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LETTER

Climate-informed environmental inflows to revive a drying lake facing meteorological and anthropogenic droughts

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Supplementary material for this article is available online

Abstract

The rapid shrinkage of Lake Urmia, one of the world's largest saline lakes located in northwestern Iran, is a tragic wake-up call to revisit the principles of water resources management based on the socio-economic and environmental dimensions of sustainable development. The overarching goal of this paper is to set a framework for deriving dynamic, climate-informed environmental inflows for drying lakes considering both meteorological/climatic and anthropogenic conditions. We report on the compounding effects of meteorological drought and unsustainable water resource management that contributed to Lake Urmia's contemporary environmental catastrophe. Using rich datasets of hydrologic attributes, water demands and withdrawals, as well as water management infrastructure (i.e. reservoir capacity and operating policies), we provide a quantitative assessment of the basin's water resources, demonstrating that Lake Urmia reached a tipping point in the early 2000s. The lake level failed to rebound to its designated ecological threshold (1274 m above sea level) during a relatively normal hydro-period immediately after the drought of record (1998–2002). The collapse was caused by a marked overshoot of the basin's hydrologic capacity due to growing anthropogenic drought in the face of extreme climatological stressors. We offer a dynamic environmental inflow plan for different climate conditions (dry, wet and near normal), combined with three representative water withdrawal scenarios. Assuming effective implementation of the proposed 40% reduction in the current water withdrawals, the required environmental inflows range from 2900 million cubic meters per year (mcm yr^{-1}) during dry conditions to 5400 mcm yr^{-1} during wet periods with the average being 4100 mcm yr^{-1}. Finally, for different environmental inflow scenarios, we estimate the expected recovery time for re-establishing the ecological level of Lake Urmia.

1. Introduction

Global fresh water resources are under growing pressure due to over-allocation of surface water (Vörösmarty *et al* 2000, Hoekstra *et al* 2012) and groundwater resources (Wada *et al* 2010, Gleeson *et al* 2012, Ashraf *et al* 2017). The compounding effects of human-centered water management and global environmental changes in the Anthropocene have altered the natural hydrologic cycle by changing the quantity and quality of water, as well as changing the time scale of the processes that replenish water resources (Vörösmarty *et al* 2010, Mirchi *et al* 2014, Nazemi and Wheater 2014, 2015a, 2015b, Hassanzadeh *et al* 2015, Mehran *et al* 2017). The disruption of regional water regimes around the globe due to increasing water stress is evident in the growing number of inland water bodies that are facing ecological degradation, especially in irrigated agricultural areas (e.g. Coe and Foley 2001, Micklin 2007, Ma *et al* 2010, UNEP 2012, Hatchett *et al* 2015, Barnum *et al* 2017).

Prime examples of drying terminal lakes in endorheic basins include the Aral Sea in Central Asia (Micklin 1988), Walker Lake and Great Salt Lake in the US (Wurtsbaugh *et al* 2017), Lake Chad in Africa (Gao *et al* 2011), and Lake Urmia in northwestern Iran (AghaKouchak *et al* 2015). These alarming cases of lake level decline as well as other less dramatic incidents have been subjects of climate change scenario and impact assessments around the world (e.g. Coe and Foley 2001, Schwartz *et al* 2004, Ma *et al* 2010, Mohammed and Tarboton 2012, Shadkam *et al* 2016). Water level serves as a key indicator of a lake's stability (Ma *et al* 2010). Lake level fluctuations depend on intra- and inter-annual hydrologic variability (Mei *et al* 2015) and water management practices in the lake basin (Coe and Foley 2001, Ma *et al* 2010). Determining whether the lake level change is primarily due to human factors or climate change bears important implications for lake restoration strategies. In theory, the chance of preserving lakes will be higher if human activities are the chief reason for the water level decline because of opportunities for taking real actions to improve water management in the lake basin.

The shrinkage of Lake Urmia, to less than 20% of its average size (i.e. more than 5000 km^2) over the last two decades (see AghaKouchak *et al* 2015, Farzin *et al* 2012, Pengra 2012) is a recent exemplar of an emerging challenge related to unsustainable water management in the face of growing demand and climatic extremes. This designated UNESCO ecosystem and one of the largest saline lakes (Sima and Tajrishi 2013, Karbassi *et al* 2010) is located at the bottom of an approximately 52 000 km^2 basin in northwestern Iran (figure 1), which is home to about five million people close to international borders with Turkey, Iraq, and Azerbaijan (IME 2013). With salinity levels ranging from six to approximately eight times higher than seawater, this shallow terminal lake is the largest natural habitat for brine shrimp Artemia (Artemia Urmiana), which attracts diverse species of migratory birds (Barigozzi *et al* 1987, Vahed *et al* 2011, Ahmadi *et al* 2011). Such massive decline in a lake area has been witnessed before in the Aral Sea Basin, where diverting Amu Darya and Syr Darya rivers during the Soviet era caused the lake to shrink to less than 10% of its original size (Micklin 1988, 2007, Gaybullaev *et al* 2012). Remarkable parallels between unsustainable water resource management in the Lake Urmia and Aral Sea basins reinforce speculations of 'the Aral Sea syndrome' being a key driver of Lake Urmia's collapse (AghaKouchak *et al* 2015), causing negative impacts on both wildlife and humans (Madani *et al* 2016, Yamaguchi *et al* 2012).

The contemporary environmental catastrophe in the Lake Urmia Basin is a tragic wake-up call to rethink the water resources management paradigm in water-scarce countries based on hard-learned lessons about the social, economic, and environmental dimensions of sustainability (Madani 2014). Since the onset of the lake's shoreline recession around the turn of the 21 century, many researchers have investigated various aspects of the problem (Gholampour *et al* 2015, Ghaheri *et al* 1999, Ahmadzadeh Kokya *et al* 2011, Barigozzi *et al* 1987, Delju *et al* 2013, Nikbakht *et al* 2013). The desiccation has been primarily attributed to climate change-induced meteorological droughts (e.g. Fathian *et al* 2015, Vaheddoost and Aksoy 2017, Arkian *et al* 2018), as well as anthropogenic drought due to supply-oriented water management (e.g. Hassanzadeh *et al* 2012, AghaKouchak *et al* 2015, Shadkam *et al* 2016, Zarghami and AmirRahmani 2017, Ghale *et al* 2018). These studies have provided a high-level understanding of the problem, highlighting the need for and complexities of synergistic efforts to revive a drying lake that is effectively struggling with 'water bankruptcy' (Madani *et al* 2016). As shown in figure 2, the drastic water level decrease after 1998 corresponds to a substantial increase (~25%) in surface water withdrawals to meet upstream potable and agricultural demands, which coincided with 48% decrease in runoff during the prolonged drought of 1998–2002. The largest water withdrawal of 4.75 bcm yr^{-1}, of which 2.7 bcm yr^{-1} was supplied from surface water was triggered by rapid agricultural expansion (i.e. 14% increase in irrigation area; IME 2014). The figure also illustrates the basin's recent wet (blue) and dry (red) periods as indicated by the standardized precipitation index (SPI; McKee *et al* 1993) and the variability of naturalized runoff.

