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Desiccation of a saline lake as a lock-in phenomenon: A socio-hydrological perspective

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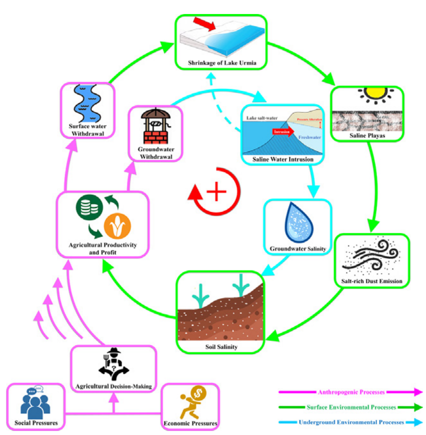
HIGHLIGHTS

- Lake Urmia appears to be on a lock-in toward a desiccation driven by human actions.
- The system of feedback loops that generates the lock-in is not fully known.
- Exploratory evidence on social and physical processes linked to the issue is gathered.
- Data suggests that the soil salinity issue has little affected the vegetation cover.
- Building on these, we propose a system of feedback loops generating the lock-in.

GRAPHICAL ABSTRACT



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ABSTRACT

Understanding of how anthropogenic droughts occur in socio-hydrological systems is critical in studying resilience of these systems. This is especially relevant when a "lock-in" toward watershed desiccation occurs as an emergent outcome of coupling among social dynamics and surface and underground water processes. How the various processes collectively fit together to reinforce such a lock-in and what may be a critical or ignored feedback worsening the state of the socio-hydrological systems remains poorly understood. Here we tackle this gap by focusing on the case of Lake Urmia in Iran, a saline lake that faces the same fate as that of Aral Sea due to over-extraction of water sources

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that feed the lake. We develop an integrative, system-level understanding of how various anthropogenic, surface and underground environmental processes collectively generate the water scarcity and soil salinization issues in the study case. To this end, we investigate a paradoxical phenomenon wherein the increase of soil salinity has not noticeably affected the level of vegetation cover in Lake Urmia Basin. The outcome of our analysis may provide useful insights for informing policymakers how to cope with drought and water scarcity issues in many fragile saline lakes around the world that are currently under threat by overexploitation.

1. Introduction

Coping with drought and freshwater scarcity has been a major challenge throughout human history. Studies of these issues have often focused on assessing the drought conditions of freshwater bodies (Falkenmark, 1997; Rodell et al., 2018; Chiang et al., 2021), investigating factors that affect the ecological state of these resources (Falkenmark, 2003; Biswas and Tortajada, 2011; Gerten et al., 2013; Pahl-Wostl et al., 2013), or examining human response and adaptation to water scarcity with an eye to sustainability (Kumar et al., 2020; Aghaie et al., 2020; Yu et al., 2020; Pouladi et al., 2019, 2021). These works have typically been static in nature—the biophysical, social, economic, or governance contexts in which a drought or scarcity occurs are assumed fixed or non-interactive. Recently, scholars have begun to view the issue through a dynamic system-level lens and focus on how droughts emerge from an array of interactive physical and social processes in coupled human-water systems (Sivapalan and Blöschl, 2015; Di Baldassarre et al., 2019; Yousefi et al., 2019; Wei et al., 2020; Aghaie et al., 2021). A growing number of studies report such emergent dynamics and systems of feedback loops that reinforce or worsen water scarcity: *supply-demand cycle* (increases in water supply leads to growth that in turn generates higher water demand), *irrigation efficiency paradox* (increasing the efficiency leads to higher consumptions), *reservoir effect* (over-reliance on reservoirs increases vulnerability to droughts), and *rigidity trap* involving water infrastructure (emergent vulnerability from long-term accumulation of complexity and stresses in reservoir or irrigation infrastructures) (Osman et al., 2016; Di Baldassarre et al., 2018; Krueger et al., 2020; Tzanakakis et al., 2020).

At the core of the phenomena above is a “lock-in” toward an undesired state or regime driven by human adaptation. In response to a water challenge, system components (including people) adjust in ways that alleviate the challenge and reduce the system sensitivity in the short run, but the outcome is often a more deeply entrenched lock-in and increased system-level fragility to the same issue in the long-run (Meng et al., 2016; Yu et al., 2015; Yu et al., 2016; Dolan et al., 2021). Breaking out of this lock-in is a difficult task. A system of feedback loops that generates such a lock-in may be unknown or only partially known. This lack of system-level understanding, in turn, may undermine effective management. This suggests that, rather than asking what is the “independent effect” of a factor on freshwater scarcity, we ought to be asking “what is the system of feedback processes that lead to freshwater scarcity, and what is the hidden or ignored feedback that critically affects which lock-in emerges?”

Here we project this question to the case of anthropogenic drought at Lake Urmia in Iran, one of the largest lakes in the world that appears to be on a lock-in toward a severe desiccation driven by human actions, a fate similar to that of the Aral Sea (AghaKouchak et al., 2015). Specifically, we develop an integrative understanding on a system of interlinked processes across physical and social domains in the case area that may be driving the problem but remains underexplored. Lake Urmia case presents a complex story of human-induced water scarcity that is all too familiar. In the past two decades, the water level in Lake Urmia has dwindled by about 90% without adequate restoration because of continuous agricultural development and the consequences have been catastrophic to the area's ecosystem, public health, tourism, agriculture, and livelihoods (Balkanlou et al., 2020; Schmidt et al., 2020; Tabrizi et al., 2020; Dehghanipour et al., 2020). Although disruptive factors such as climate change, cyclic droughts, and economic issues such as international sanctions add to worsening of the crisis in Lake Urmia, evidence suggests that human actions and governance challenges, rather than environmental drivers, are the major causes of the water crisis in Iran (Alizadeh-Choobari et al., 2016; Khazaei et al., 2019; Panahi et al., 2020; Tarkeshdouz et al., 2021; Pouladi et al., 2019, 2020, 2021).

Previous studies investigated important factors affecting the crisis, including socioeconomic conditions and inefficient agricultural activities (Eamen and Dariane, 2014; Hesami and Amini, 2016; Abadi, 2019; Molajou et al., 2021), unrestrained activities such as illegal over-extraction of groundwater resources, increased surface water impoundment in reservoirs, and over-consumption of surface water resources for irrigation purposes (Vaheddoost and Aksoy, 2018; Schulz et al., 2020), as well as governance designs that are mismatched with local realities (Danesh-Yazdi and Ataie-Ashtiani, 2019; Pouladi et al., 2021). Another important factor that may be in play is the hyper-salinity of the lake, which can cause environmental issues when the lake shoreline recedes due to desiccation (Eimanifar and Mohebbi, 2007; AghaKouchak et al., 2015). Studies have shown that the dried areas of the lakebed contain eight billion tons of salt, which makes it a main regional aerosol source (Gholampour et al., 2015; Mardi et al., 2018; Ghomashi and Khalesifard, 2020). It is suggested that the surfaces of the dried-up lakebed, which are exposed to wind erosion, have become an active source of salt-rich dust emissions causing the increase in soil salinity, disruption of lake biota, increase in soil albedo, and decrease in agricultural productivity in the area (Alizade Govarchin Ghale et al., 2017; Effati et al., 2019; Gorji et al., 2020). Additionally, it is reported that such phenomena originating from the lakebed has also played a role in the spread of respiratory, skin, and cardiovascular diseases for populated areas within the radius of 250 km from the lake (Micklin, 2007; Garousi et al., 2013; Sotoudeheian et al., 2016; Danesh-Yazdi and Ataie-Ashtiani, 2019; Gorji et al., 2020; Harati et al., 2021). However, insights into how these various processes collectively fit together to reinforce the lock-in and what may be the critical or ignored feedbacks deepening the lake desiccation issue have been less clear. Such insights on Lake Urmia are critical for improving our understanding of when and how anthropogenic droughts emerge and persist, and may have implications for other saline basins around the world facing similar situations.

The concept of lock-in has roots in systems science and is described as a situation of path dependency or inertia in which a set of positive feedback loops generate a reinforcing cycle toward a particular qualitative behavior of a system (Staal et al., 2020). In resilience thinking applied to social-ecological systems, related notions are rigidity and poverty traps. Rigidity trap occurs when system components become highly connected through more controls and a greater complexity develops in system structure (Boonstra and De Boer, 2014; Carpenter and Brock, 2008). The result is a lock-in toward losses in diversity and flexibility, high interconnectedness, and low potential for change. In contrast, poverty trap is a reinforcing cycle toward low connectedness and resilience and low potential for change due to lack of resources (Barrett et al., 2016). Another related notion in resilience thinking is critical feedback or “slow” variable that determines critical transitions in multi-stability systems (Crépin, 2007; Walker et al., 2012). It has been shown that whenever there is a marked change in system behavior, there is a corresponding change in a critical feedback affecting a slow variable in the system dynamics (Boonstra et al., 2016). Thus, identification of a critical feedback that may be ignored or unknown is thought to be crucial for enabling resilience management. Studies of lock-in effect have advanced through a gradual process of one study building on another:

begin by identifying a phenomenon of interest motivated by a few empirical cases, follow by proposing a conceptual or systems model of interacting processes capable of replicating the phenomenon, and then firmly ground the idea and model of the phenomenon on an empirical foundation by systematically building evidence across multiple places (Kurata et al., 2007; Charman and Wells, 2012).

