



Assessment of rehabilitation strategies for lakes affected by anthropogenic and climatic changes: A case study of the Urmia Lake, Iran

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Abstract: Over the last three decades, more than half of the world's large lakes and wetlands have experienced significant shrinkage, primarily due to climate change and extensive water consumption for agriculture and other human needs. The desiccation of lakes leads to severe environmental, economic, and social repercussions. Urmia Lake, located in northwestern Iran and representing a vital natural ecosystem, has experienced a volume reduction of over 90.0%. Our research evaluated diverse water management strategies within the Urmia Lake basin and prospects of inter-basin water transfers. This study focused on strategies to safeguard the environmental water rights of the Urmia Lake by utilizing the modeling and simulating (MODSIM) model. The model simulated changes in the lake's water volume under various scenarios. These included diverting water from incoming rivers, cutting agricultural water use by 40.0%, releasing dam water in non-agricultural seasons, treated wastewater utilization, and inter-basin transfers. Analytical hierarchy process (AHP) was utilized to analyze the simulation results. Expert opinions with AHP analysis, acted as a multi-criteria decision-making tool to evaluate the simulation and determine the optimal water supply source priority for the Urmia Lake. Our findings underscore the critical importance of reducing agricultural water consumption as the foremost step in preserving the lake. Following this, inter-basin water transfers are suggested, with a detailed consideration of the inherent challenges and limitations faced by the source watersheds. It is imperative to conduct assessments on the impacts of these transfers on the downstream users and the potential environmental risks, advocating for a diplomatic and cooperative approach with adjacent country. This study also aims to forecast the volumes of water that can be transferred under different climatic conditions—drought, normal, and wet years—to inform strategic water management planning for the Urmia Lake. According to our projection, implementing the strategic scenarios outlined could significantly augment the lake's level and volume, potentially by 3.57×10^9 – 9.38×10^9 m³ over the coming 10 a and 3.57×10^9 – 10.70×10^9 m³ in the subsequent 15 a.

Keywords: climate change; drought; lake ecological level; agricultural water demand; inter-basin water transfer

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1 Introduction

Globally, the challenge of freshwater scarcity coupled with unsustainable water usage critically impacts domestic needs, economic stability, and environmental health, as evidenced by the

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detrimental effects on regional socio-economic development (Cosgrove and Loucks, 2015; Dong et al., 2023). The increased demand for water, exacerbated by climate change, poses a significant risk to the world's lakes, leading to their progressive desiccation. This phenomenon is evident in several cases, including the Aral Sea, Owens Lake, Great Salt Lake, and Urmia Lake. The escalating demand for water is increased by industrial expansion, a pursuit of rapid economic gains, and a prevalent lack of awareness about severe consequences of environmental neglect.

Iran, known for its varied landscapes, has numerous lakes and wetlands recognized internationally for their distinct ecological contributions and vital environmental services. Yet, these critical ecosystems are increasingly threatened by unsustainable water use. A prime example of this ecological crisis is the Urmia Lake. The Urmia Lake, with an area of 5000 km², is known by its national significance, recognized under the Ramsar Convention on Wetlands of International Importance and designated as a United Nations Educational, Scientific, and Cultural Organization (UNESCO) Biosphere Reserve. This acknowledgement highlights its global ecological importance. Historically, the Urmia Lake's water levels naturally fluctuate, responding to patterns of annual precipitation. Notably, during 1993–1994, the lake experienced an extraordinary influx of water, approximately 13.00×10⁹ m³, due to significant rainfall and flooding. Consequently, the lake's level increased to 1288.00 m, presenting challenges for surrounding agricultural lands and communities due to its expansion. Yet, over two decades, by 2013, the lake's level had fallen to 1271.00 m, and its volume dramatically reduced to 2.30×10⁹ m³ (Khatami and Berndtsson, 2013). The lake's basin supports over 5×10⁶ people, however, it has faced severe ecological challenges in recent decades. An escalating gap between water resources and consumption, primarily due to climate change and human activities, has significantly disrupted water balance of the Urmia Lake, resulting in a dramatic reduction of the lake's volume about 87.0% (Wurtsbaugh and Sima, 2022). The significant drying up of the lake, followed by the dispersal of fine salt dust from the lakebed, will lead to major environmental challenges for the basin's residents, severely impacting local agriculture and industry. This situation underscores the urgent need for innovative management strategies to mitigate this decline and initiate recovery efforts.

The ecological revival of the lake is closely related to the preservation of biodiversity, a critical aspect demonstrated by the need to sustain genus *Artemia*, aquatic crustaceans essential for ecological balance. Their survival is contingent upon keeping the lake's salt concentration below 240 g/L, which in turn requires the water level to be maintained at 1274.00 m (Abbaspour and Nazaridoust, 2007). The watershed's renewable water resources tally up to 69.25×10⁸ m³, whereas research indicates that the lake's minimum ecological demand is 3.10×10⁹ m³, according to ecological assessments (Behboodian and Kerachian, 2020; Faryadi, 2023; Sheikha-BagemGhaleh et al., 2023).

The revival of the Urmia Lake is a multifaceted endeavor, requiring a holistic approach that considers social, economic, and environmental factors. In 2013, the Iranian government took a significant step towards addressing the ecological crisis of the Urmia Lake by establishing a national working group focused on the lake's rescue. The following year, this group proposed 26 strategies aimed at revitalizing the lake, with objectives including achieving a target water level of 1274.10 m within 10 a (Ejazi et al., 2020). Due to the inability to secure the lake's water rights from within the basin's resources, inter-basin water transfers have been considered to meet some of the environmental needs. Changes in the source watershed and the effectiveness in raising Urmia Lake's level are among the unknown and ambiguous aspects of this transfer. The Urmia Lake Restoration Plan initially aimed to restore the lake to its normal level of 1274.10 m by the year 2027 through a series of executive actions (Sima et al., 2021). Unfortunately, the executive actions did not progress as planned and instead, there was an expansion of cultivated areas and increased water withdrawal from resources.

This article aims to use predictive modeling to simulate and evaluate the impacts of various management strategies on the water volume of the Urmia Lake, investigating their effectiveness in supporting the lake's restoration. This analysis is crucial for guiding strategic water

management planning for the Urmia Lake, encouraging informed decisions that contribute to the lake's long-term sustainability and preservation.

2 Materials and methods

2.1 Study area

The Urmia Lake basin, situated in northwestern Iran and spanning parts of western Azerbaijan Gharbi, eastern Azerbaijan Shargi, and Kurdistan provinces, has an area of 51,876 km² (Fig. 1). The study area is characterized by diverse topography, with 64.6% mountainous regions, 21.1% plains and foothills, and 14.3% covered by the Urmia Lake itself. It shares its borders with the Zab, Aras, and Sefidrud river basins, lying in proximity to the international borders of Turkey and Iraq. The basin's intricate network of water sources includes 17 permanent rivers, numerous seasonal rivers, and approximately 39 streams, collectively forming the lake's surface water resources. Notably, the Zarrineh River alone accounts for 41.0% of the water resources of the Urmia Lake basin (Dehghanipour et al., 2020; Hosseini Moghari et al., 2020).

