Investigating the causes of Lake Urmia shrinkage: climate change or anthropogenic factors? Postprint

Authors: Mehri SHAMS GHAHFAROKHI, Sogol MORADIAN

Date: 2023-04-13T00:00:00+00:00

Abstract

Lake Urmia, one of the largest hypersaline lakes on Earth, has experienced serious environmental degradation. Using satellite imagery and observational data, this study investigated lake changes from 1970–2020, focusing on climate change effects and human-induced processes including population growth, excessive dam construction, low irrigation efficiency, poor water resources management, increased sediment inflow, and inadequate political-legal frameworks. Results showed slow change between 1970–1997, but rapid shrinkage from 1998–2018, with approximately 30% of the lake area disappearing. Anthropogenic factors impacted Lake Urmia far more than climate change or prolonged drought. Mismanagement of agricultural water consumption and surface/groundwater withdrawals caused sharp declines in lake surface area, posing serious challenges for water resources management in the basin. This study provides a comprehensive overview of anthropogenic influences on Lake Urmia and identifies opportunities for improved water management, serving as a guideline framework for scientists and decision-makers assessing lake water resources and formulating management strategies.

Full Text

Preamble

J Arid Land (2023) 15(4): 424–438
https://doi.org/10.1007/s40333-023-0054-z
Science Press & Springer-Verlag

Investigating the causes of Lake Urmia shrinkage: climate change or anthropogenic factors?

Mehri SHAMS GHAHFAROKHI[1], Sogol MORADIAN[2]*

[1]Department of Civil Engineering, University of Galway, Galway H91TK33, Ireland

Abstract: Lake Urmia, one of the largest hypersaline lakes on Earth, has experienced serious environmental degradation. Using satellite imagery and observational data, this study investigated lake changes from 1970–2020, focusing on climate change effects and human-induced processes including population growth, excessive dam construction, low irrigation efficiency, poor water resources management, increased sediment inflow, and inadequate political-legal frameworks. Results showed slow change between 1970–1997, but rapid shrinkage from 1998–2018, with approximately 30% of the lake area disappearing. Anthropogenic factors impacted Lake Urmia far more than climate change or prolonged drought. Mismanagement of agricultural water consumption and surface/groundwater withdrawals caused sharp declines in lake surface area, posing serious challenges for water resources management in the basin. This study provides a comprehensive overview of anthropogenic influences on Lake Urmia and identifies opportunities for improved water management, serving as a guideline framework for scientists and decision-makers assessing lake water resources and formulating management strategies.

Keywords: Lake Urmia; lake shrinkage; climate change; population growth; dam construction; water resources management

1 Introduction

Lake Urmia, located in northwestern Iran, is among the largest hypersaline lakes on Earth. Over recent decades, the lake area has decreased due to various anthropogenic factors (extensive agriculture, urban growth, land expansion, dam construction), climate change, and natural hazards such as drought (Zarghami et al., 2011; Tourian et al., 2015; Hassani et al., 2020; Schulz et al., 2020; Mohammadi Hamidi et al., 2021; Sima et al., 2021). This drying has caused biodiversity loss, destroyed bird habitats, led to aquifer desertification as lake salt is exposed, increased salinity affecting local agriculture, and created serious health consequences for residents (Zarrineh and Abad, 2014; Balkanlou et al., 2020; Nhu et al., 2020; Tabrizi et al., 2020). Therefore, identifying responsible factors for lake shrinkage and formulating management strategies is critically important.

Many studies have examined Lake Urmia's volume changes and drying factors (Gholampour et al., 2015; Khazaei et al., 2018; Ghale et al., 2019; Dehghanipour et al., 2020; Schmidt et al., 2021). Some authorities blame climate change, arguing water scarcity is periodic (Lake Urmia Restoration Program, 2014; Urmia Lake Restoration National Committee, 2015; Sobhani et al., 2019). Others believe catastrophic water shortages stem from decades of fragmented water management (Madani, 2014; AghaKouchak et al., 2015; Torabi Haghighi et al., 2018; AghaKouchak et al., 2021). Madani (2014) argued that Lake Urmia's status is affected by rapid population growth and agricultural inefficiency. AghaKouchak et al. (2015) demonstrated that shoreline retreat is not solely due to prolonged drought. Torabi Haghighi et al. (2018) showed that agricultural water mismanagement reduced inflow by up to 80%. Thus, consensus on shrinkage causes is lacking.

This paper uses satellite imagery to evaluate Lake Urmia's area changes and investigate primary shrinkage reasons, providing a guideline framework for scientists assessing water resource factors and for decision-makers formulating management strategies.