This study attempts to inform the ongoing debate about the causes of Lake Urmia's shrinkage and the planned restoration efforts. It provides a quantitative assessment of the basin's water resources and environmental water requirement as influenced by wet and dry periods, and anthropogenic water withdrawals. Understanding the large-scale interplay of green water losses (i.e. consumptive water uses in the agricultural sector) and blue water availability (i.e. surface water and groundwater) (Allan 1998, Hoekstra and

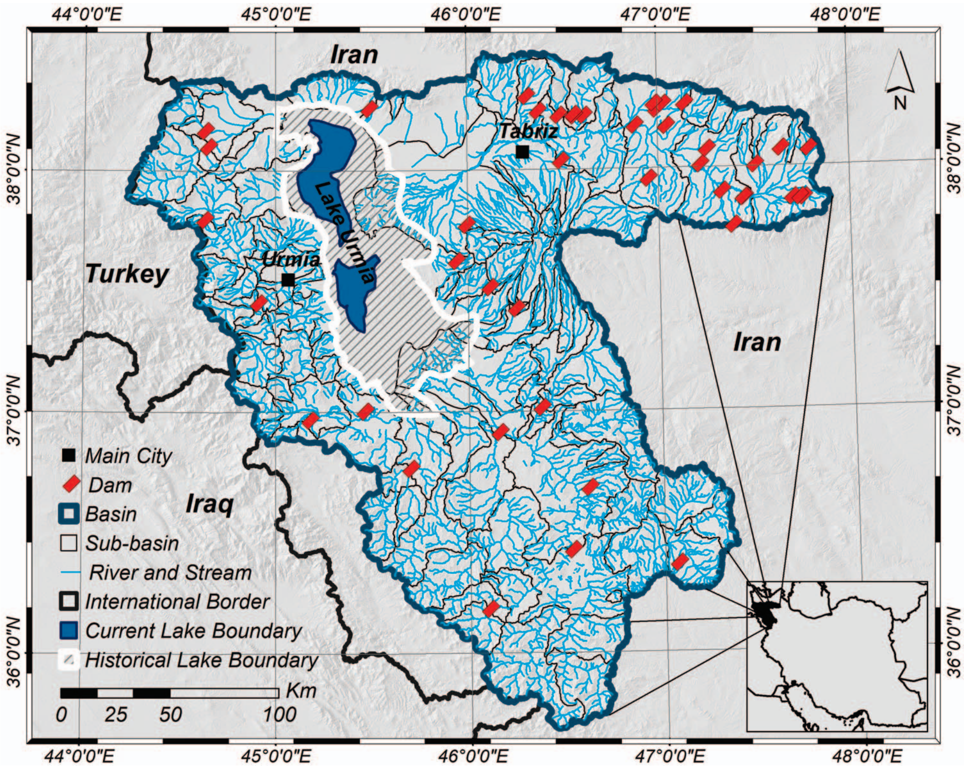
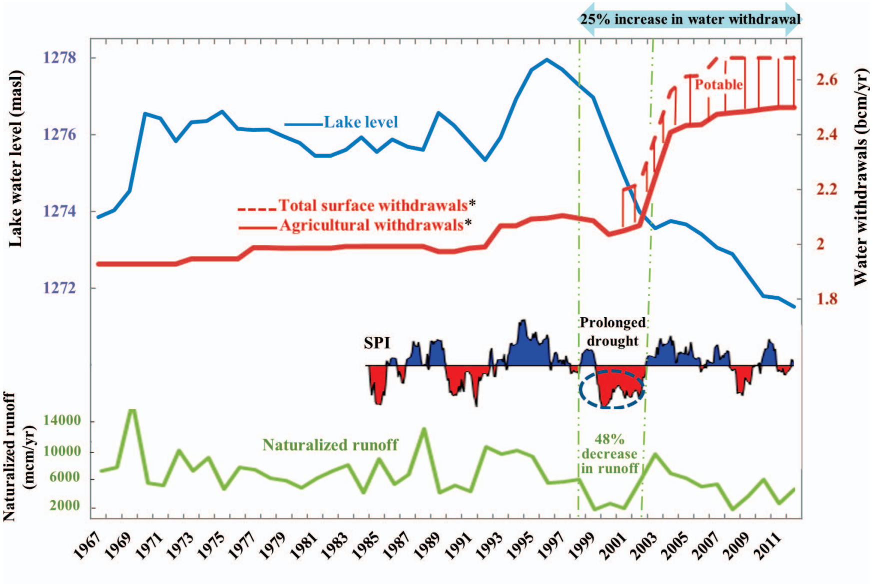


Figure 1. Lake Urmia Basin showing its 117 sub-basins, existing dams and the lake's surface area. The white boundary displays the lake's surface area in 1998 based on Landsat imagery. The second boundary depicts the current condition based on 2017 Landsat imagery (the dark blue area shows the region where water can be confidently detected from space).



* Withdrawals only from surface runoff (excluding groundwater).

Figure 2. Key attributes of the lake-basin system prior to restoration program in 2013, including observed lake level, standardized precipitation index (SPI), basin-scale naturalized runoff, and surface water withdrawal. The basin's recent wet (blue) and dry (red) periods are illustrated in SPI and naturalized runoff curves. Post-1998 drop in lake level corresponds to a substantial increase (~25%) in surface water withdrawals during the prolonged drought of 1998–2002.

Hung 2002, Falkenmark and Rockström 2004) superimposed by climate stressors in the basin is essential for effective restoration of Lake Urmia and preempting similar incidences in other areas. Re-establishing Lake Urmia's ecological integrity provides a testbed to evaluate different lake restoration policies and action plans to curb and reverse the unfolding crisis. We examine the compounding effects of climate anomalies and anthropocentric water withdrawals in this highly regulated basin to restore the lake's designated ecological water level of 1274 meters above sea level (masl) used as a monthly and annual threshold based on water quality conditions (240 g l^{-1} of NaCl) required to preserve brine shrimp Artemia (Abbaspour and Nazaridoust 2007). We develop an understanding of lake level changes using comprehensive datasets of water resources management infrastructure (i.e. reservoir capacity and operating policies), observed streamflow data, and agricultural and urban water demand data from 117 sub-basins. The paper illustrates the need for developing a dynamic, climate informed environmental inflow plan to restore the lake's ecological level. Furthermore, we investigate the lake's expected recovery time under dynamic basin-scale water management scenarios compounded with a wide range of historical climatological conditions.

2. Methodology and data

We divided the Lake Urmia Basin into 117 sub-basins (see figure 1), ranging from 16 km^2 to 3000 km^2 (average sub-basin size: 405 km^2). The sub-basins were delineated based on the presence of streamflow gauges and/or dams as an outlet (i.e. Pour Point). For each sub-basin, we used observed streamflow data to represent the combined contribution of surface runoff and baseflow. Instead of calculating irrigation water use through estimated soil moisture (i.e. from a hydrological or a land-surface model) implemented in previous basin-scale analyses of this lake (e.g. Shadkam *et al* 2016), we used a sub-basin scale dataset of monthly agricultural water demands developed by local water authorities based on irrigated area and crop water requirement (IME 2014). Thus, we accounted for green water losses over the basin and consequent reduction of the blue water flow to the lake. Likewise, the municipal and industrial demands at the sub-basin scale were obtained based on available monthly observational data (IME 2013).

MODSIM-DSS, a generalized network flow river basin model (Fredericks *et al* 1998, Labadie and Larson 2007) applied for this study, distributes the available water based on natural inflows, water demands, reservoir capacities and operating policies, and calculates the lake level based on excess water flow to the lake. This modeling tool has been widely used for basin-scale water resources planning (Graham *et al* 1986, Sprague and Carlson 1982, Ahn *et al* 2016, Berhe *et al* 2013, Ashraf Vaghefi *et al* 2017), and it is able to represent the supply/demand priorities. We coupled the sub-basin scale water resource system model with a monthly lake water balance model to better represent lake-basin interactions. Table 1 summarizes key input datasets and sources.

