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Review

40-years of Lake Urmia restoration research: Review, synthesis and next steps

Masoud Parsinejad [a,*,1], David E. Rosenberg [b,1], Yusuf Alizade Govarchin Ghale [c], Bahram Khazaei [d], Sarah E. Null [e], Omid Raja [a], Ammar Safaie [f], Somayeh Sima [g], Armin Sorooshian [h,i], Wayne A. Wurtsbaugh [j]

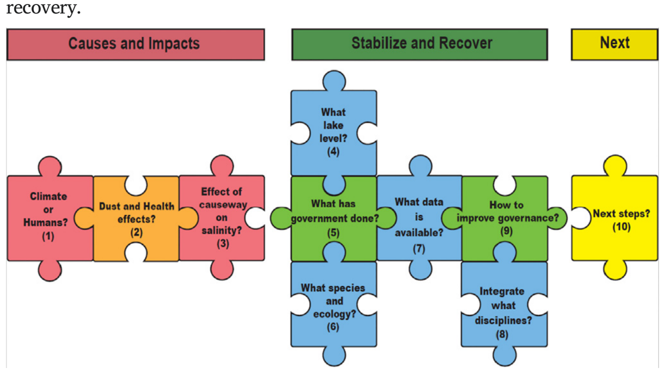
[a] Department of Irrigation and Reclamation Engineering, College of Agriculture and Natural Resources, University of Tehran, Iran
[b] Dept. of Civil and Environmental Engineering and Utah Water Research Lab, Utah State University, 8200 Old Main Hill, Logan, UT 84322-8200, USA
[c] Climate and Marine Sciences Department, Earth System Science Program, Eurasia Institute of Earth Sciences, Istanbul Technical University, Istanbul, Turkey
[d] Research Application Laboratory, NCAR, Boulder, CO, USA
[e] Watershed Sciences Dept., Utah State University, 5210 Old Main Hill, NR 210, Logan, UT 54322-5210, USA
[f] Department of Civil Engineering, Sharif University of Technology, P. O. Box 11365-9313, Azadi Ave., Tehran, Iran
[g] Faculty of Civil & Environmental Engineering, Tarbiat Modares University, Jalal Ale Ahmad Highway, Tehran, Iran
[h] Dept. of Chemical and Environmental Engineering, University of Arizona, PO Box 210011, Tucson, AZ 85721, USA
[i] Department of Hydrology and Atmospheric Sciences, University of Arizona, PO Box 210011, Tucson, AZ 85721, USA
[j] Watershed Sciences Dept., Utah State University, 8200 Old Main Hill, Logan, UT 84322-5210, USA

HIGHLIGHTS

- Reviewed 544 papers on desiccation and nascent recovery of Lake Urmia, Iran
- Agriculture, dams, and mismanagement caused lake desiccation more than climate.
- Research is fragmented by disciplines.
- Synthesized 9 next steps to better monitor, adapt, collaborate, and expand incomes
- These steps apply to different degrees to other lakes worldwide.

GRAPHICAL ABSTRACT

Key questions answered in the review and synthesis of 544 articles on Lake Urmia causes, impacts, stabilization, and recovery.



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ABSTRACT

Public concern over environmental issues such as ecosystem degradation is high. However, restoring coupled human-natural systems requires integration across many science, technology, engineering, management, and governance topics that are presently fragmented. Here, we synthesized 544 peer-reviewed articles published through September 2020 on the desiccation and nascent recovery of Lake Urmia in northwest Iran. We answered nine questions of scientific and popular interest about causes, impacts, stabilization, recovery, and next steps. We find: (1) Expansion of irrigated agriculture, dam construction, and mismanagement impacted the lake more than temperature increases and precipitation decreases. (2) Aerosols from Lake Urmia's exposed lakebed are negatively impacting human health. (3) Researchers disagree on how a new causeway breach will impact salinity, evaporation, and ecosystems in the

* Corresponding author.
E-mail addresses: parsinejad@ut.ac.ir (M. Parsinejad), david.rosenberg@usu.edu (D.E. Rosenberg), alizade@itu.edu.tr (Y.A.G. Ghale), bkhazaei@ucar.edu (B. Khazaei), sarah.null@usu.edu (S.E. Null), omid.raja@ut.ac.ir (O. Raja), asafaie@sharif.edu (A. Safaie), s.sima@modares.ac.ir (S. Sima), armin@email.arizona.edu (A. Sorooshian), wayne.wurtsbaugh@usu.edu (W.A. Wurtsbaugh).

[1] Parsinejad and Rosenberg share first authorship. The remaining authors are ordered alphabetically by last name.

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lake's north and south arms. (4) Most researchers tried to restore to a single, uniform, government specified lake level of 1274.1 m intended to recover *Artemia*. (5) The Iranian government motivated and funded a large and growing body of lake research. (6) Ecological and limnological studies mostly focused on salinity, *Artemia*, and Flamingos. (7) Few studies shared data, and only three studies reported engagement with stakeholders or managers. (8) Researchers focused on an integration pathway of climate downscaling, reservoirs, agricultural water releases, and lake level. (9) Numerous suggestions to improve farmer livelihoods and governance require implementation. We see an overarching next step for lake recovery is to couple human and natural system components. Examples include: (a) describe and monitor the system food webs, hydrologic, and human components; (b) adapt management to monitored conditions such as lake level, lake evaporation, lake salinity, and migratory bird populations; (c) improve livelihoods for poor, chronically stressed farmers beyond agriculture; (d) manage for diverse ecosystem services and lake levels; (e) engage all segments of society; (f) integrate across restoration topics while building capacity to share data, models, and code; and (g) cultivate longer-term two-way exchanges and public support. These restoration steps apply in different degrees to other Iranian ecosystems and lakes worldwide.

Contents

1. Introduction

In arid regions around the world, the increasing demand for water and sometimes global climate change have caused endorheic saline lakes to decline or nearly disappear (Wurtsbaugh et al., 2017). Such is the story of Mono Lake (USA), Walker Lake (USA), the Dead Sea (Jordan, Israel, and Palestine), the Great Salt Lake (USA), and the Aral Sea (Kazakhstan and Uzbekistan) (Edwards and Null, 2019; Elias et al., 2011; Elmore et al., 2016; Hart, 1996; HDR, 2020; Micklin, 2016; Rosenberg, 2011; White et al., 2015). In each case, lake declines caused human health, cultural, economic, and other problems. Research on these coupled human-natural systems is often fragmented and lake restoration requires integration across many science, technology, engineering, management, and governance topics.

Here, we synthesized 544 peer-reviewed articles, published through September 2020, on the causes and impacts of desiccation and the stabilization and nascent recovery of hypersaline Lake Urmia in northwest Iran. Since 2000, agricultural water development with steady precipitation has caused Lake Urmia to decrease by 4 m and lose over 90% of its volume (Fig. 1). This drawdown increased salinity and altered salt composition. The increase in salinity decreased growth of brine shrimp (*Artemia* spp.) (Abbaspour and Nazaridoust, 2007), which are thought to be the primary food source for birds such as flamingos. The lake drawdown increased the distance from resorts to water deep enough for recreation (Sima et al.,

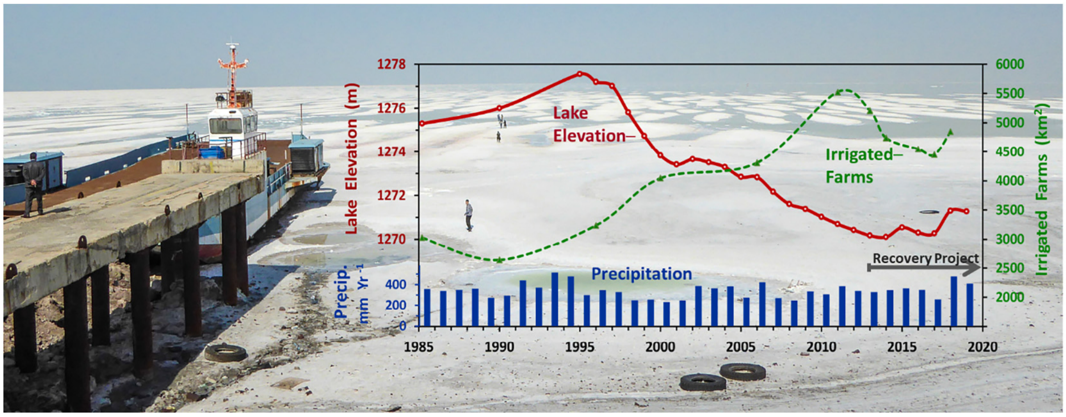

Fig. 1. Irrigated farms increased; precipitation stayed steady ($p = 0.77$) while Lake Urmia's elevation declined, causing abandonment of a ferry dock. Photo by Dr. Ali Chavoshian.

2021), and tourist resorts closed. Further drawdown exposed the lakebed and mobilized a complex mixture of aerosols that negatively impacted human health.

By 2013, the Iranian government instituted the Urmia Lake Restoration Program (ULRP): a large, multi-pronged effort to restore the lake to a water level of 1274.1 m above sea level by 2023. This *ecological level* was intended to recover brine shrimp (*Artemia* spp.) and the birds dependent upon them. A *health threshold level* of 1271.7 m was later defined in an effort to inundate more than 90% of the lake's dust-prone areas by 2022.

The research community also responded to Lake Urmia's continued desiccation with an expansive literature that includes topics and disciplines such as climatology, surface and groundwater hydrology, reservoir management, agriculture, limnology, salinity, air quality, dust impacts, wetland ecology, socioeconomics, governance, remote sensing, and others (Azimi et al., 2017). This expansive literature is also fragmented. Here we review and synthesize the literature to describe:

- Why the problem happened and how the problem became multi-faceted,
- The human and natural causes,
- How lake drawdown affected humans,
- The benefits of lake stabilization and recovery, and
- How to synthesize fragmented research into lake stabilization and recovery strategies.

This review and synthesis of the Lake Urmia literature answers nine questions of scientific and popular interest about causes, impacts, stabilization, and recovery (graphical abstract). A tenth question asks what are the next steps? Our target audience is academics, researchers, and managers. Below, we provide background information on Lake Urmia, describe our methods for reviewing and synthesizing the literature, answer the nine questions, and recommend next steps for lake stabilization and recovery that synthesize the fragmented research. We intend our approach to benefit other saline lakes around the world that suffer similar problems of desiccation from agricultural water withdrawals.

2. Study area

Lake Urmia (N 37.5°, E 45.5°) is located in the northwestern Iran (Fig. 2).

The basin covers 52,700 km^2, with elevations ranging from 1280 m to 4886 m (Eimanifar and Mohebbi, 2007). Mean precipitation in the basin is estimated at 350 mm year^{-1}. Thirteen permanent rivers feed the lake, including the two largest, Zarrineh and Simineh, that flow from the Zagros Mountains of Kurdistan Province in the south. These two rivers provide nearly half of lake inflow. River discharge is seasonal, with spring runoff flows approximately 50-fold higher than in late summer (www.ulrp.ir/fa). Direct precipitation accounts for approximately 22% of water entering the lake. Lake evaporation has been reported to be 580 to 2000 mm year^{-1} (RSRC, 2018; ULRP, 2015) with multiple reported intermediary values (Sadra, 2004; Safaie et al., 2021; Sima and Tajrishi, 2015). Since 1970, 41 small and large reservoirs have been constructed for irrigation, with a capacity to store 2×10^9 m^3. Until 1990, flow into the lake exceeded 5×10^9 m^3 year^{-1}. In the past two decades, flow decreased to 2.5×10^9 m^3 year^{-1} (Tajrishi, 2014).

The climate in the basin is a montane steppe biome. Irrigated lands cover ~10% of the basin, and rangelands dominate (56%). In irrigated valleys and river deltas, the principal crops (2014) are grains and cereals (81%), vegetables (3%) and forage plants (16%) (Alizade Govarchin Ghale et al., 2019). Of the area's farms, 71% are less than 5 ha (Hajimoradi, 2021). Canals provide a large portion of irrigation water,

Fig. 2. Lake Urmia and its contributing basin in northwest Iran.

Table 1
Key lake attributes.

Level	Elevation (m)	Volume (10^9 m^3)	% of max volume
Maximum	1278.0	34.5	100%
Ecological level	1274.1	14.6	42%
Feb 2021 level	1271.3	4.3	12%
Lake bottom	1267.1	0	0%

but legal and illegal groundwater pumping also supply agricultural production. The growing season in the basin is approximately 7 months.

The basin's population is 6.4 million, with 36% living in the metropolitan cities of Tabriz and Urmia. These cities are located 60 and 15 km east and west of the lake and are the capitals of the East and West Azerbaijan provinces, respectively. The agricultural sector accounts for 30% of employment (Alizade Govarchin Ghale et al., 2019), and the median income of inhabitants is $US 4700/year, based on the 2014 National Census.

From 1967 to 1999, lake level varied between 1274 m and 1278 m (maximum elevation) with natural climate cycles and extensive irrigation already present by the late 1800s (Günther, 1899). The lake was shallow, with mean and maximum depths of approximately 6 and 16 m, respectively (Table 1). Salinity was approximately 170 to 185 g/L (Günther, 1899; Karimi et al., 2016; Sima et al., 2021), and dominant ions were Na and Cl. As of February 2021, lake level declined to 1271.3 m, salinity exceeded 300 g/L, and 10.3 10^9 m^3 of additional water are needed to raise the lake to the 1274.1 m elevation that authorities say is needed to restore ecological function (the 'ecological level') (Abbaspour and Nazaridoust, 2007).

A causeway bisects the lake to connect the cities of Tabriz and Urmia, and a 1500 m bridge and gap in the causeway allows water exchange between the north and south arms of the lake. Brine shrimp (*Artemia* spp.) and brine flies (*Ephydra* spp.) are the only macroinvertebrates found in the hypersaline lake. The lake and surrounding wetlands once supported at least 92 bird species, with additional species in the surrounding highlands of Urmia National Park (Asem et al., 2016). The lake's importance for birds led to it being designated one of the first RAMSAR Wetlands of International Importance (Chaharborj, 2014). The lake is also an important cultural and recreational resource (Sima et al., 2021).

At Lake Urmia, restoration approaches such as inter-basin water transfers, diking, a 40% reduction in basin-wide agricultural water use, and partial and full restoration are being discussed and implemented (Aghakouchak et al., 2015). The Iranian government has also channelized rivers at their deltas to deliver water more efficiently to the lake rather than to adjacent wetlands (ULRP, 2018).

Lake Urmia's desiccation spurred a wide array of research efforts. Our initial bibliographic analysis of Lake Urmia research showed an increase in the number of papers over time after the lake level fell below 1274 m (Fig. 3). In the next section, we describe our methods for reviewing and synthesizing the Lake Urmia literature.

3. Literature review methods

This work is a joint effort of Iranian and international researchers. The research team was built organically by circulating an open invitation for co-authors among colleagues (Rosenberg, 2019). The invitation described the project, explained the online work environment, listed requirements for co-authorship, and generally followed recommendations for conducting an open, online paper (Tennant et al., 2019). The sample of papers included 544 articles from the Scopus database with the keywords "Lake" and ("Urmia" or "Ormayeh" or "Orumiyeh") up through September 2020. The research team also added other articles that addressed at least one research question. Our team read article titles, abstracts, and, if needed, portions of articles to assign each article to one or more research questions. In the end, 287 articles were assigned to at least one research question and 106 articles were assigned to two or more questions.