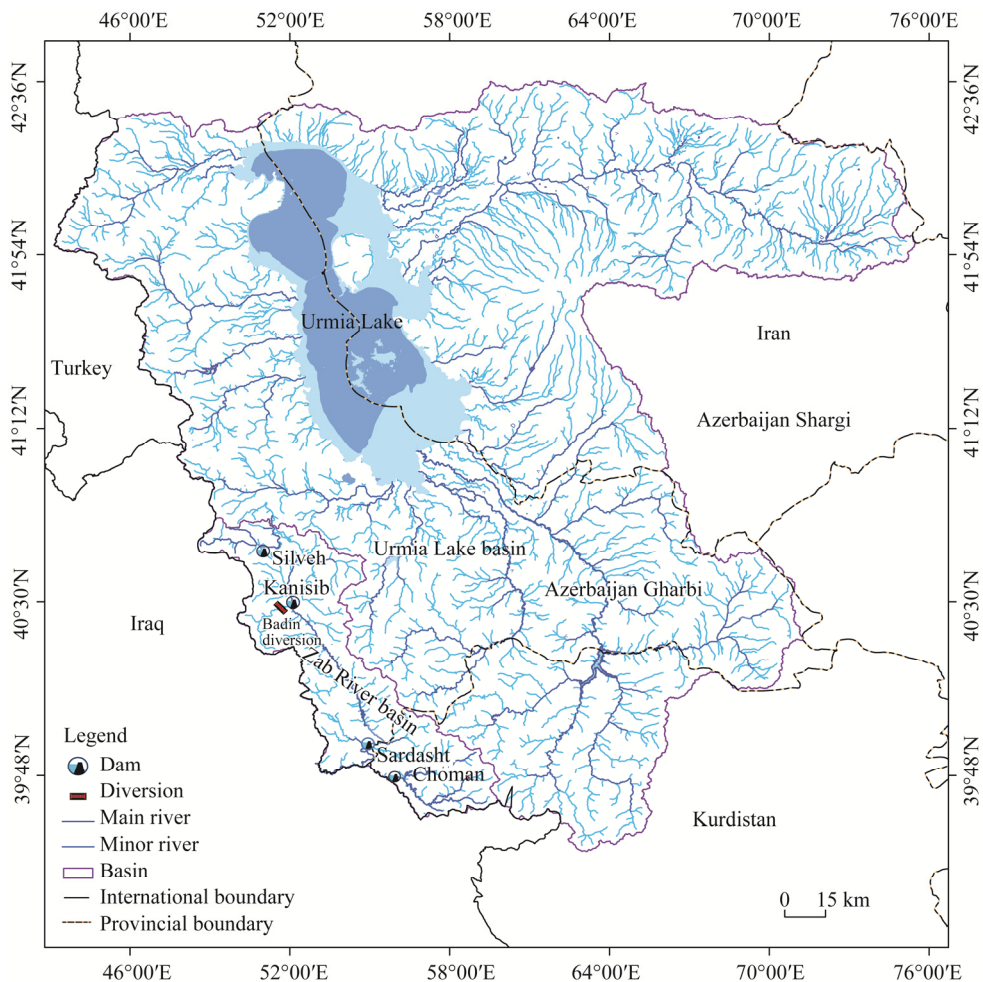


Fig. 1 Geographical overview of the Urmia Lake basin and Zab River basin

2.2 Comparison of rehabilitation plan with actual lake performance

Figure 2 demonstrates that, up until February 2023, Urmia Lake's water level has essentially remained stable, with no significant change observed from the level recorded in 2014, when the

executive operations commenced. Importantly, the process of transferring water from the Zab River basin to the Urmia Lake began on 1 March, 2023, aiming to transfer $3.00 \times 10^8 \text{ m}^3$ water. This volume is notably less than the initial ambitious target of $6.00 \times 10^8 \text{ m}^3$.

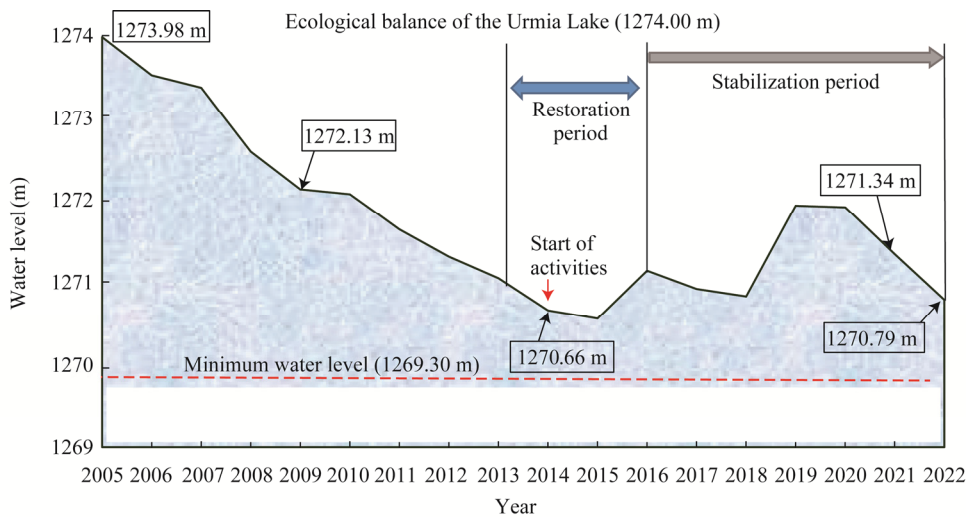


Fig. 2 Water levels in the Urmia Lake during 2005–2022

2.3 Assessing water management strategies for the restoration of the Urmia Lake

The state of the Urmia Lake is intricately linked to the inflows it receives. To understand the dynamics of these inflows, we simulated the effects of water transferring from the contributing rivers under varied hydrological conditions, including periods of drought, normal, and wet years. Our investigation assessed the impact of diverse water management strategies that specifically aimed at the rehabilitation of the lake. For accurate planning and to maximize the efficacy of these interventions in restoring the lake's water volume to desired levels, we applied the modeling and simulating (MODSIM) model. This model utilized data up to the last water measurement stations preceding the lake.

2.4 MODSIM model

The field of hydrological modeling plays a crucial role in the assessment and prediction of water systems, witnessing significant advancements. In our research, we meticulously examined a suite of models, and Venta simulation and water evaluation and planning were regarded as functionally analogous models. Our selection process was guided by several critical factors: suitability to the specific characteristics of the area under study, ease of use, simulation efficiency and speed, the ability to solve problems based on network theory, the integration capability of input and output data with existing database, and the potential to be transformed into a decision support system that meets a wide array of management needs. Among these, MODSIM emerged as the model of choice due to its holistic approach to water resource management planning. Despite the unique advantages of each model, our comparative analysis indicated that their overall effectiveness in performance was remarkably similar (Dehghanipour et al., 2019).

