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# Recent desiccation of Western Great Basin Saline Lakes: Lessons from Lake Abert, Oregon, U.S.A.



# Johnnie N. Moore \*

Department of Geoscience, University of Montana, Missoula, MT, USA

## HIGHLIGHTS

# G R A P H I C A L A B S T R A C T

- A variety of hydroclimate data is used to calculate a "natural" water balance.
- Upstream water withdrawals, not climate forcing, dominate recent desiccation.
- Without withdrawals, salinity would remain tolerable even under recent drought.
- Present water use threatens shorebird habitat in western North America.



## A R T I C L E I N F O

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# ABSTRACT

Although extremely important to migrating waterfowl and shorebirds, and highly threatened globally, most saline lakes are poorly monitored. Lake Abert in the western Great Basin, USA, is an example of this neglect. Designated a critical habitat under the Western Hemisphere Shorebird Reserve Network, the lake is at near record historic low levels and ultra-high salinities that have resulted in ecosystem collapse. Determination of the direct human effects and broader climate controls on Lake Abert illustrates the broader problem of saline lake desiccation and suggests future solutions for restoration of key habitat values. A 65-year time series of lake area was constructed from Landsat images and transformed to lake volume and salinity. "Natural" (without upstream withdrawals) conditions were calculated from climate and stream flow data, and compared to measured volume and salinity. Under natural conditions the lake would have higher volume and lower salinities because annual water withdrawals account for one-third of mean lake volume. Without withdrawals, the lake would have maintained annual mean salinities mostly within the optimal range of brine shrimp and alkali fly growth. Even during the last two years of major drought, the lake would have maintained salinities well below measured values. Change in climate alone would not produce the recent low lake volumes and high salinities that have destroyed the brine shrimp and alkali fly populations and depleted shorebird use at Lake Abert. Large scale withdrawal of water for direct human use has drastically increased the imbalance between natural runoff and evaporation during periods of drought in saline lakes worldwide but could be offset by establishing an "environmental water budget" to lay a foundation for the conservation of saline lake habitats under continued threats from development and climate change.

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\* Department of Geosciences, 32 Campus Drive, University of Montana, Missoula, MT, 59812, USA. *E-mail address:* johnnie.moore@umontana.edu.

## 1. Introduction

Large endorheic saline lakes are unique hydrologic systems that provide critical habitat for migrating shorebirds and waterbirds throughout the world. Salinity, and hence productivity, in endorheic saline lakes are controlled by hydrology of the lake basin and geochemical processes within the lake. Balance between inflow and evaporation determine the volume of the lake. The highly variable climate of arid and semiarid environments where saline lakes exist causes large seasonal to inter-annual fluctuations in lake volume and salinity. Increased runoff from spring snow-melt runoff or from broader precipitation events such as El Niño and monsoons raises lakes and subsequent evaporation during dry seasons lowers them. Longer-term climate cycles (ENSO, PDO, etc.) magnify/diminish these seasonal cycles and are critical to salt balance. Endorheic saline lakes are generally precariously balanced on the edge of viability because annual evaporation is higher than annual inflows. Inflows can change in response to natural climate variability, human-induced climate change, and diversion of upstream water sources. Both climate and direct human factors are threatening large saline lakes worldwide (Herbst, 2014; Jellison et al., 2008; Williams, 2000), so that essentially no saline lake of any significant size escapes these effects (Micklin, 2007; Lotfi and Moser, 2012; Wurtsbaugh, 2014). Populations of shorebirds dependent on saline lakes are therefore also threatened, as these critical habitats are lost to desiccation and increased salinization. The disconnect between the needs of ecological end-use (e.g., lakes as habitat for shorebirds) and the over allocation of upstream flows (e.g., desiccation of lakes because of water use for agriculture) is now defining global saline lake environments (Bedford, 2009; Jellison et al., 2008; Jeppesen et al., 2015; Williams, 1996; Wurtsbaugh, 2014). As these lakes decline (Beutel et al., 2001), managing those that remain to preserve threatened shorebird populations requires understanding lake processes in the context of climate and water development. However, because saline lakes commonly lack easilyquantifiable economic value, their hydrology is rarely monitored, making it extremely difficult to determine water balance and attribute desiccation between water use or climate.