4. Answers to research questions

4.1. Is lake drying caused by climate or humans or both?

Diagnosing the cause(s) of Lake Urmia's drawdown can help identify appropriate strategies to stabilize and restore the lake. Did the lake decline due to human actions, such as agricultural development, or to exogenous climate change and associated increases in temperature and decreases in precipitation, or was it both?

Some 110 articles reported the impacts of agricultural expansion, dam construction, water diversions/withdrawals, temperature, precipitation, streamflow, and runoff on Lake Urmia's desiccation. Determining anthropogenic and climate effects on the Lake Urmia basin is technically challenging and politically fraught because answering the question has the potential to blame one or more groups of people for lake decline. From the initial 110 articles, 63 discussed combinatory effects. Our review and synthesis shows that anthropogenic factors contributed to Lake Urmia level decline, while climate factors had a smaller or no impact (Alizade Govarchin Ghale et al., 2018; Alizadeh-Choobari et al., 2016; Chaudhari et al., 2018; Hamzekhani et al., 2016; Hassanzadeh et al., 2012; Pooralihossein and Delavar, 2020) (Table 2). A combination of temperature variations, dam construction, and higher water storage resulted in decreased available surface water, which encouraged farmers to increase groundwater extraction. In addition, gradual changes in land use toward more water consuming crops have led to lake water-level reductions. Many researchers argued

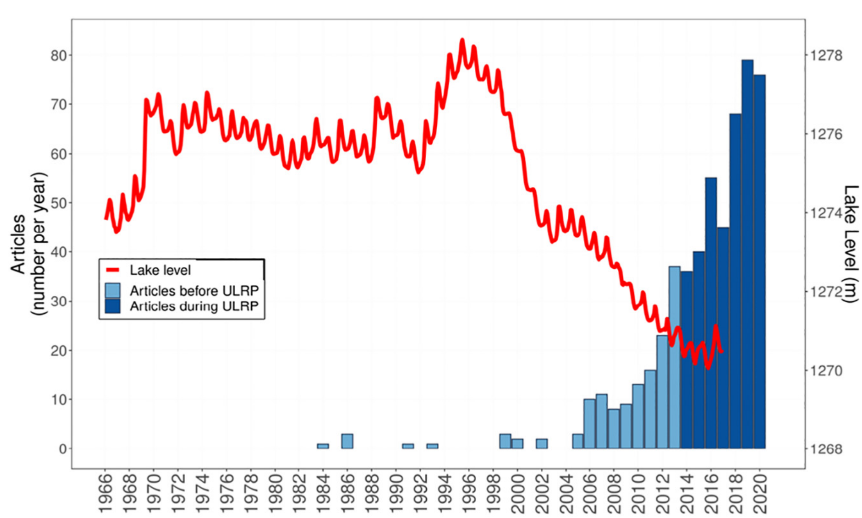

Fig. 3. Lake Urmia articles published per year (blue bars) and lake level (red line).

Table 2
Contributions of climatic and anthropogenic impacts on Lake Urmia decline.

Citation(s)	Basin	Climate impacts (%)	Human impacts (%)	Method	Period	Components (%)
(Hassanzadeh et al., 2012)	Entire	10%	90%	Simulation based, systems dynamics	1967–2006	• Climate change Overuse of surface water resources (65%) • Construct dams (25%) • Less precipitation (10%)
(Hamzekhani et al., 2016)	Entire	45%	55%	Simulation based, statistical	1966–2011	• Natural drought (45%) • Water withdrawals (40%) • Water projects (15%)
(Shadkam et al., 2016a)	Entire	60%	40%	Simulation based, statistical	1960–2010	• Irrigated agriculture area (+37%) • Annual inflow to Urmia Lake (−48%)
(Chaudhari et al., 2018)	Entire	14%	86%	Simulation based, hydrological model	1980–2010	• Agricultural area (+98%) • Urban areas (+180%) • Lake area (−86%) • Crop water demands (+300%)
(Alizade Govarchin Ghale et al., 2018)	Entire	20%	80%	Simulation based, statistical	1998–2010	• Groundwater mismanagement • (+293%, 1972–2012) • Surface water mismanagement • Dams • (+233%, 1970–2014) • Irrigated area doubled • (1985–2010)
(Farokhnia et al., 2018)	Entire	42%	58%	Simulation based, statistical	1999–2009	
(Pooralihossein and Delavar, 2020)	Ajichay Subbasin	10–27%	73–85%	Statistical, simulation based	1987–2007	• Irrigated agriculture (+400%) • Orchards (+339%) • (1976–2007) • Ajichay river streamflow (−73% to −85%)
(Hosseini-Moghari et al., 2020)	Entire	52–57%* 39–43%**	43–48%* 57–61%**	Statistical, simulation based	2003–2013	*The percentage of the total basin water loss **The percentage of the Lake Urmia water loss
(Kanani et al., 2020)	Lighvan sub-basin	65–84%	16–35%	Statistical, simulation based	1970–2014	• Lake inflow:-39–45% • residential areas: +88.9% • Gardens: +28.2% • Rangeland: −44% • Dry cultivation: +38.6%

that decreased precipitation has contributed to the lake's decline (Table 1), but our analysis of precipitation shows there has been no significant decrease (Fig. 1; $p = 0.77$).

Researchers investigated anthropogenic effects in two ways: (1) directly evaluating the human induced effects on lake degradation by looking at agriculture, reservoirs, and water management, and (2) evaluating the impacts of anthropogenic activities on the lake indirectly through the analysis of the climate variables. When no significant trends were detected in the climate variables, lake degradation was attributed to human activities. Other studies used simulation, forecasting models, and satellite images to evaluate human and climatic effects (Chaudhari et al., 2018; Dehghanipour et al., 2019; Delavar et al., 2020; Hassanzadeh et al., 2012; Hosseini-Moghari et al., 2020; Shadkam et al., 2016a). Artificial neural networks (ANN) and adaptive neuro fuzzy inference system (ANFIS) models were applied to differentiate and evaluate lake restoration measures (Valizadegan and Yazdanpanah, 2018). To assess the impacts of climate on basin streamflow, studies used trend (Alizadeh-Choobari et al., 2016), correlation (Fathian et al., 2016a; Fathian et al., 2014; Khazaei et al., 2019), Mann-Kendall (Pooralihossein and Delavar, 2020), and other statistical methods. A few studies used water balances (Bagheri et al., 2017; Tourian et al., 2015). Below we further describe work on individual factors.

4.1.1. Agriculture effects

Modern remote sensing techniques and time series analysis were used to detect trends in spatio-temporal land use and salinization over time (Table 3).

Overall, irrigated lands have expanded by 200% from 1988 to 2010 (Alizade Govarchin Ghale et al., 2018) and by nearly 400% from 1967 to 2007 (Pooralihossein and Delavar, 2020). These irrigated lands consume large volumes of freshwater resources. Rapid expansion of irrigated areas has nearly tripled irrigation water requirements within the Lake Urmia basin from 1995 to 2010 (Alizade Govarchin Ghale et al., 2019; Farokhnia et al., 2018; Fathian et al., 2016b; Fazel et al., 2017; Hesami and Amini, 2016; Kamran and Khorrami, 2018; Mehrian et al., 2016; Pooralihossein and Delavar, 2020; Shadkam et al., 2016a; Taheri et al., 2019). As a result, natural streamflow to the lake decreased by 48% from 1960 to 2010 (Shadkam et al., 2016a). These activities contributed to lake area shrinkage by 86% from 1995 to 2010 (Chaudhari et al., 2018) and an expansion of the salinized lands around Lake Urmia by 34 times from 1976 to 2015 (Naderizadeh Shorabeh et al., 2018).

Surveys and simulations show that the pattern and extent of agricultural land development differs by regions within the basin. For example, irrigated crop lands expanded by 153% in East Azerbaijan province, whereas orchards expanded by 300% in West Azerbaijan province from 1987 to 2007 (Farokhnia et al., 2018). Cropped areas from mid-spring to mid-summer increased by more than 10% between 2000 and 2015 (Khazaei et al., 2019), rainfed agricultural land was converted to irrigated land, and crop patterns changed from legumes to more water-intensive orchards, sugar beets, vegetables, melons, and watermelons (Bashirian et al., 2020). For example, apples, grapes and sugar beets expanded from 160,000 to 450,000 ha between 1979 and 2011 (Dalby and Moussavi, 2017). Another study showed that irrigated lands expanded by about 137,000 ha (32%) (Farokhnia et al., 2018). Discrepancies are likely due to differences in methods and periods of analysis, which makes direct comparisons difficult.

4.1.2. New reservoirs

Dam construction accelerated the expansion of irrigated area and decreased water flows into Lake Urmia (Alizadeh-Choobari et al., 2016; Farokhnia et al., 2018; Ghashghaie and Nozari, 2018; Kamran and Khorrami, 2018). The number of dams increased from one dam in 1970 to 56 dams in 2017. Dam capacity rose from 198 to 1758 MCM (Bozorg-Haddad et al., 2020). Simulation of six dams built since 1970 through

Table 3
Land use changes in various studies at Lake Urmia basin.

Citation(s)	Basin	Method	Variable	Change	Period
(Nezamfar et al., 2015; Fathi et al., 2015)	Urmia Lake Basin	Simulation	Water bodies	−32%	1989–2011
			Vegetation	−20%	
(Fathian et al., 2016b)	Eastern Sub Basins of Lake Urmia	Simulation	Crop area	+410%	1976–2011
			Orchard area	+330%	
			Rainfed area	+670%	
			Pasture area	−41% to −27%	
(Shadkam et al., 2016a)	Urmia Lake Basin	Statistical, simulation	Irrigated area	+37%	1960–2010d
(Chaudhari et al., 2018)	Urmia Lake Basin	Simulation	Agricultural area	+98%	1987–2016
			Urban area	+180%	
(Farokhnia et al., 2018)	Urmia Lake Basin	Simulation	Irrigated area	+32%	1987–2007
			Rainfed cropped area	+23%	
			Rangeland area	−5.8%	
(Alizade Govarchin Ghale et al., 2018)	Urmia Lake Basin	Statistical, simulation	Cultivated areas	+200%	1970–1999
					1999–2013
(Alizade Govarchin Ghale et al., 2019)	Urmia Lake Basin	Statistical, simulation	Irrigated area	+437%	1975–2011
			Irrigated area	−12%	2011–2018
(Pooralihossein and Delavar, 2020)	Ajichay Subbasin	Statistical, simulation	Irrigated area	+400%	1976–2007
			Orchard area	+340%	
(Bashirian et al., 2020)	Urmia Lake Basin	Statistical, simulation	Rangeland area	−2.76%	1984–2017
			Orchard area	+2.7%	

2005 with the Vensim systems dynamics software showed that discharges to the lake decreased by about 10% (Bozorg-Haddad et al., 2020). After reservoir construction, the inter-annual variability of stream flows decreased. Stream flows were relatively higher during dry summer months and relatively lower during wet winter months (Schulz et al., 2020). In another study of 18 dams that regulate 75% of total basinwide surface water flows, the effects of dam construction were initially found to be low, but over time, they resulted in increased water diversion for irrigation (Abdollahi et al., 2017). Ignoring the effects of climate change, modeling studies predict that the damming of rivers could further draw down the lake level (Zeinoddini et al., 2015).

4.1.3. Water management

Withdrawals of surface and groundwater also strained the lake, but few studies quantitatively and qualitatively linked both resources. Water inflow to the lake dropped from 3700 to 700 km^3 year^{-1} from 1995 to 2016. Increased irrigation water use from illegal abstraction of surface water sources decreased water flows to the lake by as much as 40% during dry years (Shadkam et al., 2016a). Lake level decline was more pronounced during the record drought of 1998 to 2002 when annual runoff decreased by 48% and surface water withdrawals increased by 25% (Alborzi et al., 2018). The three rivers–Zarineh, Simineh, and Ajichay–supply nearly 90% of the water flows into Lake Urmia, and all have been dammed for irrigation. The flow regime in the lower reaches of these rivers between 1965 and 2013 was more altered than the headwater reaches.

Increased groundwater use and overuse has accompanied the rapid expansion of irrigated agriculture. From 1989 to 2009 the number of wells increased from 55,200 to 106,200 (Bashirian et al., 2020). Other investigations showed some 75,000 new wells were drilled, including 50,618 legal and 24,700 illegal wells (Dalby and Moussavi, 2017; Stone, 2015). Simultaneously, groundwater extractions increased by about 0.36 km^3 year^{-1} according to one study (Dastranj et al., 2018) and from 1.45 to 2.53 km^3 year^{-1} (1989 to 2009) according to another. Overall, groundwater extraction increased from 0.37 to 2.26 km^3 year^{-1} (1961–2017), with a peak from 1998 to 2010 (Bashirian et al., 2020). Since 2011, extraction has declined due to droughts and groundwater depletion in the plains (Bashirian et al., 2020).

Since 2008, the mean groundwater level dropped by about 1 m due to groundwater overexploitation (Alizade Govarchin Ghale et al., 2018; Alizade Govarchin Ghale et al., 2019; Ashraf et al., 2017; Khaki et al., 2018) and possibly lower replenishment from reduced rainfall and increased evapotranspiration (Hosseinzad et al., 2019; Tourian et al., 2015). The declining water table has induced land subsidence (Nadiri et al., 2018; Kamran and Khorrami, 2018; Moghtased et al., 2012) and lowered groundwater quality (Hosseinzad et al., 2019). Saline water intruded into twelve aquifers immediately north, east, south, and west of the lake due to excessive harvesting of underground water resources, increased cultivation, and subsequent drilling of many water wells (Jafari and Eftekhari, 2013). The eastern aquifers are more vulnerable to degradation than the western aquifers (Jafari and Eftekhari, 2013; Nakhai and Vadiati, 2014). More recently, reduced water quality decreased annual groundwater extraction (Mehri et al., 2015).

4.1.4. Climate effects

Long-term temperature trends in the Lake Urmia basin are slightly increasing at an average rate of 0.05 °C year^{-1} (Alizadeh-Choobari et al., 2016; Delju et al., 2013; Farokhnia et al., 2018; Fathian et al., 2016a; Fathian et al., 2015) (Table 4). At the same time, basin precipitation has either decreased slightly (Alizadeh-Choobari et al., 2016; Chaudhari et al., 2018; Shadkam et al., 2016a) or shows no long-term trend (Fathian et al., 2015; Khazaei et al., 2019; Pooralihossein and Delavar, 2020; Shokoohi and Morovati, 2015) (Table 4 and Fig. 1 in Appendix A). Future climate scenarios predict a +1.5 °C rise in temperature and a 3 mm reduction in precipitation by the end of the century (Tisseuil et al., 2013).

In addition to temperature and precipitation changes, streamflow to the lake decreased by 55% and 16% during the 1997–2010 and 2002–2008 periods, respectively (Farajzadeh et al., 2014) and (Bagheri et al., 2017). Fathian et al. (2015) and Fathian et al. (2016a) showed a weak average correlation of 0.39 between precipitation and streamflow at 17 stations across the basin. These poor correlations suggest that other factors besides drought, such as increased water diversion, influenced streamflow

Table 4
Temperature and precipitation in the in Lake Urmia basin.

