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Decline of the world's saline lakes

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Many of the world's saline lakes are shrinking at alarming rates, reducing waterbird habitat and economic benefits while threatening human health. Saline lakes are long-term basin-wide integrators of climatic conditions that shrink and grow with natural climatic variation. In contrast, water withdrawals for human use exert a sustained reduction in lake inflows and levels. Quantifying the relative contributions of natural variability and human impacts to lake inflows is needed to preserve these lakes. With a credible water balance, causes of lake decline from water diversions or climate variability can be identified and the inflow needed to maintain lake health can be defined. Without a water balance, natural variability can be an excuse for inaction. Here we describe the decline of several of the world's large saline lakes and use a water balance for Great Salt Lake (USA) to demonstrate that consumptive water use rather than long-term climate change has greatly reduced its size. The inflow needed to maintain bird habitat, support lake-related industries and prevent dust storms that threaten human health and agriculture can be identified and provides the information to evaluate the difficult tradeoffs between direct benefits of consumptive water use and ecosystem services provided by saline lakes.

Large saline lakes represent 44% of the volume and 23% of the area of all lakes on Earth[1]. Saline lakes are located in mostly arid, endorheic basins and are diverse. The Caspian Sea is by far the largest saline lake (accounting for 41% of global saline lake volume and supports thriving fishing, shipping and mineral industries. Other large hypersaline systems such as Great Salt Lake provide a range of services, from waterbird habitat to mineral extraction. Small Andean salars and mid-eastern and African lakes support flamingos and other birds. Saline lakes across the globe are shrinking[1,2] (Fig. 1a). Increasing water use by humans, especially for agricultural irrigation[3], is a significant factor in lake desiccation. For example, agricultural water development in the Aral Sea watershed[2] has reduced lake area by 74% and volume by 90% (ref. 4). Lake Urmia in Iran has suffered a similar fate, as have many saline lakes on all continents except Antarctica (Fig. 1a). The desiccation of saline lakes is not a new phenomenon, and researchers have noted the alarming rate of decline of many of these important ecosystems[5–7]. For example, Owens Lake in eastern California was completely desiccated by 1940 after the city of Los Angeles diverted streams for agricultural and urban use (Figs 1,2a). The oldest known direct human action desiccating saline lakes was probably in the Tarim Basin, causing the collapse of the Loulon Kingdom in 645 CE (ref. 8). Other impacts are more recent due to the ever-growing demand for water. California's Salton Sea has suffered a recent and precipitous decline of over 7 m since 2000; a result of management decisions that decreased water flowing into the lake[9].

The benefits of water consumption for agricultural, industrial and municipal applications increase economic productivity and stability[10]. The ecological, sociological and economic benefits of saline lakes are diverse, but not as easily monetized. Terminal saline lakes can accumulate and recycle nutrients[11] better than freshwater systems, so these ecosystems often produce high quantities of food for fish, as is the case in the hyposaline Aral Sea. When salinities are too high for fish to survive, invertebrate food organisms are available exclusively for birds at the top of the food chain. Millions of migratory shorebirds and waterfowl utilize saline lakes for nesting and to fuel long migrations with abundant food resources such as brine shrimp (*Artemia* spp.) and brine flies (*Ephedra* spp.)[12,13]. When saline lakes are desiccated, the amount of habitat decreases and salinities can rise beyond the tolerance of these invertebrates, limiting both food and habitat for birds. Because of their immense importance to avian communities, many saline lakes such as the Great Salt Lake; Mar Chiquita in Argentina; Lake Corangamite in Australia; Lake Urmia in Iran; and Lakes Nakuru and Bogoria in Kenya have been designated as Ramsar Wetlands of International Importance[14] or as Western Hemispheric Shorebird Reserve sites[15].

Similar to freshwater systems, saline lakes are also important for recreational activities. Swimming, boating, fishing, birdwatching and waterfowl hunting are popular activites at many saline lakes[6,9,16,17]. Lake desiccation reduces or eliminates many of these uses. Even access to lakes becomes difficult when waters retreat across broad playas and marinas become distant from the water's edge.

When saline lakes are severely desiccated they become sources of fine dust that harm human health[18] and agriculture[4]. Impacts have been particularly well documented at the Aral Sea, where 12,700 km^2 of lakebed was exposed due to agricultural water withdrawals[4,19,20]. In the much smaller Owens Lake in California airborne dust has frequently exceeded US air-quality standards for large particulate particles[21] (PM_{10}) and reputedly increased the prevalence of asthma, lung infections and other respiratory diseases in the area[22]. Due to these health issues, the city of Los Angeles will spend US$ 3.6 billion over 25 years on dust mitigation from the dry bed of Owen's Lake — more than the value of the diverted water[21].