The developed MODSIM-DSS model includes 17 large on-stream and off-stream operational reservoirs (i.e. capacity >5 mcm). These reservoirs collectively store up to 1560 mcm of water, providing 97% of the total surface storage capacity in the basin (see figure S1 in supplementary materials) available at stacks.iop.org/ERL/13/084010/mmedia. Physical characteristics and operating policies embedded in model inputs include: (i) volume-area-elevation curves, (ii) net evaporation rate, (iii) maximum, minimum and initial reservoir capacities, and (iv) reservoir water allocation priorities. Where cascaded reservoirs are present, the model is capable of simulating basin-scale coordinated operation of the reservoirs, i.e. upstream-downstream coordination to meet downstream demands. Without these reservoirs, upstream water could reach the lake quickly, rendering an inaccurate representation of water availability in different parts of the basin. We used river discharge measurements and observed lake levels to validate the simulated basin-lake interactions. Simulated lake levels and lake inflows closely track the observational data (see figures S2 through S4 in supplementary materials), indicating reasonable model performance, also suggested by model efficiency coefficients (e.g. (*i*) monthly lake inflow correlation coefficient (0.96), bias (15.5%), and Nash–Sutcliffe efficiency coefficient (0.9), and (*ii*) monthly lake level correlation coefficient (0.96), bias (0.03%), and Nash–Sutcliffe efficiency coefficient (0.79)). Depending on the time of measurement, lake level elevation varies from 1270 m to 1278 masl with average elevation being 1275 masl (average depth: 5.4 m).

For the lake scenario analyses (discussed below), a normal year is assumed to receive 350 mm of rainfall (IME 2013, ULRP 2016). Furthermore, we used monthly evaporation climatology with annual evaporation of 1100 mm yr^{-1} (ULRP 2016) for the simulation period. This simplification was necessary due to unavailability of monthly evaporation time series for the entire simulation period. To validate this assumption, we compared the performance of the MODSIM-DSS model using both monthly evaporation climatology and available monthly evaporation time series for the period of 1982–2002 for which we had access to monthly lake evaporation. The comparison illustrates that lake levels are consistent with observations using monthly evaporation climatology (figure S5 in supplementary materials). Water demand is partially met using groundwater up to an observed rate of 2000 mcm yr^{-1} (IME 2014). Given the lack of long-term records, we used different constant annual rates, but considering the monthly distributions for each sub-basin based on observations (IME 2014). Under different water withdrawal scenarios, the annual groundwater withdrawals vary between 1650 mcm yr^{-1} to 2000 mcm yr^{-1} to supplement surface water supply. We acknowledge that lack of groundwater withdrawal time series introduces uncertainties in the simulations.

We simulated the interactions between the upstream water resource system and Lake Urmia under scenarios that cover a wide range of climate conditions and water withdrawals combined (figure 3). The

Table 1. Datasets used for simulating the basin-lake interactions (Source: various publications of IME).

Dataset	Spatial scale	Temporal scale
Lake level-volume-area curve	—	—
Over-lake evaporation and precipitation	Meteorological stations	Monthly average (1967–2012)
Surface water supply	Streamlines	Monthly (1967–2007)
Surface water withdrawals and irrigated area	Sub-basin	Monthly (2012)
Groundwater withdrawals	Sub-basin	Monthly mean (2012)

model uses naturalized runoff data to allocate water to different demand nodes. We estimated the naturalized runoff for each sub-basin by adding long-term upstream surface water withdrawals (including return flow) to streamflow gauge at the sub-basin outlet. The climatological scenarios are based on historic climate observations including baseline and near normal climatology and an observed historic drought (i.e. 48% decrease in runoff). The baseline period (1994–1998) is a relatively wet period that precedes the drastic decrease in the lake area. The most extreme drought condition corresponds to 1998–2002 (hereafter, referred to as drought of record scenario). We consider 2003–2007 a near normal period after the 1998–2002 drought because natural runoff during this period is close to long-term mean (1967–2012, 6500 mcm yr^{-1}). Water demand scenarios include historical baseline, maximum demand, and target demand reduction. Baseline demand refers to pre-drastic change in lake levels and water withdrawals (i.e. pre-1998). Maximum demand is associated with rapid increase in the overall water withdrawals (i.e. 2003–2012) and it is the most extreme case investigated in our analysis. Target demand is based on the recommendation of the Urmia Lake Restoration Program (ULRP 2016) that calls for an aggressive 40% decrease in 2013 agricultural water use over a 5 year period (ULRP 2016). The combination of these scenarios helps evaluate the compounding effects of climatic and anthropogenic conditions on the lake's water level.

For all nine coupled scenarios (i.e. permutations of three inflow scenarios and three demand scenarios) depicted in figure 3, we investigated both basin-scale water stress and associated changes in the lake level. We used a modified version of the water resources vulnerability index (Raskin *et al* 1997), in which environmental flow allocations are included in water stress index (WSI) calculations alongside Human Water Withdrawals (see Smakhtin *et al* 2005, Averyt *et al* 2013, Pastor *et al* 2014). The dimensionless WSI characterizes the stress imposed on the total water resources defined as the summation of both available surface water and groundwater resources (Raskin *et al* 1997, Vörösmarty *et al* 2005).

$$\mathrm{WSI} = \frac{\mathrm{HWW} + \mathrm{EFA}}{\mathrm{TWR}} \qquad (1)$$

The modified water resources vulnerability index accounts for environmental withdrawals in the water stress index formulation. A WSI of 0.6 represents a moderately exploited basin and WSI values above this threshold indicate that the basin is heavily exploited (Smakhtin *et al* 2005). Here, we consider the environmental inflow requirement of 3100 mcm yr^{-1} as Lake Urmia's annual ecological demand in the historical scenarios (Abbaspour and Nazaridoust 2007). The lake's required ecological flows were not delivered reliably prior to the implementation of the restoration plan in 2013 due to lower priority of environmental flow compared to human water use. Furthermore, we evaluate the sensitivity of the minimum inflow requirement to lake level dynamics as a critical boundary condition for effective re-establishment of the target ecological level of the lake.

3. Results and discussion

3.1. Assessment of climate-demand scenarios

Figure 4 summarizes the WSI over the basin along with the percentage of change in the lake's level relative to baseline under the combined climate-demand scenarios. The results show high water stress under all nine scenarios. The basin-wide WSI under an intentionally optimistic scenario of wet period combined with ULRP target demand stands at an alarming level of 60% (i.e. moderately exploited basin). The WSI increases to about 80% under maximum observed demand during wet period, indicating heightened vulnerability in a heavily exploited basin. A similar increasing trend is detected during the near normal period when the WSI exceeds 80%. In an extremely dry period, in which the annual runoff reduces by 48% (compared to the baseline wet period), the lake is gravely vulnerable to increases in anthropogenic water demands, elevating the WSI to a distressing level of 90%. Percentages of annual change in lake depth (relative to baseline) over the five-year simulation periods (1994–1998, 1998–2002 and 2003–2007) show an increasingly divergent, declining trend of lake-basin interactions under near normal and dry period scenarios, compounded with larger water demand scenarios. The increasing range in boxplots corresponding to change in lake level (figure 4) illustrates higher vulnerability of the lake to human water withdrawals in dry condition.