Our goal in this paper is taking a step in this path of progression—propose a conceptual and integrative system of feedbacks behind the water scarcity problem of Lake Urmia in ways that capture previously ignored or less appreciated feedbacks. This approach is in line with the recent developments in the field of socio-hydrology wherein a phenomenon is first identified through analysis of temporal and spatial data on a specific case. Such phenomena then inspire different modeling paradigms to further investigate or predict such coupled human-water systems (e.g., the modeling paradigms proposed in van Emmerik et al., 2014, Liu et al., 2015, and several others that were initially inspired by the 'pendulum swing' phenomenon presented in Kandasamy et al., 2014 and Liu et al., 2014). Our findings are expected to provide a robust foundation for following studies to numerically model such emergent dynamics not only in the case of Lake Urmia Basin but also other similar saline lakes around the world.

This paper proceeds as follows. In the following section, we elaborate the study system and methods used. Next, we present a set of exploratory evidence on multiple interlinked processes in different domains that may be associated with the lock-in toward the desiccation in Lake Urmia. We then develop an integrative understanding of these processes, and use this understanding to propose a conceptual framework of a system of feedbacks driving the lock-in. In the process, we highlight emergent linkages between social and environmental systems, and suggest a way forward for controlling the lock-in based on the knowledge developed.

2. The study system and methods

Lake Urmia, one of the saltiest lakes in the world, is located in the northwest of Iran, between West Azerbaijan and East Azerbaijan provinces (Fig. 1). Depending on the balance among flow volume entering the lake and evaporation, the lake's total surface area ranges from 4750 to 6100 km^2 (Ghale et al., 2019). The climate of the region is continental and influenced by the surrounding mountains. Air temperature goes up to 40 °C in summer and varies between −20 °C and 0 °C in winter. The average annual precipitation in the basin is between 200 mm and 300 mm (Eimanifar and Mohebbi, 2007). The measured minimum and maximum water elevation of Lake Urmia were about 1270.047 m in October 2015 and 1278.386 m in June 1995, respectively.

The socio-hydrological condition of the region is grim. Severe declines in the lake water level (by about 90%) have occurred over the past two decades because of the impact of climate change, wasteful use of water resources, and the development of more agricultural lands (Danesh-Yazdi and Ataie-Ashtiani, 2019; Nikraftar et al., 2021a). With a three-fold increase in the agricultural area and a gradual shift from planting crops with low or medium water consumption to growing water-intensive crop types that attract higher profits, the rate of desiccation has increased significantly, to the point where it has become a national issue (Bakhshianlamouki et al., 2020). The total acreage under irrigated farming in the lake basin is approximately 511,926 ha, of which 70% is farmland and 30% is orchard (Shadkam, 2017). Currently, the lake water salinity has increased by more than 400 g/L, which has negatively affected the aquatic ecosystem in the lake (Seifi et al., 2020; Nikraftar et al., 2021a).

2.1. Key data sources

As a first step to developing an integrative understanding of the lock-in, we conducted analyses of various datasets and indices that describe the time and spatial patterns of soil salinity, vegetation cover, and groundwater anomaly of Lake Urmia Basin region. A salinity index was analyzed to understand change in the spatial distribution of soil salinity levels. A vegetation index was used to capture the variations in vegetation cover. A precipitation and evapotranspiration index was examined to understand the climatic conditions. Finally, groundwater anomaly was evaluated to understand change in groundwater table. These pieces of evidence are combined with socioeconomic trends data in the next section to identify plausible processes associated with the lock-in. Below, we describe key components of our data analysis and their details.

2.2. Salinity Index (SI)

Satellite images are employed in this study to delineate the soil salinity in Lake Urmia Basin. The images were acquired from Landsat-5 OLI for the years 2000 to 2012, and Landsat-8 OLI for the years 2013 to 2020. Following Gorji et al. (2020) and Douaoui et al. (2006), we derived the salinity index (SI) for the July to October, the dry period during which soil moisture is low. Our approach is consistent with previous studies that used near-infrared and visible bands of satellite images to derive soil salinity indices and soil salinity maps (Rahmati and Hamzehpour, 2017; Davis et al., 2019; Peng et al., 2019; Abuelgasim and Ammad, 2019; Yu et al., 2018). Linear analyses have been generally applied to correlate field measurements with Remote Sensing data (Allbed and Kumar, 2013). Many studies

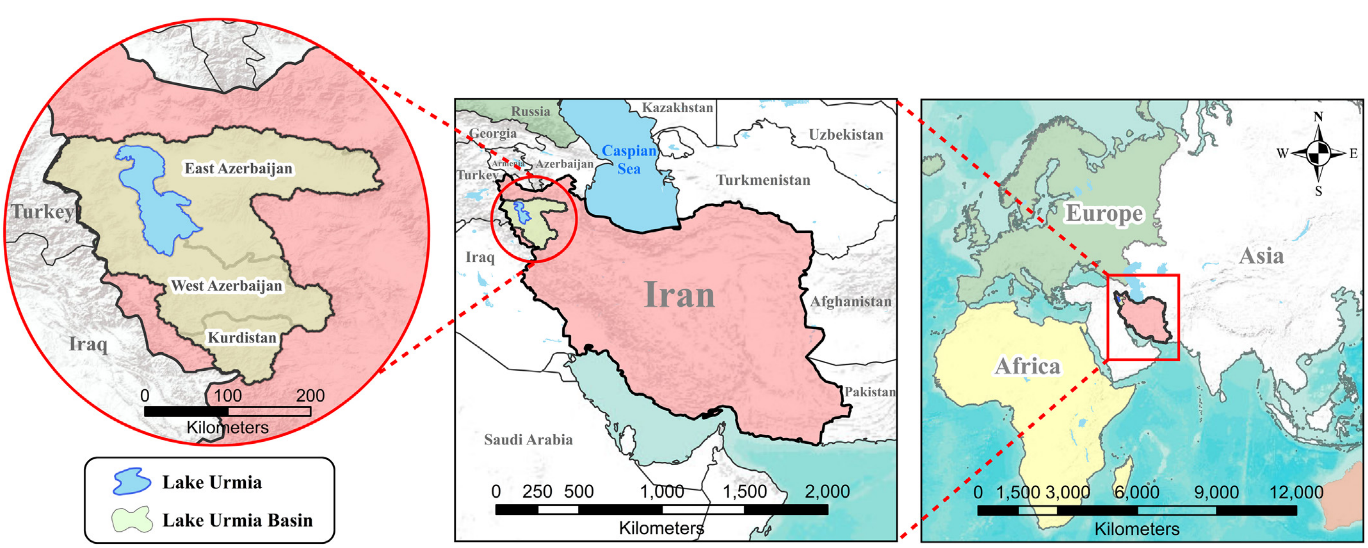


Fig. 1. The location of Lake Urmia basin, Iran.

have also employed diverse soil salinity indices, either coupled or independently with different Remote Sensing methods to predict soil salinity (Fourati et al., 2015; Taghadosi and Hasanlou, 2017; Afrasinei et al., 2017; Morgan et al., 2018; Taghadosi et al., 2019). However, there is no specific remote sensing technique or soil salinity index that can support soil salinity prediction with a high R^2 value in all regions of the world. Thus, researchers utilize the most relevant index and remote sensing technique based on the environmental and physical properties of their study region (e.g., Nouri et al., 2018; Ivushkin et al., 2019).

The data analyzed here is based on the work of Gorji et al. (2020) and Douaoui et al. (2006). Gorji et al. (2020) used two groups of datasets comprised of field measurements and satellite images for providing the soil salinity maps in Lake Urmia Basin. They collected 70 soil samples from the top 20 cm of barren land at the end of the dry season when maximum salt accumulation can be found on the top layer of soil. In order to find the optimum correlation between spectral values of indices with EC values, Gorji et al. (2020) examined more than 10 salinity indices. Among the tested indices, a salinity index proposed by Douaoui et al. (2006) revealed optimum results of correlation with EC values provided in field measurements by R^2 of 0.73. The salinity index (SI) is constructed by averaging two spectral bands, i.e., $SI = (Band\ Green + Band\ Red)/2$.