2.1 Study Area

Lake Urmia (44°13′–47°54′E, 35°40′–38°29′N; Fig. 1 [Figure 1: see original paper]) in northwestern Iran is one of Earth's largest saltwater lakes. The basin lies in Iran's arid and semi-arid region (Yazdandoost et al., 2020a), with mean annual temperatures of 6.5–13.5°C (Department of Environment of Iran, 2019). Since the 1970s, this endorheic lake has faced severe water scarcity. USGS-NASA Landsat imagery shows substantial recent area decreases (Tourian et al., 2015; Hosseini-Moghari et al., 2018; AghaKouchak et al., 2021; Sima et al., 2021; Yazdandoost and Moradian, 2021). Water retreat leaves salt crusts that generate dust storms, causing respiratory problems and damaging farmland (Rasouli et al., 2013; Ghale et al., 2018; Hossein Mardi et al., 2018; Mohammadi Hamidi et al., 2020, 2021; Hemmati et al., 2021). Climate change, population growth, excessive dam construction, low irrigation efficiency, poor water management, increased sediment inflow, and weak political-legal frameworks are main shrinkage causes (Ahmadzadeh Kokya et al., 2011; Delju et al., 2013; Ahmadi et al., 2016; Gohari et al., 2017; Alborzi et al., 2018; Moradian et al., 2019). Table 1 provides detailed lake information.

2.2 Data Collection

Landsat satellite images (www.earthexplorer.usgs) were used to calculate Lake Urmia's area changes during 1970–2020, with outputs compared to National Committee for Lake Urmia Restoration reports (https://www.ulrp.ir/en/). Precipitation data came from the Global Precipitation Climatology Centre (GPCC; https://opendata.dwd.de/climate_{environment}/GPCC/html/download_{gate}.html) (Schneider et al., 2020). Water supply/demand assessment data for domestic, industrial, and agricultural sectors were obtained from Iran's Ministry of Agriculture Agricultural Statistics and Information Center (https://irandataportal.syr.edu/ministry-of-agriculture).

2.3.1 Causes of Lake Urmia Shrinkage

To monitor area changes using Landsat and ENVI software, we calculated six remote sensing-derived water indices (Table 2). Satellite images for 1970–2020 were presented as monthly averages (Xu, 2005; McFeeters, 2013; Pettorelli, 2013; Feyisa et al., 2014; Naji, 2018; Wang et al., 2018).

The Kappa coefficient (KC) assessed index accuracy (Acharya et al., 2016; Mondejar and Tongco, 2019):

$$KC = \frac{\sum_{i=1}^{n} n_{ii} - \sum_{i=1}^{n} (n_{i+} \times n_{+i})/N}{N - \sum_{i=1}^{n} (n_{i+} \times n_{+i})/N}$$

where n is the satellite band number; n_{ij} is correctly classified pixels in category i row and j column; n_{i+} is pixels in ith row classified for a specific class; and n_{+i} is cells in jth column categorized for observed/reference data.

Precipitation data from GPCC underwent bias correction (Teutschbein and Seibert, 2012; Fang et al., 2015). The method corrects simulated precipitation distribution to match observed precipitation. Cumulative distribution functions were constructed for observed and GPCC data, then Equation 2 was applied:

$$P' = CDF_{obs}^{-1}[CDF_{GPCC}(P_{GPCC})]$$

where P' is corrected precipitation (mm); CDF_{obs} is observed precipitation CDF; CDF_{GPCC} is GPCC data CDF; and P_{GPCC} is GPCC precipitation (mm). A Gamma distribution function was used for marginal probability distribution (Thom, 1958). Equation 3 describes the Gamma distribution:

$$f_{\gamma}(x) = \frac{x^{\alpha-1} e^{-x/\beta}}{\beta^{\alpha} \Gamma(\alpha)}$$

where α and β are shape and scale parameters; x is the given parameter; and Γ is the Gamma function. The method was expressed as f_{γ}^{-1} where GPCC and obs refer to dataset and observations.

The correlation coefficient (CC) in SPSS measured variable correlations (Kremelberg, 2010; Kinnear and Gray, 2011; Verma, 2012; Davis, 2013). As drought involves chronic water shortages (Mishra and Singh, 2010), Standardized Precipitation Index (SPI) changes were investigated to monitor meteorological drought frequency and severity (McKee et al., 1993, 1995; Edwards and McKee, 1997). SPI is widely used and accepted by the World Meteorological Organization (Morid et al., 2006; Hayes et al., 2011; Shukla et al., 2011; Angelidis et al., 2012; Golian et al., 2014; Awange et al., 2016).