Direct economic losses due to desiccation and increased salinities can also be severe. A major economic benefit of salt lakes is mineral extraction. Increasing salinities can be beneficial for these industries by concentrating minerals. In severe situations, however, waters recede far from solar evaporation ponds or complete desiccation eliminates the source of easily accessible brine. Harvesting the resting eggs (cysts) of brine shrimp is another

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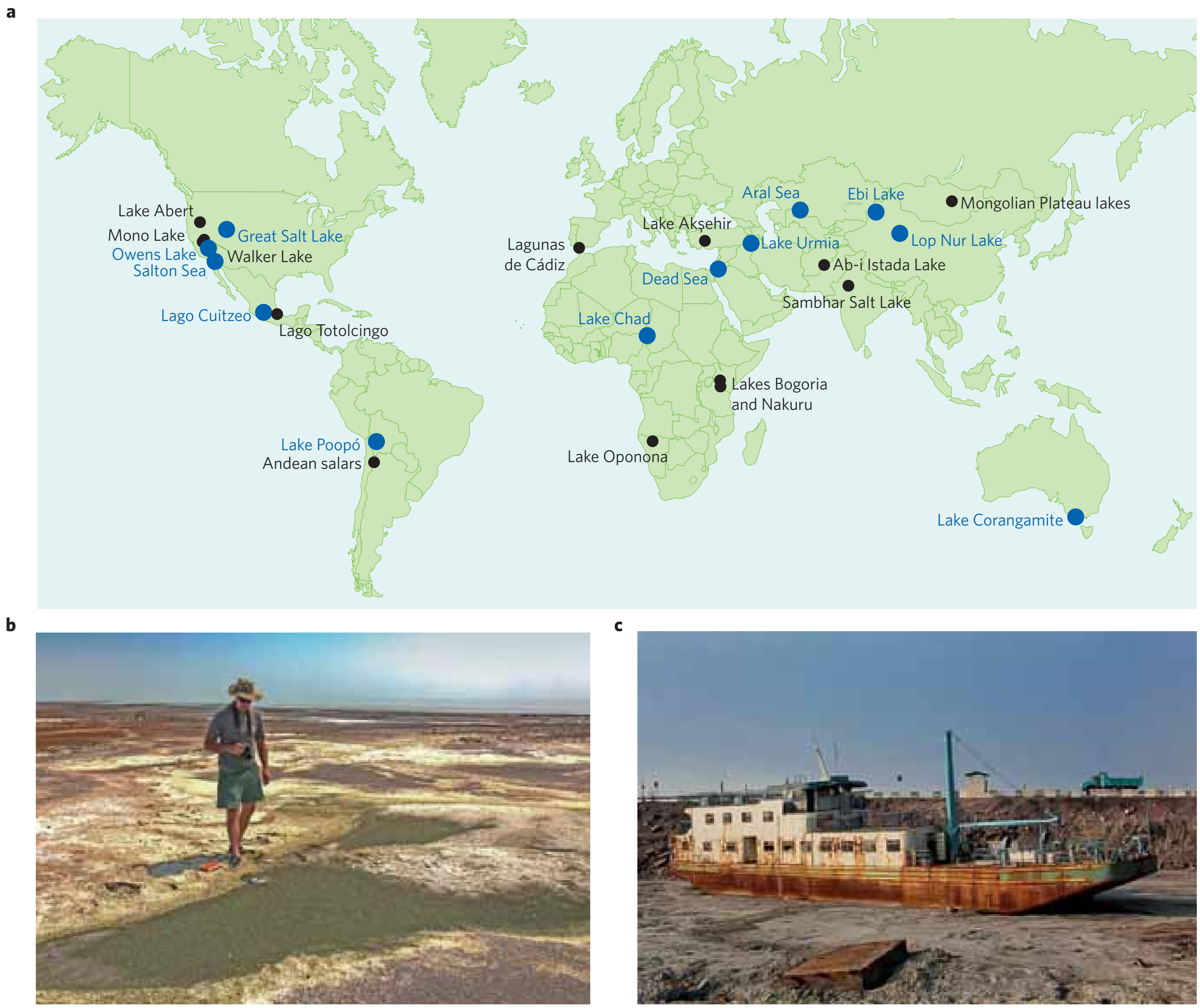

Figure 1 | The world's declining saline lakes. a, Some of the world's salt lakes that have been impaired by water diversions and/or climate change. Larger symbols indicate lakes formerly larger than 250 km^2. **b**, A limnologist inspects a pond left behind on the lakebed of the receding Great Salt Lake (USA; August 2012). **c**, Stranded ship on the dry lakebed of Lake Urmia (Iran; February 2014). Photographs courtesy of W. A. Wurtsbaugh.

multi-million dollar industry in saline lakes, but these organisms do not reproduce well at salinities exceeding 200 g l^{-1} (ref. 23,24). The near-complete desiccation of Lake Urmia increased salinity above 350 g l^{-1} and eradicated brine shrimp, with the subsequent loss of flamingos and other birds[25]. Similarly, water diversions from the Aral Sea increased salinity above levels tolerated by fish, leading to a collapse of the commercial fishery that had once harvested 40,000 metric tons annually and provided 60,000 jobs[17]. Soviet Union water developers recognized that this fishery would be lost, but argued that this loss would be more than offset by economic gains in agricultural production. They did not, however, recognize (and thus were not able to monetize) the substantial environmental costs that ensued[26].