Variable	Citation(s)	Change	Period
Temperature	Delju et al. (2013)	0.024 °C year^{-1}	1964–2005
	Fathian et al. (2015)	0.02–0.14 °C year^{-1}	1980–2007
	Alizadeh-Choobari et al. (2016)	0.02 °C year^{-1}	1951–2013
	Farokhnia et al. (2018)	0.04–0.07 °C year^{-1}	1987–2009
	Khazaei et al. (2019)	No trend	1981–2015
Precipitation	Delju et al. (2013)	9.2% reduction	1964–2005
	Farajzadeh et al. (2014)	−1.1 mm year^{-1}	1997–2010
	Fathian et al. (2015)	−7.5 to 3.8 mm year^{-1}	1966–2007
	Alizadeh-Choobari et al. (2016)	−0.9 mm year^{-1}	1951–2013
	Shadkam et al. (2016a)	−1.12 mm year^{-1}	1960–2012
	Pooralihossein and Delavar (2020)	No trend	1987–2007
	Khazaei et al. (2019)	No trend	1981–2015

reduction. Moravej (2016) also detected some non-stationaries in precipitation and streamflow time series in eight main sub-basins of the Lake Urmia basin, but there was no evidence to support climate change as a factor for streamflow declines in the Lake Urmia region. Other hydroclimate variables such as lake evaporation (Arkian et al., 2018; Moravej, 2016) and soil moisture appear unrelated to lake water level decline (Khazaei et al., 2019). Our review finds that agricultural expansion, dam construction, and mismanagement of water resources contributed more to lake shrinkage than temperature increases or decreased precipitation.

4.2. What have been the dust/health impacts?

As Lake Urmia drew down, aerosol-producing areas of the lakebed were exposed. Aerosol pollution is a concern because it impacts public health, biogeochemical cycling of nutrients, regional climate, and visibility. One of the most documented examples of another desiccated lake serving as an active source of salt and dust is the Aral Sea (Indoitu et al., 2015; Singer et al., 2003). Satellite remote sensing data of Lake Urmia provided broad temporal and spatial coverage to gain initial insights into aerosol emissions. However, in-situ data are also critically needed but are more challenging to obtain. Such data can provide more detailed information related to the actual size distribution and composition of the emitted aerosols, as recently demonstrated for the Salton Sea in California (Frie et al., 2017). Emitted aerosols can be more directly linked to health effects and impacts on climate and the environment.

We are aware of 31 publications, all since 2014, that examined aerosol pollution over the Lake Urmia region, including studies on the lakebed surface properties that are relevant to aerosol emissions. These works relied on some combination of satellite remote sensing, in-situ measurements, and transport modeling. Satellite data, instrumental for characterizing aerosol pollution over the Lake Urmia region, have two major advantages over other methods. The first advantage is the ability to provide data over longer temporal scales than in-situ studies. A second advantage is the ability to provide a broader spatial context to examine upwind regions that have the potential to mix with local emissions. However, many satellite-based studies cannot provide vertically resolved information near the Lake Urmia surface when using the common parameter, aerosol optical depth (AOD). A single AOD value cannot resolve Lake Urmia emissions near the earth's surface because aerosols in the troposphere above the earth's surface also contribute to AOD (Mardi et al., 2018).

Beginning with satellite-based studies, data from the Visible Infrared Imaging Radiometer Suite (VIIRS) suggested that the two major aerosol types over the Lake Urmia region are desert dust and marine particles. Their relative importance varies by time of year (Moghim and Ramezanpoor, 2019). Effati et al. (2019) used data from the Moderate Resolution Imaging Spectroradiometer (MODIS) to show that dust emissions over the Lake Urmia region increase as a function of higher wind speed and lower soil moisture, with soil moisture effects most important at high wind speeds. Using a combination of satellite data, surface data of particulate matter with aerodynamic diameters less than 10 μm (PM_{10}), and transport modeling from NOAA's Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model, Sotoudeheian et al. (2016) predicted that Lake Urmia's lakebed can account for ~30–60% enhancement of PM_{10} in downwind cities during dust episodes. Vertically-resolved remote sensing data from the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) sensor indicated that Lake Urmia emits most aerosols in the driest periods of the year (June–October) and that the lakebed likely emits mostly dry salt particles (Ghomashi and Khalesifard, 2019). Delfi et al. (2019) used HYSPLIT and MODIS data to show that significant amounts of PM_{10} were transported from Iraq and Syria to the Lake Urmia area. Mardi et al. (2018) used MODIS data between 2001 and 2015 and regional AOD values to reach a similar finding regarding Iraq and Syria as dust sources. Other sources include emissions from burning biomass in areas to the north such as Ukraine, Russia, Kazakhstan, and the Republic of Azerbaijan (Crosbie et al., 2014). Furthermore, they showed that the influence from the lake's emissions were most evident from the AOD parameter in non-peak dust seasons (January, February, October) and on the outside perimeter of the lake. Their results suggested that the lake's border regions are more relevant than the lakebed for aerosol emissions; in contrast, they suggested that, for the actual lakebed, activities associated with disturbing the surface—grazing, salt harvesting–could increase aerosol emissions that would be unrelated to natural factors. Remote sensing studies have additionally been helpful to characterize soil salinity in the region (Farahmand and Sadeghi, 2020).

In-situ measurements, mainly in the form of near-surface filter-based collection methods, helped characterize the physicochemical properties of emitted aerosols and established some confidence in results from satellite-based studies (Gholampour et al., 2015). Gholampour et al. (2017) showed that aerosol emissions in the vicinity of Lake Urmia occur mostly on the country's borders rather than from the actual lakebed. Measurements by various investigators for total suspended particles (TSP), PM_{10}, $PM_{2.5}$, and PM_1 showed that aerosols around Lake Urmia consist of a mineral mixture containing calcite quartz, gypsum, halite, hexahydrite, bassanite, biotite, albite, chlorite, and olivine (Ahmady-Birgani et al., 2015; Gholampour et al., 2015). Other studies have examined the geochemical character of soil and sediment samples along the lake's shore and nearby areas (Ahmady-Birgani et al., 2018; Bagheri et al., 2019; Baygan et al., 2020; Mousavi et al., 2020; Shahbazi et al., 2019). Measurements of dust fall in the city of Tabriz to the east of Lake Urmia revealed high enrichment factors for anthropogenic tracer elements suggestive of sources other than Lake Urmia crustal matter (Eivazzadeh et al., 2019). Mohammadi et al. (2018b) conducted a biomonitoring study to examine metal and sodium levels in the leaves of four types of trees around Lake Urmia. They observed hotspots for arsenic, lead, and sodium to the northwest and east of Lake Urmia. Arsenic and sodium were linked to the lake's aerosol emissions and nearby industrial cement activity (Mohammadi et al., 2018a).

Using 56 aeolian dust samplers at different heights around Lake Urmia for a period of one year, Zabihi et al. (2018) showed that aerosol fluxes from the lake were greatest in the three months of March, June, and October (53% of annual total) and that fluxes decreased rapidly with height above the soil surface. Furthermore, fluxes were strongly related to monthly precipitation and mean wind velocity, and wind direction did not influence fluxes. Other work showed that playa surface type is a key determinant of vulnerability to wind erosion over the Lake Urmia surface (Alizadeh Motaghi et al., 2020). Wet deposition samples collected around the Lake Urmia basin revealed that falling precipitation has a high likelihood of scavenging regional sub-cloud particulate matter including dust and salt species (Ahmady-Birgani et al., 2020). Finally, a transport modeling study used HYSPLIT to show that 240° winds can have the maximum impact on areas downwind from the lake, whereas the highest concentrations of aerosols can occur under 90° winds (Nasiri et al., 2014).

A few studies have aimed to link Lake Urmia emissions to health outcomes in the region quantitatively. One such study used the AirQ software package to link mortality in Northwest Iran to PM_{10} emissions from traffic exhaust and Lake Urmia emissions (Mohammadi et al., 2019). They concluded that increases in PM_{10} yielded higher relative risk for mortality. Others have also shown that the number of adverse health outcomes varies with PM_{10} (Dehghani et al., 2020). Risk will likely rise with future increases in regional PM_{10} emissions. Another study observed a link between nearby human exposure to hypersaline particles and increased levels of high-sensitive C-reactive Protein (hs-CRP) and fibrinogen, which are biomarkers of inflammation and coagulation (Samadi et al., 2019a). The same investigators also observed a link between increased exposure to hypersaline particles and higher levels of biomarkers of cardiovascular diseases, specifically total and differential white blood cell counts and homocysteine (Samadi et al., 2019b). Other efforts have aimed to find ways to reduce pollutants from Lake Urmia sediments using nano-hydrogels (Pirsa et al., 2020).

Continued monitoring of Lake Urmia aerosol emissions is warranted, especially with greater emphasis on vertically and spatially resolved data to better understand transport patterns and routes of aerosol emission and deposition. Determining the size-resolved composition of the emitted aerosols would fill in a knowledge gap to identify the exact nature of different particles that may exist in the emitted aerosol from the lake and its surroundings. Further characterization of the impacts of the emissions on public health, regional weather and cloud formation, and biogeochemical cycling of nutrients and contaminants is also of interest. Lastly, managers can use agents such as biological soil crusts (Kheirfam and Asadzadeh, 2020; Kheirfam and Roohi, 2020) and carboxymethyl cellulose (CMC) (Toufigh and Ghassemi, 2020) to reduce wind-induced aerosol transport.

Our review of the Lake Urmia aerosol literature shows:

1. Lake Urmia and its surroundings area are an important source of regional aerosol emissions.
2. The aerosol composition is complex, ranging from mineral mixtures to anthropogenically linked elements, and
3. Aerosol emissions from Lake Urmia negatively impact human health.

4.3. Effect of the causeway on salinity?

In 1994 the lake was divided into southern and northern parts by a 15 km, 28-m wide, rock-filled causeway (Shahid Kalantari Causeway) that includes a 1.7 km-long multi-span bridge with a 1.25 km opening to allow water exchange between the northern and southern basins (Eimanifar and Mohebbi, 2007; Marjani and Jamali, 2014; Okhravi et al., 2017). The causeway was built to reduce the travel distance between Urmia and Tabriz by 130 km. The causeway affects flow, salinity, and lake evaporation, all of which are important to stabilize and recover the lake (Fig. 4).

No Environmental Impact Assessment (EIA) study was done in the initial design stage of the causeway project (EIA was not required by the government at that time). Sadra (2004) conducted a detailed EIA before the construction stage of the bridge. Based on their EIA, construction of an additional 500-meter opening was recommended in the west arm of the causeway to improve the water circulation and sediment balance. However, this opening has not been constructed yet. Although the construction of the causeway has many economic and commercial benefits for the region, it may have changed geophysical characteristics of the lake (Eimanifar and Mohebbi, 2007). Excessive traffic through the middle of the lake has increased noise. The causeway can affect the water circulation and exchange patterns between the northern and southern parts. As a result, the physical-chemical properties of the lake may differ over time on both sides of the lake. Satellite images of Lake Urmia in drying (April 2018) and wet (April 2021) conditions show the difference in colors between the northern and southern basins in some seasons that are caused by the causeway (Fig. 5).

Since little to no in situ data were available, numerical models were developed to identify key driving forces affecting the salt flux and flow exchange between the north and south basins of the lake. Some numerical studies showed that wind is the main driving force in lake circulation (TU, 2017; Zeinoddini et al., 2013). Zeinoddini et al. (2013) used a three-dimensional hydrodynamic model to show that wind-generated waves have significant effects on water flow and salinity distributions in the lake. However, they assumed a spatially constant wind field over the lake, and no wave measurements were available for calibration and verification of the model. As the southern basin now receives more than 95% of total freshwater inflows, this part of the lake generally has a higher water elevation and a lower salinity level than the northern basin (Marjani and Jamali, 2014). Sima and Tajrishy (2015) sampled lake water three times in October 2009, May 2010, and July 2010 and found relatively similar salinities in the north and south basins, with a mean respective total dissolved solids (TDS) of 390 and 387 g/L—a 1% difference between the two basins. However, in May, when river flow to the south was high, the TDS was 5.5% lower in the south. In October this reversed, with 4.0% higher salinities in the south. Ab-Niroo (2017) also conducted monthly measurements of salinity and TDS in 2016. The maximum salinity differences between the two basins was 375 g/L (north arm) and 257 g/L (south arm) when river discharge was high. Sabbagh-Yazdi et al. (2020) found that river discharges and a higher water level in the south basin contributed to the water flow exchange from south to north; however, the causeway embankments block the water flow exchange and have reduced the water flow from the southern part to the northern part. Furthermore, Marjani and Jamali (2014) indicated that the exchange flow through the opening is directly influenced by the water density difference of the two basins. They showed that in the presence of the density difference between the two basins, a two-layer baroclinic flow (i.e., density-driven exchange flow) occurs through the opening such that the top layer of less dense water flows from the southern basin into the northern, while the bottom layer exhibits a north-to-south flow. Thus, the flow exchange rate between the two basins depends on wind, river inflow, lake elevation, and density difference. Review of the previous studies, some of which are contradictory, highlights that

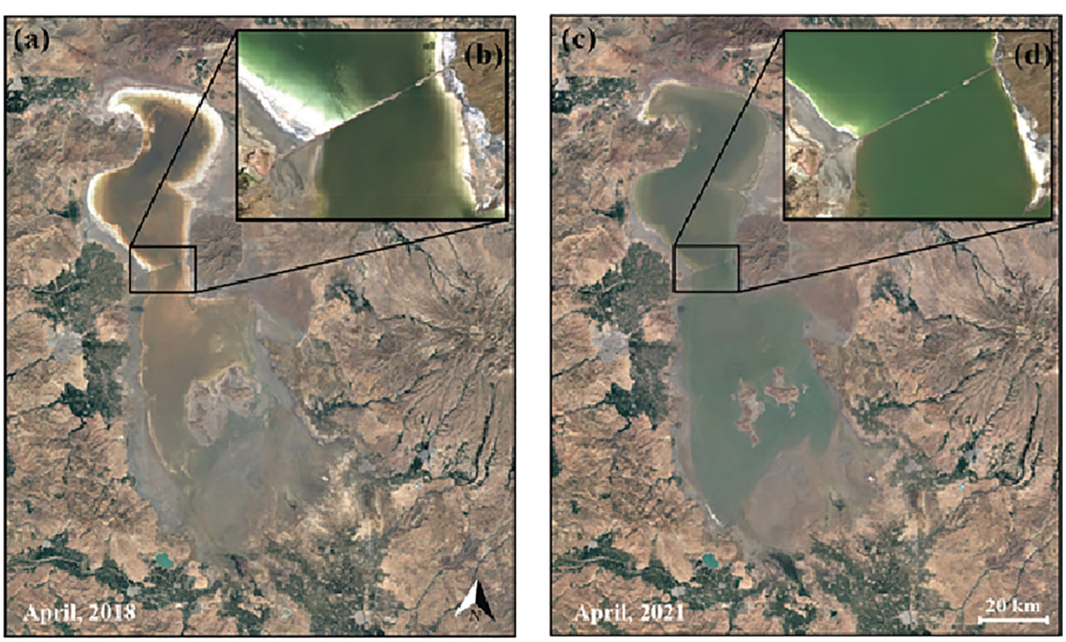

Fig. 4. Satellite images of Lake Urmia in April 2018 and April 2021. Images (a) and (c) were acquired by Landsat 8 (30 m spatial resolution), and images (b) and (d) were acquired by Sentinel-2 (10 m spatial resolution).