SPI calculation involves: (1) preparing precipitation accumulation time series; and (2) estimating variables using non-parametric empirical distribution functions (Hao et al., 2014; Farahmand and AghaKouchak, 2015; Jang, 2018; Salvador et al., 2019; Moradian and Yazdandoost, 2021). This study used the empirical Gringorten distribution function (Gringorten, 1963). Observed precipitation probability was calculated using Equation 5:

$$Prob = \frac{I - 0.44}{N + 0.12}$$

where $Prob$ is cumulative frequency estimate of the ith item; and I is order of smallest sample out of N samples. $Prob$ was standardized as Equation 6:

$$\phi = \Phi^{-1}(Prob)$$

where ϕ is standard normal distribution function. SPI standardizes percentiles using Equations 7 and 8:

$$SPI = \begin{cases} -\left(t - \frac{c_0+c_1t+c_2t^2}{1+d_1t+d_2t^2+d_3t^3}\right) & \text{if } 0.00 < Prob \leq 0.51 \\ +\left(t - \frac{c_0+c_1t+c_2t^2}{1+d_1t+d_2t^2+d_3t^3}\right) & \text{if } 0.51 < Prob \leq 1.00 \end{cases}$$

where t, c_0, c_1, c_2, d_1, d_2, and d_3 are coefficients. The Kolmogorov-Smirnov test checked distribution fit (Stephens, 1974). This non-parametric test validates using empirical distribution functions as reference (Eq. 9):

$$D = \max |R(x) - E(x)|$$

where D is maximum difference between reference $R(x)$ and empirical $E(x)$ cumulative distribution functions. The hypothesis is that the reference distribution describes the data. With 0.01 error, if P-value exceeds error, the distribution is selected.

2.3.2 Water Resources Management Based on Resiliency

After examining shrinkage drivers, developing lake regeneration scenarios using Integrated Water Resources Management (IWRM) is necessary. Basin planning involves uncertainties from ambiguous assumptions, objectives, and forecasts. Resilience's role must be determined in an integrated system considering environmental, economic, technical, and social aspects (Adger, 2000; de Bruijn, 2004; Tayia and Madani, 2017). Two resilience approaches exist: (1) engineering resilience focusing on stable equilibrium behavior and recovery speed after disturbance; and (2) system behavior near domain boundaries far from equilibrium, showing buffer capacity to absorb disturbances (de Bruijn, 2004; Nazif and Karamouz, 2009; Tahmasebi Birgani et al., 2013; Madani, 2019). Based on system responses to disturbances, three resilience aspects emerge: (1) no response; (2) response; and (3) recovery to normal state (Fig. 2 [Figure 2: see original paper]) (de Bruijn, 2004; Tahmasebi Birgani and Yazdandoost, 2014). System responses vary by disturbance magnitude (Gersonius, 2008). This study determines Lake Urmia's condition to formulate resilient revival strategies.

To investigate strategy resiliency and assess future water supply/demand, we quantitatively identified water resources and explored the hydrological cycle, demand, and consumption regionally. The Water Evaluation and Planning System (WEAP) enabled integrated assessment (Lévite et al., 2003; Yates et al., 2005; Purkey et al., 2007; Vogel et al., 2007). WEAP represents river basins through demand-side issues (allocations, usage patterns, costs, efficiencies, reuse) and supply-side aspects (surface/groundwater, transfers, reservoirs). This integrated approach simulates natural and engineering components, giving decision-makers comprehensive understanding of water system management factors (Yazdandoost et al., 2020b).

This research investigated precipitation parameters directly affected by climate change. Since runoff is influenced by dam construction and surface water withdrawals, these were examined separately to determine whether Lake Urmia's catastrophic decline is natural or anthropogenic. After applying parameters (precipitation, evaporation, agricultural/domestic/industrial withdrawals), runoff to Lake Urmia was calculated in WEAP, determining lake volume under different scenarios using data from Iran's Ministry of Agriculture.

3.1 Changes in the Area of Lake Urmia

To evaluate Lake Urmia's area changes from 1970–2020, we calculated six indices: Automated Water Extraction Index (AWEI), shadow-corrected AWEI (AWEIsh), Difference between Vegetation and Water (DVW), Modified Normalized Difference Water Index (MNDWI), Normalized Difference Vegetation Index (NDVI), and Normalized Difference Water Index (NDWI). Table 3 shows 2014 area results from these indices. NDWI performed best and was used to study area changes over the study period.

NDWI results indicated slow area changes until 1997, with rapid shrinkage from 1998–2018, when about one-third of the lake disappeared (Fig. 3 [Figure 3: see original paper]). These results align with recent studies and the lake's area-elevation-storage curve (Lake Urmia Restoration Program, 2014; Madani, 2014; Tourian et al., 2015; Urmia Lake Restoration National Committee, 2015; Rahimi and Breuste, 2021), which reported 25–50% area decreases during 1970–2020.

3.2.1 Climate Change and Meteorological Factors

To assess climate change effects, we collected GPCC precipitation data and evaluated bias-corrected precipitation changes over the target area (Fig. 4 [Figure 4: see original paper]). Results showed no specific precipitation trend from 1970–2020, with precipitation not below normal during the study period. No significant relationship existed between lake volume and basin precipitation (SPSS CC=0.24). These results are consistent with lake changes in Figure 1, which shows recent "recovery" signs, supporting Figure 4 results. Since climate change effects were negligible (Section 3.2.1), it was excluded to maintain model simplicity. Strategies were based on local consultant proposals without precise magnitude information.