The ecosystems of saline lakes exist primarily within a distinct range of salinities (Herbst, 2001; Herbst, 1999; Herbst, 1994; Williams, 1998) which leads to large numbers of specialized aquatic consumers such as brine flies (Ephydra) and brine shrimp (Artemia) that provide highenergy food sources for shorebirds to build fat reserves for long migrations (Ammon et al., 2014; Oring et al., 2013). These characteristics have resulted in saline lakes acting as crucial stepping stones along intercontinental migration routes for shorebirds. This is especially true for the Pacific and Central Flyways in North America which are used by millions of shorebirds each year. During these astonishing migrations, extending over thousands of kilometers, shorebirds depend heavily on saline lakes as both breeding and refueling stops (Oring et al., 2013; Oring and Reed, 1996; Page et al., 1992; Warnock et al., 1998). Lake Abert, in the Pacific Northwest of the United States (Fig. 1), is the largest saline lake in the Pacific Northwest (Phillips and Van Denburgh, 1971) and an extremely important breeding and staging area for migrating shorebirds and waterbirds (Oring et al., 2013). Total average annual waterbird use at Lake Abert was reported in 1995 to be 3.25 million use-days/year (Oring et al., 2013), 1.7 million usedays/year for shorebirds alone. Upwards of 15,000 Eared Grebe feed in the lake and it has had the second highest population of Wilson's Phalarope in the U.S. Killdeer, American Avocets, Willets and Snowy Plover breed at Lake Abert, and the lake ranks second only to the Great Salt Lake in importance to shorebirds. "Thus, Lake Abert is ranked as a hemispheric site under the Western Hemisphere Shorebird Reserve Network and has been declared an Area of Critical Environmental Concern (ACEC) by the [U.S. Bureau of Land Management]."(Oring et al., 2013). Similarly, the Intermountain West Joint Venture states that "The Great Basin ... stands out as enormously important for both breeding and migrating shorebirds. Of particular importance are the large hypersaline lakes, e.g., Great Salt Lake, UT; Lake Abert, OR and Mono Lake, CA, and the salt lake/playa associated marshes of Utah, Oregon and Nevada." (http://iwjv.org/shorebirds-intermountain-west).

Although extremely important to international shorebird migration, Lake Abert is under severe stress from water use and drought (Herbst, 2014). The lake was nearly completely dry in 2014 and 2015, destroying the brine shrimp and brine fly populations and dramatically decreasing shorebird use (Larson and Eilers, 2014). Even though Lake Abert is designated as a critical environmental area for shorebirds, there is no allocation of water to the lake to protect shorebird habitat from desiccation. The U.S. Bureau of Land Management has responsibility for managing the lake and the land surrounding the lake, but there is no federal or state protection for the lake itself. Flow into Lake Abert and evaporation from the lake are not measured directly, so it is difficult to attribute change in area/volume of the lake to water withdrawals or climate factors. Many ascribe the recent desiccation to the recent drought (Davis, 2014) and cite past dry periods in the early 20th century as proof of climate being the major/only cause of lake desiccation. Others blame over allocation of water resources and agricultural use upstream from the lake for exacerbating climate forcing and causing the collapse of the ecosystem (Larson and Eilers, 2014). Within such context, this paper has five objectives: 1) determine long-term trends (over the last 65 years) in lake volume and salinity; 2) estimate components of a water balance for the lake and use these to calculate natural lake conditions; 3) use the difference between calculated (natural) and measured conditions to estimate the amount of upstream withdrawals and determine the role of climate vs. direct water use; 4) determine the amount of water needed to preserve the viability of the lake's ecosystems under past and likely future conditions; and, 5) the overarching goal is to disentangle the direct human and broader climate controls on saline lake viability in order to preserve these unique habitats and the shorebird populations that use them.