The Great Salt Lake example

A water mass balance is needed to quantify causes of saline lake decline and to help evaluate tradeoffs between using water for people or ecosystems. As an illustration, we apply a simple water balance model to understand and discuss lake-level decline in Utah's Great Salt Lake. The Great Salt Lake is the largest lake by area in the western US and the eighth largest saline lake in the world[27]. The economic value of the lake is estimated at US$ 1.32 billion per year from mineral extraction, brine shrimp cyst production, and recreation[16]. Its abundant food and wetlands attract nearly 2 million shorebirds, over 1.5 million grebes (Podicipedidae) and several million migrating waterfowl[28]. The Lake is also namesake of Utah's capital city, underscoring its modern cultural significance.

In November 2016, Great Salt Lake reached its lowest level in recorded history. Although natural fluctuations in rainfall and streamflow cause Great Salt Lake to rise and fall over annual and decadal periods[29] (Fig. 2), there has been no significant long-term change in precipitation or streamflow from mountain tributaries that could have driven this change since pioneers arrived in 1847 (Fig. 3a). By contrast, water development and river diversions since 1847 have produced a persistent reduction of flow into the lake, approaching 40% in recent years (Fig. 3b). Much of the diverted water is lost via evaporation from agricultural fields, urban landscaping and industrial activity; including losses from salt ponds. At the same time, lake area has shrunk ~50%. Although droughts and wet periods cause river inputs and lake levels to fluctuate, the level has persistently declined since pioneers arrived (Fig. 3c, red line).

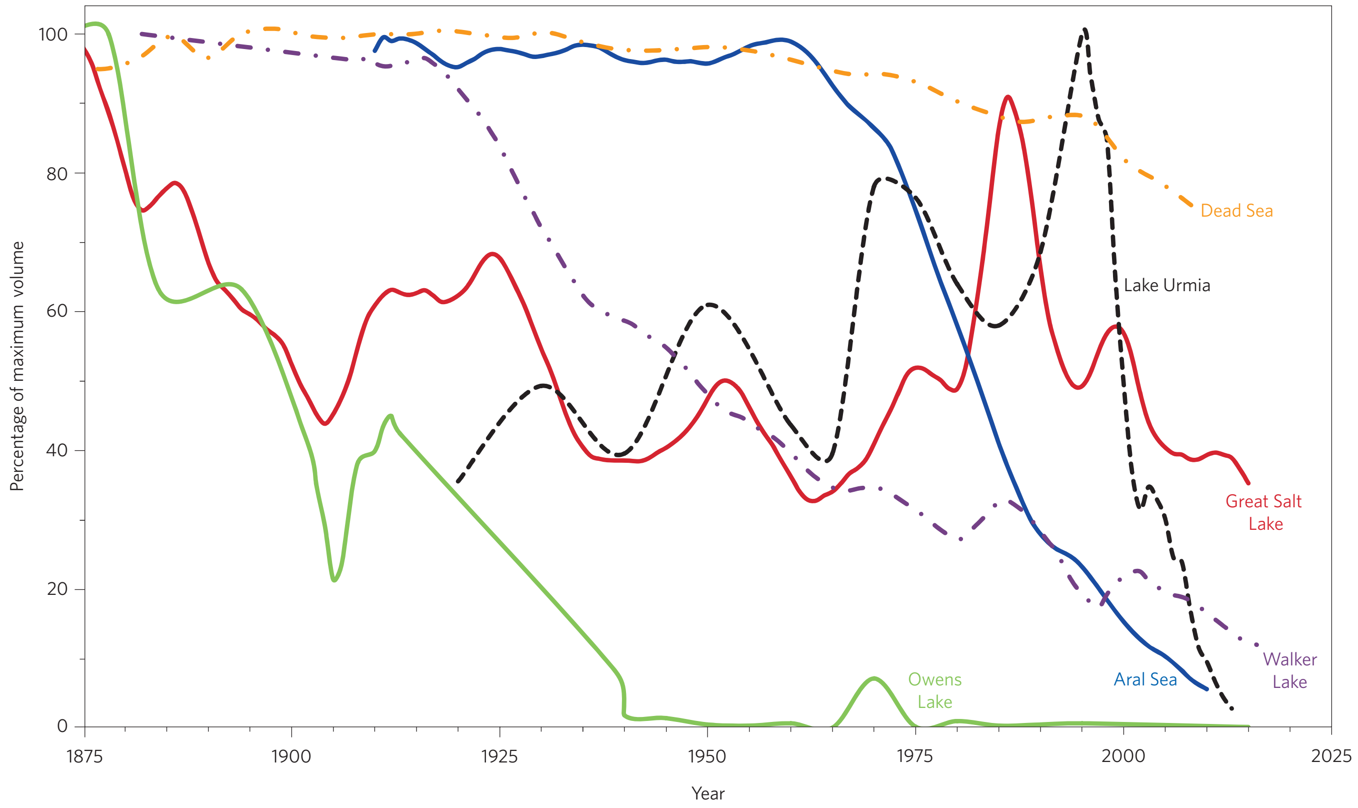

Figure 2 | Major decreases in the water volumes of important saline lakes over the past 140 years (five-year running averages). Note that the relatively small fractional decline in the volume of the Dead Sea can be explained by its great depth; the elevation of the Dead Sea has been reduced by over 28 m during this time period and impacts have been pervasive[43]. Recently, Lake Urmia has declined most precipitously from a combination of agricultural water development and drought. See Methods for details.