2.3. Groundwater anomaly

We evaluated the groundwater anomalies of the study region by quantifying its total water storage anomalies (TWSA) (e.g., Yang et al., 2020). This was done by making use of satellite measurements of the Earth's time-variable gravity from the Gravity Recovery and Climate Experiment (GRACE). GRACE provides new data for monitoring TWSA at the regional and global scales with a surface spatial resolution of 300 km. We used GRACE Release 06 Mascon Solutions 68, produced by the Center for Space Research (CSR, https://www2.csr.utexas.edu/grace/RL06_mascons.html) to extract groundwater storage anomaly. The mascon solutions can be applied in both regional and global scales and provides a heigh signal-to-noise ratio (Rodell et al., 2018), which is more suitable for such arid areas as the Lake Urmia region. The Mascon solutions have the advantage of smaller leakage error in comparison with other solutions such as spherical harmonic solutions. The CSR Release-06 is available at a 0.25° resolution. Furthermore, the Mascon solution is ready to use in hydrological assessments without any additional preprocessing steps.

The GRACE TWSA contains seasonal fluctuations and long-term linear trends of total water storage including groundwater storage, soil moisture, surface canopy water, and snow water equivalent. The groundwater storage anomalies (GWSA) have been calculated based on the equation $GWSA_{i,\,n} = TWSA_{i,\,n} - SMA_{i,\,n} - SWEA_{i,\,n} - CWSA_{i,\,n} - SWSA_{i,\,n}$, where i and n stand for month (i.e., $i = 1, 2, \ldots, 12$) and years (i.e. $n = 2002, 2003, \ldots, 2019$), respectively. The terms *GWSA*, *TWSA*, *SMA*, *SWEA*, *CWSA* and *SWSA*, stand for time series of groundwater storage anomaly, total water storage anomaly, soil moisture, snow water equivalent, canopy water storage, and surface water storage, respectively. Data on soil moisture, snow water equivalent, and canopy water storage are obtained from GLDAS 2.1 datasets.

2.4. Standardized Precipitation Evapotranspiration Index (SPEI)

We make use of the standardized precipitation evapotranspiration index (SPEI) to assess the trend of drought in the study region. SPEI is an extension of the widely used Standardized Precipitation Index (SPI) and captures both potential evapotranspiration (PET) and precipitation. It is increasingly applied to analyze the trend of drought. SPEI represents the degree of deviation of wet conditions and regional drought from the climatological mean, through standardizing the difference between precipitation and potential evapotranspiration. Therefore, unlike the SPI, the SPEI captures the principal impact of raised temperatures on water demand. The SPEI can be measured on a range of timescales from 1 to 48 months.

We used SPEI based on the method presented by Vicente-Serrano et al. (2010). The main computation steps of the index are as follows: 1) defining the balance between potential evapotranspiration (PET) and precipitation (Pre) (Pre-PET) at different time scales (3- and 12-months timescale for this study) and 2) fitting Pre-PET series into log-logistic probability distribution to obtain the SPEI index series. The basin averaged SPEI datasets used in this study have been downloaded from United Nations Office for Outer Space Affairs (UNOOSA) website (https://un-spider.org/links-and-resources/data-sources/spei-global-drought-monitor-csic).

2.5. Standardized Vegetation Index (SVI)

We used the standardized vegetation index (SVI) to assess the agricultural drought in a region. This index is a standardized form of normalized difference vegetation index (NDVI) and is calculated through measuring NDVI. NDVI is the ratio of the difference of red and near-infrared reflectance (NIR) over their sum, i.e., $NDVI = (NIR - Red)/(NIR + Red)$. Radiometric measurements of red and NIR are needed to calculate NDVI. We employed the Advanced Very High-Resolution Radiometer (AVHRR) data acquired by the National Oceanic and Atmospheric Administration's (NOAA) satellites to extract NDVI. AVHRR sensor series have been in operation since 1978 on the TIROS-N satellite, and have been equipped on the NOAA Polar Orbiting Environmental Satellite (POES) series from July 1981 to the present, providing global daily coverage at coarse spatial resolution (Giglio and Roy, 2020). AVHRR sensors have five radiometric channels including non-overlapping channels of NIR (730–980 nm) and red (585–680 nm), which enable the computation of NDVI. The daily monitoring frequency of the AVHRR sensors facilitates the detection of seasonal development of NDVI across the earth. The newest version of the GIMMS NDVI dataset (3rd generation, version 1; available at https://nex.nasa.gov/nex/projects/1349) spans from 1982 to 2020. For the Lake Urmia Basin, we extracted averaged time series of NDVI and converted them to SVI using the technique described by Farahmand and AghaKouchak (2015) and Nikraftar et al. (2021a, 2021b).

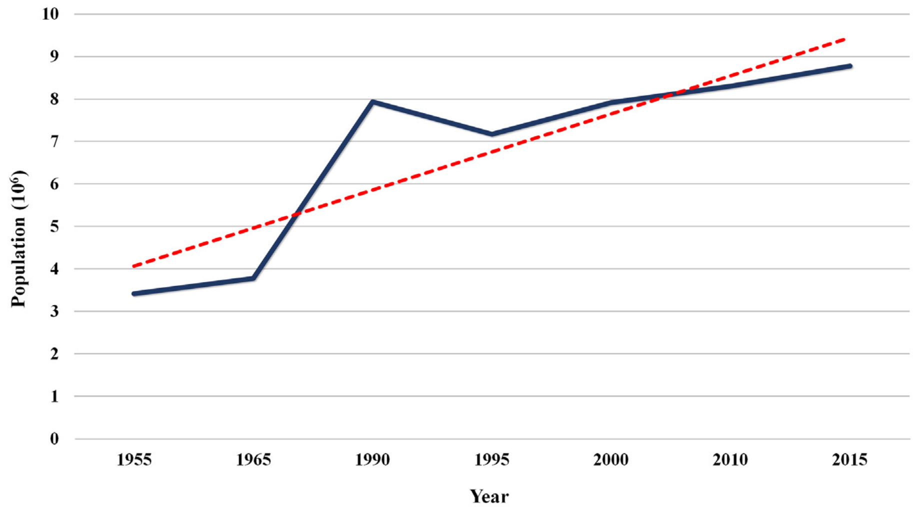
3. Exploratory evidence: key processes of the lock-in toward the lake desiccation

We integrate scattered notions and construct a set of exploratory evidence on a system of interactive processes across social, hydrological, meteorological, as well as soil and agricultural domains that taken together, may be driving the lock-in toward the region's anthropogenic drought. The time and spatial patterns of soil salinity, vegetation cover, and groundwater anomaly and the socio-economic trends data were analyzed for this purpose. Our analysis focused on the hyper-salinity of Lake Urmia, its role as a main aerosol source in the region, and how the resulting aerosol effect and human response may have created a socio-hydrological feedback loop that progressively exacerbates the lake desiccation. Below, we provide exploratory evidence for each of the key processes identified.

3.1. Anthropogenic processes

Looking back into history, before 1963, a feudalistic land tenure system was widespread in the Urmia Lake Basin. Peasants were obliged to live on the lands owned by aristocrats and give them homage, labor, and a share of the produce. In 1963, a nationwide land reform called the “White Revolution” was launched, which in effect ended the feudal system in the region and forced the landlords to sell their lands to the rural peasants at 30% below the market price as a 25-year loan at very low-interest rates (Lenczowski, 1978). Through the process, a peasant family obtained 3 or 4 parcels of land with an average area of 2–3 ha. The region witnessed a substantial population growth in the last half a century (Fig. 2a) and as a result, agricultural lands were successively subdivided into smaller parcels to support new farmers. This trend continued to the point that small-holder farming was becoming economically less viable (Schmidt et al., 2020).

Small-holder agriculture became dominant and the core of the economic structure in the Urmia Lake Basin. To support increased agricultural activities, the state expanded water reservoirs and water storage facilities in



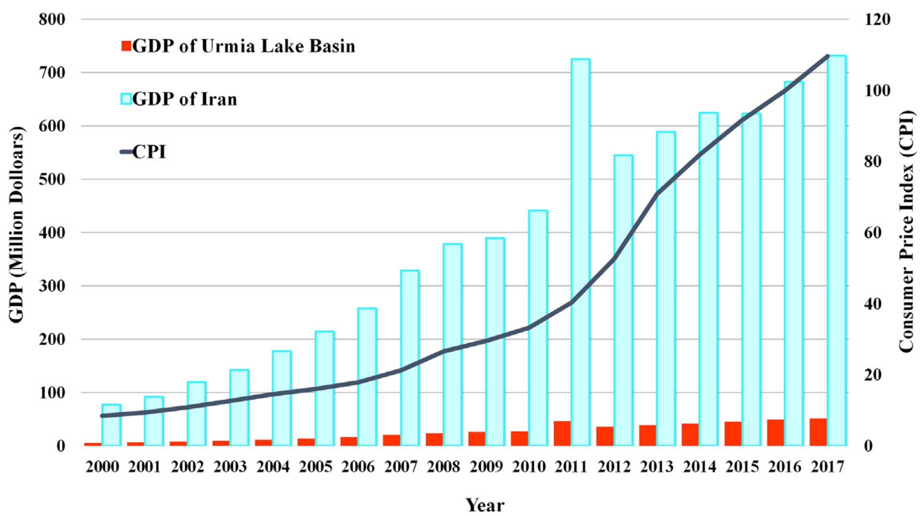


Fig. 2. (a) Population growth in Lake Urmia Basin from 1955 to 2015; (b) Economic indicators including Gross Domestic Product (GDP) of Iran and Lake Urmia Basin, and Consumer Price Index of Iran from 2000 to 2017 (source: Central Bank of Iran).

the region, and regulated the streams feeding Lake Urmia to increase the volume of water for irrigation. This led to a significant reduction in the lake's inflow (Fig. 3a). With the aid of water infrastructure (Fig. 3b and c), agricultural activities greatly expanded in the region and reached the point where the ecological capacity of the basin is maximally challenged (Ghale et al., 2019). Currently, the total area of the irrigated lands in the basin is approximately 511,926 ha, 70% of which are farmlands, and 30% are orchards (Shadkam, 2017).