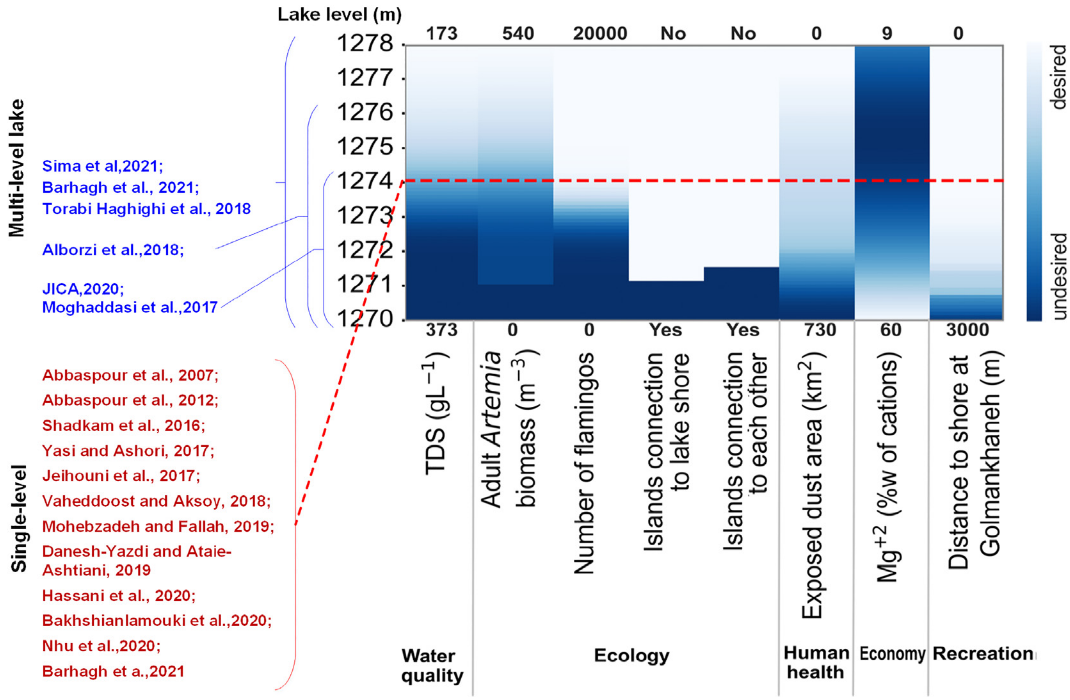

Fig. 5. Single (red) and multiple (purple) lake level research and the associated lake ecosystem services (dark to light blue). Derived from Sima et al. (2021).

investigating the effect of the causeway on salinity and lake circulation relies upon correctly identifying the underlying driving factors.

A few studies attempted to assess impacts of the causeway on the lake ecosystem (mostly using a numerical approach), yet the causes and effects are controversial. For example, Tabriz University (TU, 2017) pointed out that the maximum fetch length of the lake along the south-north direction was reduced due to the presence of the causeway embankments, and this limits the development of wind-driven waves and currents in the lake (TU, 2017). In addition, the causeway influences the wave pattern, and it significantly damps the wave field near the embankments (Dadashzadeh et al., 2020; TU, 2017). Consequently, the causeway has a significant effect on changing flow patterns and salinity regimes (Hemmati et al., 2020; Hemmati et al., 2021; Tarh-e-Noandishan, 2020). Alavipanah et al. (2007) also used Landsat satellite data and suggested that the causeway has limited water circulation and hydraulic connection between the north and south parts and has altered density and salinity in the two basins. Conversely, Bayati and Danesh-Yazdi (2021) used Sentinel-2 and Landsat-8 satellite data and found a salinity difference between the two basins during high river-flow seasons due to the limitation on flow exchange between the basins; however, their results showed the causeway has a minimal effect on lake circulation at other seasons. Furthermore, Zeinoddini et al. (2009) used a hydrodynamic model and stated that, while wind affects the flow pattern in the lake, evaporation, rainfall, and river discharge are the main factors influencing the salinity regime; therefore, the causeway has not had, and should not have, significant impacts on the overall salinity patterns in Urmia Lake over the long term as compared to the natural (pre-causeway) conditions. On the other hand, other numerical studies have found that the construction of the causeway has led to a reduction in the flow exchange rate between the southern and northern arms of the lake (Ab-Niroo, 1995; Sadra, 2004; Tarh-e-Noandishan, 2020). The rate of this decrease was estimated to be about 25% at a water level of 1270.3 m and 43% at a water level of 1278 m (Tarh-e-Noandishan, 2020). This is also important because the south-to-north flow through the opening is the major source of water supply to the north basin to compensate for the surface evaporation loss (Marjani and Jamali, 2014). This reduction in exchanged discharges has increased the salinity differences between the two basins (Soudi et al., 2019) and, as a result, contributes to a lower salinity level in the southern part and a saltier northern part of the lake (Safavi et al., 2020; Tarh-e-Noandishan, 2020). The difference in salinity between the north and south arms allows a portion of the lake to remain at a lower salinity to support *Artemia* and other invertebrates (Abatzopoulos et al., 2006). This is similar to the situation in the Great Salt Lake (USA), where a railroad causeway greatly reduces mixing between the two major sections of the lake, resulting in a saturated brine in the north arm, and salinities around 150 g/L in the south arm where nearly all the rivers enter. Without the causeway, the salinity of both these arms would be too high to support *Artemia franciscana* (Johnson et al., 2019; White et al., 2015).

Several remedial actions have been proposed to decrease the consequences caused by the construction of the causeway. However, previous studies have produced contradicting results regarding the effectiveness of remedial actions. For example, Sadra (2004) found that adding a new 500-meter opening in the west arm of the existing causeway would result in a 40% increase in water exchange between the south and north basins as well as an improvement in salinity circulation. TU (2017) and Tarh-e-Noandishan (2020) also suggested that adding extra openings to the causeway could help the lake to return to conditions before 1979. In contrast, Zeinoddini et al. (2014) found that none of the solutions could change the overall salinity patterns compared to pre-causeway conditions. They also found that adding new openings would only have local effects on the flow and salinity regimes near the causeway. In addition, simulation results of Zeinoddini et al. (2009) in both wet and dry periods showed that neither adding new openings nor removing the whole causeway could improve the lake hydrodynamic and salinity regimes. Sabbagh-Yazdi et al. (2020) also indicated that adding another opening in the causeway will provide little or no improvement in the flow circulation pattern between the north and south arms. Moreover, Hamidi-Razi et al. (2019) used a 2D shallow water model (MOHID) to determine the effectiveness of restoration scenarios for the lake. The scenarios include destruction of the bridge and closing the causeway (dividing the lake in two independent water bodies), no intervention (preserving the current status), construction of a dike in the southern part of the lake, reducing the agricultural water consumption in the basin, and transferring water from the Zarrinehrood River to the Siminehrood River. The results indicated that improving agricultural methods and cultivation of low-water-use crops can play the most effective role in the partial rehabilitation of the lake. Other scenarios would have little effect on reviving the lake.

Several reasons may explain the contradictory results from these studies:

- Governing equations of hydrodynamic models, including continuity, momentum, temperature, salinity, and density equations, need to be coupled and solved simultaneously, and calibrated against in situ observations such as lake levels, velocity profiles, wave data, temperature profiles, and salinity concentrations (Hamidi-Razi et al., 2019; Sabbagh-Yazdi et al., 2020; Sadra, 2004; Safaie et al., 2017a; Safaie et al., 2017b; TU, 2017). Previous studies did not simulate temperature structure, calibrated only to lake level (Hamidi-Razi et al., 2019), and did not validate model results against observations (Sabbagh-Yazdi et al., 2020). Some studies used a decoupled hydrodynamic-salinity model (TU, 2017) or a decoupled hydrodynamic-wave model (Sadra, 2004).
- Two-dimensional depth-averaged models, rather than three-dimensional models, were used in a number of studies to simulate the hydrodynamics of Lake Urmia (Ab-Niroo, 1995; Hamidi-Razi et al., 2019; Sabbagh-Yazdi et al., 2020; Sadra, 2004). Two-dimensional models may overestimate the lake salinity concentrations and variations in the flow velocity (Zeinoddini et al., 2009). Moreover, neglecting the effect of density difference underestimates water exchange between the northern and southern basins. Thus, the density difference of the two basins might be overestimated (Marjani and Jamali, 2014). In addition, the previous studies commonly utilized a 3-D model (MIKE) with the UNESCO equation of states, which is only valid for water densities up to 1037 g/l (Dadashzadeh et al., 2020; Hemmati et al., 2020; Sadra, 2004; Tarh-e-Noandishan, 2020; TU, 2017). Lake Urmia's water density is much higher (Soudi et al., 2019; Zeinoddini et al., 2009).
- A proper temporal resolution is needed to accurately simulate the hydrodynamics of the lake and assess the effect of the causeway. However, observed flow and salinity data for some rivers were not available, and sometimes river inputs were assumed to be constant for each month throughout the simulations (Zeinoddini et al., 2009).
- The accuracy of hydrodynamic models depends on accurate reconstruction of the meteorological forcing over the lake as well as reconstruction of bathymetry at unsampled locations (Safaie et al., 2017a). Weather stations around Lake Urmia have sparse and inhomogeneous distribution in time and space. Therefore, a few studies used a single weather station and assumed that atmospheric forcing such as wind speed was spatially constant over the lake (Zeinoddini et al., 2013).
- Changes in the lake bathymetry due to salt dissolution and precipitation have been ignored by the previous studies. Additionally, (Tarh-e-Noandishan, 2020) and (Safaie et al., 2021) showed that the salt precipitation and dissolution make major contributions to the salinity balance of the lake, yet these contributions were neglected in the previous studies.

Previous studies have shown that the causeway has changed the lake circulation and limited the flow exchange between the northern and southern basins of Lake Urmia. Therefore, the residence time of both water and salinity have changed. As a result, the basins have relatively different physical-chemical properties. These changes have altered the salinity distribution in the lake. However, due to the lack of in situ observations, the significance of the causeway's impact on salinity is widely debated. Hence, more in situ observations, combined with an integrated study, are needed to quantify the impacts of the causeway. Moreover, the effects of the causeway on lake circulations and salinity regimes are more pronounced at higher water levels (Tarh-e-Noandishan, 2020; TU, 2017). Thus, follow-up studies at different water levels and wider climatic conditions are needed. Further research is also needed to investigate the impacts of the causeway on wildlife and water pollution.

Our review of causeway research shows:

1. The causeway reduces water circulation between the north and south arms;
2. The decreased circulation causes small differences in the chemical and biological properties, but these differences are primarily transitory during spring runoff that primarily flows into the south arm;
3. Results are contradictory about whether opening an extra breach in the causeway will modify salinities; effects on evaporation are unknown, and
4. More work is needed to identify the impact of the causeway on the lake ecosystem.

4.4. What hydrologic and water management research has considered lake levels besides the ecological level of 1274.1 m?

The stated goal of the ULRP was to raise Lake Urmia's elevation to 1274.1 m to presumably recover *Artemia* populations, even though different lake elevations provide many other ecosystem services. Here, we reviewed the literature to learn what lake levels and ecological services researchers and managers considered for lake stabilization and recovery.

Only six of 18 articles that discuss lake levels considered restoration lake levels different from the ecological target level of 1274.1 m or its associated equilibrium inflow of 3.1 km^3 year^{-1} (Fig. 6). Moghaddasi et al. (2017) considered restoration inflows of 3.1 km^3 and 65% of that amount (~1273 m) for four levels of drought. They show that restoration lake areas will vary between 2500 and 4000 km^2 (corresponding to lake level of 1270–1274 m) when water and crop management strategies are adopted. Alborzi et al. (2018) also simulated lake levels between 2003 and 2013 under different water withdrawal scenarios. Torabi et al. (2018) modeled the lake level under various upstream environmental flows allocation for rivers. They showed that lake level can fluctuate from 1270 to 1278 m as environmental flow releases increase from 1.6 km^3 up to 3.2 km^3. JICA (2020) used MIKE-SHE to simulate lake level during a 30-year period as a result of annual lake inflows ranging from 0.5 to 4 km^3. Barhagh et al. (2021) used a system dynamic model to assess the status of Lake Urmia under four restoration scenarios including a 40% reduction of irrigated lands, improving irrigation efficiency, reduction of the lake area, and inter-basin water transfer. They showed that applying each of these scenarios will increase the lake level; however, all activities must be implemented to reach the ecological level of 1274.1 by 2023. Sima et al. (2021) synthesized salinity, adult *Artemia* density; bird count; ion and cation; island; distance from resorts to shoreline; and hypsographic data and showed that the ecological level of 1274.1 m is insufficient to reduce lake salinity below 240 g/L NaCl and conserve *Artemia* and flamingo populations. A higher lake level may be needed. Furthermore, Sima et al. (2021) identified a diverse range of ecological, human health, and recreational objectives that vary widely with lake level and currently are not considered in the ecological lake level. Tradeoffs among the objectives are murky.

The remaining studies were all water balance or modeling studies that assumed the uniform lake level of 1274.1 m defined by Abbaspour and Nazaridoust (2007) will successfully restore Lake Urmia. These studies (1) assessed the volume of lake inflows needed to reach the ecological level (Hassani et al., 2020; Jeihouni et al., 2017); (2) assessed the feasibility of reaching the ecological level under climate change scenarios (Abbaspour et al., 2012); (3) investigated the upstream land and water management practices (Bakhshianlamouki et al., 2020); (4) recommended sustainable

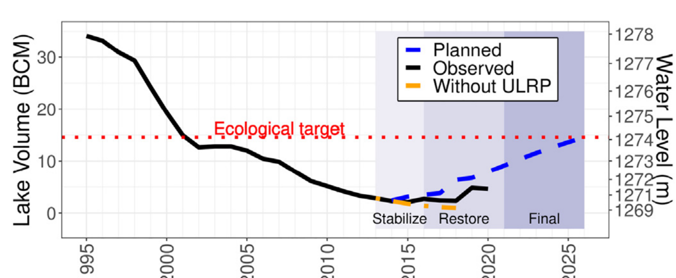

Fig. 6. Lake Urmia water level (black), planned (dashed blue), and predicted result if ULRP actions not implemented (orange dash line) (ULRP, 2020).

environmental flow releases (Shadkam et al., 2016b; Yasi and Ashori, 2017); (5) improved water balance calculations to improve decision-making (Mohebzadeh and Fallah, 2019); (6) quantified lake level effects from accelerated used of groundwater (Vaheddoost and Aksoy, 2018); (7) identified model and data inaccuracies as reasons lake level targets have not been met (Danesh-Yazdi and Ataie-Ashtiani, 2019); and (8) predicted the time horizon to reach the ecological level (Hassani et al., 2020). Hassani et al. (2020) pointed out that multiple lake levels are needed to restore different ecological aspects of a saline lake. However, their restoration strategy suggested an Aral Sea approach that would require diking the southern part of the lake or closing the causeway so that water within the reduced lake area could reach 1274 m. Nhu et al. (2020) quantified and visualized how lake, island, and exposed lakebed area have changed as lake level has declined, although they do not provide thresholds to maintain islands and lake area, or to limit dust from exposed playa. All these studies simulated lake levels for different hydro-climate conditions and management strategies, but only one study considered or discussed which lake services will be totally or partially lost or achieved at various lake levels.