In a wet climate and under the maximum demand scenario, the lake level drops by 10%, which highlights the significance of anthropogenic demand alone on the lake water depth. However due to ample surface runoff during a wet period, the lake level remains above the prescribed ecological threshold. Unlike the wet period, the lake is vulnerable to anthro-

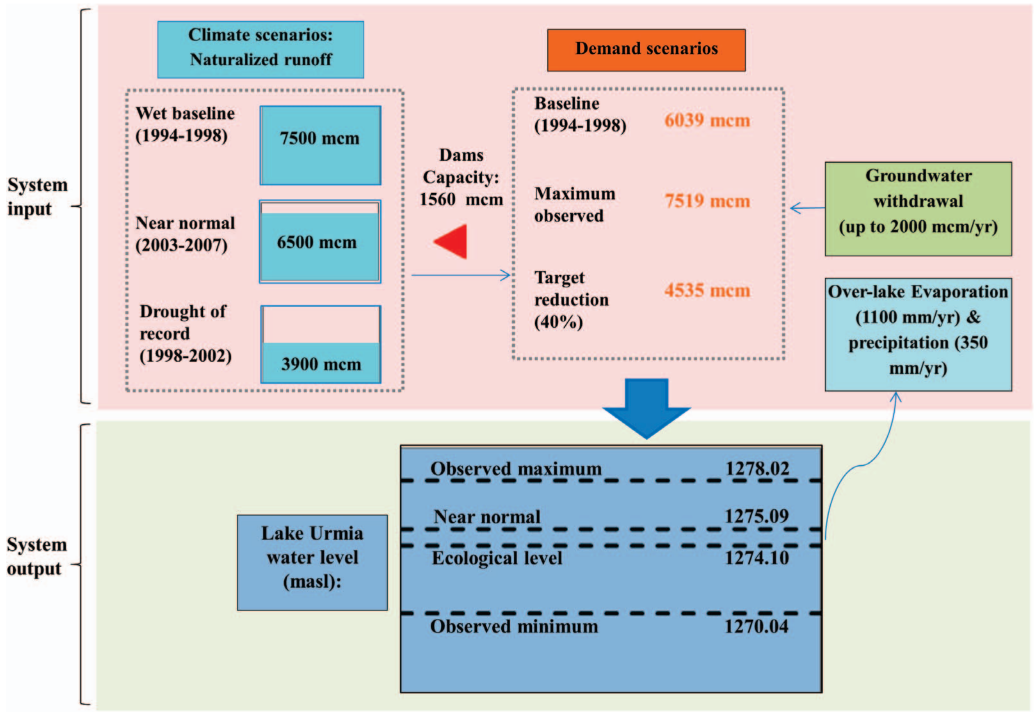


Figure 3. MODSIM-DSS model inputs and outputs along with climate and demand scenarios.

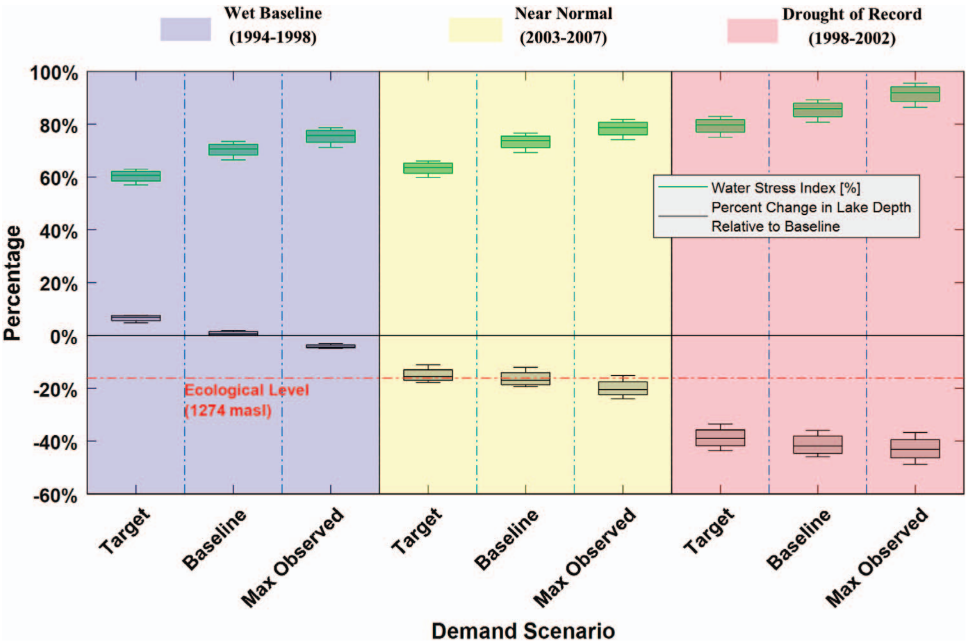


Figure 4. WSI in percentage over the lake basin (green boxplot) and the percentage of change in the lake level relative to the baseline (gray boxplot) under different combinations of climate-demand scenarios. Shaded regions represent wet baseline (purple), near normal (yellow), and dry (pink) periods. Dashed vertical lines demarcate three demand scenarios (i.e. target reduction (40%), baseline, and maximum historical) in each period.

pogenic demand during a near normal condition and the lake-basin interactions under the ULRP target demand will be at a fragile hydrologic balance. This means that any rise in demand above the targeted values leads to lake level dropping below the ecological threshold. Notably, even a 5% increase in water demand during the near normal condition pushes the lake level below the ecological level. Expectedly, the largest decline in the lake level (i.e. 1.5 m drop below the ecological threshold) occurs during the dry period with maximum observed demand, which is the most extreme case in our analysis. This result confirms the 'double devil effect' of 25% increase in water withdrawal in the Lake Urmia Basin during the drought of 1998–2002 that pushed the lake water budget severely out of balance and caused a lasting, drastic drop in the lake level (figure 4).

3.2. Lake level departure from the ecological threshold

Figure 5 illustrates the sensitivity of lake level to different combinations of total available water resources (including both surface water and groundwater) and total water withdrawal over the basin. The contours were derived from lake level as a model output under different simulation scenarios, which depends on water withdrawals (x-axis) and available water resources (y-axis). It is important here to distinguish between basin-scale total water withdrawal and water demand; total water withdrawal depends on the water availability in the basin, and therefore, it may be smaller than the total water demand. With a low supply reliability of 55%–80% (IME 2013), the Lake Urmia Basin faces water deficit, which necessitates water use restrictions. Sectoral water demands are met according to ordinal allocation priorities of domestic, industrial, agricultural, and finally environmental needs. Total water availability (5500 mcm) and water withdrawal (3500 mcm) over the basin during the drought of 1998–2002 caused the lake level to fall to around the 1273.5 contour line (figure 5(*a*)), which is consistent with the observed lake level in the aftermath of this prolonged drought.

We examined the sensitivity of the lake's environmental inflow requirement to initial lake level as a boundary condition in order to quantify the implications for maintaining the lake's ecological level. Figure 5(*b*) illustrates the results of lake level contours under coupled climate-withdrawal scenarios for initial lake levels of 1275 masl, 1274 masl, and 1273 masl, which represent water levels above, at, and below the ecological level, respectively. The lake's ability to absorb water stresses while remaining above the critical threshold (i.e. safe ecological zone) declines significantly when the initial lake level decreases as indicated by dramatic decline of the estimated lake level. In the case of low initial water volume, a moderate withdrawal in a near normal climate condition may drive the lake level below the critical ecological threshold. This effect is seen in the post-drought scenario when low runoff for three consecutive years resulted in lake level decline (1373.5 masl) below the critical level. Although the region had near-normal precipitation and runoff immediately after the drought of record (i.e. during the 2003–2012 period), the lake levels continued to fall due to growing water withdrawal and failure to increase the lake's environmental inflow. These results demonstrate the need to prescribe dynamic, climate-informed environmental inflow requirements to sustain the lake as opposed to the existing, static ecological water demand of 3100 mcm yr^{-1}.