The economic decline of Iran has also added to the financial hardship of small-holder farmers. In response, many farmers switched to growing water-intensive crops such as sugar beet and alfalfa. These crops yield higher profits in comparison to other conventional crops in the region, especially crops low in water consumption such as barley and corn (Dalby and Moussavi, 2017). Significant over-extraction of surface water and groundwater resources ensued, and the use of low-efficiency irrigation systems (which accounts for almost 33% of the irrigation systems in the region) only made things worse (Anvari and Valaie, 2015; Schmidt et al., 2020). This situation is a prime example of “tragedy of the commons', where individually rational human actions in the use of open-access commons such as unregulated or poorly regulated freshwater resources, when aggregated, result in a collectively worse outcome (e.g., resource depletion) for everyone (Hardin, 2009).

The trends in three socioeconomic measures (Fig. 2b), the Consumer Price Index (CPI) of Iran, the Gross Domestic Product index (GDP) of Iran, and the GDP of the Lake Urmia Basin, suggest the growing economic hardship of the small-holder farmers in the study region. The CPI measures price change from the perspective of consumers, while GDP pertains to price change from the perspective of domestic production of services and goods. As can be seen from Fig. 2b, the CPI is following an upward trend, but the GDP of Lake Urmia Basin is not increasing correspondingly. This growing disparity between the CPI and the regional GDP suggests that the region's small-holder farmers are under pressure to increase their agricultural productivity and income. This, in turn, indicates that farmers are motivated to elevate their agricultural productivity through expansion of agricultural farmlands, cultivating water-intensive, higher-value crops. Field observations are consistent with this view (e.g., Schmidt et al., 2020; Pouladi et al., 2021). More farmers are turning to intensive farming with crops high in water consumption, citing their economic condition as the main reason (Danesh-Yazdi and Ataie-Ashtiani, 2019; Pouladi et al., 2019).

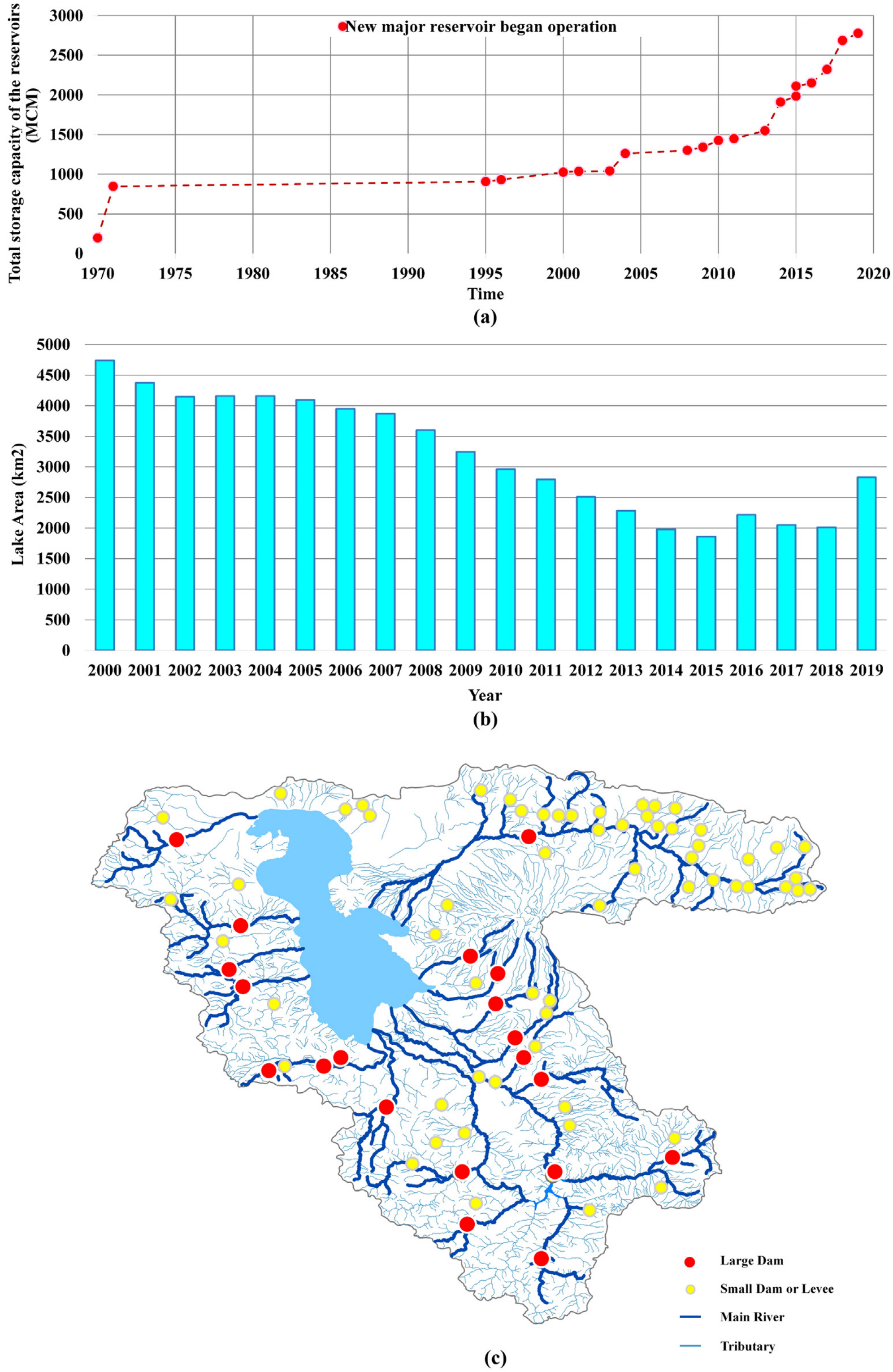


Fig. 3. (a) The timeline of the operation of major dams and corresponding total storage capacity of the reservoirs in Lake Urmia Basin; (b) The shrinkage of Lake Urmia surface area (km^2); (c) The location of the main reservoirs and small dams or levees in Lake Urmia Basin.

Studies also suggest that loopholes in governance from insufficient consideration of the local social conditions and subtleties of human-water interactions are contributing to the water problems in the Lake Urmia Region. Competitions over water resources, ethnic conflicts, lack of sufficient agricultural knowledge, wrong environmental beliefs, and insufficient public participation in planning and implementation of management actions, among others, undermine the water governance efforts underway in the region, leading to unsatisfactory outcomes in terms of water sustainability (Pouladi et al., 2021).

3.2. Surface environmental processes

Increased use of surface water for irrigation has caused the hypersaline lake waterbody to be less fed by inflowing streams. The surface area of the lake has shrunk substantially in the last two decades as a result (Fig. 3a). A critical outcome of this shrinkage is the widespread recession of shorelines that leaves salt-rich dried-up lands behind and exposed to wind shear forces as schematically demonstrated in Fig. 4 regarding Lake Urmia Basin. Exposure of these hypersaline playas to wind shear forces, in turn, can result in aeolian dispersion of salt-rich dusts over a long distance. As suggested by the figure, the saline dust emissions have been expanding in the basin through the past two decades (details are presented in Fig. 5). An irreversible and direct repercussion of saline dust emissions from desiccated areas of the lake is soil salinization, which would be followed by vegetation degradation.

Fig. 5 suggests that there has been continuous salinity expansion over Lake Urmia Basin in the past two decades. For this study, we categorized the SI into (a) low salinity (SI: 0.2–0.3), (b) medium salinity (SI: 0.3–0.6), and (c) high salinity (SI: 0.6–1) based on the areal scale of the expansion and the intensity of the salinity. Fig. 5c shows the main surges in the high salinity class took place in years 2000, 2006, 2011 and 2015. The main surges in the medium salinity class (Fig. 5b) happened in years 2000, 2003, 2006, 2009, 2011, and 2018. And, the surges in low salinity class (Fig. 5a) were mostly followed the average pattern of the medium salinity class except for the year 2003, when medium salinity class were dominating. However, the most significant point about low salinity class is its expansion in highest areal scale with a peak of 19,929.62 km^2 in year 2009 at Lake Urmia Basin.