SPI was calculated to monitor meteorological drought severity and frequency. Figure 5 [Figure 5: see original paper] shows annual SPI time series from bias-corrected GPCC data, where negative red SPI indicates drought and positive blue SPI indicates drought end. No severe prolonged drought threatened Lake Urmia during 1970–2020 (SPSS CC=0.23).

3.2.2 Population Increase

Increasing domestic consumption and population growth raised total water demand in the basin (Madani, 2014). Agricultural Statistics data show basin population increased from 1.86$\times10^{6}$ in 1970 to 5.48$\times10^{6}$ in 2020. An inverse relationship existed between population growth and lake volume (SPSS CC=–0.71) (Fig. 6 [Figure 6: see original paper]). However, since domestic consumption constitutes only 3% of total basin consumption (Urmia Lake Restoration National Committee, 2015), population growth's impact on other factors like agricultural development must be examined.

3.2.3 Excessive Dam Construction

Lake Urmia has 13 permanent main water sources from surrounding mountains in Iran and Turkey, forming a closed basin. Currently, over 74 dams on these rivers have caused sharp lake volume declines. Reservoir volume is about 5.20$\times10^{9}$ m^3. From 1995–2010, 43 dams with 3.89$\times10^{9}$ m^3 annual adjustability caused a 7 m lake depth decrease. Considering extra water retained by large dams, their profound crisis impact became apparent (Lake Urmia Restoration Program, 2014; Tourian et al., 2015; Urmia Lake Restoration National Committee, 2015; Rahimi and Breuste, 2021). Proper dam management (temporarily opening large dams during wet periods, preventing new dams) could be effective.

3.2.4 Agricultural Water Use

Between 2010–2015, total water consumption and renewable sources exceeded 4.83$\times10^{9}$ and 7.00$\times10^{9}$ m^3, respectively. Agricultural use consumed 4.30$\times10^{9}$ m^3—about 65% of renewable sources and 93% of total basin use (Lake Urmia Restoration Program, 2014). Acceptable withdrawals should be 20–40% of total consumption (Sachs et al., 2021). Water-based farmland increased from 3.50$\times10^{5}$ to 5.00$\times10^{5}$ hm^2 between 1986–2013 (Lake Urmia Restoration Program, 2014). Figure 7 [Figure 7: see original paper] shows lake volume and agricultural water use changes from 1970–2020. High agricultural consumption dramatically reduced lake volume (SPSS CC=–0.77). Crucial planning is needed to reduce agricultural consumption and protect lake volume.

3.2.5 Water Resources Management

The study attributed Lake Urmia's water decline to increasing surface and groundwater withdrawals during 1970–2020. In the basin, 61% of domestic water came from surface sources and 39% from groundwater. Industry used 42% surface and 58% groundwater. Agriculture used 56.5% surface and 43.5% groundwater. Figure 8 [Figure 8: see original paper] shows high withdrawals caused dramatic lake volume decline (SPSS CC=–0.86).

Additionally, approximately 88,000 semi-deep and deep wells existed in 2014, with about 50% illegally constructed (Urmia Lake Restoration National Committee, 2015), tremendously reducing inflow.

3.3 Resilient Water Resources Management in Lake Urmia Basin

Lake Urmia normally holds 16.27$\times10^{9}$ m^3 (Lake Urmia Restoration Program, 2014; Ahmadaali et al., 2018). However, available water varied from 17.52$\times10^{9}$ m^3 in 2000 to 4.10$\times10^{9}$ m^3 in 2020—a 13.42$\times10^{9}$ m^3 amplitude over 20 years. To compensate, we examined management strategies in WEAP. Using 2010 consumption data, we validated WEAP for 2011–2018, with strategies assumed operational from 2021. Model validation results are in Tables 4 and 5. Detailed WEAP model information appears in Yazdandoost et al. (2020b).

Strategies included: (1) Basic strategy (S1)—predicting basin conditions (2021–2040) with no action, using 1.10%, 5.00%, and 5.00% growth rates for domestic, industrial, and agricultural consumption; (2) 25% demand reduction in industrial and domestic sectors (S2); (3) 40% demand reduction in agriculture (S3);

(4) Water transfer to Lake Urmia (S4) (Urmia Lake Restoration National Committee, 2015). A hybrid scenario with 25% reduction in all demands (S5) was also analyzed. Since climate change effects were negligible (Section 3.2.1), it was excluded to maintain model simplicity. Strategies were based on local consultant proposals without precise magnitude information.

Figure 9 [Figure 9: see original paper] shows modeled water volumes. The 40% agricultural reduction (S3) reaches normal state soonest, but compulsory agricultural allocation reduction may create social and economic impediments. Inter-basin water transfer (S4) ignores drying process dynamics—short-term relief may cause long-term tensions. Therefore, inter-basin transfers are inadequate and may cause unintended negative consequences.