The focus on restoration to elevation 1274.1 m ignores species abundance, richness, and habitat quantity or quality. The focus on a single lake level will lead to cascading errors in modeling, management, restoration, and decision-making. Considering scenarios with different lake levels in new research and management work and relating specific ecosystem services to different lake levels (Sima et al., 2021) can help managers identify restoration actions. Managers of other saline lakes have linked different ecosystem services to different lake levels (Null and Wurtsbaugh, 2020). They also identified restoration actions such as water conservation, environmental water purchases, inter-basin water transfers, diking, shallow flooding, and managed wetlands to preserve ecosystem services (Null and Wurtsbaugh, 2020).

This review of lake stabilization and recovery levels finds that:

1. Nearly all studies on lake hydrology and water management uncritically treated the "ecological level" of 1274.1 m as a goal that would restore the lake's functions.
2. The target lake level may not maintain important lake functions, and
3. Considering a range of lake levels in new management work and research will help to identify which lake services are fully or partially lost or achieved at different lake levels.

4.5. What effect have ULRP efforts had on restoration?

In an effort to attain the ecological level of 1274.1 m, the ULRP has invested about $US 1 billion since 2013 to transfer water from adjacent basins, dredge and channelize rivers at their outlets, and convey treated wastewater to the lake (Bakhshianlamouki et al., 2020). The ULRP also started many demand management and operations programs such as making targeted environmental releases from reservoirs, prohibiting new dams and new water right grants (Hesami and Amini, 2016), monitoring and controlling illegal surface and groundwater extraction (ULRP, 2017), and reducing water use in the agricultural sector by 40% (8% per year). The ULRP reduced water use in agriculture by increasing productivity, investing in new technology, and controlling irrigated land expansion (Shadkam et al., 2016a; ULRP, 2020).

Few studies tried to identify the separate and combinatory effects of new supply and demand management projects and climate anomalies on lake level rise. Danesh-Yazdi and Ataie-Ashtiani (2019) confirmed the lake stabilization from 2016 to 2018 and Saemian et al. (2020) attributed lake stabilization in 2015–2019 to increased water releases from upstream reservoirs and the anomalous precipitation in 2016 and 2019. Alizade Govarchin Ghale et al. (2019) showed a 1000 km^2 lake area increase between 2014 and 2016. Sima et al. (2021) also indicated an increased crop yield and agricultural revenue between 2012 and 2016 with the same lake level and similar reservoir releases to agriculture. Increasing counts of peer-reviewed publications suggest that, since 2013, the ULRP mobilized academics and researchers to work on lake restoration projects (Fig. 3).

Concurrent with new infrastructure and engineering projects and near record precipitation from 2018 to 2020 (Fig. 1 in Appendix A), the lake level rose about 1 m and stabilized (2013 to 2019) (Fig. 7). Record precipitation resulted in flooding, and an increase in river flows to the lake by 0.35 10^9 m^3 per year. Critics of the ULRP suggest that stabilization efforts will be short-lived or fragile. For example, flooding will swing back to droughts. Lake inflows will spread over the large shallow southern portion of the lake and evaporate quickly (Saemian et al., 2020). Other critics point to past years when precipitation was also high, but lake level decreased.

Several researchers also discussed the feasibility of reaching the ULRP's so-called ecological target of 1274.1 m under different climate change and water management scenarios. The most optimistic estimate is by Alborzi et al. (2018), which suggests 3 to 16 years are needed under different future climate scenarios. The timeframe may increase to 30 to 50 years under different water management policies (JICA, 2020). Other studies show that the lake level will only reach 1274 m by reducing cultivated areas in the basin (Barhagh et al., 2021; Hassani et al., 2020).

Preventive efforts such as stopping new dam construction and farmland expansion have helped stabilize the lake. Inter-basin water transfers and discharge of treated wastewater to the lake are not yet complete. Projects to modernize irrigation technologies, apply smart agriculture, and plant higher value crops need application at larger scales. These projects may produce unintended consequences as they proceed, such as reduced water consumption encouraging farmland expansion or reduced agricultural releases from reservoirs driving further groundwater depletion (Paul et al., 2019). Monitoring water conservation is difficult. ULRP (2017) and ULRP (2020) efforts require more transparency and accountability. On the

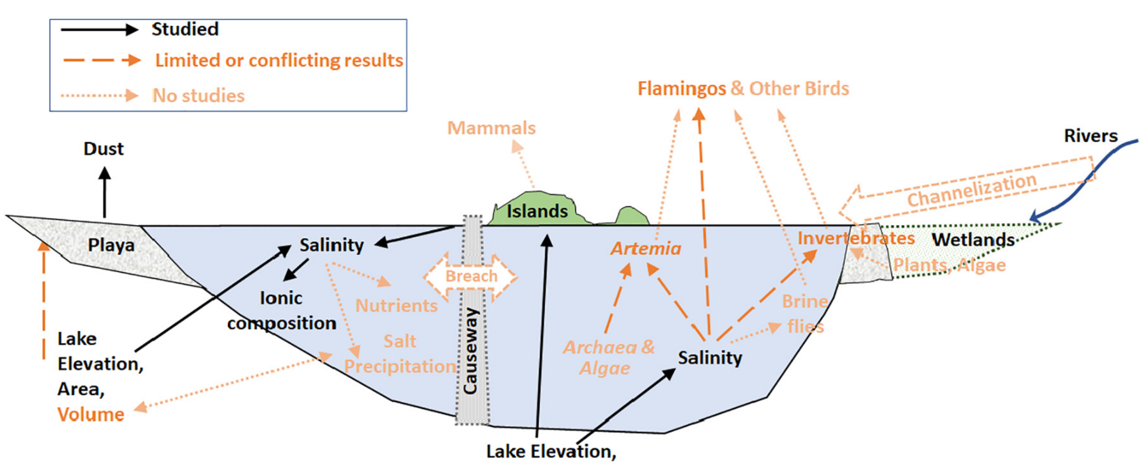

Fig. 7. State of knowledge of linkages between Lake Urmia ecosystems and adjoining wetlands.

positive side, the ULRP reported cooperation with many international universities, organizations, companies and foreign government agencies (ULRP, 2017, 2018). Assessing the impacts of ULRP efforts will take more time and a comprehensive approach.

This review of ULRP stabilization and recovery efforts shows:

1. The ULRP motivated and funded researchers to work on lake projects.
2. The ULRP increased basin crop yield.
3. The ULRP helped stabilize lake level and inundate dust-producing areas with the help of high rainfall from 2018 to 2020.
4. Gains may falter when precipitation and inflows decline.
5. More water conservation projects are needed to help recover the lake.
6. More studies are needed to comprehensively assess the impact of ULRP efforts to stabilize the lake and those studies need more time, data, and integrated analysis.

4.6. What do we know about Lake Urmia's limnology and ecology to facilitate recovery?

The goal to raise lake level to 1274.1 m is intended to increase the ecological functions of the lake. Those functions include recovering *Artemia* and the birds dependent on them. Thirty-two articles focused on the ecology of Lake Urmia and nearby wetlands. Some processes and species are not well understood (Fig. 8). Many Lake Urmia papers explored genetics and taxonomy of the biota, with limited applicability for management. Several authors provided general reviews of the lake's characteristics (Asem et al., 2014; Eimanifar and Mohebbi, 2007; Günther, 1899; Lotfi and Moser, 2012).

4.6.1. Physical-chemical limnology

Kelts and Shahrabi (1986) reviewed Lake Urmia Basin geology. The lake is in the tectonic mush zone of the colliding Eurasian and Arabian plates. The complex lithology results in a lake dominated by NaCl (90%). The elevation, area, shape, volume and major ion chemistry are markedly similar to that of the Great Salt Lake in the USA (Kelts and Shahrabi, 1986).

The published literature indicates that the lake's depth-area-volume morphometry has not been carefully measured. Karimi et al. (2016) estimated the lake's morphometry using satellite remote sensing coupled with field measurements made with an echosounder to estimate lake depths. However, they did not correct for the much higher speed of sound in saturated brine (Al-Nassar et al., 2006) and likely underestimated lake depths and volumes by ~23%. Additionally, the number and distribution of depth measurements were not sufficient to cover the entire lake, particularly shallow coasts and areas near islands. Despite these uncertainties, their bathymetric map and level-area-volume relationships have been officially used for Lake Urmia management. Alipour (2006) surveyed the western half of the lake in 2002–2003 and found a maximum depth of 9 m when

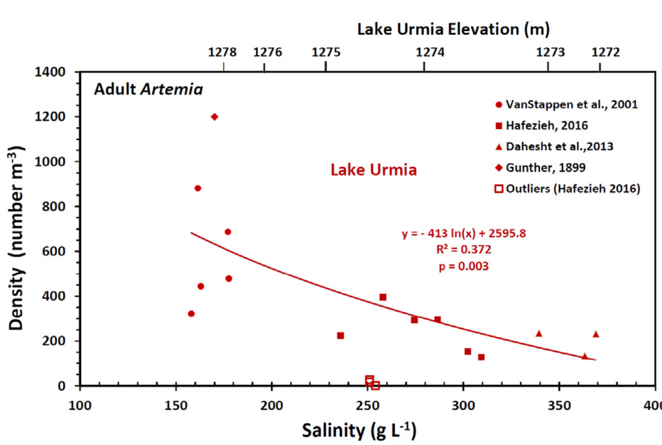

Fig. 8. Relationships between salinity and adult *Artemia* in Lake Urmia. Open symbols indicate outliers not included in the regression analysis (Sima et al., 2021).

the lake's elevation was near 1273.5 m. Sima and Tajrishy (2013) also calculated depth-area-volume curves using satellite imagery to find the exposed lake bed perimeter at different elevations, and then they extrapolated the lake's depth in inundated sections to obtain area and volume estimates. All of these approaches have serious limitations that have affected some of the fundamental metrics for lake recovery. Fortunately, the Iranian Geology Survey Institute (GSI) recently made morphological measurements with a sounding line that may rectify the problem (Sima, personal communication, 2021).

Water depths change, not only because of changes in lake elevation, but with precipitation of salts on the lakebed, creating an additional problem with estimate the lake's morphometry. Karimi et al. (2016) estimated salt deposition on the lake bottom between 2013 and 2015 using satellite imagery calibrated to measurements made with the improperly scaled depth sounder. They estimated that an average salt deposition of 64 cm occurred in the 2-year period. However, the lake drop of 0.15 m during this period, and the decrease in volume of the saturated brine should only have resulted in 2.2 cm of salt, on average, deposited on the bottom, 29 times less than Karimi et al.'s estimate. Consequently, additional salt deposition measurement work using more accurate in-situ techniques is needed.

In addition to the dominant ion, NaCl (95%), several authors have documented lesser amounts of SO_4^{-2}, Mg^{+2}, and K^+ ions prior to 1999 (Alipour, 2006; Dahesht et al., 2010; Karbassi et al., 2010; Sima and Tajrishy, 2015). Lake desiccation, however, resulted in an expected precipitation sequence, with NaCl and carbonates lost from the water column. With this precipitation, respective concentrations of Mg^{+2} and SO_4^{-2} are now equal to those of Na^+ and Cl^- (Sharifi et al., 2018).

No significant vertical stratification of salinity or temperature has been found in the shallow, wind-swept lake (Alipour, 2006; Sima and Tajrishy, 2015). Mean winter and summer water temperatures are <3 °C and 26 °C, respectively (Dahesht et al., 2010; Sima et al., 2013).

From 1967 to 1999, before the lake desiccated, its elevation ranged from 1274 to 1278, with a mean of 1276 ± 0.8 m. We refer to this mean elevation as the *pre-development level*, although we recognize that extensive irrigation was already occurring in the basin before 1898 (Günther, 1899). Also, in closed-basin lakes, elevations can vary widely with natural climate cycles. At the pre-development level, the lake had an approximate area of 5030 km^2, a volume of 23.1 km^3, and a salinity near 185 g/L (Karimi et al., 2016; Sima et al., 2021). In February 2020, the lake had an elevation of 1271.3 m and a respective area and volume of 56 and 18% of the pre-development level. At the target ecological level of 1274.1 m, the area and volume would be 85 and 62% of the pre-development level.

Relatively little is known about nutrient concentrations in the lake that support primary producers. Dahesht et al. (2010) reported exceedingly high concentrations of PO_4^{-2} (104–875 mg/L) and NO_3^{-1} (330–4104 mg/L), although it is unclear whether they reported concentrations of P and N, or of the oxidized ions. Regardless, these concentrations would classify the lake as hypereutrophic (Carlson and Havens, 2005), but chlorophyll levels and phytoplankton densities suggest the lake is oligotrophic or ultra-oligotrophic (see below).

4.6.2. Biological limnology

A few studies address the algae in Lake Urmia and its wetlands at salinities >300 g/L. Dahesht et al. (2010) found 14 phytoplankton genera, including 10 diatoms, two genera of green algae, and two of cyanobacteria. The halotolerant green alga, *Dunaliella* spp. composed 92% of the lake's phytoplankton, and genomic analyses by Hejazi et al. (2016) suggest that several different varieties of this alga may be present. Dahesht et al. (2013) studied chlorophyll concentrations, an index of algal abundance, in Lake Urmia when the salinity was >300 g/L. Mean concentrations were 0.8 μg/L, with a high of only 2.4 μg/L found in June. Another survey (Iranian Water and Power Resources Development Company, 2018), however, found concentrations varying from 4 to >10 μg/L in fall and winter, respectively. This discrepancy suggests that a thorough monitoring program is needed to assess how plankton in the lake respond to salinity changes. Also, note that other microbes (Archaea) often become the dominant primary producers under hypersaline conditions, and these organisms do not have chlorophyll. Archaea in Lake Urmia have been associated with *Artemia* (Rahmani et al., 2016), and *Artemia* can feed on them (Lopes-dos-Santos et al., 2019). Little is known about the benthic primary producers in Lake Urmia, although their production in both freshwater and saline lakes can equal or exceed that of phytoplankton in the water column (Vadeboncoeur and Power, 2017; Wurtsbaugh, 2009).

Benthic macroinvertebrates are an important component of the food web in saline lakes. In hypersaline systems, species of brine flies, *Ephydra* spp., dominate, but different species have different salinity tolerances (Herbst, 2001; Herbst, 1999; Herbst, 2006). Larvae of *Ephydra urmiana* inhabited Lake Urmia when salinities were lower (Asem et al., 2014; Günther, 1899), but their current status has not been documented.