Fig. 6 illustrates the water level of Lake Urmia in those years wherin a peak in SI value happened. It should be noted that we masked the shape of the lake waterbody in the year 2000 from the basin to calculate the SI from 2000 to 2020 in computation processes. As can be seen in Fig. 6, the peaks in SI mainly happened in late Summer (September) and early Fall (October) when water level of the lake were almost at its lowest. Subsequently, there have been highest amount of saline playa areas being exposed to wind erosion. Thus, the increase in emission of salt-rich dusts over the basin caused major surges in soil salinity. Moreover, in addition to the role of human activities in the expansion of salinity as discussed earlier, the intensification in the density of salt-rich dust emissions is correlated with the dry and wet periods. In this regard, we employed the SPEI to determine the drought, as it captures the main impact of increased temperatures on water demand by taking into account both potential evapotranspiration and precipitation. Table 1 represents the values of SPEI index and its corresponding drought categories.

Fig. 7a demonstrates the variations of SPEI over 3 and 12-month timescale from 2000 to 2019. 3-month timescale indicates a high temporal frequency of dry and wet periods. With increasing timescale, 12-month, drought and wet periods demonstrates a lower temporal frequency and a longer duration. This is because the 3-month timescale for presented indices captures short-terms (seasonal) characteristics of drought, while the 12-month timescale visualizes the long-term characteristics of drought.

A comparison between Fig. 6 and Fig. 7a indicates that the surges in the Salinity Index took place when Lake Urmia Basin were undergoing dry conditions. On the other hand, when the basin experienced

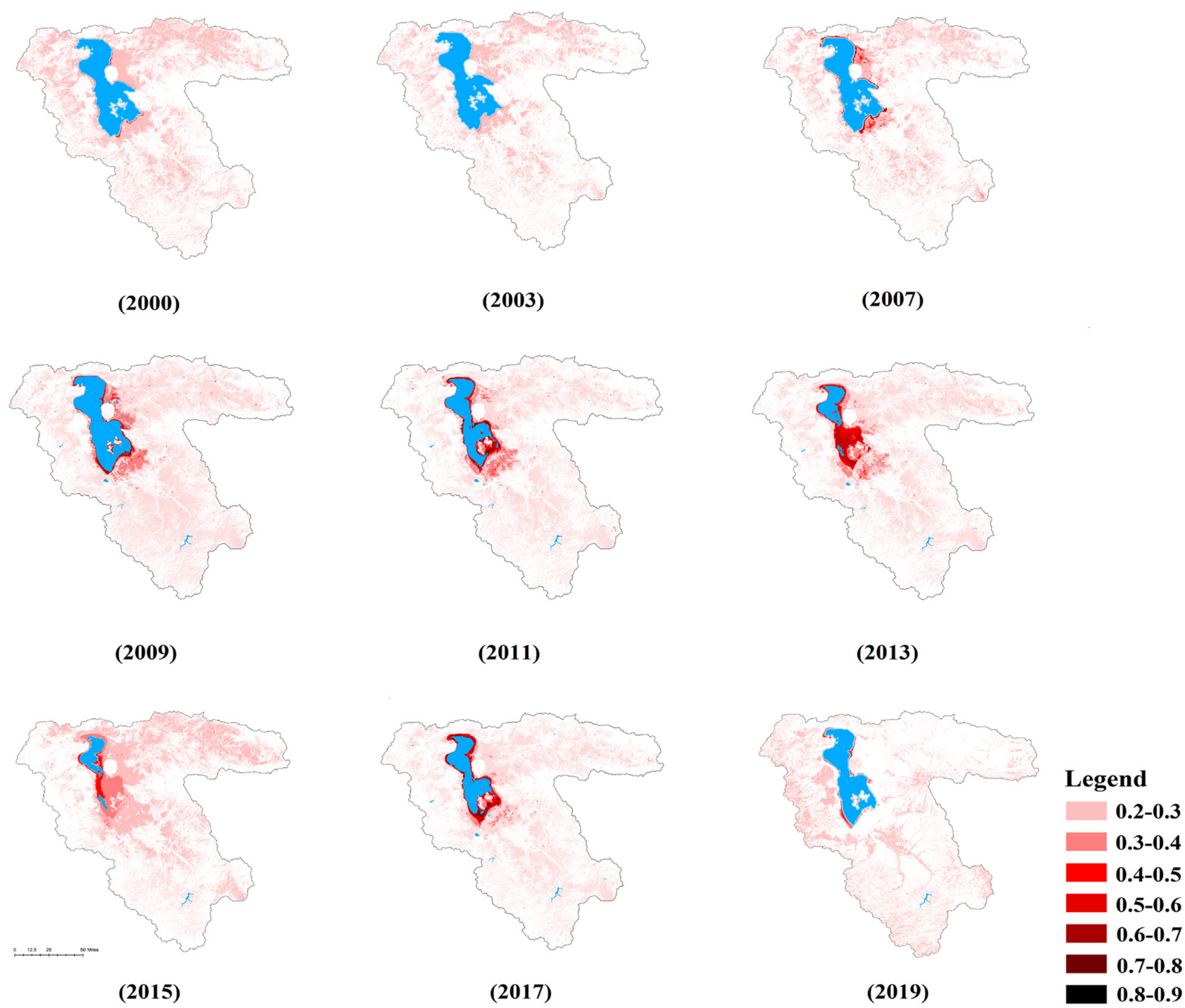


Fig. 4. Schematic overview of salinity expansion over Lake Urmia Basin and increase in area of saline playas due to shrinkage of Lake Urmia.

Fig. 5. Changes in the soil salinity of Lake Urmia Basin assessed by Salinity Index (SI). The SI of Lake Urmia Basin from 2000 to 2020 has been categorized based on the areal scale of the expansion and the intensity of the salinity into (a) low salinity (SI: 0.2–0.3), (b) medium salinity (SI: 0.3–0.6), and (c) high salinity (SI: 0.6–1).

wet condition, there were declines in Salinity Index (see Fig. 6). While it is expected that the increased soil salinity should follow some sort of decrease in the vegetative cover for the upcoming agricultural years, SVI highlights a paradoxical situation in which despite the drought condition and increase in soil salinity, farmers were maintaining a high level of agricultural productivity. Fig. 7b illustrates the variations in the SVI through 3 and 12-month timescale from 2000 to 2020.

Another comparison between Fig. 7a and b indicates two contrasting behaviors during 2000 and 2020 between SPEI and SVI. First, based on SVI 3-month timescale, wet conditions in SVI anomalies are dominated during the 2000s to 2006s, whereas the SI (Fig. 5) shows surges in soil salinity, and SPEI index (Fig. 7a) shows a multiple consecutive prolonged drought condition in this period, with an exception of slight wet condition during 2003–2004. Second, according to SPEI 3-month (Fig. 7a), multiple prolonged drought conditions occurred from 2007 to 2014, with particularly

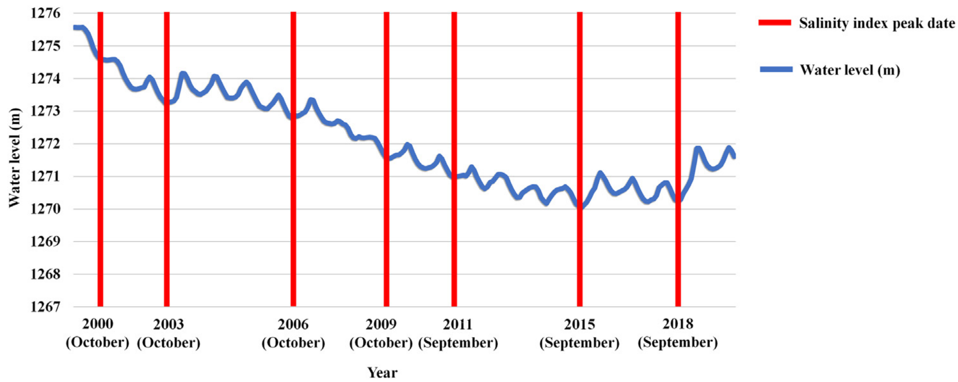


Fig. 6. The main surges in Salinity Index happened at the time of shore-line recessions of Lake Urmia (2000 – 2020). At these times, more saline playas got exposed to the wind shear force, and correspondingly, there were considerable increase in salt-rich dust emissions that resulted in increase in soil salinity.

severe events during the 2007–2009, 2011–2012, and 2014. These extreme long drought events are more vivid in SPEI 12-month timescale. The 3-month and 12-month SVI indices shows an extreme drought state during 2007–2008 and prolonged drought event for 2011–2012 and 2014. Also, we observed that the wet events for SVI during 2011–2012 and 2014 are quite short and have lower magnitudes. This is because the dominant signals of NDVI are related to agricultural activities in the region and vegetation cover in non-agricultural areas were affected by prolonged drought. In 2010 when a moderately wet condition occurred, the 3-month SVI shows a strong positive anomaly, which imply that in addition to the agricultural growth, the vegetation cover in non-agricultural areas is functioning in the presence of precipitation. The 3-month SPEI shows a relatively severe wet condition in years 2015 and 2016, while the 12-month SPEI shows a near normal condition since it does not response strongly to sudden seasonal wettings after the prolonged drought of 2012–2014 (Fig. 7a). On the other hand, we observed three consecutives wetting and strong drying phases in 3-month SVI with a strong wetting episode of SVI during 2015 during 2015–2017 (Fig. 7b). These repeating strong abnormal drought episodes after wettings may be explained through highlighting that the NDVI signal in Lake Urmia Basin, which is mostly related to agricultural growth and non-agricultural vegetative areas, could be still under stress as a result of the previous drought event. We also observed similar situation in 2018–2019 strong wetting periods in which SVI shows more severe condition compare to SPEI.