#### 2. Hydrologic setting

Lake Abert occupies one of nine major sub-basins within the Oregon Closed Basins hydrologic unit watershed (HUC6: 171200), covering about 45,000 km<sup>2</sup> (17,000 mi<sup>2</sup>) in the northern extension of the Great Basin Ecoregion (Lev et al., 2012). The region is dominated by arid to semiarid landscapes, but also contains freshwater and saline wetlands and lakes, such as Lake Abert. Historically the lake has fluctuated in size dramatically. Phillips and Van Denburgh (1971) identified the highest "recent" lake stand at 1301.4 m elevation (4269.7 ft) (Fig. SI-1), possibly formed during an early-mid 19th Century pluvial (Woodhouse et al., 2005). When at this level, the lake had an area about 20,200 ha (50 thousand acres, ta) and a volume of about  $1200 \times 10^6$  m<sup>3</sup> (Mm<sup>3</sup>; 1000 thousand acre feet, taf) (Phillips and Van Denburgh, 1971). This high stand is about 3 m (10 ft) higher than any level recorded at Lake Abert over the last 100 years. On the low end, Lake Abert was reported dry or nearly dry in five years from 1924 to 1937 (Phillips and Van Denburgh, 1971), during the extensive early 20th century drought in North America (Woodhouse et al., 2005; Woodhouse, 2004). However, quantifying these early low stands/periods of desiccation are difficult because there were few measurements of lake elevation during these early years. Phillips and Van Denburgh (1971) estimated lake levels during this time by using a simple hydrologic model based on the flow in the Chewaucan River, the main source of water to the lake. Their time series shows the lake recovering between dry periods (their Fig. 13), and relatively high lake stands previous to 1924. Since 1940, the lake has not fallen as low until the summers of 2014 and 2015, when the lake was nearly completely dry.

At Lake Abert, Phillips and Van Denburgh (1971) estimated that annual evaporation (~99 cm/~39 in.) far exceeds precipitation (~30 cm/ ~12 in.). This local precipitation deficit is made up mostly by runoff from the high-elevation mountain ranges to the west that supply snowmelt runoff to the Lake Abert watershed via the Chewaucan River



Fig. 1. Location map showing main features mentioned in text.

(Fig. 1), and other smaller tributaries. Without this snowmelt runoff Lake Abert would be a seasonal playa and not a highly productive, mostly (historically) perennial saline lake. The Chewaucan River watershed (1690 km<sup>2</sup>/652 mi<sup>2</sup>), composed mostly of forest and rural ranch and farm land, provides most of the inflow to Lake Abert. Lesser amounts of snowmelt dominated inflow also originate from un-gaged tributaries in the lower Chewaucan watershed, especially Crooked Creek, Willow Creek, and Moss Creek. Short-term runoff from rain is also added from parts of the watershed immediately surrounding Lake Abert, the Sand Canyon-Lake Abert watershed (HUC 1712000605;  $696 \text{ km}^2/269 \text{mi}^2$ ), and perennial springs on the eastern edge of the lake (Phillips and Van Denburgh, 1971). Flow directly into Lake Abert from all these sources is not measured. Only the Chewaucan River near Paisley, OR has a long, nearly continuous discharge record (1915-present), but this gage is 37 km (~23 miles) upstream from the inlet to the lake, with large amounts of irrigated farmland between.

Excess evaporation over inflows has concentrated dissolved salts in Lake Abert. In the first and only detailed geochemical study of the lake, Phillips and Van Denburgh (1971) found that Lake Abert was highly alkaline (pH = 9.7), with salinity ranging from 1.9–9.5% from 1939 to 1963. Geochemistry of the lake is dominated by Na<sup>+</sup>, CO<sub>3</sub><sup>2-</sup>, and Cl<sup>-</sup> (90% of total ions), with secondary K<sup>+</sup>, HCO<sub>3</sub>, and SO<sub>4</sub><sup>2-</sup> (9%). Ca<sup>2+</sup> and Mg<sup>2+</sup> are very low (<5 ppm; see Table 29 in Phillips and Van Denburgh (1971) for detailed geochemistry).

Below the Chewaucan River near Paisley gage, but above the inlet to Lake Abert, about 14,200–22,300 ha (35–55 ta) are irrigated for hay crops, including the former upper and lower Chewaucan marshes, which have been completely transformed from natural systems to agricultural lands. Although there is no direct measurement of the amount of water withdrawn/consumed for irrigation upstream of Lake Abert,

Phillips and Van Denburgh (1971) estimated that on average from 1924 to 1964 about half of the flow of the Chewaucan River at Paisley made it to Lake Abert. However, water rights on the Chewaucan River are extensive (Fig. SI-2), allocating substantially more than the mean annual flow in the river (http://www.oregon.gov/owrd/pages/WR/ wris.aspx). Additionally, one shallow reservoir covering about 223 ha (550 acres) impounds the Chewaucan River and Crooked Creek (the largest tributary above Lake Abert and below Paisley) immediately upstream from Lake Abert. This reservoir stores about  $2.27 \times 10^6$  m<sup>3</sup> (Mm<sup>3</sup>, 1840 acre feet) of water, so that Lake Abert receives river flow only when that flow exceeds the storage capacity of this reservoir, or is released from a small outlet drain. Lake Abert has no "water right" and is therefore not officially considered in water management of the Chewaucan River basin. Therefore, inflow to the lake is dependent entirely on the flows remaining after withdrawals are made upstream when irrigation/other demands are lower than river flows or the diversion infrastructure cannot extract the entire flow of the river during short-term, high flow spring runoff.

