variables**
Total supply GW	Population	Crop cultivated land
Natural recharge	Domestic demand	Horticultural cultivated land
Returned water	Mineral demand	Crop demand average
Groundwater extraction	Industrial demand	Horticultural demand average
Natural discharge	Horticultural demand	Number of mines
Groundwater volume change	Crop demand	Number of industrial factories
Wastewater percolation SW	Agricultural demand	Runoff
Precipitation volume	Total demand	Volume–area relationship
Perception height	Total supply SW	A1B scenario
Margin area	Inflow to basin	A2 scenario
Margin precipitation height	Inflow	B1 scenario
Unmeasured surface inflow volume	Surface water percolation	Evaporation intensity
Evaporation	Wastewater GW percolation	Lake's water level
Urmia Lake volume	Irrigation percolation	Volume–elevation relationship

Extreme condition test

The structure in an SD model should allow the representation of an extreme combination of levels in the system. Examining the model structure for extreme conditions leads to increased confidence in a model's ability to behave rationally in a wide range of conditions.

To test the extreme condition in this SD model, the evaporation intensity (the only outflow of the lake) was assumed equal to zero. As shown in Figure 15, the lake's volume would rise progressively in the absence of evaporation.

Behavior-reproduction test

The generated model's behavior was investigated with the historical performance. Figure 16 shows the observed vs. estimated values for the lake's water level.

The values of R^2 and RMSE were obtained as 0.90 and 0.37, respectively, which means that the simulation results were acceptable. After this successful model verification, the impact of restoration plans can be considered.

Impact of restoration plans

The impacts of these plans were considered once separately and then simultaneously to investigate if the lake could be saved by a combination of these plans. Table 4 summarizes the results.

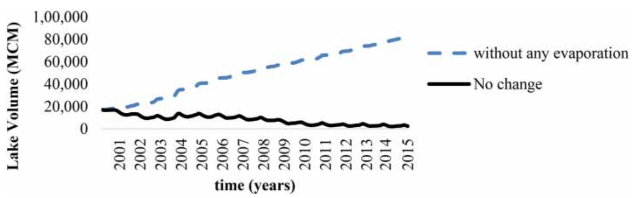

Figure 15 | Change of the Urmia Lake volume with and without evaporation.

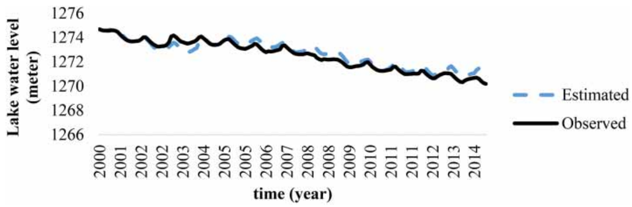

Figure 16 | Observed and estimated water level by the Urmia Lake SD model.

Table 4 | Impact of implying restoration plans on the Urmia Lake

Plans	Description	The effect of the plans (%) to achieve target ecological water level
Plan 1	Increasing irrigation efficiency	11
Plan 2	Reducing cultivated area	1
Plan 3	Changing crop pattern	6
Plan 4	Inter-basin water transfer	3
Plan 5	Increasing irrigation efficiency and changing crop pattern	19
Plan 6	Increasing irrigation efficiency, reducing cultivated area, changing crop pattern	24
Plan 7	Increasing irrigation efficiency, reducing cultivated area, changing crop pattern	20
Plan 8	Increasing irrigation efficiency, reducing cultivated area, changing crop pattern, inter-basin water transfer	25

Figure 17 shows every plan's impact on the Urmia Lake water level in the horizon of 2030.

Sustainability assessment

The lake sustainability was calculated based on the concepts of reliability (Equation (5)), resiliency (Equation (6)), and vulnerability (Equation (7)). The results of these evaluations are shown in Table 5.

The results showed that when implementing the individual plans none caused Urmia Lake to be restored. Due to different management practices, on average, at least 30% of water consumption should be reduced to restore the lake and make it sustainable. This result aligned with the ULRP research output (ULRP 2014).

According to Table 5, while the most vulnerable plans are reducing cultivated lands and inter-basin water transfer, respectively, among the hybrid plans, Plans 8 and 7 are the least vulnerable ones. The lake restoration was made possible by implementing the hybrid plans of increasing the irrigation efficiency, reducing cultivated area, changing crop pattern, and water transfer (Plan 6 and Plan 8). The results indicated that about eight years after applying Plan 8 (combination of the four individual plans mentioned above), the lake level will achieve the ecological level and remain sustainable in the future. According to Equation (8), the SI for Plans 6 and 8 were 0.0021 and 0.0079, respectively. Due to the higher resiliency and lower vulnerability of Plan 8, it is the most sustainable plan; by excluding this plan, Plan 6 was the most reliable one in restoring the lake.