3.3. Underground environmental processes

Looking at the big picture, comparison between SI, SPEI, SVI, and Lake Urmia water level indicates that while the soil salinity was booming, farmers managed to increase their agricultural productivity through compensating for their extra water need from the groundwater resources (Fig. 8a).

We show in Fig. 8a that the first considerable steep decline in average groundwater anomaly (i.e. significant drop in groundwater table) took place in 2006 during which there have been an extreme surge in almost all classes of soil salinity (Fig. 6). Afterward, the steepest decline in the average groundwater anomaly in the whole Lake Urmia Basin happened in the year 2007–2008, which can be the consequence of the surge of soil salinity in 2006 as well. In 2011–2012, another episode of extreme surge in soil salinity took place in the whole basin (Fig. 5). Similarly, the second steep decline in the average groundwater anomaly can be seen in 2011–2012. Next, third steep decline in the average groundwater anomaly took place in 2014–2015, which is the result of cumulative impact from both drought condition and increase in soil salinity. Moreover, despite the fact that it has been anticipated that the increase in soil salinity negatively affect the agricultural productivity, the impact of increasing soil salinity has been mainly offset by more groundwater abstraction. Fig. 9 illustrates the groundwater anomaly caused by agricultural activities in Lake Urmia Basin.

The amplifications in groundwater anomaly can be also related to (a) the drought condition, (b) the considerable increase in soil salinity due to salt-rich dust emissions from the lake's saline playas, and (c) increase in the salinity of the groundwater itself. The salinization of the groundwater is a direct consequence of over-exploitation of groundwater resources. In particular, as the groundwater table in the area gain a downward trend, the pressure alteration prompts salt-water intrusion from lake's bed to surrounding aquifers.

There were also socio-economic drivers that contributed in the intense changes of groundwater anomaly. For instance, in 2010, to manage groundwater overexploitation, the Parliament of Iran issued a prohibition on illegal drilling of wells for irrigation but allowed active illegal water wells, which were drilled before 2006 to be authorized in some cases. It was assumed that the law would stop additional drilling of illegal wells, but in fact, it incited many farmers to drill wells quickly and claim that they had been drilled before 2006. Another shortcoming was the absence of considerable penalty for those drilling new wells after 2010. Thus, the number of illegal wells increased, and many abandoned illegal wells were revived by drilling deeper to get a water extraction license. Another socio-economic driver can be related to the management actions such as deauthorizing water right from farmers with an equivalent value of 500 MCM of water per year. Consequently, to avoid any potential economic losses, farmers considered illegal groundwater abstractions for irrigate their farmlands (Pouladi et al., 2021). In all cases, there was a need and motivation to increase the amount of water for irrigation purposes to overcome the salinity and provide enough water for maximum agricultural productivity, which contributed in the pressure alteration of water tables and salt-water intrusion as discussed earlier. In this regard, Fig. 8b and c demonstrate the average increase in groundwater electrical conductivity (EC) in both West Azerbaijan and East Azerbaijan provinces.

Table 1
SPEI categories.

Category	SPEI
Extreme drought	Less than − 2.00
Severe drought	− 1.50 to − 1.99
Mild drought	− 1.00 to − 1.49
Near normal	− 0.99 to + 0.99
Mildly wet	+ 1.00 to + 1.49
Severely wet	+ 1.50 to + 1.99
Extremely wet	More than + 2.00

4. Socio-hydrological feedback and lake desiccation

Thus far, we have used scattered data and notions to build exploratory evidence on various processes that may be associated with desiccation in

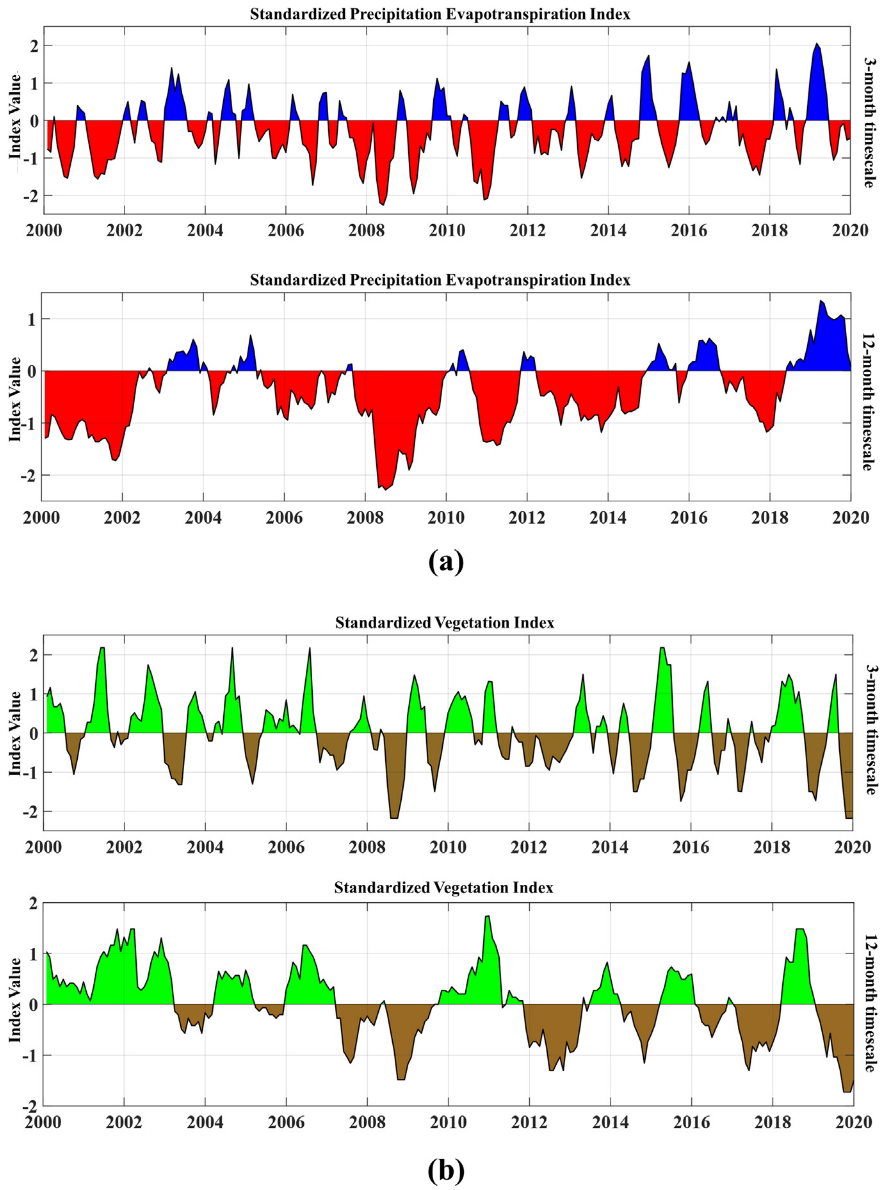


Fig. 7. (a) Standardized Precipitation Evapotranspiration Index (SPEI) representing the climatic conditions of Lake Urmia Basin; (b) Standardized Vegetation Index (SVI) representing agricultural drought of Lake Urmia Basin, 2000–2020.

Lake Urmia. Although deeper investigation into each process is important, it is equally important to develop insights into how these processes fit together and collectively generate the lock-in toward desiccation and what may be ignored or less-appreciated components of the feedback. This integrative understanding, however, has been less clear. Here, building on the preceding analyses, we propose a system of feedback loops that encapsulates various surface and underground environmental processes as well as anthropogenic activities within Lake Urmia Basin. We posit that the lock-in toward desiccation is an emergent outcome of this system of processes that constitute a complex socio-hydrological feedback.