3.3. Lake Urmia's tipping phase and recovery trajectory

Lake Urmia reached a tipping point in the early 2000s when the lake basin's hydrologic carrying capacity was significantly exceeded due to compounding pressures from climatological factors and unsustainable water management practices. Improved understanding of the compounding stressors will be critical to devise an effective restoration process for implementation within a realistic timeframe. The remarkable contrast between lake level simulations under natural (i.e. excluding anthropogenic withdrawals) and existing conditions reveals the critical role of anthropocentric water management in creating this environmental catastrophe. The lake's severely disrupted water balance failed to rebound after the drought of record because the cumulative effect of the routine practice of increasing water diversions to keep up with growing upstream water demand acted as 'the last straw that broke the camel's back.' Our simulations show that by 1998, total water withdrawals in the basin had already overshot the basin's hydrologic capacity to sustain the lake, although in reality, water withdrawals continued to increase beyond 1998 levels. Even water withdrawals 40% lower than 2012 withdrawals (i.e. target withdrawal reduction for restoration) would not have been sufficient to prevent a significant decline in the lake level below the ecological level immediately after the drought of record, although the reduction would have markedly ameliorated the situation. Simulation results show that maintaining the lake's ecological level would have been attainable by keeping water withdrawals 55% lower than the 2012 levels.

The key structural and non-structural restoration measures set forth by the ULRP include re-connecting the tributaries and the lake, major water transfers from trans-boundary river basins (e.g. Zab and Silveh Dam), limiting additional water withdrawal in the basin, and paying farmers to fallow the surrounding agricultural lands, among others (ULRP 2016). Water conservation practices in various demand sectors across the lake basin will be crucial for moving in the direction of recovery and should be prioritized. This is particularly important based on the lessons learned from implementing various inter-basin water transfer projects to address water shortage problems in the central plateau of Iran, where the problems have persisted despite artificial increase of surface water supply (Gohari *et al* 2013, Gohari *et al* 2017). Adoption of low water consuming crops (e.g. grape) in the basin along with increasing irrigation efficiency with the ultimate goal of reducing net water consumption can facilitate the attainment of an ambitious 40% decrease in withdrawals as prescribed by the ULRP (ULRP 2016).

Our analysis suggests that the ULRP timeline is overambitious (figure 7). Depending on climatic conditions and assuming effective implementation of the proposed 40% reduction in the current water withdrawal, the required environmental inflows

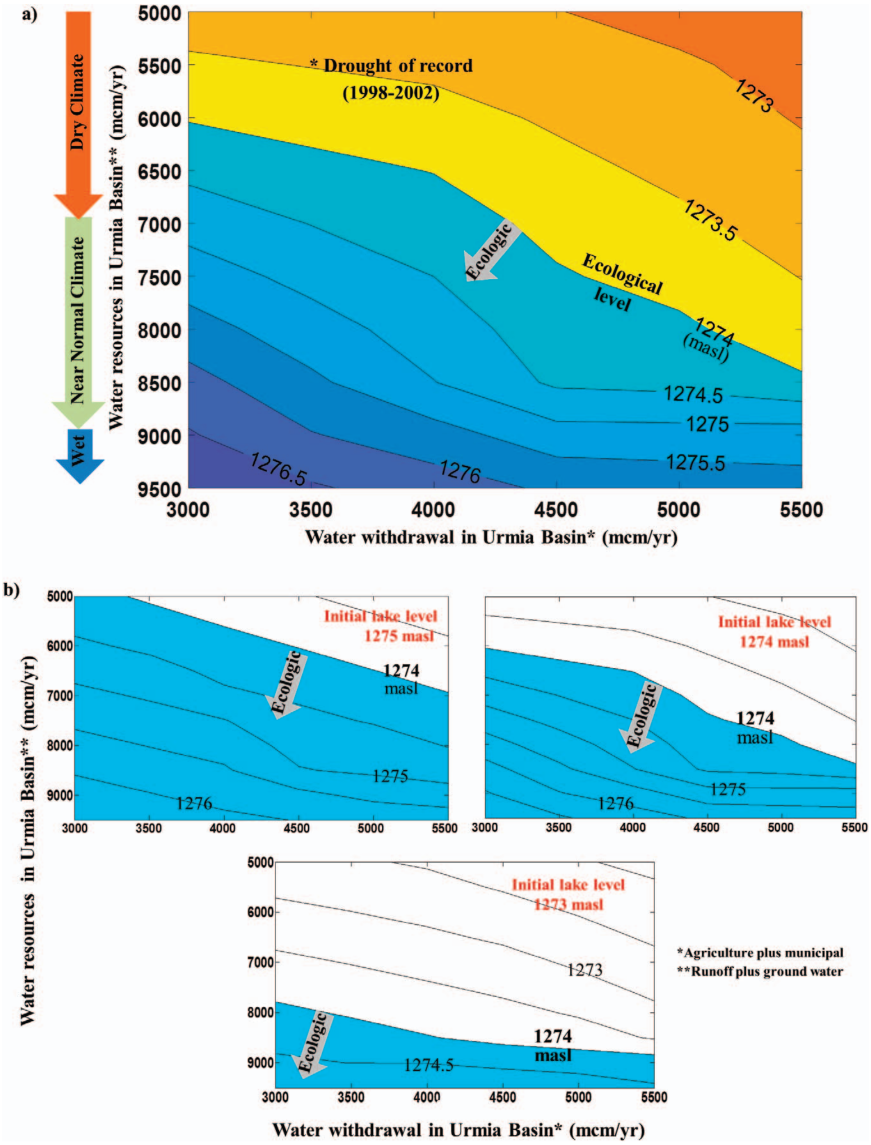


Figure 5. Average lake level contours under different combinations of water availability and water withdrawals with the initial lake level fixed at 1274 masl (*a*), and when the initial lake level is changed as a variable boundary condition (*b*).

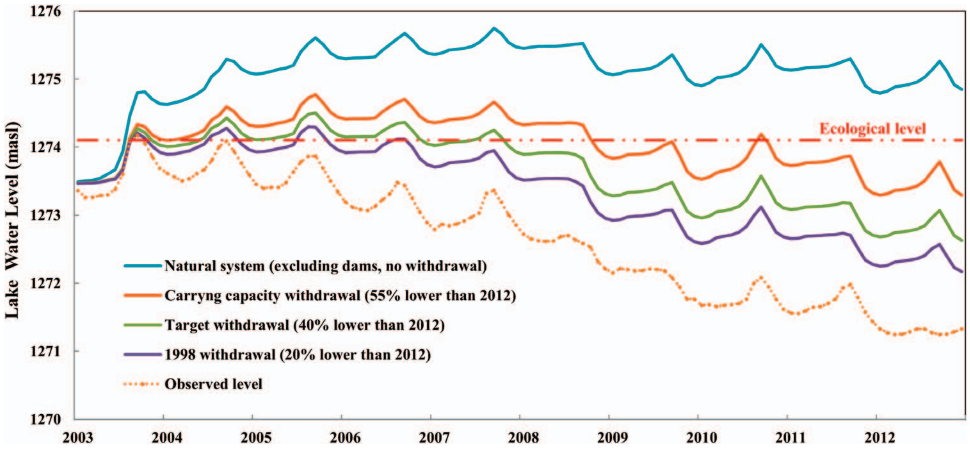


Figure 6. Lake Urmia level under different water withdrawal scenarios. The natural system simulation (i.e. no anthropogenic withdrawals) and different withdrawal scenarios illustrate the overshoot of the basin's hydrologic carrying capacity to sustain the lake due to anthropocentric water management after an extreme drought.