This study proposes better basin management: hybrid scenarios considering all demands (S5), changing cultivation patterns (reducing water-intensive crops, cultivating low-demand crops), decreasing cultivated areas, improving irrigation efficiency (modern drip/sprinkler systems), and providing farmer technical support (Richter et al., 2017; Ahmadaali et al., 2018; Emami and Koch, 2018). These measures reduce impediments without compulsory agricultural withdrawal reductions.

---

4 Conclusions

In recent years, large portions of Lake Urmia have dried up. This study indicates that change rates in recent decades, particularly 1998–2018, were considerable, with about 30% of the lake area disappearing. Climate change effects on shrinkage were negligible; while climate and meteorological factors contribute, anthropogenic factors play the major role. These challenges have serious implications for short- and long-term water resources management. Decision-making must consider IWRM principles based on resilient water management, requiring scenarios encompassing environmental, economic, technical, and social aspects in an integrated system.

References

Abbaspour M, Nazaridoust A. 2007. Determination of environmental water requirements of Lake Urmia, Iran: an ecological approach. *International Journal of Environmental Studies*, 64(2): 161–169.

Acharya T D, Lee D H, Yang I T, et al. 2016. Identification of water bodies in a Landsat 8 OLI image using a J48 decision tree. *Sensors-Basel*, 16(7): 1075, doi: 10.3390/s16071075.

Acharya T D, Subedi A, Lee D H. 2018. Evaluation of water indices for surface water extraction in a Landsat 8 scene of Nepal. *Sensors*, 18(8): 2580, doi:

10.3390/s18082580.

Adger W N. 2000. Social and ecological resilience: are they related? *Progress in Human Geography*, 24(3): 347–364.

AghaKouchak A, Norouzi H, Madani K, et al. 2015. Aral Sea syndrome desiccates Lake Urmia: Call for action. *Journal of Great Lakes Research*, 41(1): 307–311.

AghaKouchak A, Mirchi A, Madani K, et al. 2021. Anthropogenic drought: definition, challenges, and opportunities. *Reviews of Geophysics*, 59(2): e2019RG000683, doi: 10.1029/2019RG000683.

Ahmadaali J, Barani G A, Qaderi K, et al. 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): 160, doi: 10.3390/w10020160.

Ahmadi A, Abbaspour M, Arjmandi R, et al. 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, et al. 2011. Evaluation of salt effects on some thermodynamic properties of Urmia Lake water. *International Journal of Environmental Research*, 5(2): 343–348.

Alborzi A, Mirchi A, Moftakhari H, et al. 2018. Climate-informed environmental inflows to revive a drying lake facing meteorological and anthropogenic droughts. *Environmental Research Letters*, 13(8): 084010, doi: 10.1088/1748-9326/aad246.

Angelidis P, Maris F, Kotsovinos N, et al. 2012. Computation of drought index SPI with alternative distribution functions. *Water Resources Management*, 26: 2453–2473.

Awange J L, Mpelasoka F, Goncalves R M. 2016. When every drop counts: analysis of droughts in Brazil for the 1901–2013 period. *Science of The Total Environment*, 566–567: 1472–1488.

Balkanlou K R, Müller B, Cord A F, et al. 2020. Spatiotemporal dynamics of ecosystem services provision in a degraded ecosystem: A systematic assessment in the Lake Urmia basin, Iran. *Science of The Total Environment*, 716: 137100, doi: 10.1016/j.scitotenv.2020.137100.

Davis C. 2013. *SPSS for Applied Sciences: Basic Statistical Testing*. Melbourne: CSIRO Publishing, 1–175.

de Bruijn K M. 2004. Resilience and flood risk management. *Water Policy*, 6(1): 53–66.

Dehghanipour A H, Panahi D M, Mousavi H, et al. 2020. Effects of water level decline in Lake Urmia, Iran, on local climate conditions. *Water*, 12(8): 2153, doi: 10.3390/w12082153.

Delju A H, Ceylan A, Piguet E, et al. 2013. Observed climate variability and change in Urmia Lake Basin, Iran. *Theoretical and Applied Climatology*, 111(1–2): 285–296.

Department of Environment of Iran. 2019. *Urmia Lake Challenges, Actions, and the way forward* (1st ed.). [2019-04-28]. https://www.ulrp.ir/wp-content/uploads/2019/04/node_{1420}.pdf.

Edwards D C, McKee T B. 1997. Characteristics of 20th century drought in the United States at multiple time scales. *Atmospheric Science Paper*, 634: 1–30.

Emami F, Koch M. 2018. Agricultural water productivity-based hydro-economic modeling for optimal crop pattern and water resources planning in the Zarrine River basin, Iran, in the wake of climate change. *Sustainability*, 10(11): 3953, doi: 10.3390/su10113953.

Fang G H, Yang J, Chen Y N, et al. 2015. Comparing bias correction methods in downscaling meteorological variables for a hydrologic impact study in an arid area in China. *Hydrology and Earth System Sciences*, 19(6): 2547–2559.