The observation of falling lake level (Fig. 3c) in the presence of constant natural input (Fig. 3a) and increasing consumptive uses (Fig. 3b) makes a clear case for the detrimental effect of human water use on lake level. Current state water resources evaluations indicate total consumptive use of approximately 1.8 billion m^3: composed of agriculture (63%); lake water extraction for salt pond mineral production (13%); municipal and industrial uses (11%); evapotranspiration from constructed wetlands (which probably replaced loss from natural wetlands, 10%); and reservoir evaporation (3%). Although there is uncertainty in these estimates of consumptive use, the dominance of agricultural consumption is clear and typical of arid landscapes with irrigated agriculture.

The cause of lake-level decline is illustrated by using a water-balance model that estimates lake elevation without consumptive water uses (Fig. 3c, blue line). This analysis indicates that without consumptive water use, the long-term trend in the lake level since 1847 would have been flat with a natural mean elevation of 1,282 m (4,206 feet; Fig. 3c, blue line) — that is, the relationship between consumptive use and the declining lake level over the past 170 years (Fig. 3) is supported by this independent accounting of consumptive use and related changes in lake evaporation. Water consumption is responsible for an observed lake lowering of approximately 3.4 m (11 feet), representing a reduction in lake volume of 48%.

Decreased lake elevation affects various bays of Great Salt Lake differently. The lake's two shallow eastern areas — Bear River Bay and Farmington Bay — are particularly impacted (Fig. 4). In 2016, more than 75% of their lakebeds were exposed. These bays are usually brackish 'estuaries' and provide particularly important bird habitat[28]. Great Salt Lake is suffering many of the other problems of shrinking saline lakes worldwide: boat harbours are inaccessible; mineral companies have difficulty accessing brines for processing; brine shrimp are under increasing stress from high salinity; and dust storms from the lake's dry playas are afflicting the two million people in the nearby Salt Lake City metropolitan area[23,30,31].

Any future water development will further reduce lake inflow and exacerbate desiccation. For example, the state's Division of Water Resources estimates that water consumption from a proposed development of the lake's primary tributary, the Bear River[32], would decrease the level of Great Salt Lake by approximately 0.2 m. Although this change seems small, it will further increase salinity and reduce biodiversity of the ecosystem, and expose another 80 km^2 of lakebed, contributing to more severe dust events[27]. The consequence is clear: if less water is delivered to the lake, the lake level will drop, the ecosystem will be degraded and human health and economic impacts will occur.

Water development, climate change and the way forward

The world is facing difficult water management challenges with increasing human population and changing climate. Natural variability and climate change — when incorrectly cited as reasons for lake decline — provide no basis for a solution and can result in inaction. For example, managers of Great Salt Lake and Oregon's Lake Abert[33] previously blamed declining lake levels only on natural precipitation cycles, without a direct analysis of the cause. However, after water-budget analyses were done it was clear that water diversions were the primary cause of the long-term lake-level decline. Even with uncertainty in estimates of water depletion and supply, we argue that a basic water budget is critical to supporting science-informed discussions on the difficult tradeoffs between consumptive use and maintaining saline lakes at sustainable levels.

There is a tendency to invoke 'climate change' as the culprit for the decline of saline lakes without fully understanding all of the