Benthic macroinvertebrates in freshwater and hyposaline wetlands are also important food for birds. Wetlands are estimated to cover 260 km^2 around the margin of Lake Urmia (Personal communication, West Azerbaijan Bureau of Environment), although desiccation, channelization, and eutrophication are degrading some of the wetlands (Alibakhshi et al., 2017). Ahmadi et al. (2011) found 32 taxa of invertebrates in the Zarrineh estuary at the southern end of Lake Urmia. Midges (Chironomidae) and a diverse set of other invertebrates dominated freshwater ponds. In areas with salinities > 10 g/L, salt-tolerant taxa such as water boatman (*Trichocorixa verticalis*), brine shrimp (*Artemia urmiana*), and brine flies (*Ephydra* spp.) dominated. The taxonomic shifts occurring with increased salinity are similar to those seen in the Great Salt Lake (Armstrong and Wurtsbaugh, 2019). No studies have been conducted on the mudflats around Lake Urmia, even though they were/are likely important foraging areas for migratory shorebirds and ducks (Eimanifar and Mohebbi, 2007).

The target species for recovery of Lake Urmia is the brine shrimp, including sexually-reproducing *Artemia urmiana*, which are dominant in the pelagic zone, and parthenogenic *Artemia* sp., which live primarily in bordering lagoons (Agh et al., 2007). *Artemia* are an important food source for birds in hypersaline lakes (Hammer, 1986; Roberts, 2013; Wurtsbaugh, 2018) and presumably in Lake Urmia. An artisanal industry of *Artemia* cyst collection for aquaculture around the shores of Lake Urmia has existed since 1996 (Dahesht et al., 2013). The lake's size suggests a potential for a significant cyst harvesting industry similar to that existing in the Great Salt Lake and other hypersaline lakes in the world (Marden et al., 2020). Cysts and nauplii of *A. urmiana* are considerably larger than the dominant commercial species (*A. franciscana*) used in aquaculture, which limits their utility for prawn and marine fish culture but are preferable for aquaculture of freshwater fish (Abatzopoulos et al., 2006; Peykaran et al., 2011). Laboratory experiments by Abatzopoulos et al. (2006) indicated that the cysts of *A. urmiana* sank at salinities up to 200 g/L, making harvest difficult at lower salinities. However, Günther (1899) reported large floating rafts of cysts when the salinity was near 170 g/L, so additional work is needed, particularly at salinities near the ecological target level of 267 g/L.

The available data indicate that *Artemia* densities measured in Lake Urmia decline substantially with increasing salinities (Sima et al., 2021). When the lake was above 1274 m and salinity was 168 g/L, mean *Artemia* densities were 669/m^3 (Günther, 1899; Van Stappen et al., 2001). Subsequent measurements demonstrated that densities declined significantly to approximately 160/m^3 at salinities over 350 g/L (Dahesht et al., 2013; Hafezieh, 2016). However, the high variability in all of these studies demonstrate the need for more intensive field sampling to determine the true relationship between salinity and *Artemia* densities. Note that several measurements from these studies have found near-zero *Artemia* densities at salinities of 250–260 g/L, in contrast to significant densities at salinities above 300 g/L. The cause(s) of this discrepancy is unknown. Sima et al. (2021) summarized results of laboratory bioassays to determine the salinity tolerance of *A. urmiana* and found that the salinity allowing 50% survival of growing nauplii varied from 110 to 245 g/L (Agh et al., 2008; Larti et al., 2012; Mohammadi et al., 2009). This wide range is likely due to different experimental procedures used to test the *Artemia*.

Abbaspour and Nazaridoust (2007) derived the "Ecological Level" assuming that a salinity of 240 g NaCl/L (267 g/L total salinity) would be suitable for the maintenance of *Artemia*. However, Sima et al. (2021) pointed out that the "Ecological Level" is based only on anecdotal information. Sima et al. (2021) also indicated that the ecological level of 1274.1 may, at best, recover half of the pre-development densities of *Artemia* in Lake Urmia (Fig. 9) (Ghorbanalizadeh et al., 2020). The actual density of *Artemia* needed to support large bird populations is unknown.

Asem et al. (2016) lists a total of 225 bird species in Urmia National Park. The lake's aquatic habitat is used by one flamingo species (Phoenicopteriformes), 25 duck, goose, and swan species (Anseriformes), 50 sandpiper, plover and gull species (Charadriiformes), 12 pelican and cormorant species (Pelecaniformes), three grebe species (Podicipediformes), and two gannet and booby species (Suliformes). Although the hypersaline lake itself has supported bird species such as flamingos, it is likely that the

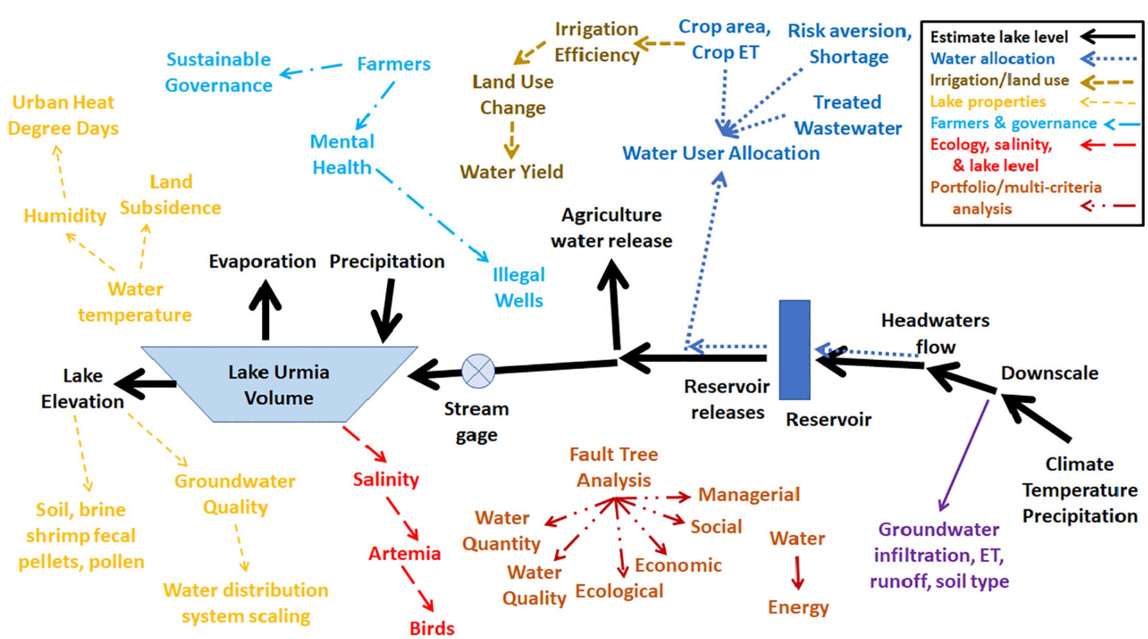

Fig. 9. Lake Urmia restoration topics that researchers linked. Colors and line dashes show the subsets of topics that multiple papers link. Line thickness indicates the number of papers that made the linkage.

freshwater and hyposaline wetlands at river outlets historically supported more birds, as has been found in Great Salt Lake (Paul and Manning, 2002; Wurtsbaugh, 2018) and Laguna Mar Chiquita in Argentina (Bucher, 2006). There are species lists but only one description of Lake Urmia bird populations and ecology. Sima et al. (2021) indicated that flamingos at Lake Urmia decreased from a mean population of 21,000 to nearly zero as salinities increased from 210 to over 350 g/L. Flamingo diets at Lake Urmia have not been assessed, although flamingos are assumed to feed on *Artemia*. Elsewhere, flamingos forage on a range of invertebrates, many of which live in hyposaline wetlands (Britton and Johnson, 1987). Surveys of bird populations in the lake and its wetlands are badly needed to help understand bird responses to changing lake levels.

Islands in Lake Urmia are important habitat for several bird species and two threatened mammals: Armenian wild sheep (*Ovis gmelini*) and Persian fallow deer (*Dama mesopotamica*) (Eimanifar and Mohebbi, 2007; Sima et al., 2021). With the desiccation of Lake Urmia, land bridges have developed that connect many of the islands to the mainland and allow islands to join. These bridges allow predators to invade and increase competition between the sheep and deer, which formerly inhabited separate islands (Sima et al., 2021). No studies have been published on the ecology of the species inhabiting the islands nor if the land bridges have caused the predicted problems.

We find:

1. Lake Urmia limnology and ecology research has a narrow focus on salinity and *Artemia*.
2. Descriptions of the food webs of the lake and adjacent wetlands will help managers determine the salinity and other habitat requirements of important species.

4.7. What research materials are available for others to access and how have managers engaged in research?

In a multidisciplinary recovery effort like for Lake Urmia, researchers and managers can share data and engage managers from the onset to build stronger collaborations and outcomes (Langsdale et al., 2013). In our review of the 544 papers on Lake Urmia, we found only one paper that made its data, models, code, directions, and other research materials publicly available (Sima et al., 2021). The ULRP started a data portal at http://ulsdi.ir/. The portal appears to have a small fraction of total Urmia data. For example, the portal does not include data from major studies by the Food and Agricultural Organization (FAO), JICA (2020), or Iranian consulting firms (Ab-Niroo, 1995; Ab-Niroo, 2017; Tarh-e-Noandishan, 2020; TU, 2017). The data have not been quality controlled. Other data in the repository for salinity, lake level, crop types, and yield should be synthesized. These low levels of data availability and reproducibility are also found in other fields like hydrology (360 papers; Stagge et al., 2019), computer systems science (613 papers; Collberg et al., 2014), psychology (100 papers; Aarts et al., 2015), and 204 papers published in *Science* (Stodden et al., 2018). To make materials available and reproducible, researchers need locally available and acceptable repositories, training in how to make materials available and reproducible (Rosenberg et al., 2020), and incentives to invest the extra time and resources to make materials available and reproducible (Rosenberg et al., 2021). Making research materials available will allow Lake Urmia researchers to more directly share their results with each other, managers, and the public to more quickly build on prior work. Making materials available will also allow researchers to cross-examine and compare their results and outcomes with other projects.

Three papers mentioned collaborations with stakeholders and lake managers. Gavahi et al. (2019) discussed with managers from the Ministry of Power their work to develop an adaptive forecast-based real time water allocation model for Bukan reservoir that partitioned water between the lake and other users. In their drought risk analysis, Moghaddasi et al. (2017) established a working group that organized workshops for stakeholders to determine feasible measures to reduce agricultural water allocation. As part of this effort, stakeholders identified water consumption figures for the three provinces. Sima et al. (2021) obtained Flamingo data from the Iranian Department of the Environment and shared their multi-lake level results with that agency and the Ministry of Energy. These three studies show a wide gap between Lake Urmia researchers and managers. Researchers can fill this gap earlier on in the definitional stages of projects to engage key stakeholders and managers and consult regularly with managers as a project progress (Langsdale et al., 2013). Researchers can narrow the gap by establishing more formal mechanisms to engage stakeholders and share research results.

Our review of the Lake Urmia literature found:

1. Just one paper made data, model, code, or research materials available for others to reuse (Sima et al., 2021);
2. Only three articles indicated they collaborated with stakeholders or managers;
3. Involve stakeholders and managers early in the definitional stage of research, and
4. Researchers can better promote their work and their findings to the public.

4.8. What research integrates across restoration topics?

Like data sharing, a multidisciplinary recovery project will benefit when the participants integrate and synthesize across topics and disciplines. Of the 544 Lake Urmia articles we reviewed, the team found 34 articles that integrated across two or more lake restoration topics. These papers were grouped into eight common linkages (Fig. 10, color intensity). Articles that only examined lake evaporation, precipitation, reservoir releases, or other singular topics were excluded from this integration analysis.

A first group of eight articles (Fig. 10, black) used all or some combination of future predictions of precipitation and air temperature, downscaling, headwater flows, river flows, basin- or sub-basin scale agricultural diversions, flow to lake, lake precipitation, and lake evaporation to estimate lake level (Ahmadaali et al., 2018; Alborzi et al., 2018; Ashraf et al., 2019; Chaudhari et al., 2018; Emami and Koch, 2019; Ghashghaie et al., 2014; Sarindizaj and Zarghami, 2019; Torabi et al., 2018). Another key motivator was to discern whether lake level decline was caused by climate or humans (see Section 4.1). Another key motivator was to determine whether the lake level would meet the ecological target of 1274.1 m (see Section 4.4). To link across restoration topics, these papers used individual models or cascades of models. The models included lake water balances (Ahmadaali et al., 2018; Alborzi et al., 2018; Hassani et al., 2020; Torabi et al., 2018), the Water Evaluation And Planning model (WEAP21) model (Ahmadaali et al., 2018), MODSIM-DSS (Alborzi et al., 2018; Emami and Koch, 2019), ratios of human withdrawals to basin inputs (Ashraf et al., 2019), a global water balance model (Chaudhari et al., 2018), the CORDEX regional climate model (Emami and Koch, 2019), Soil Water Assessment Tool (Emami and Koch, 2019), and systems dynamics modeling (Bakhshianlamouki et al., 2020; Ghashghaie et al., 2014; Hassanzadeh et al., 2012; Sarindizaj and Zarghami, 2019). These works show the important role mathematical models play in linking restoration topics.

A second group of six papers (Fig. 10, dark blue) explored water allocation and consumptive use among domestic, industrial, agricultural, and ecosystem water uses at basin, sub-basin, or finer spatial scales (Azizifard et al., 2020; Gavahi et al., 2019; KhazaiPoul et al., 2019; Taheri et al., 2019; Tarebari et al., 2018a; Tarebari et al., 2018b). Taheri et al. (2019) used precipitation data to estimate evapotranspiration and potential evaporation of crops and cropping patterns in three different years to estimate crop water demand. The other studies included reservoir operations. These studies characterized the tradeoff between cropped area, water allocated to agriculture, and the lake (KhazaiPoul et al., 2019); considered risk aversion, utility, supply, cost, and shortage objectives (Tarebari et al., 2018a; Tarebari et al., 2018b); allowed waste-water treatment and reuse (Azizifard et al., 2020); or used streamflow forecasts to inform reservoir operations (Gavahi et al., 2019). Azizifard et al. (2020) asked whether managers should discharge treated wastewater to agriculture or the lake. The

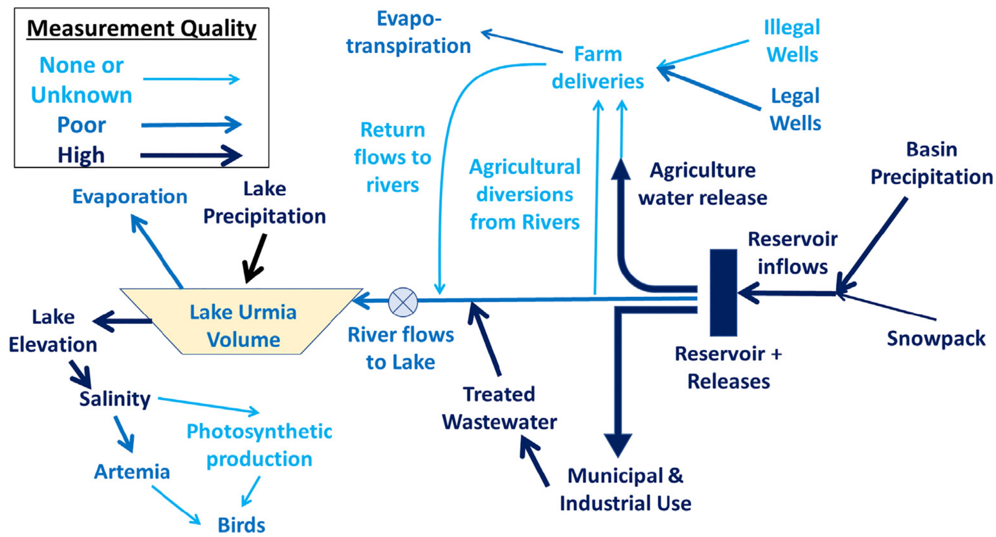

Fig. 10. Quality of water flow measurements in the Lake Urmia basin.

tools for these studies included SEBAL remotely sensed images and single-objective, multi-objective, and compromise optimization programs.