Farahmand A, AghaKouchak A. 2015. A generalized framework for deriving nonparametric standardized drought indicators. *Advances in Water Resources*, 76: 140–145.

Feyisa G L, Meilby H, Fensholt R, et al. 2014. Automated Water Extraction Index: a new technique for surface water mapping using Landsat imagery. *Remote Sensing of Environment*, 140: 23–35.

Gao B C. 1996. NDWI—A normalized difference water index for remote sensing of vegetation liquid water from space. *Remote Sensing of Environment*, 58(3): 257–266.

Gersonius B. 2008. Can resilience support integrated approaches to urban drainage management? In: *11th International Conference on Urban Drainage*. Edinburgh, Scotland, UK.

Ghale Y A G, Altunkaynak A, Unal A. 2018. Investigation anthropogenic impacts and climate factors on drying up of Urmia Lake using water budget and drought analysis. *Water Resources Management*, 32(1): 325–337.

Ghale Y A G, Baykara M, Unal A. 2019. Investigating the interaction between agricultural lands and Urmia Lake ecosystem using remote sensing techniques and hydro-climatic data analysis. *Agricultural Water Management*, 221(20): 566–579.

Gholampour A, Nabizadeh R, Hassanvand M S, et al. 2015. Characterization of saline dust emission resulted from Urmia Lake drying. *Journal of Environmental Health Science and Engineering*, 13: 82, doi: 10.1186/s40201-015-0238-3.

Gohari A, Mirchi A, Madani K. 2017. System dynamics evaluation of climate change adaptation strategies for water resources management in Central Iran. *Water Resources Management*, 31(5): 1413–1434.

Golian S, Mazdiyasni O, AghaKouchak A. 2014. Trends in meteorological and agricultural droughts in Iran. *Theoretical and Applied Climatology*, 119(3–4): 679–688.

Gringorten I I. 1963. A plotting rule for extreme probability paper. *Journal of Geophysical Research*, 68(3): 813–814.

Hao Z C, AghaKouchak A, Nakhjiri N, et al. 2014. Global integrated drought monitoring and prediction system. *Scientific Data*, 1: 140001, doi: 10.1038/sdata.2014.1.

Hassani A, Azapagic A, D'Odorico P, et al. 2020. Desiccation crisis of saline lakes: A new decision-support framework for building resilience to climate change. *Science of The Total Environment*, 703: 134718, doi: 10.1016/j.scitotenv.2019.134718.

Hayes M, Svoboda M, Wall N, et al. 2011. The Lincoln declaration on drought indices: universal meteorological drought index recommended. *Bulletin of the American Meteorological Society*, 92(4): 485–488.

Hemmati M, Ahmadi H, Hamidi S A, et al. 2021. Environmental effects of the causeway on water and salinity balance in Lake Urmia. *Regional Studies in Marine Science*, 44: 101756, doi: 10.1016/j.rsma.2021.101756.

Hossein Mardi A, Khaghani A, MacDonald A B, et al. 2018. The Lake Urmia environmental disaster in Iran: A look at aerosol pollution. *Science of The Total Environment*, 633: 42–49.

Hosseini-Moghari S M, Araghinejad S, Tourian M J, et al. 2018. Quantifying the impacts of human water use and climate variations on recent drying of Lake Urmia basin: the value of different sets of spaceborne and in-situ data for calibrating a hydrological model. *Hydrology and Earth System Sciences*, 24(4): 1939–1956.

Jang D. 2018. Assessment of meteorological drought indices in Korea using RCP 8.5 scenario. *Water*, 10(3): 283, doi: 10.3390/w10030283.

Khazaei B, Khatami S, Alemohammad H, et al. 2018. Climatic or regionally induced by humans? Tracing hydro-climatic and land-use changes to better understand the Lake Urmia tragedy. *Journal of Hydrology*, 569: 203–217.

Kinnear P R, Gray C D. 2011. *IBM SPSS Statistics 18 Made Simple*. Hove, East Sussex: Psychology Press, 120–600.

Kremelberg D. 2010. *Practical statistics: A quick and easy guide to IBM® SPSS® Statistics, STATA, and other statistical software*. Sauzendoaks, California: SAGE publications, 1–528.

Lake Urmia Restoration Program. 2014. *Lake Urmia, Causes of Drought and Possible Threats*. Official Report. Tehran, Iran: Lake Urmia Revival Headquarters. (in Persian)

Lévite H, Sally H, Cour J. 2003. Testing water demand management scenarios in a water-stressed basin in South Africa: application of the WEAP model. *Physics and Chemistry of the Earth, Parts A/B/C*, 28(20–27): 779–786.

Lyon J G, Yuan D, Lunetta R S, et al. 1998. A change detection experiment using vegetation indices. *Photogrammetric Engineering and Remote Sensing*, 64(2): 143–150.

Madani K. 2014. Water management in Iran: What is causing the looming crisis? *Journal of Environmental Studies and Sciences*, 4: 315–328.