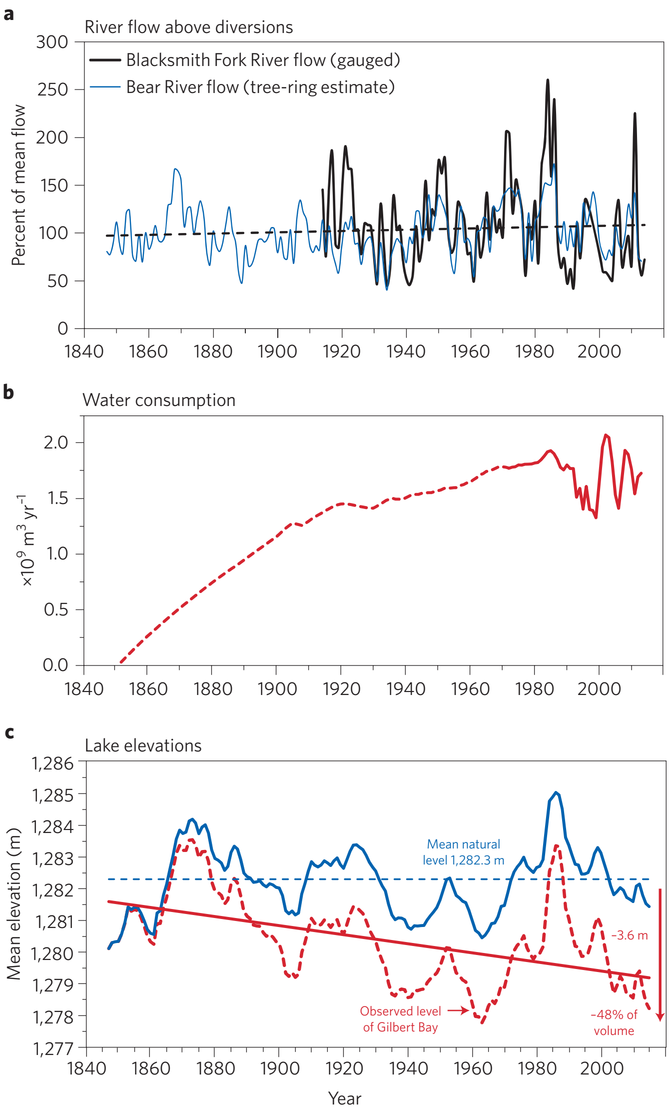

Figure 3 | Temporal changes in water inputs, water use and elevation of Great Salt Lake, Utah, USA. a, Water flow in Great Salt Lake headwater streams above diversions. Estimated flows in the Bear River are based on tree-ring reconstructions[49]. **b**, Estimated consumptive use of water for agriculture, salt ponds, wetlands and cities. **c**, Observed level of Great Salt Lake (red line) with modelled lake elevation in the absence of consumptive water uses (blue line). Consumptive water uses have lowered the lake 3.6 m and decreased its volume by 48%. See Methods section for details.

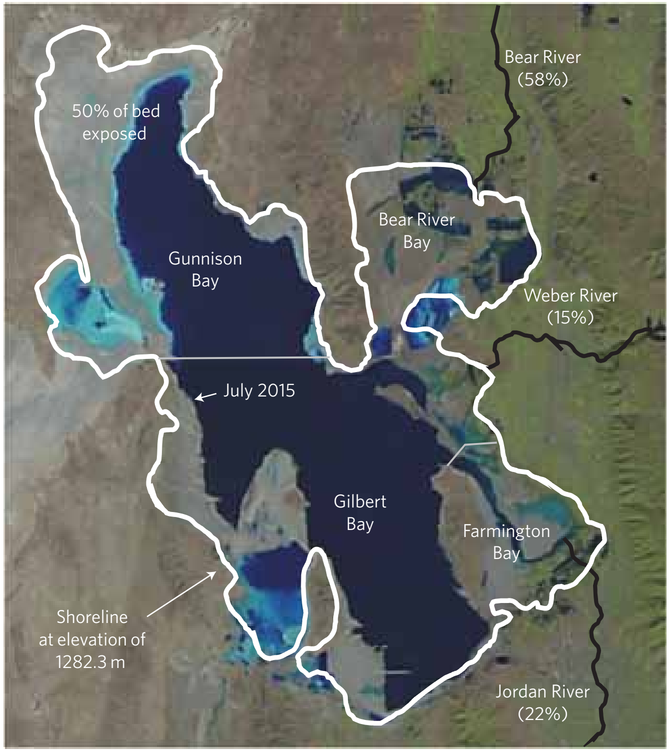

Figure 4 | Influence of water use on the areal extent of Great Salt Lake, Utah. The white line shows the lake margin at the average no-diversion elevation of 1,282.3 m (see Fig. 3b). The July 2015 NASA image shows the lake at near-record-low levels, exposing half of the lakebed.

hydrological balances[34]. Climate change — with warmer temperatures, increased evaporation and altered precipitation — does indeed represent a pervasive long-term problem for saline lake sustainability. The impacts of long-term climate change can be estimated and will influence the degree and type of action needed. For example, runoff in Great Salt Lake basin is estimated to decline by approximately 11–20% by the mid-twenty-first century[35] and increased temperatures will increase lake evaporation. In other places, saline lakes may receive more water from increased precipitation and glacial melting. The huge Lake Issyk-Kul in Kyrgyzstan and Mar Chiquita in Argentina may be experiencing these effects[36,37].

Although climate change has an impact on saline lakes, water development in arid basins generally represents a larger and more immediate challenge[6,38,39]. The Aral Sea, Lake Urmia, Great Salt Lake, Lake Abert, Walker Lake, Lake Poopó and Owens Lake are examples of lakes for which the primary impact has been water development for agriculture, mining and cities. Whether climate change augments or moderates the impact of consumptive water use, the water needed to preserve saline lakes in most cases will come from the same source; that is, reductions in consumptive use.

Two approaches have been applied to preserve saline lakes. One is the 'Aral Sea solution' in which lake area, and hence the evaporative surface, is artificially reduced to match the decreased discharge into the lake[40]. For the Aral Sea, a 13-km-long dyke was constructed in 2005 at a cost of US$ 106 million (2017 dollars), and preserved a small hyposaline lake approximately 5% the size of the former lake[40]. This action re-established a smaller, more-stable fishing industry and protected some endemic species (though the remaining 95% lake area is hypersaline or dry, and salt-dust storms continue to harm crops and human health)[40]. Despite the rescue of a much smaller Aral Sea, the loss of the larger water body is considered one of the largest ecological disasters humans have caused[2,4]. In many situations, building dykes or dams to restrain the size of the lake may not be logistically or financially feasible. In other cases — for example, Lake Urmia and Great Salt Lake — existing transportation causeways already cross the lake and could perhaps be used to manage lake levels and salinity[25,41]. However, the cost of constructing a smaller lake, together with the loss of ecosystem services and the costs of mitigating dust impacts, needs to be included in evaluating tradeoffs between water withdrawals and reduction of lake area.