#### 3. Methods

#### 3.1. Data analyses

All data reading, formatting, analyses, and plotting utilized the statistical and data analyses package *R* and additional analyses packages within R (https://www.r-project.org). Conventional American water resource units ("English") were used for all datasets and analyses and then transformed into SI units for plotting. Both are presented in the text because American water resource units are used exclusively in U.S. water measurement, allocation, and management.

# 3.2. Lake area and elevation data

The basic data used to measure Lake Abert change from 1972 to 2015 is the digitized area of the lake derived from Landsat satellite images (termed "Landsat area data"). Natural color images from Landsat 8 OLI, 7 ETM +, 4-5 TM, and 1-5 MSS were selected using the U.S. Geological Survey's Landsat Look Viewer (http://landsatlook.usgs.gov/ viewer.html). Images were limited to those with <30% cloud cover, and digitized at a scale of approximately 1:144,000. More recent images were sharp and easily digitized at this scale, while shorelines of some older MSS images were less distinct. A total of 493 images from 1972-07-25 to 2015-09-29 were digitized, with areas ranging from a low of 236 ha (583 acres) to a high of 17,564 ha (43,405 acres). The interval between images ranged from about a week to several months. Fifty-eight images were re-digitized to check precision of the digitizing method (Fig. SI-3a). All but six replicates were within about  $\pm$  1% of the original area; those six were within  $\pm 4\%$ . Generally smaller lake areas and poorer quality images resulted in the lowest precision. Absolute precision for all replicates was about  $\pm 162$  ha ( $\pm 400$  acres) (Fig. SI-3b), however, 45 of the 58 (~80%) replicates were within  $\pm$ 81 ha  $(\pm 200 \text{ acres})$ . In general, as area increased, absolute precision also increased.

Area determinations were extended farther back in time using elevation data and an elevation-area-volume relationship for the lake from Phillips and Van Denburgh (1971). Those data were fit with a cubic spline to calculate area from elevation and volume from area. The hypsometric relationship was applied to the USGS elevation data (Fig. SI-4a), producing an area time series from 1951 to 1972. The USGS area time series was then attached to the measured Landsat area data to construct a complete lake area time series from 1950 to 2015. The Phillips and Van Denburgh (1971) area-to-volume curve was used to transform the area time series to volume (Fig. SI-4b). One caveat on the transformations is that lake volume for a specific area is highly dependent on the shape of this hypsographic curve at that area. As a result, changes in volume are very insensitive to change for areas below about 12,140 ha (30 ta) and very sensitive above 12,140 ha.

A monthly time series of area and volume for Lake Abert was constructed by calculating the mean of data in each month and filling the missing months with values estimated from a cubic spline fit to the measured area. This resulted in a continuous, monthly time series of area and volume from 1950 to 2015. This monthly time series, along with monthly time series of evaporation, precipitation and river discharge (see Section 3.4), were aggregated into water year (WY, Oct 1 to Sep 30) time series. These water-year time series were then used to construct an annual water balance for the lake from WY1951– WY2015, and to determine "natural" (without any upstream withdrawals) and "measured" (with upstream withdrawals) conditions for the lake. Water years were considered more appropriate for water management and policy decisions. Aggregation to water year also smoothes artificial fluctuations produced by the spline fit of missing monthly data, providing a better foundation for calculating the water balance.

#### 3.3. Salinity data and calculations

Phillips and Van Denburgh (1971) and Van Denburgh (1975) previously showed that salinity in Lake Abert is controlled by lake elevation dominantly through volume dilution and removal/transformation of precipitated salts by physical/geochemical processes, resulting in a relatively simple relationship between lake volume and salinity. Salinity data reported in previous work (Denburgh, 1975; Herbst, 1994; Larson and Eilers, 2014; Phillips and Van Denburgh, 1971) were used to construct an area-salinity relationship for Lake Abert by fitting a cubic spline to the volume-salinity data (Fig. SI-5). This spline was then used to predict a monthly salinity record from 1951 to 2015 based on the complete time series of volume. Monthly salinity data were aggregated into water year to determine difference between natural and measured salinity over time, based on volume differences.