Madani K. 2019. The value of extreme events: What doesn't exterminate your water system makes it more resilient. *Journal of Hydrology*, 575: 269–272.

McFeeters S K. 2013. Using the Normalized Difference Water Index (NDWI) within a geographic information system to detect swimming pools for mosquito abatement: A practical approach. *Remote Sensing*, 5(7): 3544–3561.

McKee T B, Doesken N J, Kleist J. 1993. The relationship of drought frequency and duration to time scales. In: *8th Conference on Applied Climatology*. 17–22 January 1993. Anaheim, California, USA, 179–184.

McKee T B, Doesken N J, Kleist J. 1995. Drought monitoring with multiple time scales. In: *9th Conference on Applied Climatology*. 15–22 January 1995. Dallas: American Meteorological Society, 233–236.

Mishra A K, Singh V P. 2010. A review of drought concepts. *Journal of Hydrology*, 391(1–2): 204–216.

Mohammadi Hamidi S, Nazmfar H, Rezayan A, et al. 2020. Futurology of the economic drivers of Urmia Lake water level fluctuations on the spatial unbalanced. *The Journal of Spatial Planning*, 24(4): 69–97.

Mohammadi Hamidi S, Nazmfar H, Fürst C, et al. 2021. Water level decline at Iran's Lake Urmia: changing population dynamics. *Environmental Hazards*, 21(3): 254–273.

Mondejar J P, Tongco A F. 2019. Near infrared band of Landsat 8 as water index: a case study around Cordova and Lapu-Lapu City, Cebu, Philippines. *Sustainable Environment Research*, 29(1): 16, doi: 10.1186/s42834-019-0016-5.

Moradian S, Taleai M, Javadi G H. 2019. A decision support system for water allocation in water scarce basins. *Remote Sensing & GIS*, 11(1): 19–32.

Moradian S, Yazdandoost F. 2021. Seasonal meteorological drought projections over Iran using the NMME data. *Natural Hazards*, 108(1): 1089–1107.

Morid S, Smakhtin V, Moghaddasi M. 2006. Comparison of seven meteorological indices for drought monitoring in Iran. *International Journal of Climatology*, 26(7): 971–985.

Naji T A H. 2018. Study of vegetation cover distribution using DVI, PVI, WDVI indices with 2D-space plot. *International Journal of Physics: Conference Series*, 1003(1): 012083, doi: 10.1088/1742-6596/1003/1/012083.

Nazif S, Karamouz M. 2009. Algorithm for assessment of water distribution system's readiness: planning for disasters. *Journal of Water Resources Planning and Management*, 135(4): 244–252.

Nhu V H, Mohammadi A, Shahabi H, et al. 2020. Monitoring and assessment of water level fluctuations of the Lake Urmia and its environmental consequences using multitemporal Landsat 7 ETM+ images. *International Journal of Environmental Research and Public Health*, 17(12): 4210, doi: 10.3390/ijerph17124210.

Pettorelli N. 2013. *The normalized difference vegetation index*. Oxford: Oxford University Press, 24–193.

Purkey D R, Huber-Lee A, Yates D N, et al. 2007. Integrating a climate change assessment tool into stakeholder-driven water management decision-making processes in California. *Water Resources Management*, 21(1): 315–329.

Rahimi A, Breuste J. 2021. Why is Lake Urmia drying up? Prognostic modeling with land-use data and artificial neural network. *Frontiers in Environmental Science*, 9: 603916, doi: 10.3389/fenvs.2021.603916.

Richter B D, Brown J D, DiBenedetto R, et al. 2017. Opportunities for saving and reallocating agricultural water to alleviate water scarcity. *Water Policy*, 19(5): 886–907.

Sachs J, Kroll C, Lafortune G, et al. 2021. *Sustainable Development Report 2021*. Cambridge: Cambridge University Press.

Salvador C, Nieto R, Linares C, et al. 2019. Effects on daily mortality of droughts in Galicia (NW Spain) from 1983 to 2013. *Science of The Total Environment*, 662: 121–133.

Schmidt M, Gonda R, Transiskus S. 2021. Environmental degradation at Lake Urmia (Iran): exploring the causes and their impacts on rural livelihoods. *GeoJournal*, 86: 2149–2163.

Schneider U, Becker A, Finger P, et al. 2020. GPCC full data monthly product version 2020 at 1.0°: monthly land-surface precipitation from rain-gauges built on GTS-based and historical data. Deutscher Wetterdienst: Global Precipitation Climatology Centre (GPCC), doi: 10.5676/DWD_{GPCC}/FD_{M_V}2020_{100}.

Schulz S, Darehshouri S, Hassanzadeh E, et al. 2020. Climate change or irrigated agriculture – what drives the water level decline of Lake Urmia. *Scientific Reports*, 10(1): 236, doi: 10.1038/s41598-019-57150-y.