A second solution to preserve saline lakes is to estimate and litigate minimum water delivery needed to preserve them. This approach requires increased water conservation or water transfers. For example, when minimum stream flows into California's Mono Lake were litigated in 1994 using the Public Trust Doctrine[42], the metropolitan area of Los Angeles lost 12% of its water supply, which was balanced by substantial water conservation. With improved water use efficiency, Los Angeles water use has remained relatively constant in the face of substantial growth[42]. Water transfers from

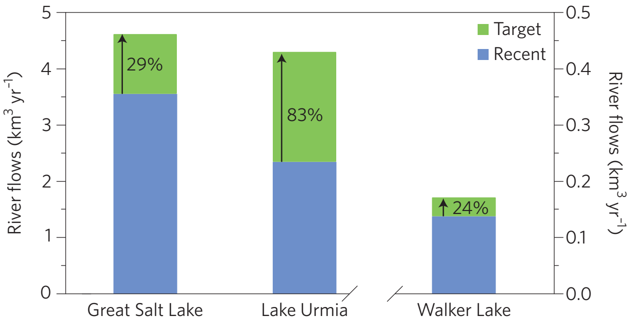

Figure 5 | River inflows and target recovery flows needed for three threatened saline lakes. Blue bars show recent river inflow (20–50 year records) and green bars show the mean sustained increase needed to reach targets and return the lakes to fully functioning ecosystems. Ordinary weather cycles would produce natural shorter-term variations in these lake levels and resulting salinities. Target elevations, salinities and uses for each lake are: Great Salt Lake, 1280 m, 130 $g\ l^{-1}$, multiple uses[47]; Lake Urmia, 1274 m, 250 $g\ l^{-1}$, brine shrimp and dust control[25]; Walker Lake, 1205 m, 12 $g\ l^{-1}$, native trout and biodiversity[46].

adjoining basins can also help recover/protect saline lakes. The Middle East's Dead Sea may soon receive water from the higher elevation Red Sea via a multi-billion dollar pipeline, but this project is controversial[43]. A diversion and pipeline from an adjoining watershed has also been proposed to help boost water levels in Iran's Lake Urmia[25], and Utah's Great Salt Lake basin already receives a small amount of water via a diversion from the Colorado River Basin[44]. These projects, however, are frequently costly and often deprive users and ecosystems in the donor basin of needed water.

The key to implementing a conservation solution for saline lakes is to identify the river inflow needed to restore and sustain lake size, elevation and salinities that will support ecosystem services within a range of natural variability. Targets for success have ranged from simply keeping the lakebed wet enough to mitigate dust problems (Owens Lake[45]), to maintaining water fresh enough to support trout (Walker Lake[46]). For Great Salt Lake and Nevada's Walker Lake, mean annual inflows would need to be increased by approximately 24–29% to maintain lake levels that would protect wildlife, lake access, human health and other beneficial uses[46,47] (Fig. 5). In contrast, managers of Iran's Lake Urmia would need to increase current lake inflows by approximately 83% to achieve the lake elevation and salinity necessary to recover brine shrimp and birds, and to minimize dust impacts to agriculture and the human population. Such a large increase will be difficult to attain and managers may have to consider an Aral Sea type solution. Target elevations chosen for lake 'recovery' are not absolute, because in most cases lake elevations and salinities do not represent absolute thresholds for particular species or uses, but rather points along a continuum where species or habitat decline as lake levels fall. For example, brine shrimp production, and thus food available for birds, declines along a continuum from 75 to 225 $g\ l^{-1}$ salinity[23]. Consequently, target lake elevations can be chosen to reflect societal values that balance different beneficial uses of water entering these ecosystems.

The services provided by saline lakes merit protection, but proposals to allocate additional water to preserve saline lakes will meet social, political and economic challenges. The direct benefits of consumptive use are easily quantified and often supported by existing law and management practice[48], as well as deeply held values regarding population growth and agricultural history. The ecosystem services provided by saline lakes are real, but less easily quantified, and may have a constituency that is less well established in law, business and social practice. Science can provide the information needed to support the difficult choice between saline lake preservation and ongoing increases in consumptive use of water. This information includes the ecosystem services provided by saline lakes, the lake elevation needed to sustain those services, and the amount of inflow required to sustain that lake level. Importantly, the information must be provided with sufficient lead-time so that solutions can be developed and implemented before saline lakes are desiccated. The impact of natural climatic variability on lake levels can be understood and should not act as an impediment to effective decision-making. In many cases, reduction to lake inflows is dominated by large and growing consumptive uses rather than climate change. Regardless of the relative influence of climate change and water consumption, the primary conservation response to sustain lake levels is to maintain lake inflows, which must be accomplished through reductions in consumption Implementing these changes will probably not be easy, but as the Mono Lake, Los Angeles example demonstrates, significant conservation can be achieved and saline lakes restored when there is sufficient social and political will.