The proposed system of socio-hydrological feedback consists of two feedback loops—outer and inner loops—that compound the lock-in. The outer loop (the outer circle in Fig. 10) is driven by the surface environmental and anthropogenic processes. It starts with farmers' agricultural decision-making centered around making changes in their crop-type, adjustments in their farmlands, and how much irrigation water to use for maintaining agricultural productivity. This decision-making is influenced by profitability considerations and socioeconomic pressures (box 1 of Fig. 10). Following the standard economic theory of self-interested behavior, it is safe to assume that farmers prefer higher profits. At the same time, there are social comparison and economic pressure that motivate farmers to compete for more irrigation water because they would want to sustain, or even exceed, the past year's agricultural productivity (box 2). This view is consistent with the theory of common-pool resource dilemma (Dietz et al., 2003). The goal of having high agricultural productivity and profit, thus, lead to diversion and subtractive use of more water for irrigation from the streams that feed the lake (box 3). The lake shrinks and its shoreline recedes over time as a result (box 4). The exposed lake beds are then dried up through evaporation, resulting in salt-rich playas exposed to air (box 5). Next, Aeolian dispersion of salt-rich dusts occurs over long distances, a less perceptible phenomenon that gradually leads to widespread soil salinization (box 6). Specifically, saline playas are eroded by wind shear forces and the resulting salt-rich dust emissions carry and deposit salts over a large area, intensifying soil salinization across the whole region (box 7). The net result is a decline in agricultural productivity because of the increase in soil salinity (box 7 to 2).

Fig. 8. (a) The groundwater anomaly and the number of wells in Lake Urmia Basin (2002–2019) indicating that farmers managed to make up for their irrigation water need through drilling more water wells and increasing their groundwater withdrawals; (b) The average groundwater electrical conductivity (EC) in West Azerbaijan Province (2002–2016) representing the increase in groundwater salinity; (c) The average groundwater electrical conductivity (EC) in East Azerbaijan Province (2002–2016) representing the increase in groundwater salinity.

Farmers' adaptation to the situation above completes the outer loop (box 1 to 2). In each upcoming agricultural year, to negate the salinization of the soil and sustain the same agricultural productivity as the past year, farmers have to use more water to wash the salinity out of soil (box 3). That is, farmers must use additional water for leaching purposes on top of the crop water requirement. As farmers divert more water for irrigation from the lake's inflow streams in the following agricultural year, the lake further shrinks and saline playas expand spatially. What emerges is a spiraling cycle of environmental degradation: more saline playas are subjected to erosion through wind shear forces, more salt-rich dust emissions and deposition occur, soil salinization intensifies, and further consumption of surface water and lake shrinkage occur.

Meanwhile, the inner loop operates in tandem to reinforce the lock-in (the inner circle in Fig. 10). The blue loop is driven by the underground environmental process and associated social dynamics. As illustrated in the previous section, evidence suggests that, due to declining surface water resources and because of the need for more water, farmers often supplement their total water use by pumping groundwater for irrigation (box 9). But the groundwater in the region is saline. When the irrigated groundwater on the field evaporates, salts remain in the soil and cause increases in soil salinity (box 11 to 7). This amplifies the same environmental issue. In the upcoming agricultural years, farmers need to extract more water from both the lake's inflow streams and groundwater sources for irrigation and leaching purposes, thereby reinforcing both the outer and inner loops. What is interesting here is that there is likely to be another critical factor that links the surface and underground environmental processes in a subtle way. As more groundwater abstraction occurs, there is likely to be greater saltwater flux from the lake bed into the region's groundwater system (box 9 to 10). This inflow from the lake into the groundwater system not only makes groundwater more saline (box 10 to 11) but also triggers further

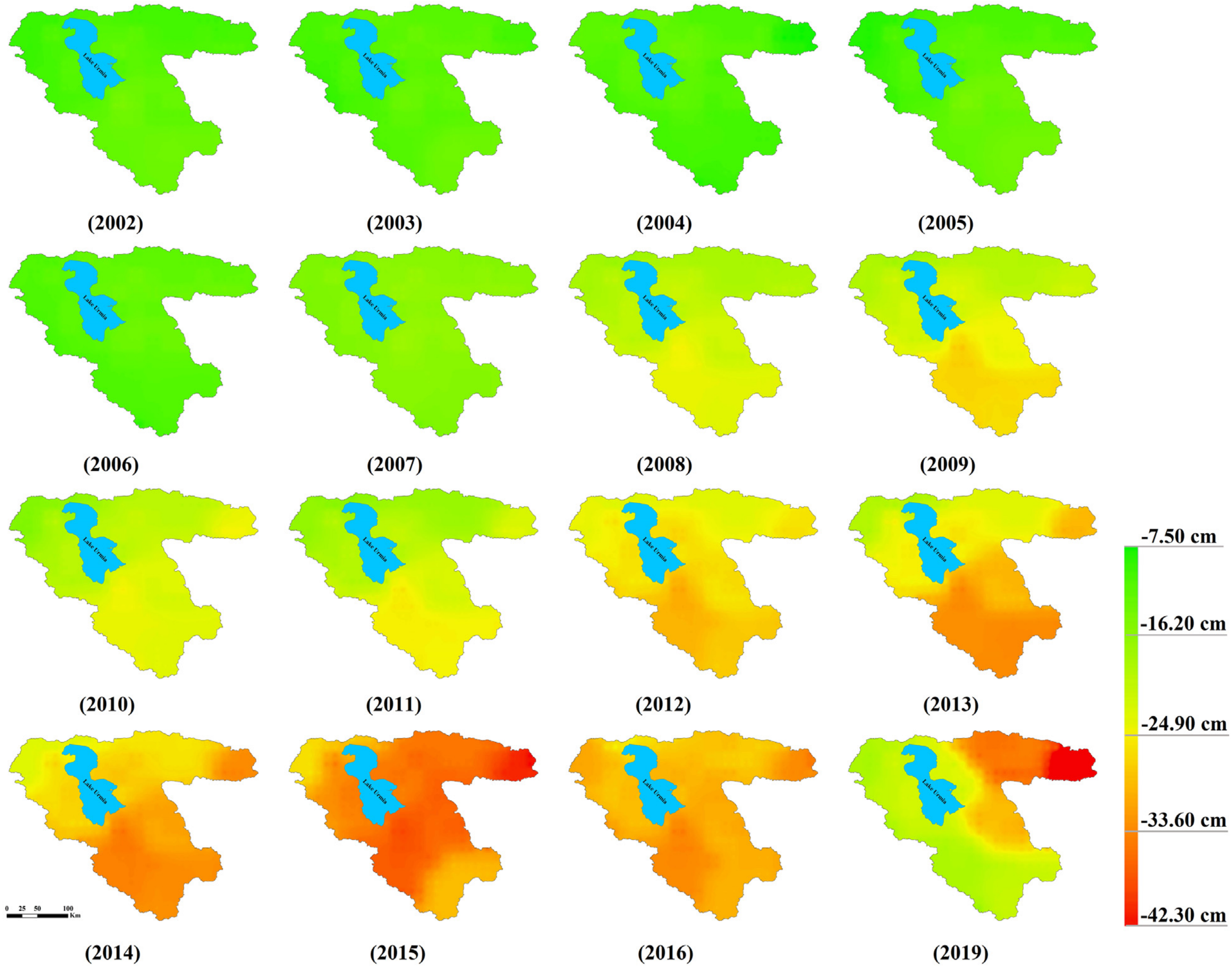


Fig. 9. Groundwater anomalies in Lake Urmia Basin represents that while there were increase in soil salinity and drought of surface water resources, farmers managed to compensate for their irrigation water needs through considerable withdrawals from groundwater resources.

lake shrinkage (box 10 to 4). Again, the shrinkage of the water body gives rise to the emission of salt-rich dust from saline playas to surrounding regions (box 4 to 7). Therefore, to preserve the productivity of the past years, more water must be exploited from surface and groundwater resources for meeting the consumptive and agronomic agricultural water requirements (box 2 to 3 and 9). This completes the blue loop. Note that our discussion so far suggests the possibility of an interconnection between the inner and outer loops: agricultural decision-making by many farmers (human system component) and hydraulic linkage between the surface and ground water systems (water system component). This interconnection should be the subject of further scrutiny and analysis in order to devise effective strategies for weakening the lock-in effect of the two loops.