Three studies (Fig. 10) used spatially-explicit scenarios of increased irrigation efficiency and reduced agricultural withdrawals to show land use changes (Balkanlou et al., 2020) and estimate subbasin water yield (Shirmohammadi et al., 2020a; Shirmohammadi et al., 2020b). Balkanlou et al. (2020) also used their results to recommend numerous management strategies to address land use changes.

Several papers connected different lake physical properties to each other (Fig. 10, orange). Roshan et al. (2016) used the air pollution modeling software to connect lake elevation, temperature, humidity, and urban heating degree days. Hamzehpour et al. (2018) and Stevens et al. (2012) used soil sampling to reconstruct historical lake water levels dating back 180,000 years at the very course temporal resolution of 2000 to 55,000 years. Stevens et al. (2012) also used isotopes, brine shrimp fecal pellets, and pollen in their dating. Moghtased et al. (2012) used wavelet analysis to correlate surface water temperature and global positioning system measurements of land subsidence. Javadzadeh et al. (2020) found that 15 neighboring groundwater aquifers contribute water to the lake while the numerical simulations by Sheibani et al. (2020) found that, regardless of the lake bottom sediment thickness, fresh water principally flows to the lake rather than to the aquifers. Zazouli et al. (2018) sampled groundwater quality from around the lake and used measurements to estimate the effects of scaling and corrosion on urban water distribution systems. Jeihouni et al. (2018) found that groundwater levels are declining faster than lake level and salinity is increasing. These changes lead to a large net negative groundwater balance. Saatloo et al. (2019) and Saatloo et al. (2020) used general circulation models and the visual hydrologic evaluation of landfill performance (HELP) model to investigate the recharge rate of groundwater for different soil types on the west shore of Lake Urmia.

Two papers surveyed farmers to examine governance (Fig. 10, teal). Alipour and Olya (2015) found that a bottom-up stakeholder involvement is needed to arrive at stainable governance for the future. Zenko and Menga (2019) connected water stress, failing governance, financial difficulties, isolation, chronic psychological stress, intra-community conflicts, despair, hopelessness, depression, and anxiety. They also showed that these chronically stressed farmers lack access to government irrigation systems. Thus, the farmers dig and use illegal wells to survive.

Another group of papers (Fig. 10, red) linked lake elevation to total dissolved solids (Sattari et al., 2020) and lake elevations and volumes to salinity, brine shrimp, and birds (Abbaspour and Nazaridoust, 2007; Ghorbanalizadeh et al., 2020). These papers are further reviewed in Sections 4.2 and 4.6.

Three final papers (Fig. 10, maroon) used WEAP to attempt water and energy portfolio planning (Yazdandoost and Yazdani, 2019), fault tree (Gachlou et al., 2019) and multi-criteria analysis (RazaviToosi and Samani, 2019) to link water quantity, quality, ecological, economic, social, and managerial sub-systems. These later analyses assume stationarity of the inputs and are undertaken at such coarse spatial and temporal scales that results are difficult to believe or act on (Fig. 10, dashed maroon lines).

The visual depiction of linkages shows considerable work along the climate and agricultural water release pathways to estimate lake elevation (Fig. 10, black). A great disconnect exists between the modeling of water allocations and social, policy, and management factors that might implement recommendations. The social system of farmer behaviors, governance, mental health, and illegal wells also has poor coverage and is disconnected from other work. Treatment of groundwater is limited. Wetlands and other ecosystem services (see Section 4.6) are not integrated. Significant work remains to integrate numerous topics for effective lake restoration.

When we looked at integration across topics, we saw:

1. Lake Urmia research is fragmented,
2. The articles that did integrate across topics tended to focus on a pathway of climate, downscaling, reservoir operations, agricultural water releases, river flow, and lake water level,
3. We recommend linking water allocations to implementation, farmer decision making, mental health, groundwater use, governance, and ecology to improve research and management outcomes.

4.9. How to improve governance in the Lake Urmia basin?

All of the above activities can help build governance to implement and sustain lake stabilization and recovery efforts. Yet expanded agriculture, dam construction, and water mismanagement discussed in Section 4.1 contributed to poor governance. Eight additional papers diagnose problems of poor governance in one or a few sentences (Aghakouchak et al., 2015; Azarnivand et al., 2014; Bui et al., 2020; Dalby and Moussavi, 2017; Henareh et al., 2014; Pouladi et al., 2020; Schmidt et al., 2021; Zad et al., 2013). For example, Kurdistan has slightly underused water rights and is being pressured to release water to the lake (Henareh et al., 2014; Zad et al., 2013). This situation disenfranchises the ethnic Kurdish minority and contributes to ethnic conflicts that prevent cooperation on canal systems (Pouladi et al., 2020). The national economy experienced marked fluctuations. Experts and legislators do not directly talk to each other (Azarnivand et al., 2014). Flat water rates have led to environmental degradation and lake desiccation, salt deposits, health issues, outmigration, and collapse of the tourism industry. Farmers have drilled deeper wells and installed larger pumps (Schmidt et al., 2021). International sanctions prevented Iranians from purchasing agricultural technology and machinery to invest in farm water management, while local factors promoted agricultural expansion for short-term economic gain (Dalby and Moussavi, 2017). At the same time, farmers shifted to commodity-based agriculture and mono-cropping to grow higher yielding, more valuable, and more water intensive commercial crops like sugar beets and alfalfa (Henareh et al., 2014; Pouladi et al., 2020). Disputed statistics exist on the rate and volume of agriculture expansion in recent decades, despite specific and clear prohibitive legislation. Sugar beet production, for example, was to be limited to local factory capacity.

Nine additional studies went deeper into the causes of poor governance using surveys of 15 to 384 farmers (Abadi, 2019; Alipour and Olya, 2015; Khosravi et al., 2019; Mohammadzadeh et al., 2014; Zenko and Menga, 2019), as well as SWAT, game theory, MODSIM, and spatial soil or land-use modeling (Ahmadzadeh et al., 2016; Jeihouni et al., 2018; Mohammadpour and Bagheri, 2017; Torabi et al., 2018). These studies show that politicians focus on large, national, perceived strategic projects such as dams, while disregarding environmental impact assessments (Alipour and Olya, 2015; Khosravi et al., 2019), and farmers can use nearly all available water without penalties (Dalby and Moussavi, 2017; Khosravi et al., 2019; Torabi et al., 2018). More positive farmer attitudes toward water saving are an important antecedent to reviving Lake Urmia, as are place attachment, environmental attitudes, and environmental beliefs (Abadi, 2019; Shojaei et al., 2019).

Apple orchardists do not adopt drip irrigation because of the high cost of irrigation systems, a lack of water well licenses, and the need to produce alfalfa and manure for fodder and higher income (Mohammadzadeh et al., 2014). Farmers are psychologically stressed, and that is contributing to their isolation, community conflicts, despair, depression, and anxiety (Zenko and Menga, 2019). Some farmers are unaware of or do not care about environmental issues or lake desiccation. Projects to create pressurized irrigation systems can improve water productivity, but they reduce diversions and return flows and do not save water or return more water to the lake (Ahmadzadeh et al., 2016). Another challenge is a significant lack of cooperation between the government and the local community (Alipour and Olya, 2015). Saltwater intrusion can increase the risk of secondary soil salinization, reduce crop yield, decrease crop lands area, threaten agricultural livelihoods, and lead to desertification and dust storms (Jeihouni et al., 2018). Neither West nor East Azerbaijan provinces are incentivized to deliver their full environmental water allocations to the lake (Mohammadpour and Bagheri, 2017).

Sixteen of above studies also provide recommendations to improve governance (Abadi, 2019; Aghakouchak et al., 2015; Ahmadzadeh et al., 2016; Alipour and Olya, 2015; Balkanlou et al., 2020; Dizaj et al., 2019; Henareh et al., 2014; Khosravi et al., 2019; Mahdavi et al., 2019; Mohammadpour and Bagheri, 2017; Mohammadzadeh et al., 2014; Oftadeh et al., 2016; Sarindizaj and Zarghami, 2019; Schmidt et al., 2021; Shojaei et al., 2019; Valizadeh et al., 2020). Below, we organize the recommendations to improve Lake Urmia governance by level of engagement, category, and depth of analysis (Table 5). These recommendations suggest working with farmers to improve the process, provide more continuity and transparency, and engaging at levels of time commitment from one-time to near continuous. Improving governance requires advancing a large number of approaches on the ground simultaneously (Sarindizaj and Zarghami, 2019).

The ULRP has taken some recommended steps to improve governance such as encouraging farmers to plant higher-value crops like medicinal crops, transplant rather than plant seed, reduce high-water-demanding crops such as sugar beets, introduce drought-tolerant grain cultivars, and prevent second cropping. The government approved and implemented water right quotas (for the lake and agriculture sector) but amounts often change in response to temporal basin water availability and politics. Many steps remain, including finding ways to reach many farmers and sustain their engagement. These observations serve as wake-up calls for academics to take on-the-ground action to follow their recommendations and improve governance.

Table 5
Recommendations to improve Lake Urmia governance in four categories at different levels of effort (■ one-sentence recommendation, ▶ recommendation backed by survey, modeling, or analysis).

Improve hydrology		
One time	■	Restore Zagros forests (headwaters)
	■	Reverse Zarinehrud to Tabriz pipeline
Improve economic conditions		
One time	■	Provide regulated subsidies to farmers to adopt less water consuming crops & improve irrigation efficiency (4 studies)
	■	Increase water and energy prices
	■	Provide alternative livelihoods—algae, mineral, medicinal plants, mud/tourism
	▶	Provide low interest loans for water conservation plans
	▶	Increase attractiveness of rural areas by introducing new employment
Improve process		
A few times	■	Engage stakeholders and incorporate local knowledge
Near continuous	■	Introduce strategic environmental assessment of policies, plans, and programs
	■	Foster dialogue between physical and social scientists
	▶	Repeat process to build trust and cooperation
	▶	Encourage farmers to participate in environmental NGOs
	▶	Develop farmer values and beliefs in communities
	▶	Put farmer communities in charge of water governance
Work with farmers		
One time	■	Reduce direct evaporation losses (3 studies)
	■	Reduce cultivated area, limit high water consuming crops, encourage deficit irrigation (4 studies)
A few times	▶	Identify and publicize intention to conserve water
	▶	Disseminate technologies such as mulching, drought-resistant seeds, smart water control systems, modern irrigation methods, drip and sprinkler irrigation
	▶	Provide workshops on irrigation practices
	▶	Change irrigation scheduling, depth, and timing; planting date; and crop pattern to increase farmer revenue and decrease water use.
	▶	Develop livestock farming
	▶	Emphasize risk perception, self-efficacy, and potential negative effects
	▶	Increase long-term production
	▶	Leverage place attachment (2 studies)
	▶	Facilitate more contact with agricultural extension services (2 studies)
	▶	Establish farmer sense of responsibility to deal with water scarcity
Near continuous	▶	Establish pilot farms
	▶	Use combination of methods to reduce water use

Better governance is critical to stabilizing and recovering Lake Urmia. Possible ways to improve governance include the following:

1. Improve farmer income and health.
2. Increase farmers' conservation attitudes and trust in their government with better community engagement, communication, transparency, continuity, and accountability.
3. Empower farmer unions so that they can engage more directly in governance and local policies.
4. Give farmers, managers and government officials more flexibility to respond to changes in water availability.

5. Next steps

Numerous opportunities exist to improve on and synthesize prior research to help stabilize and recover Lake Urmia. Synthesis requires coupling the human and natural components of the system – consider the entire basin by bringing together pieces from the answers to the nine popular and research questions. Admittedly, these next steps are easier to describe than implement.

5.1. Improve water monitoring throughout the basin

Measure to manage. We found many suggestions to reduce agricultural water use, observe water rights, limit high water demanding crops, improve irrigation technologies, and restrict further conversion of rain-fed farming to irrigated farming. These efforts will succeed when they are coupled with flow monitoring throughout the Lake Urmia basin. Several of the Lake Urmia water balance components are poorly measured or are not currently measured (Fig. 10). We recommend establishing a continuous water accounting and auditing system for Lake Urmia Basin. This system will help researchers, managers, and stakeholders to track the numerous human and natural components that effect the basin water balance shown in Fig. 10. Monitoring will help better understand changes in each component over time. More systematic monitoring can provide Lake Urmia managers more insights on where and how to encourage users to save water. A systematic measurement system can also enhance transparency of water data and policy that, in turn, can facilitate stakeholders' involvement in Lake Urmia conservation projects and verify the farm water saving techniques discussed in Sections 4.5 and 4.9.

5.2. Improve livelihoods for local communities beyond agriculture

Together, farmers, researchers, extension agents, and supporting non-governmental organizations can identify and facilitate lower-water-intensive livelihoods as an alternative to agriculture. Alternative livelihoods can include *Artemia* harvesting, birding, ecotourism, handcrafts, mud baths, boating, and magnesium and potash mining. New livelihoods in *Artemia* harvesting and birding will require sustained ecological data collection and descriptions of the food webs that support target species (Sections 4.6).

Opportunities to improve water productivity and add value to existing agricultural livelihoods may include the following:

- Launch new nursery businesses to grow seedlings for transplant rather than direct sowing of seed (specifically for sugar beets).
- Cultivate higher value medicinal, salt-tolerant, or dust-stabilizing crops.
- Process harvests of existing or new crops into products such as herbal extracts, jams, juices, or canned, baked, or other goods and. Label these products as originating from Lake Urmia.
- Market products inside and outside the basin under a theme like "*Help People, Help the Lake*." Market these products in ways that encourage Iranian customers to buy goods that advance lake restoration and improve the Urmia economy.

A better cropping project called *Behkasht* introduced plans such as implementing revised cropping patterns, growing crops with lower water demand, planting short season crops, transplanting rather than planting from seed, and placing limits on high-water-demand crops (HajGhadiri, 2020).

These changes require investment in local communities and businesses to build infrastructure that can support and sustain a wider variety of livelihoods. The following are some examples. (1) Improve infrastructure—build new education facilities and communications networks and expand energy generation capacity. With this infrastructure, residents will have incentives to stay and pursue alternative livelihoods rather than migrate to urban areas. Building this infrastructure can create jobs and new non-agricultural livelihoods. (2) Start working with the farmers who already have attachment to the place and positive attitudes toward water conservation. (3) Offer financial and other incentives to encourage early adaptors to try new crops, irrigation technologies, and dust mitigation methods. (4) Develop communication platforms to link early adopters, non-governmental organizations, extension agents, and other farmers to speed information spread.

The governmental and private sectors can invest to create alternative livelihoods in the Urmia basin. This investment will be challenged because alternative livelihoods to agriculture are not widely developed in Iran. Also, Lake Urmia is a National Park, which precludes some commercial activities, and international investment in Iran is very limited.