Methods

Methods, including statements of data availability and any associated accession codes, are available in the online version of this paper.

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Author contributions

All authors contributed equally to writing the paper. S.E.N. produced Fig. 1. W.A.W produced Figs 2, 4 and 5. C.M., R.J.D. and W.A.W. produced Fig. 3.

Additional information

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Competing financial interests

The authors declare no competing financial interests.

Methods

Figure 2 analyses. Lake volume decline, shown in Fig. 2, is derived from measured lake elevation data and hypsographic curves from the following sources: Aral Sea — hypsographic curve[50], lake elevation data provided by P. Micklin, Western Michigan University, Kalamazoo, USA; Dead Sea — elevation and hypsographic information provided by the Israel Hydrologic Service and A. Oren, The Hebrew University of Jerusalem, Israel; Lake Urmia — hypsographic and water elevation data provided by the Water Research Institute of the Iranian Ministry of Energy; Walker Lake — hypsographic curve data derived from a morphometric map[51] and lake elevation data from the US Geological Survey[52]; Great Salt Lake — hypsographic curve information provided by D. Tarboton[53], and lake elevation data by the US Geological Survey[54]; Owens Lake — elevation data supplied by G. McCarley Holder of the Great Basin Unified Pollution Control District, Bishop, California, USA, and hypsographic curve information from Mihevc *et al.*[55]. Error estimates are not available for any of the hypsographic curves or lake elevation data. However, Hokanson[56] estimated that maximum percentage errors in volume estimates for a reasonably well-surveyed lake are between +0.4% to −0.6%.

We calculate that Great Salt Lake reached its lowest level in recorded history in November 2016. This is based on the average elevation of the two major bays (Gilbert, 1277.8 m; Gunnison 1276.8 m), yielding an area-weighted mean elevation of 1277.5, lower than the 1277.6 m recorded in October 1963.

Figure 3 analyses. *Figure 3a.* River flow in upper, non-diverted tributaries is based on: (i) a 100-year continuous record from the Blacksmith Fork (USGS gauge no. 10113500), a tributary to the Bear River, the largest tributary to Great Salt Lake, and; (ii) temporally stable, tree-ring-derived estimates of precipitation and river flow (https://www.ncdc.noaa.gov/paleo-search/study/19299). In low-precipitation years, trees form narrower growth rings, and in high precipitation years, wider growth rings. Water-year precipitation and mean annual stream flow are highly correlated, allowing us to reconstruct an estimate of stream flow, once correlated, calibrated, and verified against instrumental measurements. Here, we presented flow estimates for the Bear River at a site high in the watershed above water diversions (USGS gauge no. 10011500)[49]. The regression line in Fig. 3a is a composite of the gauged flow on Blacksmith Fork and the tree-ring estimated flow for the Bear River, and shows a slightly upward trend, but no significant change (% of mean = −54.22 (±179.3) + 0.081 (±0.092) × year (95% confidence interval in parentheses); $n = 267$; $p = 0.085$). Similarly, no significant temporal trends are found for the Blacksmith Fork ($n = 98$; % of mean = 4.073 (±6.308) −0.00152 (±0.00321); $p = 0.349$) and for the Bear River tree-ring data ($n = 165$; % of mean = −36.63 (±150.75) + 0.070 (±0.078); $p = 0.078$) when analysed separately. Rainfall data (not shown) for Salt Lake City is from a composite rain gauge available from the National Oceanographic and Atmospheric Administration (http://w2.weather.gov/climate/xmacis.php?wfo=slc). Despite droughts and wet cycles, there has been no significant long-term change in precipitation from 1875–2015 ($n = 140$; mm yr^{-1} = 626.6 (±695.3) −0.118 (±0.357) × year [±95% confidence interval]; $p = 0.52$).

Figure 3b. Consumptive use estimates are based on current methods used by the Utah Division of Water Resources to develop water budgets for state water planning. Consumptive uses prior to 1989 are from R. Palmer and G.L. Whittaker (Unpublished data, Utah Division of Water Resources). Post-1989 data are more accurate and have a greater time resolution that shows short-term responses to droughts and wet cycles. The later data are relevant for understanding the current response of the lake to water use, because the lake elevation and area reach an equilibrium with reduced water inputs within 15 years[57]. Estimates of agricultural consumptive use for the last 30 years are based on annual surveys of crop use[58] in the basin and net crop evapotranspiration[59,60], reduced by winter carryover soil moisture storage on a per-hectare basis. Estimated crop areas for alfalfa, pasture, hay, grain and corn, as well as their mean, minimum and maximum annual water consumption are given in Supplementary Table 1. Reservoir evaporation is calculated as net average annual evaporation times 80% of maximum reservoir surface area in order to account for variable reservoir levels. Monthly reservoir evaporation rates are determined using E-LAKE Blaney Criddle coefficients from nearest weather station[59,60]. Thirty-year (1971–2000) temperature and precipitation inputs were extracted from PRISM[61]. Municipal residential water consumption is calculated as landscaped area multiplied by average net turf evapotranspiration[59] estimated for the nearest weather station data. A 4% loss from indoor use is added. Turf irrigation evapotranspiration is applied to 20% percent of commercial area and 80% of institutional area. Metered industrial water use is assumed to be completely consumed[62]. Evaporation from impounded open water wetlands is estimated using wetland area of 226 km^2 multiplied by the net average annual evaporation[63]. Water evaporation from solar evaporation ponds is calculated as 75% of lake withdrawals (Compass Minerals Corporation, personal communication). The average amount of water imported from the Colorado River Basin[44] (0.16 $\text{km}^3\ \text{yr}^{-1}$) is gauged and added to the water balance. The data in Fig. 3b are smoothed with a five-point running average. A 39% decrease in river inflow (2003–2012 average) to Great Salt Lake was calculated using total consumptive use of 1.79 $\text{km}^3\ \text{yr}^{-1}$ relative to total water input of 4.63 $\text{km}^3\ \text{yr}^{-1}$, which includes both consumptive use and current river inflow to the lake[57] of 2.84 $\text{km}^3\ \text{yr}^{-1}$.