From the biogeochemical perspective, the inner and outer loops lead to accumulation of salt in soil, either in the root zone or on the soil surface. This negatively affects the ecological functions of soil through variations in the chemical and physical characteristics and loss of soil fertility. For instance, salinity restricts soil–water storage capacity and water seepage, leading to surface run-off and erosion. Also, salinity limits soil processes including residue decomposition, denitrification, nitrification through diminishing soil biodiversity and microorganism activity. It is estimated that the amount of salt sediments in the lake varies from 6 to 10 billion tons. Additionally, it has been observed that the thickness of saline sediments can reach up to 4 m in the deep areas of the lake (Haqshenas, 2018). Since the lake's water is hypersaline (more than 350 g/L), the inflow water to the lake will be compounded with hypersaline water and after diluting a low amount of salinity, the water will become saline-saturated and the extra salts will remain suspended. It is estimated that the average amount of salinity that reaches the lake through the inflow streams can be up to 2.2 million tons per year (ACECR, 2015; Wurtsbaugh et al., 2017). Ultimately, all of these consequences directly and indirectly contribute to entrenching the proposed lock-in phenomenon.

5. Conclusion

In this study, we conducted exploratory analyses to develop a system-level understanding of desiccation in Lake Urmia, a serious environmental degradation problem in progress that may be of relevance to other saline lakes around the world. We focused on how various anthropogenic components and surface and underground environmental processes collectively generate the lock-in effect of lake desiccation and soil salinization in the study system. By investigating the variations in soil salinity, vegetation cover, groundwater anomaly, and socio-economic data, we highlighted a paradoxical situation in which the increase of soil salinity has not noticeably affected the vegetation cover in Lake Urmia Basin, an indication that the region's farmers are extracting more irrigation water to compensate for the declining agricultural productivity. We then combined key pieces of our exploratory evidence to propose the possibility of a socio-hydrologic feedback, a system of feedback loops comprised of anthropogenic processes and surface and underground environmental processes, that generate the lock-in effect. This socio-hydrological feedback provides an integrative system-level understanding that has been lacking in the literature. We mapped the underlying linkages between ongoing surface and

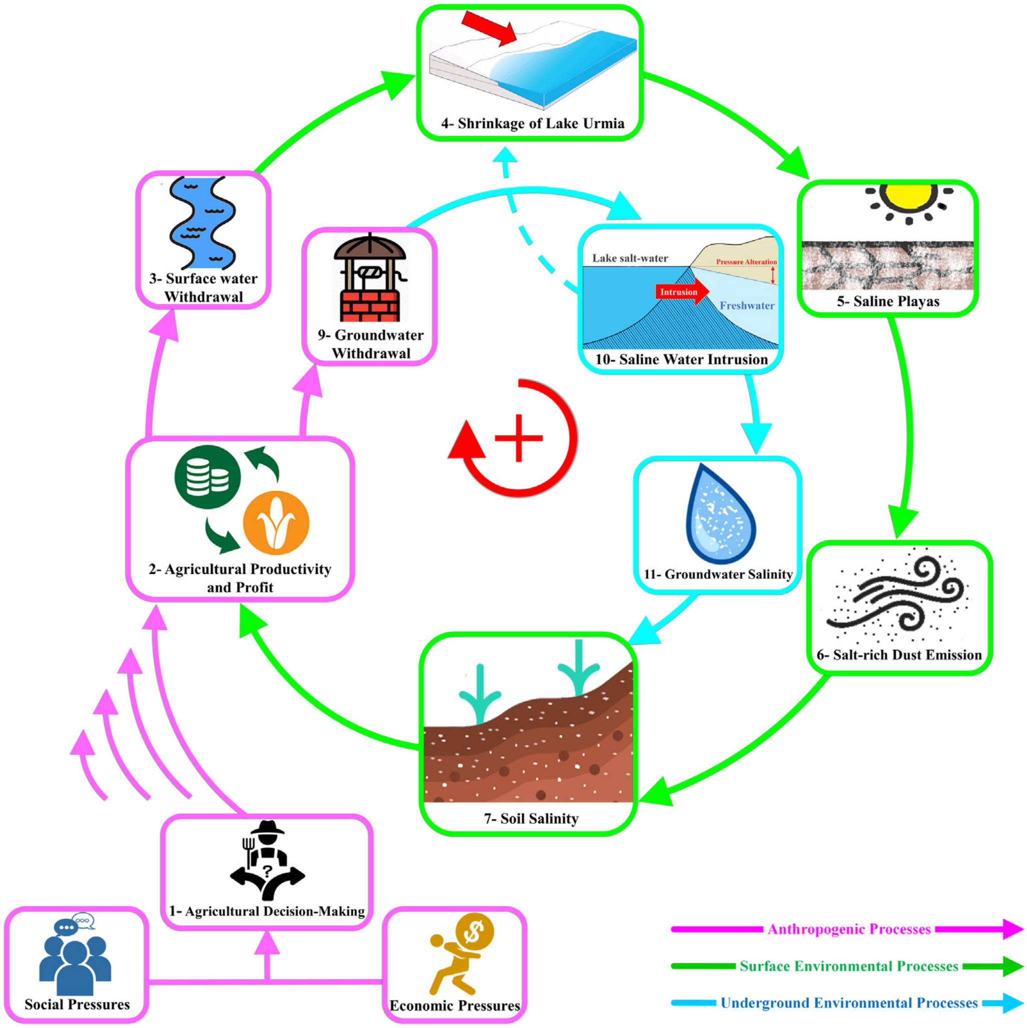


Fig. 10. The socio-hydrological feedback is comprised of two mutually reinforcing loops: the outer and inner loops. Both loops compound the lock-in toward lake desiccation. The outer loop is driven by the surface environmental and anthropogenic processes. The inner loop is based on the underground environmental and anthropogenic processes. These two loops are connected via human decision-making and salt-water flux from the lake into the groundwater system.

underground environmental processes as well as anthropogenic processes as well as associated social and economic pressures in the proposed system of feedback loops. There are several potential solutions that may temporarily reduce the saline-dust emissions from Lake Urmia playas such as dust consolidation, expanding non-agricultural vegetation cover, and polymer dust stabilizers. However, each of the mentioned methods may eventuate in negative environmental impacts, and in the long run, the proposed lock-in would prevail as it will be strengthened via socio-economic drivers and the socio-hydrologic feedback each year.

To sum it up, the inner and outer loops of the proposed socio-hydrological feedback may represent an exorable trap in their entirety. The more farmers adapt by increasing water use, the more water they will need in following agricultural years to deal with the same issue. This trap or lock-in may have been in effect in the past two decades, as suggested by the significant shrinkage of the lake and the rising salinity issue over 2000–2019 (Figs. 3a and 4). This raises the question of how to weaken or break out of the lock-in to halt, or even reverse, the trend of lake desiccation. Although this question is outside the scope of the present study, some clues can be drawn by noting the fact that the fundamental nature of the region's problem is that of the tragedy of the commons. That is, farmers are driven to compete for limited irrigation water because of the incentives they face. A useful starting point is, therefore, considering what may be an ignored or missing feedback loop for addressing the social and economic pressures and the innate desire for equal or higher profitability. Studies show that, although water governance and lake restoration efforts have been put into place in the study region to curb water extractions, the results have been less than satisfying because of various barriers to governance. These barriers include insufficient consideration of the local social conditions in governance design, lack of monitoring, and lack of awareness among farmers about the subtleties of underlying environmental processes (Pouladi et al., 2021). Therefore, additional measures, such as participatory decision-making in water allocation and distribution rules, improved monitoring of farmers' behavior, and more active role of science in communicating the effects of water resource system dynamics and human influence, are needed to address the barriers to governance.

Both a limitation and strength of the current study is its exploratory nature in development of a system-level understanding of desiccation in Lake Urmia. By assembling a number of key pieces of exploratory evidence, we were able to portray a plausible, integrative picture on how lake desiccation emerges from the interplay of social and hydrological processes. Future studies should strength the internal validity of the proposed system of feedback loops by conducting more detailed analyses of various components of the feedback loops. For example, the social tensions, financial difficulties, and demographic changes serving as the strength source of the proposed socio-hydrological loop may be investigated in detail with socio-economic approaches. Furthermore, future studies should investigate the external validity of our hypothesis by exploring the proposed socio-hydrological feedback in other saline basins in the world. This can lead to more holistic understanding of similar situations for other basins around the world and the lessons learned in one context can be transferrable to others. One may also study the existence of other possible emergent lock-ins by searching for and detecting hidden critical feedback loops that influence the lake desiccation. Additionally, the proposed socio-hydrological feedback loop in this study can be further considered for more quantitative analysis and scenario predictions through different modeling approaches.

CRediT authorship contribution statement

Parsa Pouladi: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Visualization. **Amir Reza Nazemi:** Data curation, Investigation. **Mehrsa Pouladi:** Data curation, Investigation, Visualization. **Zahir Nikraftar:** Data curation, Investigation, Visualization, Methodology. **Mohammadreza Mohammadi:** Investigation, Visualization, Data curation. **Peyman Yousefi:** Investigation, Writing – original draft. **David J. Yu:** Resources, Supervision, Writing – original draft, Writing – review & editing. **Abbas Afshar:** Supervision. **Antoine Aubeneau:** Supervision. **Murugesu Sivapalan:** Supervision.

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.

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