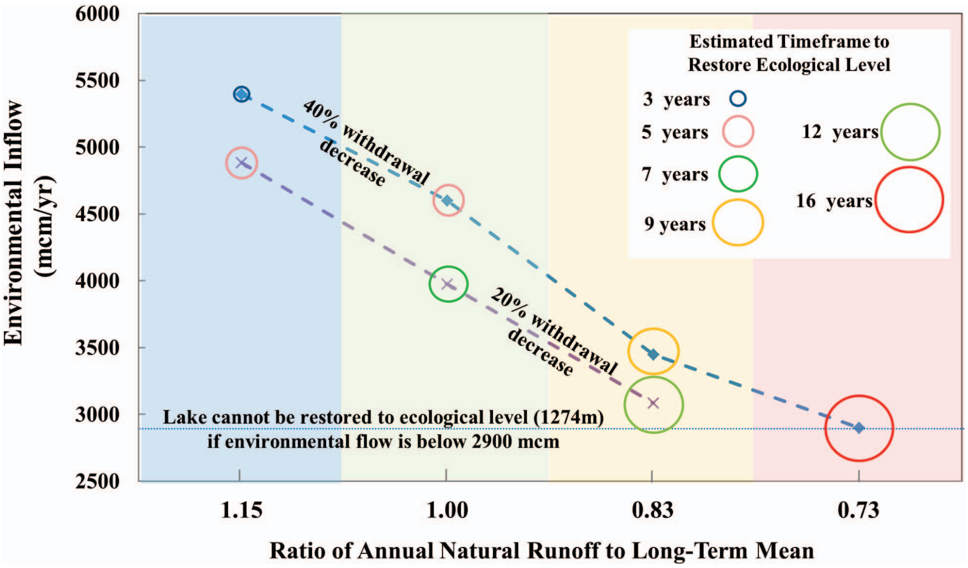


Figure 7. Environmental inflow along with estimated timeframe to restore to ecological level (1274 masl), considering 20% and 40% decrease in water withdrawals over the basin, given the initial lake level of 1270.7 masl. Long-term mean (i.e. 1967–2012) naturalized runoff in the Lake Urmia Basin is estimated at 6500 mcm yr^{-1}).

range from 2900 mcm yr^{-1} (during dry conditions) to 5400 mcm yr^{-1} (during wet conditions) with the average being 4100 mcm yr^{-1}. Under a more realistic 20% water withdrawal reduction these values are estimated to range from 3100 mcm yr^{-1} (during dry conditions) to 4900 mcm yr^{-1} (during wet conditions) with the average being 4000 mcm yr^{-1}. Despite restoration efforts after 2013, the lake level in 2017 was more than 3 m below the ecological threshold after reaching a post-collapse maximum of 1271.3 masl that has been attributed to implementation of a stabilization phase from 2014–2016, and large precipitation events in a relatively normal hydroclimatic period. Enforcement of the 40% decrease in agricultural water withdrawals through purchasing water rights within a five-year period starting in 2015 is a key measure of the ULRP during the rehabilitation phase (i.e. 2017–2022). Using the observed lake level in 2017 as the initial condition, we investigated the sensitivity of the lake's ecological level recovery timeline to reducing the agricultural water withdrawals by projecting lake level into the future under different climate scenarios. Figure 7 shows that under scenarios of increased aridity, when meeting the environmental inflow requirement of the lake will be difficult, restoring the ecological level can take up to 16 years, even if the proposed 40% reduction in agricultural water withdrawal is realized. Failing to reduce agricultural water withdrawals and/or providing the environmental inflows will result in delaying the attainment of the ecological level.

The lake is currently in grave need of receiving adequate environmental inflows. The natural flow regime (Poff *et al* 1997) provides a theoretical framework for implementing ecosystem-based water management in the Lake Urmia sub-basins to mitigate adverse socio-ecological impacts. To this end the ULRP includes radical proposals to revive the lake, e.g. operating the reservoirs exclusively for lake restoration purposes, as well as improving the monitoring and regulation of surface water and groundwater withdrawals (ULRP 2016). However, transitioning to an ecosystem-based water management paradigm by meeting dynamic environmental inflows in the Lake Urmia Basin is evidently difficult because of the presence of multi-sectoral tradeoffs (e.g. financial losses to stakeholders and population redistribution) that put the agricultural economy and socio-ecological sustainability at odds. On the one hand, the water resources that are exploited beyond the basin's natural supply capacity are supporting agrarian and urban livelihoods with significant green and blue water footprints (Hoekstra and Chapagain 2006, Mekonnen and Hoekstra 2011). On the other hand, the loss of tourism (Maleki *et al* 2018) and potential public health effects due to salt blowouts from the exposed lake bed (Griffin and Kellogg 2004) are side-effects that have considerable socioeconomic implications. The high water stress even during wet periods underscores the prevalence of a chronic anthropogenic drought. To cope with this situation, investigating an 'environmental hedging' approach guided by hydrologic and biologic forecasting (Adams *et al* 2017) may offer a practical strategy to facilitate progress towards ecological recovery of the lake while meeting human demands within the constraints of basin scale water availability and ecological functions of Lake Urmia.

4. Conclusions

The Lake Urmia Basin in northwestern Iran is an exemplar of how unsustainable water management to meet growing water demand can create massive socio-ecological challenges. We developed a detailed water resources systems model of the basin to investigate the causes of Lake Urmia's shrinkage based on a quantitative assessment of the water balance under wet and dry periods and water withdrawal scenarios. Furthermore, we evaluated potential effectiveness of the planned restoration measures. Our simulations include comprehensive datasets of water resources management infrastructure (i.e. reservoir capacity and operating policies), observed streamflow data, and agricultural and urban water demand data from 117 sub-basins. Results demonstrate that a growing anthropogenic drought combined with meteorological drought drove the lake toward a state of hydrological overshoot and collapse. The rapid water level decline after the drought of record (1998–2002) when annual runoff decreased by 48% is synchronous with an approximately 25% increase in surface water withdrawals, especially in the agricultural sector, which continued long after signs of the lake's tipping phase appeared. The lake level remained significantly below the designated ecological threshold (m above sea level) even in a relatively normal period immediately after the drought. In the absence of the unsustainable water resources development and growing anthropogenic water stress, the lake would have resisted the climatologic shock without collapsing.

Re-establishing Lake Urmia's ecological integrity requires aggressive restoration policies and action plans aimed at maintaining environmental inflows in the face of compounding climate anoMalies and water withdrawals. A dynamic and climate-informed environmental inflow plan is critical for reviving the lake. Taking into account both climatic conditions and assuming the already proposed 40% reduction in the current water withdrawals, we estimate that the lake's environmental inflow requirements range from 2900 mcm yr^{-1} (during dry conditions) to 5400 mcm yr^{-1} (during wet conditions) with the average being 4100 mcm yr^{-1}. These estimates for a more realistic 20% water withdrawal reduction would be 3100 mcm yr^{-1} (during dry conditions) to 4900 mcm yr^{-1} (during wet conditions) with the average being 4000 mcm yr^{-1}. Depending on the climatic condition, water withdrawal reduction plan, and environmental releases, Lake Urmia's recovery time can range from 3 to 16 years.