MODSIM model is instrumental in analyzing the behavior of water resource systems on a basin scale, facilitating the examination of different scenarios to provide valuable insights into potential system management and outcomes. A distinctive feature of MODSIM model is its simulation-optimization mechanism, which employs the network flow programming (NFP) technique. This method is adept at iteratively solving the optimization challenge of minimizing network flow costs. In practice, this involves the strategic allocation of water among diverse uses at every simulation step, aiming to achieve optimal resource distribution throughout the basin. This process is informed by data on crucial components such as storage capacity, conveyance

systems, pumping operations, and diversion protocols. A noteworthy aspect of the MODSIM model is its independence from the geographical locations of demand nodes. Allocations are determined by the priorities assigned to these nodes, ensuring an objective and efficient distribution of water resources.

The general formulation of the NFP algorithm used in each time step in the MODSIM model is as follows (Mohsenizadeh and Shourian, 2018):

$$\text{Minimize } \sum_{l \in A} c_l q_l, \quad (1)$$

Subject:

$$\sum_{l \in O_i} q_l - \sum_{k \in I_i} q_k = 0; \text{ for all } i \in N, \quad (2)$$

$$l_l \leq q_l \leq u_l; \text{ for all } l \in A, \quad (3)$$

where A is the number of flow channels within the network; c_l is the cost coefficient of flow in channel l (negative weighting coefficients or unit profit of flow rate in output channel l , which is calculated by allocation priorities among needs); q_l is the flow rate in the output channel l (m^3/s); q_k is the amount of flow in relation to the incoming channel k (m^3/s); o_i is the number of channels that originate from node i (outgoing channel); I_i is the number of channels that conclude at node i (incoming channel); N is the total number of nodes; l_l and u_l are the lower and upper flow limits, respectively, within a channel (m^3/s).

In scenarios lacking comprehensive economic analysis and aiming for optimal allocation of water resources among various demands, we established the cost coefficients within the NFP objective function based on the relative importance for meeting those demands, as specified by the user.

To evaluate the annual inflow to the Urmia Lake, we utilized surface flow data from the final hydrometric stations of 16 primary rivers, spanning the water years from 2014–2015 to 2020–2021. This seven-year dataset formed the basis for both executing and calibrating the MODSIM model. Looking ahead, the model was tasked with forecasting the lake's inflow for the next 10–15 a (2021–2022 to 2035–2036), integrating surface flow data based on various scenarios and including inputs from the adjacent watershed and within the Urmia Lake basin itself. This approach accounted for several key factors: (1) inter-basin water transfer: surface flow transfers from the Zab River basin, which includes water transferred from the Silveh and Kanisib dams; and (2) intra-basin water resources, included the potential for water conservation through up to a 40.0% reduction in agricultural usage via operational dams, similar reductions from other rivers, strategic water releases from dams during off-peak agricultural periods, and the integration of treated wastewater. The effectiveness of these interventions was rigorously evaluated through the model. The methodology, detailed in the flowchart of Figure 3, facilitated an in-depth analysis by considering a broad spectrum of factors that affect water inflow into the Urmia Lake.

The strategies contemplated in this study align with 26 resolutions established by the national task force committed to restoration of the Urmia Lake. These resolutions span both direct interventions aimed at enhancing the lake's water inflow and supportive strategies designed to facilitate and maintain the lake's recuperation (Urmia Lake Rehabilitation Program, 2014). A strategic framework has been designed to lower water usage and increase the yearly inflow to the Urmia Lake, resulting in the formulation of nine targeted scenarios. Within this framework, six initiatives aim to conserve water, featuring measures like inter-basin transfers and the reduction of direct agricultural withdrawals from water sources, while ensuring the preservation of areas designated for garden crops. Additionally, the plan introduces three focused strategies to eliminate water-intensive practices in irrigation networks and to decrease the area of cultivated land. Implementation of model involves several critical phases: constructing the network by mapping out nodes and their connections, setting the simulation timeframe, entering the necessary data, calibrating the model for precision, detailing various scenarios for examination, executing the model for specified current and future periods, extracting the results, and conducting a