#### 3.4. Climate and river flow data sources

Climate data were used to construct a time series of potential inflow (precipitation and river flow) and outflow (evaporation) from Lake Abert for the period from October 1950 through September 2015 with the objective of estimating an annual water balance (by WY) for the lake. However, climate data at the lake were not available, so data from relatively nearby stations were used to estimate lake conditions. Daily and/or monthly precipitation data were available from weather stations at Paisley, Summer Lake, Lakeview, Alkali Lake, and Valley Falls, OR. Paisley (about 27 km/17 mi northwest of Lake Abert) had the most continuous and complete climate record, so were used as a main source for Lake Abert precipitation data. A combination of data from Paisley and stations at Summer Lake (about 53 km/33 mi northwest of Lake Abert) and Lakeview (about 48 km/30 mi south of Lake Abert) were used to estimate evaporation from the lake from 1951 to 2015 (see Section 3.5). Precipitation and evapotransporation data were downloaded from the NOAA National Centers for Environmental Information, Climate Data Online web portal (http://www.ncdc.noaa. gov/cdo-web/), the Bureau of Reclamation's Pacific Northwest Region AgriMet web site (http://www.usbr.gov/pn/agrimet/), and the U.S. Geological Survey hydroclimatologic data network (HCDN, Vogel and Sankarasubramania, 2005, http://daac.ornl.gov/cgi-bin/search/hcdn. pl?d=810).

Mean daily flows in the Chewaucan River near Paisley, OR (Station 10384000), about 37 river km (23 mi) upstream from the inlet to Lake Abert, are available from 1924-present at the Oregon Department of Water Resources (OWRD) web site (http://www.oregon.gov/OWRD/ pages/index.aspx). However, no river discharge data are available for flow directly into Lake Abert from the Chewaucan River or from intermittent streams leading directly into the lake. Nor is flow measured on streams flowing into the Chewaucan River between the Paisley gage and the inlet to the lake. Daily discharge data for the river at the Paisley gage were downloaded and daily flow transformed to monthly flow for comparison to other monthly time series and aggregated into water year for water balance calculations. Estimates of the three main un-gaged tributaries (Crooked, Willow and Moss creeks) were made using the U.S.G.S. StreamStats (v. 3 Beta) equations for southern Oregon (Risley et al., 2008) and the flow data from the Chewaucan River. Water rights data for the Chewaucan River were downloaded from OWRD for comparison to river flow data. No data were available for water used and consumed upstream from Lake Abert, only that allocated in water rights.

#### 3.5. Estimating lake evaporation rate

There are very few measurements/calculations of evaporation in the immediate vicinity of Lake Abert for the complete study period. Therefore, two different datasets of calculated evapotranspiration (ET) were used to construct a complete time series of evaporation from the beginning of WY1951 to the end of WY2015 and then corrected for lake salinity. The best documented and highest resolution data for ET is available from the U.S. Bureau of Reclamation, AgMet station at Lakeview, OR (LAKO station), about 48 km (30 mi) south of Lake Abert. Kimberly-Penman ET is calculated at LAKO from a nearly continuous daily record from April 1988 through May 2015. Missing intervals in this dataset (mostly from 1 to 6 days with one interval of 11 days) were filled using a spline function and then monthly cumulative ET was calculated for all months. The second ET dataset used was monthly potential ET data from the U.S. Geological Survey Hydroclimatologic Data Network (HCDN) for Paisley, OR, 27 km (17 mi) northwest of Lake Abert (Vogel and Sankarasubramania, 2005) (http://daac.ornl.gov/cgi-bin/search/ hcdn.pl?d=810). The Paisley HCDN data (termed PAIS) extended

from 1951 to 1990. To construct a continuous monthly dataset from WY1951 to WY2015, 32 months of overlapping data between LAKO and PAIS were used to construct a polynomial regression between the two stations (Fig. SI-6). The regression equation was used to build a continuous monthly time series of ET for the period after 1990 based on the PAIS station data (April 1988 through May 2015). This resulted in a continuous monthly dataset of ET (termed ABERT\_ET), representing a best estimate of ET in the vicinity of Lake Abert.