5.3. Monitoring program for key lake limnology and ecological health

Limited information exists on key aspects of Lake Urmia limnology and ecology such as *Artemia*, aquatic invertebrates, birds, and food webs, including what birds feed on (Section 4.6). This ecosystem information can help managers identify the timing, magnitude, and duration of water saving practices. We recommend a lake monitoring program to include at least monthly sampling at 10–15 stations and at different depths in the lake, local wetlands and main river bays. Parameters to monitor include:

- Salinity, ionic composition, temperatures, depths, *Artemia* densities and size structure, chlorophyll concentrations, benthic invertebrates such as brine flies (*Ephydra* sp.), and the densities and seasonality of all dominant birds that use the lake.
- Nutrients, dissolved oxygen, algal species composition, wetland salinity, depth, invertebrates, and bird densities.
- Survey of island, wetland, and playa habitats for bird and mammal use, foraging, and nesting.
- Lake bathymetry (storage-area-elevation relationships).

Because Lake Urmia is now severely desiccated and is at salt saturation, studies of salinity effects on invertebrates and birds will need to turn to other saline lakes such as the Great Salt Lake (Baxter and Butler, 2020), Mono Lake (National Research Council, 1987), and the Salton Sea, or, alternatively, use macrocosms or tanks (Barnes and Wurtsbaugh, 2015; González et al., 1998; Herbst, 2006; Herbst and Blinn, 1998). Store collected data in public repositories (Section 4.7) and use data to validate remote sensed and modeling products. We also recommend the use of local knowledge in addition to the governmental data to cover data gaps and motivate public participation.

5.4. Manage for multiple lake levels and ecological services

Nearly all of the work we reviewed focused on restoring Lake Urmia to the uniform ecological level of 1274.1 m. Future lake restoration efforts will benefit by considering more diverse lake levels and the diverse ecosystem services that those diverse levels provide. As monitoring of wetlands and lake limnology progress (Section 5.3), information about the diverse ecosystem services will improve over time. The lake level will fluctuate from year to year, so managers, academics, and researchers can add scenarios representing different water levels to their projects, models, and analysis to consider this uncertainty and highlight the benefits and drawbacks of different levels for different ecosystem services.

5.5. Adapt human activities to available water

Human activities, agricultural diversions, dams, and mismanagement of water played an outsized role in lake level decline (Section 4.1). They illustrate a win-lose tradeoff between water for agriculture and the lake (Sima et al., 2021). This tradeoff will turn to lose-lose (shrinking pie) if basin temperatures increase, precipitation declines, runoff declines, evapotranspiration increases, or lake evaporation increases. The lose-lose tradeoff may be converted into more positive processes by giving agricultural, municipal, industrial, and lake water managers more flexibility to adapt their consumption and conservation decisions to year-to-year variations in temperature, precipitation, runoff, lake evaporation, and evapotranspiration. For example:

1) Adapt lake water deliveries to Lake Urmia's only outflow—evaporation—which varies greatly according to the measurement method used (Table 6) and from year to year (Fig. 2 in Appendix A). When annual lake deliveries exceed evaporation, the lake level will rise and advance recovery efforts. If lake water deliveries equal evaporation, the lake

Table 6
Reported Lake Urmia evaporation rates.

Study	Time period	Method	Evaporation rate (mm year^{-1})
(Sadra, 2004)	Long term average from 1955 to 1985	Modified monthly pan evaporation from stations around the lake	1222
(Sima and Tajrishi, 2015)	2010	BREB (Bowen Ratio Energy Balance)	1136
(ULRP, 2015)	Unknown	Class A Pan	1250 to 2000
(Alborzi et al., 2018)	Validated for 1982–2002	ULRP data (2016)	1100
(Torabi et al., 2018)	Unknown	Potential evaporation data from OWWMP (2011)	1050 to 1550
(RSRC, 2018)	Water year 2016–2017	BREB (1st method)	1367
		BREB (2nd method)	1697
		Dalton	2001
		Ryan-Harlemen	991
		Priestley-Taylor	1411
		DeBruin-Keijman	1571
		Penman	1997
		Stephen-Stewart	855
		Papadakis	580
(ULRP, 2020)	2000–2017	DeBruin-Keijman	783–1216
(Safaie et al., 2021)	2016	COARE algorithm	1238

level will stabilize, and restoration efforts will delay one year. If lake water deliveries are less than lake evaporation, the lake level will fall and set back lake restoration efforts. Annual lake evaporation gives managers a target for lake water deliveries.

2) Give lake managers an annual financial budget. Let managers temporarily lease water from agricultural users and require that recipients of payments invest some of that money in new farm water conservation efforts. New investments in farm water conservation will keep farmers in agriculture, keep money in the local economy, and make more water available for lease in future years (Rosenberg, 2021b). New investments also give agricultural users time to develop conservation ethics and practices.

A challenge of these adaptive approaches is monitoring agricultural water deliveries, return flows, lake deliveries, and lake evaporation (Section 5.1 and Fig. 11) and managing in the face of temporal and methodological variability (Table 6; Fig. 2 in Appendix A). For example, lake salinity, area, and vapor pressure are needed to estimate lake evaporation (Mohammed and Tarboton, 2012). Despite available models, eight Lake Urmia studies used 13 estimation methods and showed evaporation varied from 580 to 2000 mm per year.

5.6. Define restoration objectives for changes in the causeway

Once the suggested monitoring program for key lake limnology and ecological health (Section 5.3) is underway, use the observational data to assess the impact of the causeway and structural changes to it on the lake ecosystem (Section 4.3). Extra openings to the causeway may improve the flow exchange between the northern and southern sections of the lake and help restore the natural flow circulation in the lake. At the same time, mobilization of material from the filled-rock embankment may change salinity distribution, ions concentrations, salt dissolution and precipitation processes, bathymetry, *Artemia*, and other key components of aquatic ecosystems. Managers and researchers can use numerical models, physical models, or both types of models to predict and validate changes to the causeway.

5.7. Share data, models, code, directions, and research materials

Only one article we reviewed publicly shared data, models, code, and directions (Section 4.7). The ULRP is working to deploy a data repository and data policy for Lake Urmia work. Until the repository comes online, researchers can post materials on discipline-specific repositories such as Hydroshare.org, general repositories such as Harvard Dataverse, Figshare, Dryad, and GitHub, or institutional repositories. After the Urmia data repository is available, investigators can create resources that link to the original data sources. Sharing data, models, code, and directions will require Urmia researchers to develop new skills. To incentivize researchers, make data sharing a requirement for approving new projects. Train researchers in proper data sharing techniques, create data repositories that are easy for the public to access, and encourage citizens to share their data (citizen science). Researchers who publicly share their data will increase their impact by increasing the number of persons who can access, use, and extend their work. These researchers will also improve trust in their work, reduce effort to respond to data requests, make work easier for future students, and narrow the gap between researchers and practice.

5.8. Better connect research topics, researchers, stakeholders, and managers

We found a low level of integration across restoration topics and only three articles that mentioned work with stakeholders and managers (Sections 4.7 and 4.8). We want to see Lake Urmia researchers work more with each other, stakeholders, and managers. These collaborations will help future research consider and identify linkages between the lake and adjacent wetlands and to connect surface and groundwater, illegal water withdrawals, and agricultural return flows. Further, we see the need to connect lake inflows, salt precipitation, salt dissolution, evaporation, and lake bathymetry that together affect lake volumes and level. Lake restoration requires integration.

We offer these ideas to bring researchers, stakeholders, and managers together:

- Conduct pilot studies at the local farm level to demonstrate practical field water and crop management techniques to improve crop water productivity under existing irrigation systems.
- Link researchers to agricultural extension agents, farmer-formed engagement agencies, water diversion cooperatives, and canal water masters.
- Hold workshops, meetings, 1:1 visits, and conferences to help managers, stakeholders, and researchers connect with each other. Focus efforts on describing problems, brainstorming collaborations to address problems, and launching new projects.
- Encourage ministries to get involved and support university projects. University administrators can negotiate broad cooperative agreements with ministries.
- Encourage Ministries to share data with researchers.
- Provide training for interdisciplinary teams of researchers, stakeholders, and managers to find a common work language.
- Recognize, reward, and prioritize funding for interdisciplinary works within universities, government, and other organizations.
- Engage international organizations such as the United Nations Educational, Scientific and Cultural Organization (UNESCO), United Nations Development Programme (UNDP), World Meteorological Organization (WMO), World Bank (WB), and Islamic Development Bank (IDB). Over

the past five years, the ULRP has engaged with international organizations, and such engagements can deepen by holding more events to connect researchers.

5.9. Better couple Lake Urmia's human and natural systems to improve function and management

Each of the prior 8 recommended next steps couples one or more human and natural system components to improve lake function and management. Couplings can help capture two-way feedbacks between lake water deliveries, conservation, reservoir releases, and causeway breaches and natural system components such as lake level, lake evaporation, lake salinity, and food webs that support migratory birds. Couplings can also help convert technology-focused fixes such as inter-basin diversions or treatment of urban wastewater into longer-term and more holistic solutions that improve livelihoods, encourage water conservation, change behavior, and sustain lake water deliveries. Better couplings can give managers more flexibility to adapt restoration efforts over time to changing conditions.

Lake Urmia researchers and managers can also better couple human and natural system components by growing local cooperation efforts into sustainable two-way exchanges with international organizations that seek to recover other saline lakes such as Great Salt Lake, Aral Sea, Owens Lake, etc. Two way exchanges can celebrate joint successes, identify common challenges, experiment, and learn together. Sustainable exchanges require sustained funding and sustained interest.

6. Conclusions

Restoring coupled human-natural systems requires integration across many science, technology, engineering, management, and governance topics. Here, we synthesized 544 peer-reviewed articles published up through September 2020 on the desiccation, stabilization, and nascent recovery of Lake Urmia in northwest Iran. We found that:

1. Expanding irrigated agriculture, dam construction, and mismanagement impacted the lake more than temperature increases and precipitation decreases.
2. Dust from Lake Urmia's exposed lakebed negatively impacted human health.
3. Researchers disagree on how a new causeway breach will impact salinity, evaporation, and ecosystems in the lake's north and south arms.
4. Most researchers tried to restore to a single, uniform, government specified lake level of 1274.1 m thought to recover *Artemia*.
5. The ULRP motivated and funded researchers to work on a large and growing number of peer-reviewed lake stabilization and restoration projects.
6. Ecology and limnological studies mostly focused on salinity, *Artemia*, and Flamingos.
7. Few studies shared data and only three studies reported engagement with stakeholders or managers.
8. Research is fragmented across disciplines.
9. Numerous suggestions to improve farmer livelihoods and governance require implementation.

We see an overarching next step for restoration is to couple human and natural system components. Coupling can capture two-way feedbacks, convert technology-focused fixes into longer-term and more holistic solutions, and give managers more flexibility to adapt restoration efforts over time to changing conditions. Example next steps that couple include:

a. Describe and monitor the system's food webs, hydrologic, and human components.
b. Adapt lake water deliveries, conservation, reservoir releases, and causeway breaches to monitored system components such as lake level, lake evaporation, lake salinity, and bird populations.
c. Improve livelihoods for poor, chronically stressed farmers beyond agriculture.
d. Manage for diverse ecosystem services and lake levels.
e. Engage more segments of society to formulate and execute restoration work.
f. Integrate across restoration topics while build capacity to share data, models, and code.
g. Cultivate longer-term two-way exchanges and public support.

These next steps apply to different degrees to degraded saline lakes worldwide and to ecosystems across Iran such as Zayander rud, Govkhooni, Anzali, Neiriz, Shadegan, and Hamoon.

Our work is a product of an ongoing international collaboration between researchers with joint interests to tackle natural resources management problems. These problems are large, complex, and long lasting. Progress requires diverse and integrated expertise, deep engagement, steady funding, and dogged perseverance in the face of many domestic and international challenges that are usually beyond researchers' control. We welcome interested people from Iran and other countries. Visit https://digitalcommons.usu.edu/lake_urmia/ to join our efforts.

Ethical approval

All authors have seen and approved the manuscript and have contributed significantly to preparing the manuscript.

Consent to participate

All authors have read and understood the provided information and have had the opportunity to ask questions. We understand that our participation is voluntary and that we are free to withdraw at any time, without giving a reason and without cost. We understand that we will be given a copy of this consent form. All authors share equal responsibility for errors of commission or omission.

Consent to publish

All authors give their consent for the publication of the paper to be published in this Journal. We confirm that we have seen and been given the opportunity to read both the Material and the article to be published. We understand that papers in this journal may be available in both print and online and will be available to a broader audience. Therefore, anyone can read material published in the Journal.

Availability of data and materials

The data, code, and editable versions of figures are available at Rosenberg (2021a).

CRediT authorship contribution statement

MP and DER drafted the Abstract, Introduction, Next Steps, and Conclusions. WW drafted the Study Area and Section on Limnology and Ecology. DER drafted the Literature Review Methods and sections on Integration, Availability of Materials, Stakeholder and Manager Engagement, and Governance. AS drafted the section on Dust/Health Impacts. SS and SEN drafted the section on Restoration to Levels besides 1274.1 m. YAG and AS drafted the section on the Causeway and Salinity. OR, BK and MP drafted the section on Humans, Climate, or Both. OR, MP and SS drafted the section on ULRP Efforts.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

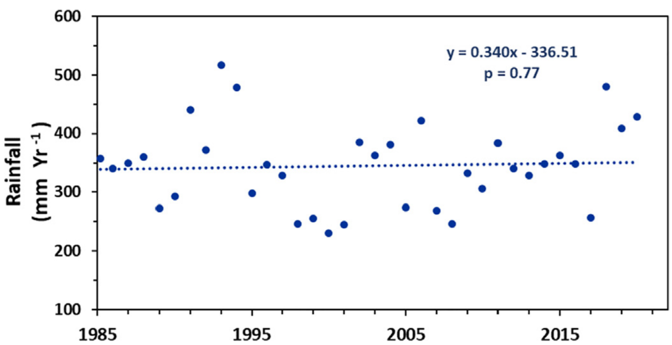

Fig. 1. Mean annual basin precipitation over time.

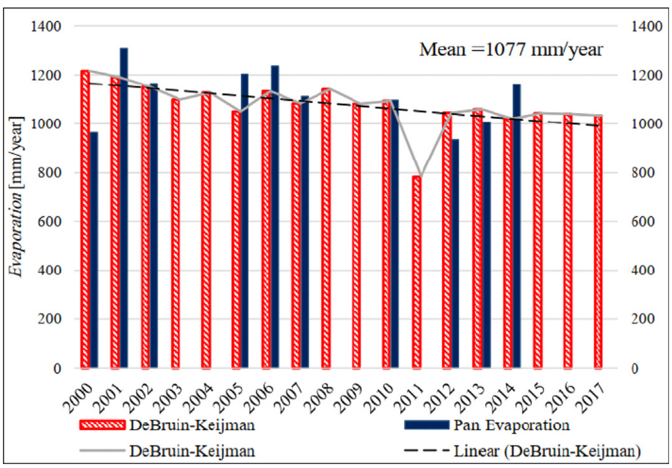

Fig. 2. Comparisons of annual evaporation rates of Lake Urmia calculated based on the DeBruin-Keijman method with evaporation pan data measured at Golmankhaneh station from 2000 to 2017 (ULRP, 2020).

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