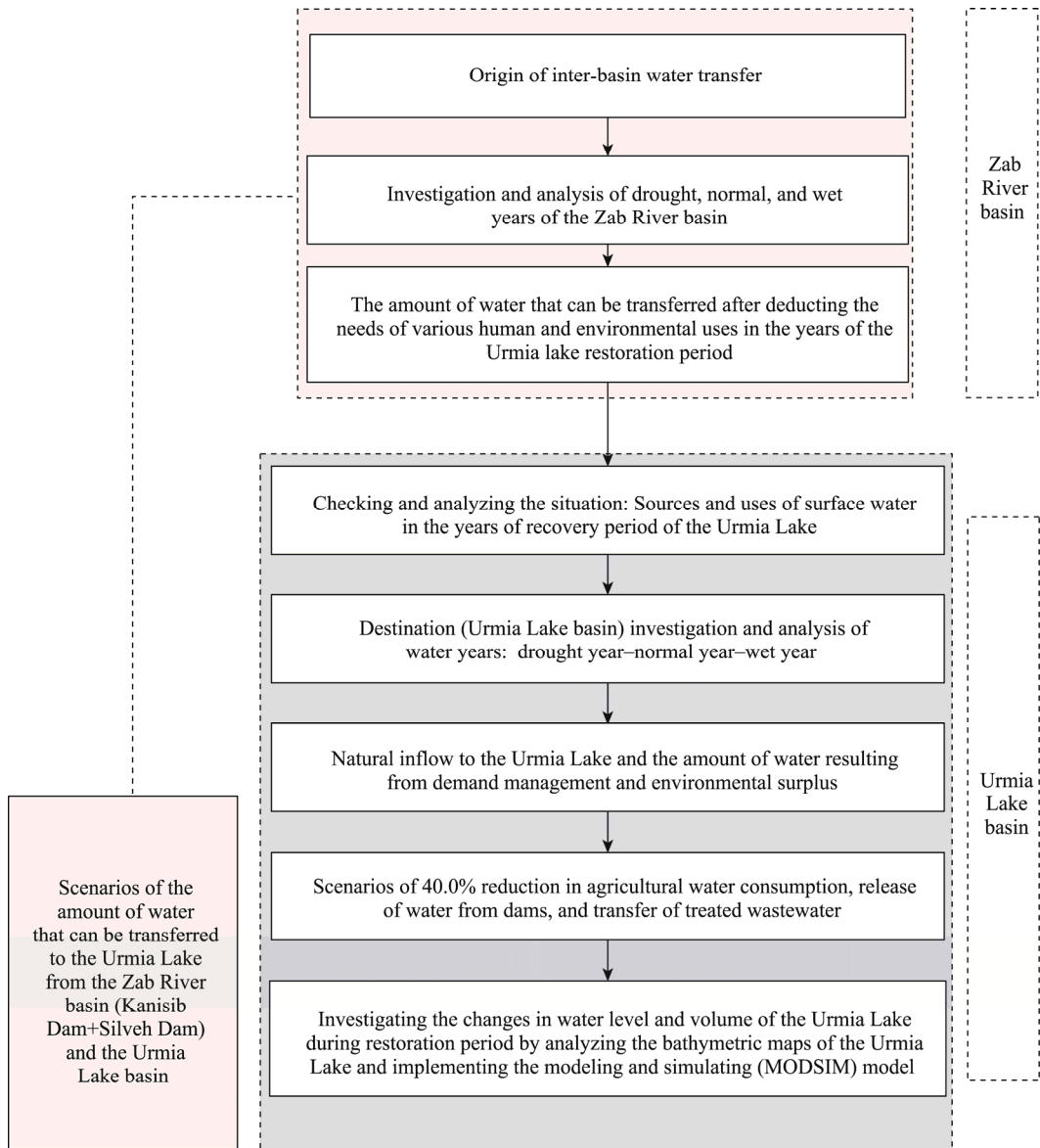


Fig. 3 Flowchart illustrating the process of this study

comprehensive analysis that leads to meaningful conclusions. Specifically, in the case of the Urmia Lake modeling (Fig. 4), the model incorporates 16 principal river connections that flow into the lake, with a goal of increasing its water level. The enumerated strategies are: a reduction in agricultural water use from operational dams, quantified at $3.77 \times 10^8 \text{ m}^3$; conservation efforts leading to a decrease in agricultural water drawn from other rivers, amounting to $2.76 \times 10^8 \text{ m}^3$; an ambitious inter-basin water transfer scheme introducing $0.60 \times 10^8 \text{ m}^3$ to the lake, which includes $0.44 \times 10^8 \text{ m}^3$ from the Silveh Dam and $5.56 \times 10^8 \text{ m}^3$ from the Kanisib Dam; rerouting of $2.07 \times 10^8 \text{ m}^3$ of treated wastewater to the Urmia Lake; strategic release of $3.00 \times 10^8 \text{ m}^3$ of water from operational dams directly into the Urmia Lake during non-agricultural season, specifically autumn and winter, extending into the latter half of April as agricultural water demand decreases; expected annual inflow from 16 principal rivers flowing into the lake is carefully adjusted for scenarios that span from severe to mild drought years. Notably, the surface flow volumes entering the lake in these scenarios— 10.86×10^8 , 14.60×10^8 , and $18.62 \times 10^8 \text{ m}^3$ —are derived from historical hydrological data (Table 1).

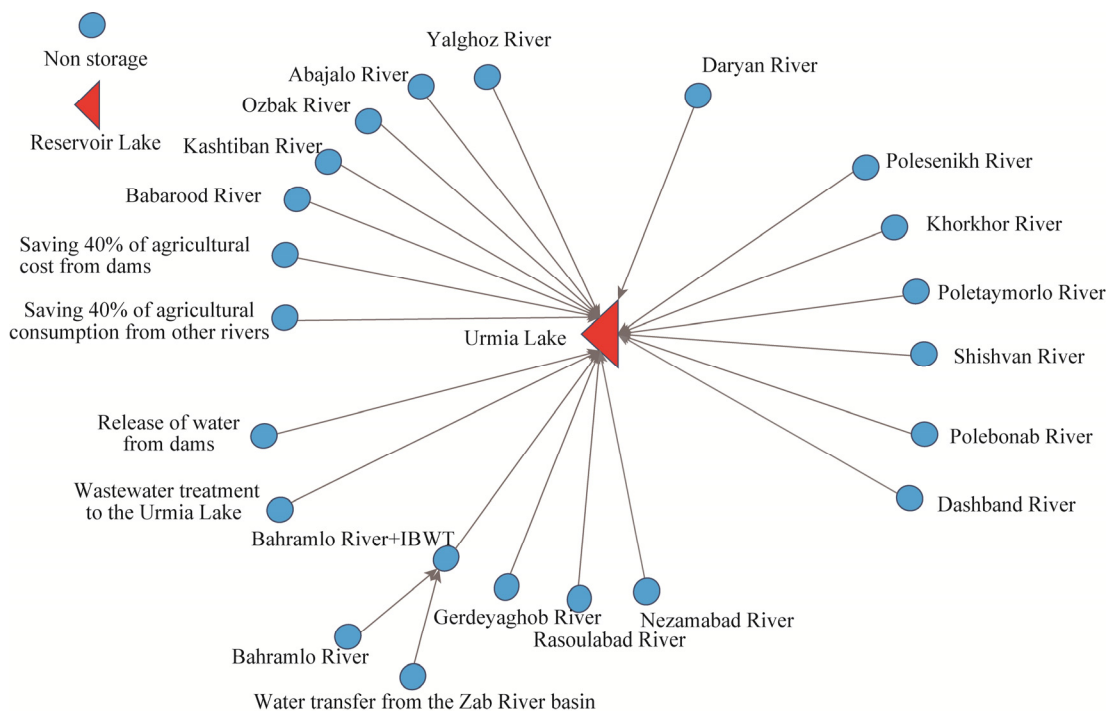


Fig. 4 Schematic diagram of the modeling and simulating (MODSIM) model. IBWT, inter-basin water transfer.

For the assessment of scenarios presented in Table 1, we employed data from two downstream hydrometric stations, Alvot and Choman, to evaluate the condition of source basin and the volume of surface runoff leaving the Zab catchment area without water transfer to the Urmia Lake. The data proved crucial for simulating water volumes under scenarios involving water transfer to the Urmia Lake, effectively representing the water flow across Iran's border. Our analysis covered a spectrum of hydrological conditions, including drought, normal, and wet years.

Following the application and analysis of the model under various scenarios aimed at identifying the most appropriate water management strategies, this study engaged 10 senior experts, each with over 25 a of experience in water resources management. These experts completed a survey encompassing questions about the prioritization of proposed scenarios. Then we employed analytical hierarchy process (AHP) to evaluate and rank the most effective strategies based on their insights.

In the domain of multi-criteria decision-making, numerous methods exist with AHP recognized for its widespread use and efficacy. The choice of a decision-making model depends on the specific goals of the problem and the existing conditions, as each issue requires bespoke computational tools and analytical methods. To aid the restoration of the Urmia Lake, this study harnessed the expertise of seasoned professionals to establish a decision-making hierarchy, assign weights, and prioritize relevant factors. This comprehensive approach enabled a detailed pairwise comparison of all criteria. This process involves creating a hierarchical tree for decision-making, structured across four tiers: overarching goals at the top level, followed by main criteria, sub-criteria, and specific alternatives at the bottom. AHP methodology is applied to assign weights to these criteria and alternatives, with pairwise comparisons made at every criterion level. An inconsistency rate of below 0.1 in these comparisons is deemed acceptable, ensuring the reliability and validity of the process (Momeni, 2020).

The analysis of AHP questionnaire data is conducted using the Expert Choice software. Although it's feasible to evaluate up to nine criteria, this study strategically focused on the most significant ones for the restoration of the Urmia Lake, recognizing that an excess of criteria might affect result accuracy or introduce potential errors. Four pivotal criteria were determined:

reduction of surface water consumption, reduction of groundwater consumption, redirection of treated wastewater, and water transfer from adjacent basins. These criteria are necessary to the governmental restoration policies for the Urmia Lake.