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References

Abbaspour M and Nazaridoust A 2007 Determination of environmental water requirements of Lake Urmia, Iran: an ecological approach *Int. J. Environ. Stud.* **64** 161–9

Adams L E, Lund J R, Moyle P B, Quiñones R M, Herman J D and O'Rear T A 2017 Environmental hedging: theory and method for reconciling reservoir operations for downstream ecology and water supply *Water Resour. Res.* **53** 7816–31

AghaKouchak A, Norouzi H, Madani K, Mirchi A, Azarderakhsh M, Nazemi A and Hasanzadeh E 2015 Aral Sea syndrome desiccates Lake Urmia: call for action *J. Great Lakes Res.* **41** 307–11

Ahmadi R, Mohebbi F, Hagigi P, Esmailly L and Salmanzadeh R 2011 Macro-invertebrates in the wetlands of the Zarrineh estuary at the south of Urmia Lake (Iran) *Int. J. Env. Res.* **5** 1047–52

Ahmadzadeh Kokya T, Pejman A, Mahin Abdollahzadeh E, Ahmadzadeh Kokya B and Nazariha M 2011 Evaluation of salt effects on some thermodynamic properties of Urmia Lake water *Int. J. Environ. Res.* **5** 343–8

Ahn S R, Jeong J H and Kim S J 2016 Assessing drought threats to agricultural water supplies under climate change by combining the SWAT and MODSIM models for the Geum River basin, South Korea *Hydrolog. Sci. J.* **61** 2740–53

Allan J A 1998 Virtual water: a strategic resource global solutions to regional deficits *Groundwater* **36** 545–6

Arkian F, Nicholson S E and Ziaie B 2018 Meteorological factors affecting the sudden decline in Lake Urmia's water level *Theor. Appl. Climatol.* **131** 641–51

Ashraf Vaghefi S, Abbaspour K C, Faramarzi M, Srinivasan R and Arnold J G 2017 Modeling crop water productivity using a coupled SWAT–MODSIM model *Water* **9** 157

Ashraf B, AghaKouchak A, Alizadeh A, Baygi M M, Moftakhari H R, Mirchi A and Madani K 2017 Quantifying anthropogenic stress on groundwater resources *Sci. Rep.* **7** 12910

Averyt K, Meldrum J, Caldwell P, Sun G, McNulty S, Huber-Lee A and Madden N 2013 Sectoral contributions to surface water stress in the coterminous United States *Environ. Res. Lett.* **8** 35046

Barigozzi C, Varotto V, Baratelli L and Giarrizzo R 1987 The artemia of Urmia Lake (Iran): mode of reproduction and chromosome numbers *Atti Accad. Naz. Lincei Cl. Sci. Fis. Mat. Nat. Rend. Ser.* 8 **81** 87–90

Barnum D A, Bradley T, Cohen M, Wilcox B and Yanega G 2017 *State of the Salton Sea—A science and monitoring meeting of scientists for the Salton Sea (USGS Numbered Series No. 2017–1005)* (Reston, VA: US Geological Survey)

Berhe F T, Melesse A M, Hailu D and Sileshi Y 2013 MODSIM-based water allocation modeling of Awash River Basin Ethiopia *CATENA* **109** 118–28

Coe M T and Foley J A 2001 Human and natural impacts on the water resources of the Lake Chad basin *J. Geophys. Res.: Atmos.* **106** 3349–56

Delju A, Ceylan A, Piguet E and Rebetez M 2013 Observed climate variability and change in Urmia Lake Basin, Iran *Theor. Appl. Climatol.* **111** 285–96

Falkenmark M and Rockström J 2004 *Balancing Water for Humans and Nature: the New Approach in Ecohydrology* (London: Earthscan) p 247

Farzin S, Ifaei P, Farzin N, Hassanzadeh Y and Aalami M 2012 An investigation on changes and prediction of Urmia Lake water surface evaporation by chaos theory *Int. J. Environ. Res.* **6** 815–24

Fathian F, Morid S and Kahya E 2015 Identification of trends in hydrological and climatic variables in Lake Urmia Basin, Iran *Theor. Appl. Climatol.* **119** 443–64

Fredericks Jeffrey W, Labadie John W and Altenhofen Jon M 1998 Decision support system for conjunctive stream-aquifer management *J. Water Res. Pl. Asce.* **124** 69–78

Gao H, Bohn T J, Podest E, McDonald K C and Lettenmaier D P 2011 On the causes of the shrinking of Lake Chad *Environ. Res. Lett.* **6** 034021

Gaybullaev B, Chen S-C and Kuo Y-M 2012 Large-scale desiccation of the Aral Sea due to over-exploitation after 1960 *J. Mt. Sci.* **9** 538–46

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

Ghale Y A G, Altunkaynak A and Unal A 2018 Investigation anthropogenic impacts and climate factors on drying up of Urmia Lake using water budget and drought analysis *Water Resour. Manage.* **32** 325–37

Gholampour A, Nabizadeh R, Hassanvand M S, Taghipour H, Nazmara S and Mahvi A H 2015 Characterization of saline dust emission resulted from Urmia Lake drying *J. Environ. Health Sci. Eng.* **13** 82

Gleeson T, Wada Y, Bierkens M F and van Beek L P 2012 Water balance of global aquifers revealed by groundwater footprint *Nature* **488** 197–200

Gohari A, Mirchi A and Madani K 2017 System dynamics evaluation of climate change adaptation strategies for water resources management in central Iran *Water Resour. Manage.* **31** 1413–34

Gohari A, Eslamian S, Mirchi A, Abedi-Koupaei J, Massah Bavani A and Madani K 2013 Water transfer as a solution to water shortage: a fix that can backfire *J. Hydrol.* **491** 23–39

Graham L P, Labadie J W, Hutchison I P G and Ferguson K A 1986 Allocation of augmented water supply under a priority water rights system *Water Resour. Res.* **22** 1083–94

Griffin D W and Kellogg C A 2004 Dust storms and their impact on ocean and human health: dust in Earth's atmosphere *EcoHealth* **1** 284–95

Hassanzadeh E, Zarghami M and Hassanzadeh Y 2012 Determining the main factors in declining the Lake Urmia level by using system dynamics modeling *Water Resour. Manage.* **26** 129–45

Hassanzadeh E, Elshorbagy A, Wheater H, Gober P and Nazemi A 2015 Integrating supply uncertainties from stochastic modeling into integrated water resource management: a case study of the Saskatchewan River Basin *ASCE J. Water Resour. Plan. Manage.* **27** 05015006

Hatchett B J, Boyle D P, Putnam A E and Bassett S D 2015 Placing the 2012–2015 California-Nevada drought into a paleoclimatic context: insights from Walker Lake, California–Nevada USA *Geophys. Res. Lett.* **42** 8632–40

Hoekstra A Y and Hung P Q 2002 Virtual water trade: a quantification of virtual water flows between nations in relation to international crop trade *Value of Water Research Report Series 11* 166, UNESCO-IHE

Hoekstra A Y, Mekonnen M M, Chapagain A K, Mathews R E and Richter B D 2012 Global monthly water scarcity: blue water footprints versus blue water availability *PLoS ONE* **7** e32688

Hoekstra A Y and Chapagain A K 2006 Water footprints of nations: water use by people as a function of their consumption pattern *Integrated Assessment of Water Resources and Global Change* ed E Craswell, M Bonnell, D Bossio, S Demuth and N Van De Giesen (Dordrecht: Springer) pp 35–48

Iran's Ministry of Energy (IME), Deputy of Water and Wastewater, Macro Planning Bureau 2013 *The National Water Master Plan Study in the Aras, Sefidrood, between Sefidrood and Haraz, Atrac and Urmia: Water allocation for the development projects in Urmia Lake Basin* Report Number: 2385070-2050-24142, 2385070-2050-24142 (isi-mip.org) (Accessed: 24 March 2016)

Iran's Ministry of Energy (IME), Deputy of Water and Wastewater, Macro Planning Bureau 2014 *The National Water Master Plan Study in the Aras, Sefidrood, between Sefidrood and Haraz, Atrac and Urmia: agricultural water use study in Urmia Lake Basin* Report Number: 2385070-4420-19464, 2385070-4420-19464 (isi-mip.org) (Accessed: 24 March 2016)