Shukla S, Steinemann A C, Lettenmaier D P. 2011. Drought monitoring for Washington State: indicators and applications. *Journal of Hydrometeorology*, 12(1): 66–83.

Sima S, Rosenberg D E, Wurtsbaugh W A, et al. 2021. Managing Lake Urmia, Iran for diverse restoration objectives: Moving beyond a uniform target lake level. *Journal of Hydrology: Regional Studies*, 35: 100812, doi: 10.1016/j.ejrh.2021.100812.

Sobhani B, Zengir V S, Kianian M K. 2019. Drought monitoring in the Lake Urmia basin in Iran. *Arabian Journal of Geosciences*, 12(15): 448, doi: 10.1007/s12517-019-4571-1.

Stephens M A. 1974. EDF statistics for goodness of fit and some comparisons. *Journal of the American Statistical Association*, 69(347): 730–737.

Tabrizi J S, Farahbakhsh M, Sadeghi-Bazargani H, et al. 2020. Health consequences of Lake Urmia in crisis in the disaster area: a pilot study. *Disaster Medicine and Public Health Preparedness*, 14(4): 442–448.

Tahmasebi Birgani Y, Yazdandoost F, Moghadam M. 2013. Role of resilience in sustainable urban stormwater management. *Scientific Professional Quarterly*, 1(1): 42–50.

Tahmasebi Birgani Y, Yazdandoost F. 2014. A framework for evaluating the persistence of urban drainage risk management systems. *Journal of Hydroenvironment Research*, 8(4): 330–342.

Tayia A, Madani K. 2017. Resilient transboundary water management institutions. *World Environmental and Water Resources Congress*, doi: 10.1061/9780784480595.055.

Teutschbein C, Seibert J. 2012. Bias correction of regional climate model simulations for hydrological climate-change impact studies: Review and evaluation of different methods. *Journal of Hydrology*, 456: 12–29.

Thom H C S. 1958. A note on the gamma distribution. *Monthly Weather Review*, 86(4): 117–122.

Torabi Haghighi A, Fazel N, Hekmatzadeh A A, et al. 2018. Analysis of effective environmental flow release strategies for Lake Urmia restoration. *Water Resources Management*, 32(11): 3595–3609.

Tourian M J, Elmi O, Chen Q, et al. 2015. A spaceborne multisensor approach to monitor the desiccation of Lake Urmia in Iran. *Remote Sensing of Environment*, 156: 349–360.

Urmia Lake Restoration National Committee. 2015. *Necessity of Lake Urmia resuscitation, causes of drought and threats*. Report Note ULRP-6-4-3-Rep 1. Tehran, Iran.

Verma J P. 2012. *Data Analysis in Management with SPSS Software*. New Delhi: Springer Science & Business Media.

Vogel R M, Sieber J, Archfield S A, et al. 2007. Relations among storage, yield, and instream flow. *Water Resources Research*, 43(5): W05403, doi:10.1029/2006wr005226.

Wang X B, Xie S P, Zhang X L, et al. 2018. A robust multi-band water index (MBWI) for automated extraction of surface water from Landsat 8 OLI imagery. *International Journal of Applied Earth Observation and Geoinformation*, 68: 73–91.

Xu H Q. 2005. A study on information extraction of water body with the modified normalized difference water index (NDWI). *Journal of Remote Sensing*, 9(5): 589–595. (in Chinese with English Abstract)

Xu L Y, Xie X D, Li S. 2013. Correlation analysis of the urban heat island effect and the spatial and temporal distribution of atmospheric particulates using TM images in Beijing. *Environmental Pollution*, 178: 102–114.

Yates D, Sieber J, Purkey D, et al. 2005. WEAP21—A demand-, priority-, and preference-driven water planning model Part 1: Model characteristics. *Water International*, 30(4): 487–500.

Yazdandoost F, Moradian S, Izadi A, Aghakouchak A. 2020a. Evaluation of CMIP6 precipitation simulations across different climatic zones: Uncertainty and model intercomparison. *Atmospheric Research*, 250: 105369, doi: 10.1016/j.atmosres.2020.105369.

Yazdandoost F, Moradian S, Izadi A. 2020b. Evaluation of water sustainability under a changing climate in Zarrineh River Basin, Iran. *Water Resources Management*, 34(15): 4831–4846.

Yazdandoost F, Moradian S. 2021. Climate change impacts on the streamflow of Zarrineh River, Iran. *Journal of Arid Land*, 13(9): 891–904.

Zarghami M, Abdi A, Babaeian I, et al. 2011. Impacts of climate change on runoffs in East Azerbaijan, Iran. *Global and Planetary Change*, 78(3–4): 137–146.

Zarrineh N, Abad M A N. 2014. Integrated water resources management in Iran: Environmental, socio-economic and political review of drought in Lake Urmia. *International Journal of Water Resources and Environmental Engineering*, 6(1): 40–48.

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv — Machine translation. Verify with original.