Table 1 Water conservation and management scenarios for the Urmia Lake

Number	Description of options
1	Conservation from currently operating dams+saving from other rivers+release from currently operating dams in non-cultivation months+treated wastewater transfer+annual river input ending in the lake amounting to $10.86 \times 10^8 \text{ m}^3$ in severe drought years.
2	Conservation from currently operating dams+saving from other rivers+release from currently operating dams in non-cultivation months+treated wastewater transfer+water transfer from the Zab River basin+annual river input ending in the lake amounting to $10.86 \times 10^8 \text{ m}^3$ in severe drought years.
3	Conservation from currently operating dams+saving from other rivers+release from currently operating dams in non-cultivation months+treated wastewater transfer+annual river input ending in the lake amounting to $14.60 \times 10^8 \text{ m}^3$ in moderate drought years.
4	Conservation from currently operating dams+saving from other rivers+release from currently operating dams in non-cultivation months+treated wastewater transfer+water transfer from the Zab River basin+annual river input ending in the lake amounting to $14.60 \times 10^8 \text{ m}^3$ in moderate drought years.
5	Conservation from currently operating dams+saving from other rivers+release from currently operating dams in non-cultivation months+treated wastewater transfer+annual river input ending in the lake amounting to $18.62 \times 10^8 \text{ m}^3$ in mild drought years.
6	Conservation from currently operating dams+saving from other rivers+release from currently operating dams in non-cultivation months+treated wastewater transfer+water transfer from the Zab River basin+annual river input ending in the lake amounting for $18.62 \times 10^8 \text{ m}^3$ in mild drought years.
7	Savings from stopping irrigated agricultural cultivation in the irrigation network of operating dams ($4.52 \times 10^8 \text{ m}^3$ average irrigated cultivation consumption from dams over the last 8 a)+savings from stopping irrigated agriculture supplied by other rivers ($8.28 \times 10^8 \text{ m}^3$ according to the third round of survey)+water release from dams in non-cultivation months ($3.00 \times 10^8 \text{ m}^3$)+treated wastewater transfer ($2.07 \times 10^8 \text{ m}^3$)+water transfer from the Zab River basin ($6.00 \times 10^8 \text{ m}^3$)+annual river input ending in the lake ($10.86 \times 10^8 \text{ m}^3$ in severe drought years).
8	Savings from stopping irrigated agricultural cultivation in the irrigation network of operating dams ($4.52 \times 10^8 \text{ m}^3$ average irrigated cultivation consumption from dams over the last 8 a)+savings from stopping irrigated agriculture supplied by other rivers ($8.28 \times 10^8 \text{ m}^3$ according to the third round of survey)+water release from dams in non-cultivation months ($3.00 \times 10^8 \text{ m}^3$)+treated wastewater transfer ($2.07 \times 10^8 \text{ m}^3$)+water transfer from the Zab River basin ($6.00 \times 10^8 \text{ m}^3$)+annual river input ending in the lake ($14.60 \times 10^8 \text{ m}^3$ in moderate drought years).
9	Savings from stopping irrigated agricultural cultivation in the irrigation network of operating dams ($4.52 \times 10^8 \text{ m}^3$ average irrigated cultivation consumption from dams over the last 8 a)+savings from stopping irrigated agriculture supplied by other rivers ($8.28 \times 10^8 \text{ m}^3$ according to the third round of survey)+water release from dams in non-cultivation months ($3.00 \times 10^8 \text{ m}^3$)+treated wastewater transfer ($2.07 \times 10^8 \text{ m}^3$)+water transfer from the Zab River basin ($6.00 \times 10^8 \text{ m}^3$)+annual river input ending in the lake ($18.62 \times 10^8 \text{ m}^3$ in mild drought years).

In Figure 5, we illustrate the hierarchical structure to assess restoration strategies for the Urmia Lake, utilizing both internal and external water resources. This framework is organized around four main criteria: climate, water usage, socio-economic implication, and environmental impact. Each of these criteria is further broken down into sub-criteria, including drought severity, river and dam water withdrawal, groundwater extraction, agricultural expansion impact, river flow sustainability, and the implementation of inter-basin water transfer.

We determined the target of a 40.0% reduction in water usage for agriculture based on prior comprehensive research conducted by the team from the Sharif University of Technology, Iran, focusing on the restoration of the Urmia Lake (Sima et al., 2021).

3 Results

3.1 Observational and simulated volume of the Urmia Lake

In this study, we used the MODSIM model to simulate the volume of the Urmia Lake from 2014–2015 to 2020–2021 water year. The findings, illustrated in Figure 6, compared the observed and simulated volume values. Notably, the model's initial volume for the beginning of 2014–2015 water year was based on the lake's most recent bathymetry chart, totaling $1.29 \times 10^9 \text{ m}^3$.

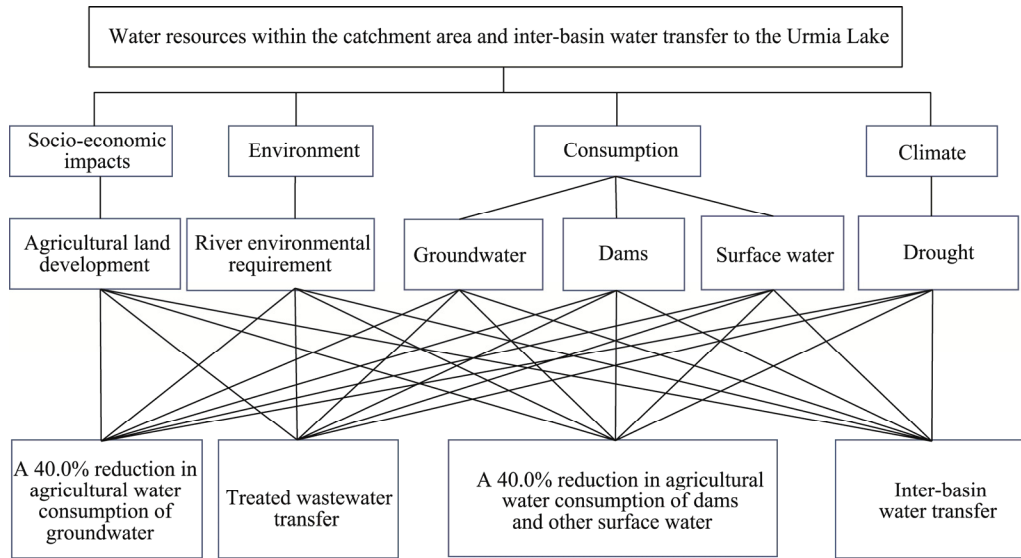


Fig. 5 Conceptual model illustrating the impact of reduced consumption and inter-basin water transfer with environmental goals to the Urmia Lake

Calibrated model closely aligns with observational data, evidenced by strong correlation metrics. Specifically, the coefficients of determination (R^2), root mean square error (RMSE), and Nash-Sutcliffe efficiency (NSE) were 0.96, $0.42 \times 10^6 \text{ m}^3/\text{a}$, and 0.91, respectively. The high R^2 and NSE values, coupled with the low RMSE value highlighted the model's high accuracy. These metrics confirmed the model's efficacy in precisely simulating the water conditions of the Urmia Lake.