The outcomes of the Drought Risk Management Plan for the Urmia Lake Basin were consistent with the results of the present study. According to the results of that research, in different levels of droughts, taking into account the parameters of a 50-year simulation and full water allocation, the lake level can reach 1,273.06 m. Based on the results, the impact of all management measures will lead

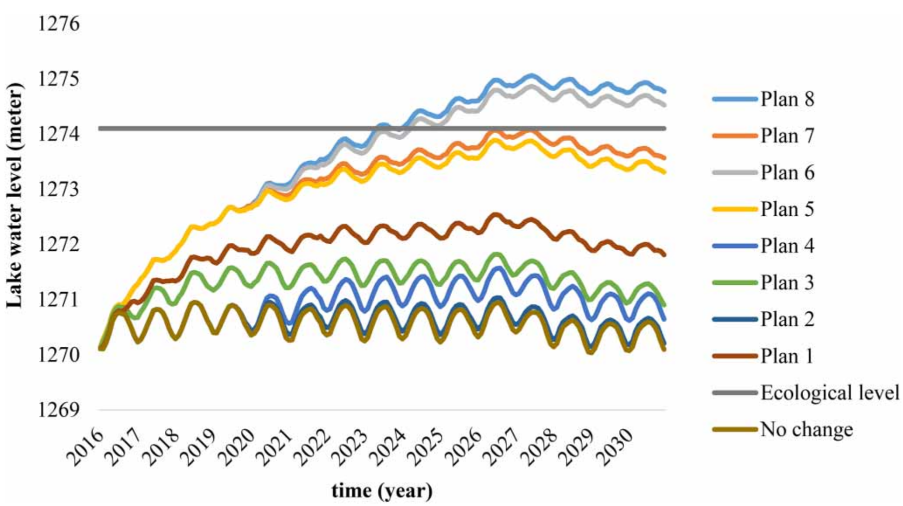

Figure 17 | Impact of restoration plans on the Urmia Lake water level in the period of 2016–2030.

Table 5 | Watershed sustainability indices of considered restoration plans

Plan	Vulnerability	Reliability	Resiliency	Sustainability index
Plan 1	2.17	0	0	0
Plan 2	3.48	0	0	0
Plan 3	2.78	0	0	0
Plan 4	3.16	0	0	0
Plan 5	1.10	0	0	0
Plan 6	1.43	0.52	0.01	0.0021
Plan 7	0.97	0	0	0
Plan 8	0.72	0.50	0.02	0.0079

to a 10 to 20% reduction in water consumption (CIWP & Tarbiat Modares University 2012). In fact, the combined restoration plans could be implemented along with the drought risk management measures to achieve the total 30% reduction in water consumption in the basin (with the assumption of the linear effect of plans) that is necessary for restoring the lake.

Also, the results of this research correspond with the study of Zarghami & AmirRahmani (2017). In their study, policies such as increasing irrigation efficiency, reducing agricultural area, seeding clouds, and water transfer were considered for restoring Urmia Lake. The study showed that among these policies, increasing irrigation efficiency and reducing agricultural area were the most effective policies, but none of them caused the lake to be restored (Zarghami & AmirRahmani 2017). As mentioned before, the agricultural sector is the most important part to manage. NGOs and local authorities should become involved and educate farmers about the impact of their essential role in saving the Urmia Lake ecosystem. In addition, government should consider paying some subsidies to farmers who have lost some of their income due to the management plans. These kinds of considerations may encourage farmers to adapt to restorations plans; however, ultimately, a facilitated process is vital for their cooperation.

CONCLUSION

Urmia Lake's SD model provided an integrated simulation of the complex case of the lake. In this way, the effect of various restoration plans could be seen before applying them to the basin. Therefore, this SD model can help all the managers and stakeholders to understand how to deal with the Urmia Lake crisis. Overall, it is hoped that the study will further demonstrate the value of SD modeling in similar management issues for environmental stewardship.

To improve the efficiency of the developed SD model, some general recommendations for effective management of Urmia Lake are listed here: constructing hydrometric stations near the lake to monitor the exact water inflow to the lake, considering the cooperation of stakeholders, and assessing the effect of climate change on the groundwater level variations. An assessment of the accuracy of the assumption that evaporation is the only outflow from the lake is suggested. A consideration of the salinity concentration effect on the water level and the impacts of this phenomenon are also suggested. Furthermore, the operation cost of plans should be considered and a comprehensive comparison including economical, technical, and operational aspects should be made in future studies.

Downscaling the results of GCMs using the LARS-WG model revealed that the Urmia Lake basin would have a warmer climate in the horizon of 2030, especially during summer. According to the results, precipitation will have an increasing trend in autumn and winter, and there will be a decreasing trend in spring and summer.

The Urmia Lake SD model describes variables that affect the lake level. Assessing the impact of various restoration plans revealed that, on average, water consumption should be reduced by at least 30% in order to restore the lake. Paying special attention to the agricultural sector as the most important influencing factor, the lake basin water balance is vital. The results revealed that no single restoration plan is sufficient to restore the lake. Among the hybrid restoration plans, that of increasing irrigation efficiency, reducing cultivated area, changing crop pattern, and inter-basin water transfer is the most sustainable plan. If this plan is adopted, the lake should achieve the desired ecological level after about eight years.

Through considering comprehensive factors, the proposed model can help watershed managers to take the necessary measures for sustainable restoration of this ecosystem. Therefore, the research provides an integrated simulation for this complex case that is also suggested for other cases where multidisciplinary water resources problems are concerned, especially those in semi-arid regions.

ACKNOWLEDGEMENTS

The authors would like to thank the Urmia Lake Restoration Program for providing watershed characteristics and required data. We also appreciate the comments of Dr. Masoud Bagherzadeh Karimi (Department of Environment), Dr. Nasim Saffari, Ata Akbari, Reza Samadzadeh Fahim, Mahsa Zarei (University of Tabriz), Mohammad Ali Olyaei (University of Tehran), and Kevin M. Smith (Tufts University).

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First received 18 December 2017; accepted in revised form 10 July 2018. Available online 9 August 2018