Estimates of water depletions are based on a large number of uncertain inputs, including occasional summaries of land use and estimates of evapotranspiration, ungauged inflows and irrigation return flow. Given the importance of water in Utah, methods for estimating depletions are frequently revised in order to develop a consistent mass balance and accepted water adjudication. Internal checks on some elements of the water budget are possible in locations with multiple gauges, although a formal error analysis of the current Utah water budget has not been made. A thorough study of uncertainty in water budgets for the US–Canadian Great Lakes drainage basins found that cumulative error in water budgets can vary between 8% and 41% (ref. 64). The abundance of gauges on Utah streams and diversions suggests that error in Utah water budget is not likely to be at the high end of this error range.

The effect of water budget uncertainty on estimated Great Salt Lake elevation can be evaluated based on an independent test of lake elevation sensitivity to changes in lake input. Other researchers have tested how a constant percentage change in lake inflow would influence lake level[57]. They ran an ensemble of 30-year lake elevation simulations using a 25% increase of inflows drawn from the 1950–2010 historical record[57]. The change in inflow averaged 0.71 km^3 over that period, which is 41% of our estimated depletions of 1.72 km^3 over the same 61-year record. In the simulations, a 25% increase in inflow increased lake elevation by an average of 0.75 m (ref. 57). These simulations were started at the lake elevation in 2010, which was considerably lower than most of the range of lake elevations over the simulation period. Lake evaporation is much larger at higher lake levels, so the simulated rise in lake elevation is larger than would occur for a historical simulation such as ours. The sensitivity of lake level to increased inflows is specifically relevant to our finding that consumptive water use accounts for the entire lake-level drop over the past 165 years. If we have overestimated consumptive use, our lake inflow would be too small, lake level would have dropped less, and not all of the drop in lake elevation could be attributed to consumptive use. Based on the independent lake-level simulation[57], a simulated increase in lake inflow (0.71 km^3) that is large (41% of estimated consumptive use) relative to likely error in our water balance produced an increase in lake level (0.75 m); that is, 22% of our estimated 3.4 m drop in lake elevation since 1850. The simulated increase in lake level is larger than would apply to historical simulations at higher lake levels, so the actual error in estimated lake level is actually smaller than 22%. Consequently, our finding that most of the drop in Great Salt Lake elevation is due to consumptive water use is robust.

Figure 3c. The observed elevation of Great Salt Lake is based on a gauge at Saltair Boat Harbor[54]. There has been a highly significant ($p < 0.0001$) decline in lake elevation (red line): Lake Elevation (m) = 1308.0 − 0.01430 × year. To estimate lake elevation in the absence of consumptive use, we started from the natural lake elevation in 1847 of 1280.1 m and added an annual flow equivalent to human caused depletion for each year, and then recalculated lake evaporation as a function of area and salinity. The salinity of the lake was determined by using a lake salt load of 4.56 billion tonnes divided by the volume of the natural lake each year. Calculated evaporation rates used these salinities, lake areas, nearby weather data and Penman's equation[65] adjusted for salinity-dependent saturation vapour pressure[66]. Salinity influenced unit annual evaporation rate about 15% between minimum and maximum lake elevations and had a much smaller effect on total lake evaporation compared to lake surface area[66].

Figure 5 analyses. River inflow estimates for Great Salt Lake use a 50-year river flow record[57]. The river inflow necessary to sustain a target elevation of 1,280 m was based on the estimated salt-corrected evaporation rate[57] for the lake surface area at that elevation[47]. For Lake Urmia, the recent flow record is for 20 years prior to 2016 (personal communication, H. Shahbaz, Sharif University of Technology, Tehran) and utilizes a target lake recovery elevation of 1274 m and a salinity of 250 g l^{-1} (ref. 25). For Walker Lake current inflows were measured for 1971–2000 and a target elevation of 1,204.6 m, set by managers to provide viable native biodiversity of the lake[46]. For each lake, additional years of supplemental inflow, above-average inflow, or both, would be needed to raise the lake-surface altitude and dilute salts to reach a quasi-equilibrium state.

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