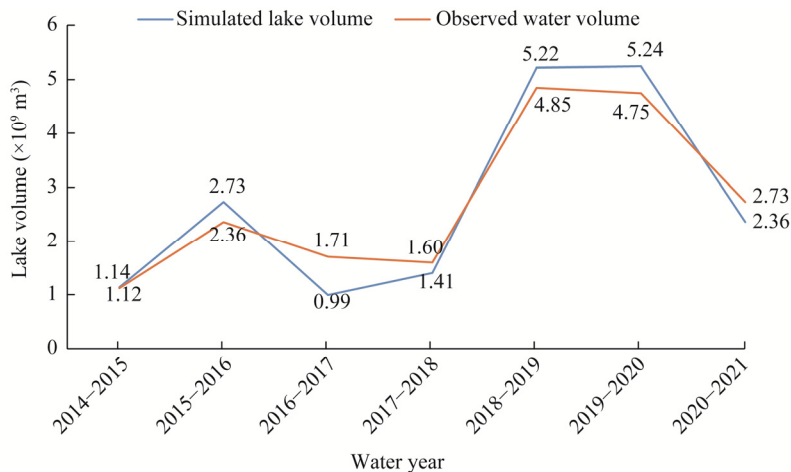


Fig. 6 Comparative analysis of simulated and observed lake volumes using MODSIM model from 2014-2015 to 2020-2021 water year

3.2 Assessing the effectiveness of scenarios in increasing lake volume

The impact of targeted scenarios on the volume of the Urmia Lake in 10 and 15 a periods is illustrated in Figure 7 and Table 2. The analysis indicated that Scenarios 4 and 6 led to the most significant increases in the lake's volume, contingent on the availability of adequate precipitation and inflow. Importantly, Scenario 1 consistently shows no change in volume across both 10 and 15 a periods. In scenarios that halt water-intensive agriculture within the Urmia Lake basin (Scenarios 7, 8, and 9), the timeline to achieve the decreases in ecological water level is shown.

Specifically, Scenario 9 reached the ecological level in the shortest time, within 13 a. In contrast, Scenarios 7 and 8 fell short of the ecological threshold by about 1.0–1.5 m during both 10 and 15 a projections.

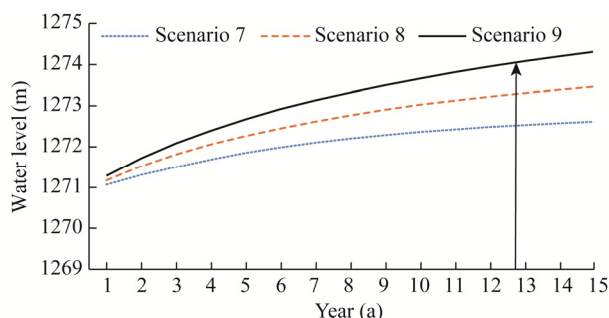


Fig. 7 Impact on water levels of the Urmia Lake from implementing Scenarios 7, 8, and 9

Table 2 Effectiveness of scenarios in MODSIM model on enhancing volume of the Urmia Lake

Scenario number	Equivalent level of the Urmia Lake (m)	Effectiveness on volume of lake water in 10 a period ($\times 10^9$ m ³)	Equivalent water level of the Urmia Lake (m)	Effectiveness on volume of lake water in 15 a period ($\times 10^9$ m ³)
1	1270.92	3.57	1270.92	3.57
2	1271.27	4.77	1271.35	5.00
3	1271.24	4.65	1271.29	4.80
4	1272.03	7.40	1272.21	8.00
5	1271.63	5.97	1271.86	6.75
6	1272.59	9.38	1272.94	10.70
7	1272.40	8.57	1272.60	9.50
8	1273.00	11.00	1273.50	12.85
9	1273.70	13.70	1274.30	16.45

Table 3 shows the data on the volume of surface water exiting Iran via the Zab River basin in the absence of water transfer. The findings highlight that water outflow attains its lowest levels during periods of drought, underscoring the significant impact that effective water transfer strategies can have.

Table 3 Surface water flow exiting Iran via the Zab River basin without inter-basin water transfer

Year	Surface flow output from the Zab River basin ($\times 10^9$ m ³)
Normal	17.48
Wet	42.93
Drought	7.69

3.3 Evaluation of surface flow quantitative status in the source watershed

Table 4 details the volume of water transferred from the Zab River basin to the Urmia Lake after the complete implementation and operation of the proposed plans across different scenarios.

Table 5 presents data on the volume of Iran's outgoing water flow after the transfer of water from the Zab River basin to the Urmia Lake, following execution and full operation of various project scenarios. Observations of surface flow changes during water transfer revealed that in conditions resembling normal hydrologic condition, the outflow from the Zab River basin showed a decrease of 30.0%–48.0% compared with usual conditions. In the event of drought, the reduction in surface outflow from the Zab River basin became even more significant, ranging

Table 4 Volume of inter-basin water transfer from the Zab River basin to the Urmia Lake

Condition	Inter-basin water transfer from the Zab River basin to the Urmia Lake ($\times 10^8 \text{ m}^3$)
Scenario of IBWT from the Kanisib+Silveh dams (short term)	6.00
Scenario of IBWT from the Kanisib+Silveh dams (long term)	5.28
Scenario of IBWT from the Kanisib+Silveh+Sardasht dams (long term)	7.43
Scenario of IBWT from the Kanisib+Silveh+Sardasht+Choman dams (long term)	8.34

Note: IBWT, inter-basin water transfer.

Table 5 Outflow from the Zab River basin under various scenarios

Scenario	Outflow from the Zab River basin					
	Normal year ($\times 10^8 \text{ m}^3$)	Percent (%)	Wet year ($\times 10^8 \text{ m}^3$)	Percent (%)	Drought year ($\times 10^8 \text{ m}^3$)	Percent (%)
Scenario of IBWT from the Kanisib+Silveh dams (short term)	11.48	-34.0	36.93	-14.0	1.69	-78.0
Scenario of IBWT from the Kanisib+Silveh dams (long term)	12.20	-30.0	37.65	-12.0	2.41	-69.0
Scenario of IBWT from the Kanisib+Silveh+Sardasht dams (long term)	10.05	-42.0	35.50	-17.0	0.26	-97.0
Scenario of IBWT from Kanisib+Silveh+Sardasht+Choman dams (long term)	9.14	-48.0	34.59	-19.0	-0.65	0.0

from 69.0% to 97.0%. In the hypothetical scenario of the maximum water transfer from the Zab River basin during drought year, which would include additional diversions from both the Sardasht and Choman dams, it is posited that there would be no water flow towards the outlet. This indicated that in drought years, implementing scenarios that allow for the maximum water transfers from the Zab River basin resulted in a substantial decrease in the downstream discharge levels of the Zab River.

Application of AHP and Expert Choice software facilitated a detailed analysis of stakeholder preferences across four critical criteria: climate, consumption, socio-economic impact, and environment. Preferences for each criterion were quantified on a scale from 1 to 9, enabling effective pairwise comparisons. The resulting analysis produced a pairwise comparison matrix, highlighting an inconsistency rate of 0.08 as determined by Expert Choice software. This result indicated a coherent and reliable aggregation of stakeholder priorities regarding the factors influencing water transfer decision (Tables 6 and 7). The analysis revealed a clear prioritization among criteria: socio-economic impact emerged as the most critical, accounting for 47.9% of decision-making weight. Climate was the next, with a 25.0% weight, followed by the impact of agricultural water use at 15.1%. Environmental flow stability was determined to be the least weighted but still significant factor, comprising 12.1% of the decision criteria.