Karbassi A, Bidhendi G N, Pejman A and Bidhendi M E 2010 Environmental impacts of desalination on the ecology of Lake Urmia *J. Great Lakes Res.* **36** 419–24

Labadie J W and Larson R 2007 MODSIM 8.1: River basin management decision support system: user manual and documentation (Accessed: 6 October 2014) (ftp://dwrftp.state.co.us/cdss/projects/MODSIM/MODSIMv8.1UserManual.pdf)

Ma R, Duan H, Hu C, Feng X, Li A, Ju W and Yang G 2010 A half-century of changes in China's lakes: global warming or human influence? *Geophys. Res. Lett.* **37** L24106

Madani K 2014 Water management in Iran: what is causing the looming crisis? *J. Environ. Stud. Sci.* **4** 315–28

Madani K, AghaKouchak A and Mirchi A 2016 Iran's socio-economic drought: challenges of a water-bankrupt nation *Iranian Stud.* **49** 997–1016

Maleki R, Nooripoor M, Azadi H and Lebailly P 2018 Vulnerability assessment of rural households to Urmia Lake drying (the case of Shabestar region) *Sustainability* **10**

McKee T, Doesken N and Kleist J 1993 The relationship of drought frequency and duration to time scales *Proc. 8th Conf. Applied Climatology, 17–22 January 1993* (Boston, MA: American Meteorological Society) pp 179–84

Mehran A, AghaKouchak A, Nakhjiri N, Stewardson M J, Peel M C, Phillips T J and Ravalico J K 2017 Compounding impacts of human-induced water stress and climate change on water availability *Sci. Rep.* **7** 6282

Mei X, Dai Z, Du J and Chen J 2015 Linkage between three Gorges Dam impacts and the dramatic recessions in China's largest freshwater lake, Poyang Lake *Sci. Rep.* **5** 18197

Mekonnen M M and Hoekstra A Y 2011 The green, blue and grey water footprint of crops and derived crop products *Hydrol. Earth Syst. Sci.* **15** 1577

Micklin P 2007 The Aral Sea disaster *Annu. Rev. Earth Pl. Sc.* **35** 47–72

Micklin P P 1988 Desiccation of the Aral Sea: a water management disaster in the Soviet Union *Science* **241** 1170

Mirchi A, Watkins D W, Huckins C J, Madani K and Hjorth P 2014 Water resources management in a homogenizing world: averting the growth and underinvestment trajectory *Water Resour. Res.* **50** 7515–26

Mohammed I N and Tarboton D G 2012 An examination of the sensitivity of the Great Salt Lake to changes in inputs *Water Resour. Res.* **48**

Nazemi A and Wheater H S 2014 Assessing the vulnerability of water supply to changing streamflow conditions *Eos, Trans. Am. Geophys. Un.* **95** 288–8

Nazemi A and Wheater H S 2015a On inclusion of water resource management in Earth system models–Part 1: problem definition and representation of water demand *Hydrol. Earth Syst. Sci.* **19** 33–61

Nazemi A and Wheater H S 2015b On inclusion of water resource management in Earth system models-Part 2: representation of water supply and allocation and opportunities for improved modeling *Hydrol. Earth Syst. Sci.* **19** 63

Nikbakht J, Tabari H and Talaee P H 2013 Streamflow drought severity analysis by percent of normal index (PNI) in Northwest Iran *Theor. Appl. Climatol.* **112** 565–73

Pastor A V, Ludwig F, Biemans H, Hoff H and Kabat P 2014 Accounting for environmental flow requirements in global water assessments *Hydrol. Earth Syst. Sci.* **18** 5041–59

Pengra B 2012 The drying of Iran's Lake Urmia and its environmental consequences *UNEP-GRID* (Sioux Falls: UNEP Global Environmental Alert Service) (https://na.unep.net/geas/getUNEPPageWithArticleIDScript.php?article_id=79)

Poff N L, Allan J D, Bain M B, Karr J R, Prestegaard K L, Richter B D, Sparks R E and Stromberg J C 1997 The natural flow regime: a paradigm for river conservation and restoration *Bioscience* **47** 769–84

Raskin P, Gleick P, Kirshen P, Pontius G and Strzepek K 1997 Water futures: assessment of long-range patterns and problems *Comprehensive Assessment of the Freshwater Resources of the World* (Stockholm: SEI)

Schwartz R C, Deadman P J, Scott D J and Mortsch L D 2004 Modeling the impacts of water level changes on a Great Lakes community *J. Am. Water Resour. Assoc.* **40** 647–62

Shadkam S, Ludwig F, van Oel P, Kirmit Ç and Rezaei Kabat P 2016 Impacts of climate change and water resources development on the declining inflow into Iran's Lake Urmia *J. Great Lakes Res.* **42** 942–52

Sima S and Tajrishy M 2013 Using satellite data to extract volume–area–elevation relationships for Lake Urmia, Iran *J. Great Lakes Res.* **39** 90–9

Smakhtin V, Revenga C and Döll P 2005 *Taking into Account Environmental Water Requirements in Global-scale Water Resources Assessments* (International Water Management Institute)

Sprague R H Jr and Carlson E D 1982 Building effective decision support systems *Prentice Hall Professional Technical Reference* (Upper Saddle River, United States)

United Nations Environment Program (UNEP) 2012 *The Drying of Iran's Lake Urmia and its Environmental Consequences* (http://na.unep.net/geas/getUNEPPageWithArticleIDScript.php?article_id=79)

Urmia Lake Restoration Program (ULRP) 2016 Approved Solutions, the Executive Status and progress of projects 2 (http://ulrp.sharif.ir/sites/default/files/field/files/02%20Urmia%20Lake%20Projects%20-%20%2094.09.02.pdf) (Accessed: 10 March 2016) (in Persian)

Vahed S Z, Forouhandeh H, Hassanzadeh S, Klenk H P, Hejazi M A and Hejazi M S 2011 Isolation and characterization of Halophilic bacteria from Urmia Lake in Iran *Microbiology* **80** 834–41

Vaheddoost B and Aksoy H 2017 Structural characteristics of annual precipitation in Lake Urmia basin *Theor. Appl. Climatol.* **128** 919–32

Vörösmarty C J, Douglas E M, Green P A and Revenga C 2005 Geospatial indicators of emerging water stress: an application to Africa *AMBIO: J. Hum. Environ.* **34** 230–6

Vörösmarty C J, Green P, Salisbury J and Lammers R B 2000 Global water resources: vulnerability from climate change and population growth *Science* **289** 284–8

Vörösmarty C J *et al* 2010 Global threats to human water security and river biodiversity *Nature* **467** 555–61

Wada Y, van Beek L P, van Kempen C M, Reckman J W, Vasak S and Bierkens M F 2010 Global depletion of groundwater resources *Geophys. Res. Lett.* **37**

Wurtsbaugh W A, Miller C, Null S E, DeRose R J, Wilcock P, Hahnenberger M and Moore J 2017 Decline of the world's saline lakes *Nat. Geosci.* **10** 816

Yamaguchi N, Sakotani A, Ichijo T, Kenzaka T, Tani K, Baba T and Nasu M 2012 Break down of Asian dust particle on wet surface and their possibilities of cause of respiratory health effects *Biol. Pharm. Bull.* **35** 1187–90

Zarghami M and AmirRahmani M 2017 A system dynamics approach to simulate the restoration plans for Urmia Lake, Iran *Optimization and Dynamics with their Applications* ed A Matsumoto (Singapore: Springer) pp 309–26