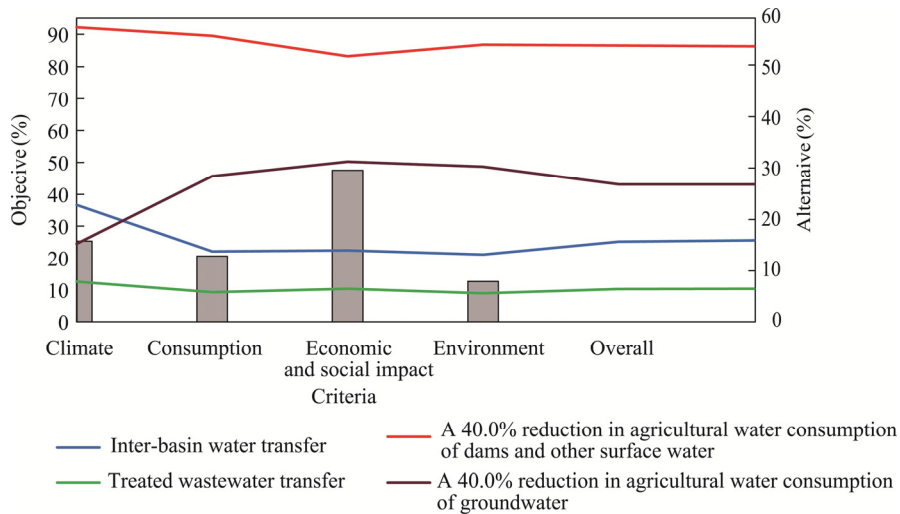
Figure 8 presents the outcomes of a model sensitivity analysis. In the figure, different options are depicted as columns, organized by their priority level from top to bottom. This layout serves to demonstrate the sensitivity of each option to the criteria shown along horizontal axis.

Table 6 Prioritization of main criteria based on importance

Rank	Criteria	Weighted value (%)
1	Socio-economic impact	47.9
2	Climate	25.0
3	Consumption	15.1
4	Environment	12.1

Table 7 Ranking of options based on weighted value

Number	Option	Weighted value (%)	Rank
1	Inter-basin water transfer	15.5	3
2	A 40.0% reduction in agricultural water consumption of dams and other surface water	51.9	1
3	Treated wastewater transfer	6.5	4
4	A 40.0% reduction in agricultural water consumption of groundwater	26.1	2

**Fig. 8** Outcome of model sensitivity analysis

4 Discussion

The restoration of the Urmia Lake, a critical ecological measure, stands at a crossroad, demanding immediate action. The lake's future hinges on a comprehensive approach that integrates water management with conservation efforts. Water resource development projects, while beneficial, come with their own set of challenges, including significant environmental impacts. Our investigation has delineated a comprehensive approach through six water-conservation strategies, which include inter-basin water transfer and mitigating the reliance on water-intensive agricultural practices within the Urmia Lake. Our analysis underlines the urgent requirement to decrease agricultural water usage by 40.0% across all sources as a fundamental measure to protect the Urmia Lake. Subsequently, the need for prioritizing inter-basin water transfer becomes evident, necessitating an in-depth evaluation of the originating watersheds' challenges and constraints. It is essential to assess the consequences for downstream users and the potential environmental risks, underscoring the importance of engaging in proactive water diplomacy with neighboring country. Moreover, our findings underscore that under drought years, achieving the annual transfer goal of $6.00 \times 10^8 \text{ m}^3$ is impractical due to significantly diminished outflow from the Zab River basin. It is crucial to recognize that the successful restoration of the Urmia Lake is contingent upon the full implementation of all recommended strategies, which are projected to augment the lake's volume by 3.57×10^9 – $10.70 \times 10^9 \text{ m}^3$ over the next 10–15 a. Nevertheless, achieving this increase still not meet the ecological threshold required for the lake's complete restoration. Implementing an additional strategy that involves reducing the current area of cultivated land and eliminating water-intensive agricultural practices within irrigation systems merges as a viable pathway for the Urmia Lake's ecological recovery. If conditions remain conducive, these strategic changes have the potential to restore the lake's ecological balance within the forthcoming 15 a. This approach underscores the critical role of sustainable agricultural transformation in conservation efforts.

It should also be underscored that Scenario 1, encompassing conservation from currently operating dams, savings from other rivers, water release during non-cultivation months, treated wastewater transfer, and annual river input culminating in a total of 10.86×10^8 m³ during severe drought years, yields consistent results across both 10 and 15 a projections. This outcome is attributed to the scenario's representation of a dry year, during which the lake's evaporation rates exceed the comparatively low water inflow. Consequently, this leads to a stagnant water volume in the lake over successive years, underscoring the critical challenge of managing water resources in periods of drought.

Insights from prior studies shed light on the critical challenges faced by lakes worldwide due to increased water consumption and ecological degradation. A focused study on the Urmia Lake basin, using global registry of acute coronary events satellite data and the WaterGAP model (Hosseini Moghari et al., 2020), indicates that human actions have led to a 52.0%–57.0% decline in the basin's total water reserves. Parsinejad et al. (2022) conducted a thorough analysis of literature through 2020 to identify the causes of the Urmia Lake's desiccation. They determined that 62.0% of the lake's water reduction resulted from water resource development projects, while climate changes accounted for 38.0%. Significantly, their study underscores that the effects of agricultural practices, dam construction, and management failures have had a more profound impact on the lake's declining levels than those of increased temperature and decreased rainfall. Yasi (2017) also pinpointed the development of water resources and the broadening of agricultural areas as primary factors depleting underground water reserves in plains and diminishing the flow of surface and subsurface waters to the Urmia Lake. He argued that the key to preserving the Urmia Lake lies in efficiently managing and reducing water usage within its watershed.

Agriculture represents the most water-intensive sector within the Urmia Lake basin, accounting for merely 13.0% of the region's gross domestic product and 2.0% of its employment (Wurtsbaugh and Sima, 2022). In contrast, the services sector, utilizing just 1.0% of the total water, contributes the majority of both the product (55.0%) and employment (44.0%) across the three provinces in the Urmia Lake basin. Unfortunately, in recent decades, the Urmia Lake basin has witnessed a considerable expansion of cultivated lands by over 2×10^5 hm², shifting towards more water-intensive agricultural practices. This shift, along with the construction of new dams, extensive well drilling, and unauthorized water extraction, has led to a dramatic increase in the use of both underground and surface water sources. As a result, the consumption of renewable water resources in the watershed now exceeds 70.0%. The research team from the Sharif University of Technology has proposed a pivotal solution for the lake's restoration, suggesting a 40.0% reduction in agricultural water use (Sima et al., 2021). This measure, endorsed by the government, aimed at increasing the runoff reaching the lake to aid in its recovery. However, the realization of this significant reduction in agricultural water consumption demands a comprehensive strategy, as current trends show a concerning expansion in water usage rather than the intended decrease (Koochani et al., 2023). To effectively reduce water consumption in agriculture by 40.0% within the Urmia Lake basin, the following actions are necessary: initiating cultural and social initiatives to change attitudes and behaviors related to water consumption, ensuring coordination and alignment for full cooperation among executive agencies and the public, modifying cultivation practices to optimize water usage by adjusting cultivation levels and patterns, and implementing monitor and control tools to effectively manage and track consumption levels. Masoumi et al. (2016) proposed strategies to curtail agricultural water use in the Zarrineh-Rud and Simineh-Rud sub-basins, highlighting the lack of an integrated approach in the management of water, soil, and plant systems, as well as the provision for the Urmia Lake's environmental water needs, which has led to rampant over-extraction of water resources. Through the adoption of optimized cultivation patterns and comprehensive resource management practices, they discovered that it was possible to reduce agricultural water consumption by approximately 39.0%, thereby improving water productivity and yielding economic advantages.

In the realm of water resource management, projects that facilitate the transfer of water between basins are commonly undertaken to fulfill the necessities of drinking water, industrial use, and agriculture. These endeavors, both within Iran and around the globe, have historically

been associated with a myriad of challenges, including technical difficulties, and social and environmental conflicts, despite the overarching goal to meet critical water needs. Nonetheless, the project under discussion in our article diverges from this traditional path by centering its aim on environmental conservation. Specifically, it endeavors to rejuvenate the Urmia Lake, a critical ecological issue in Iran, thus representing a significant shift towards restoring the ecosystem. However, the implementation of water resource development projects, particularly those that involve inter-basin transfers, is known to significantly modify the natural flow patterns of rivers. These modifications inevitably bear consequences on the environmental, economic, and social conflict of both source and destination regions, necessitating a recalibration of strategies to accommodate these altered conditions. A case in point is the scenario during drought years, where executing a strategy that maximizes the flow of water transfer could drastically reduce the discharge from the downstream of the Zab River basin. This scenario presents a complex array of downstream challenges that are environmental, social, and political aspects in nature, thereby emphasizing the crucial role of water diplomacy in mitigating potential adverse impacts. Given these complex issues, the long-term feasibility of transferring water from the Zab River basin to the Urmia Lake is fraught with uncertainties, primarily due to the logistical and environmental challenges involved in significantly reducing the overall water discharge flow in Iran. Adhering to international standards for inter-basin water transfers, as outlined by the UNESCO, and embracing an integrated water resources management (IWRM) framework, could pave the way for more favorable outcomes. Rawshan et al. (2019) examined the water yield trends of the Zab Kochak River, a crucial feeder for the Dukan Dam in Iraq, from 1964 to 2013. Their research revealed a decline in the dam's inflow, primarily due to reduced rainfall. Despite the absence of inter-basin water transfer projects during the study period, they forecasted that future development projects for the upstream of the Dukan Dam would exacerbate water shortages. This result underscores the urgent need for adaptive strategies to address anticipated challenges of water scarcity for the dam's operations.

Studies in other areas also underscore the importance of thoughtful water transfer approaches and compensatory measures for area donating water (Tian et al., 2019; Bui et al., 2020). The study by Zhou et al. (2017) indicates that implementing intelligent water allocation strategies can effectively lessen the detrimental impacts of inter-basin water transfer projects, thereby improving the reliability, resilience, and reducing the vulnerability of water supply in the basins that provide the water.

Drawing lessons from global counterparts provides essential insights for the restoration of the Lake Urmia, utilizing the experiences of similar efforts worldwide. The historical challenges and solutions applied to lakes such as the Aral Sea, Owens Lake, and the comparative study of the Great Salt Lake offer a wealth of successful strategies and lessons. The Aral Sea's history, particularly the catastrophic consequences of river diversion for agriculture in the 1960s, serves as a stark warning. The construction of the Kokaral Dam in 2004 aimed to revive the North Aral Sea, with subsequent initiatives focusing on improving water management, promoting sustainable agriculture, and enhancing environmental awareness (Micklin et al., 2014; Sobirova et al., 2023). Owens Lake in California, desiccated due to water diversion to Los Angeles in 1913, became a significant source of dust storms. Restoration efforts have involved flooding shallow areas, managing native vegetation, and using gravel mulching to control dust emissions (Karimian Eghbal and Hamzehpour, 2014). Similarly, the Urmia Lake shares many characteristics with the Great Salt Lake, including size, elevation, and salinity. Both are segmented by causeways that disrupt water flow and affect salinity, impacting their ecosystems. Despite these similarities, Urmia Lake has seen a more rapid water level decline due to climate change and intensive agricultural water use. Unlike the Great Salt Lake, where agriculture involves only a small fraction of the population, Urmia Lake basin has a higher population density and a substantial portion of its workforce engaged in agriculture, exacerbating the lake's issues. Given these ecological parallels, Urmia Lake could benefit from adopting economic activities similar to those around the Great Salt Lake, which leverages tourism, mineral extraction, and fishing to support local economies. This approach could provide alternative livelihoods for farmers, reducing the strain on water resources, and aiding the lake's recovery. Wurtsbaugh and Sima (2022) recommend collaborative

community efforts, a shift from agriculture-centric economies to diverse production and services, and leveraging lake ecosystem services like mineral resources, recreational opportunities, and wildlife habitats for sustainable lake management. These strategies aim to address the direct and indirect causes of degradation in saline lakes like the Urmia Lake.

5 Conclusions

The study highlighted the necessity of reducing agricultural water consumption by 40.0% from all sources to recover the Urmia Lake. And inter-basin water transfer was designed and assessed. It is crucial to consider the impacts on downstream users and environmental risks, emphasizing the importance of water diplomacy with neighboring country. Moreover, achieving annual goal of transferring $6.00 \times 10^8 \text{ m}^3$ under drought years becomes impossible due to the reduced outflow from the Zab River basin. The successful restoration of the Urmia Lake is contingent upon the comprehensive implementation of all suggested strategies, with the priorities and impacts of each scenario clearly outlined. These measures are projected to potentially increase the lake's volume by 3.57×10^9 – $10.70 \times 10^9 \text{ m}^3$ over the next 10–15 a. However, this increase will not be sufficient to restore the lake's ecological health. Implementing further measures, such as reducing cultivated land and halting water-intensive farming in irrigation networks, is an effective path to ecological recovery. Yet, the capability of the Urmia Lake to maintain its functions during this timeframe necessitates thorough assessment by environmental experts. The revival of the Urmia Lake necessitates a coordinated strategy and robust coordination among executive agencies, alongside community involvement in decision-making. The adoption of water conservation measures and stringent actions against unauthorized water usage are imperative. Policy makers must prioritize the formulation and enactment of strategies that are both economically viable and environmentally responsible. These efforts aim to rejuvenate the lake and protect local communities from the impacts of desiccation. The limitation of this study stems from the challenge in accessing data from border and cross-border regions of neighboring country. This difficulty significantly constrains our ability to comprehensively explore social, economic, and environmental impacts influenced by water management practices.

Conflict of interest

The authors declare no competing financial interests or personal relationships that might have influenced the work reported in this paper.

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