The ABERT\_ET dataset was validated by comparison to the Global Historical Climatology Network (GHCN) Summer Lake station, about 53 km (33 mi) northwest of Lake Abert. The Summer Lake stations has a record of "daily" pan evaporation (Ep) from 1961 through 2014 (http://www.ncdc.noaa.gov/cdo-web/). Although Summer Lake daily Ep data extends over much of the 1951-2015 study period, missing data makes it unusable as a primary dataset. When consolidated to monthly Ep, missing days resulted in 6 months without data in all years and as many as 12 months in others. There were also some large discrepancies between daily values for adjacent days, with some values several times greater than values on either side of those days. The data gaps and outliers made filling data with a spline or other functions unrealistic, so the Summer Lake Ep was used only to check/validate the constructed ABERT\_ET time series. All overlapping months in the composite ABERT\_ET time series and Summer Lake Ep record were compared using linear regression. Before comparison the Ep data was adjusted with a pan coefficient of 0.7 to allow for the difference in ET and Ep. The regression had an  $R^2 = 0.93$  (p < 0.0001), indicating that the composite time series captured the timing and magnitude of change in measured Ep at Summer Lake (Fig. SI-7) and was likely a good representation of ET in the area. The ABERT\_ET time series was then used to calculate evaporation from Lake Abert based on area and salinity of the lake.

#### 3.6. Determining the effect of salinity on lake evaporation

As salinity increases in saline lakes, the ratio of evaporation rate from saline water to fresh water (E<sub>sal</sub>/E<sub>fw</sub>) decreases (Calder and Neal, 1984; Harbeck, 1955; Mohammed and Tarboton, 2011). This salinity effect dominates effects due to temperature changes (Harbeck, 1955), so that a first order approximation of the salinity effect on  $E_{sal}/E_{fw}$  can be determined from salinity alone. Harbeck (1955) developed simple analytical relationships between E<sub>sal</sub>/E<sub>fw</sub> and salinity of natural waters and found that E<sub>sal</sub>/E<sub>fw</sub> response to salinity was also affected by the total amount of evaporation, with higher evaporation levels shifting the polynomial relationship to higher ratios. These experiments show a range of scatter of E<sub>sal</sub>/E<sub>fw</sub>, but generally follow the theoretical predictions of Harbeck. To adjust Lake Abert evaporation estimates for salinity, average coefficients for 2nd-order polynomial regressions to five of these empirical datasets were used (Fig. SI-8). Evaporation from Lake Abert was determined by using that polynomial equation to adjust the evaporation time series (ABERT\_ET) with the monthly lake salinity time series. The salinity of Lake Abert from 1950 to 2015 ranged from a low of about 2% to a high of 28%. At the lowest salinities, corrected evaporation results in values close to that of fresh water ( $E_{sal}/E_{fw} \sim 0.99$ ); at the highest salinities evaporation decreased to about 60% of that for fresh water ( $E_{sal}/E_{fw} \sim 0.60$ ), so salinity has a larger effect on water balance as the lake decreases in volume/area and salinity rises.

#### 4. Results and discussion

#### 4.1. Area and volume time series

The area time series for Lake Abert (Fig. 2a) shows a dynamic lake, with changing area on several time scales. Over much of the record, from 1950 to 2005, the lake maintained large areas mostly >15,000 ha (~45 ta), with mostly small annual/seasonal declines. Large declines down to areas of about 6100 ha (~15 ta) occurred in only three years,

1950, 1992, and 1994. This "high stand" period changed after 2000, with the lake systematically shrinking to lower areas. Since 2005, the lake has fallen to areas much lower than in any other part of this record and seasonal highs since 2012 have not reached previous lows. In 2014 and 2015 the lake nearly completely desiccated, reaching minimum areas of 236 ha (583 ac) and 666 ha (1646 ac), respectively. This makes the last decade one of uniquely low lake areas in the last 65 years of record.

Changes in lake area directly affect habitat availability for aquatic insect productivity. Larvae and pupae of brine flies and brine shrimp rely on boulders/cobbles in shoreline habitats egg attachment and protection from predators. This upper shoreline habitat is narrow — it is available only at areas above about 13,000 ha (33 ta) (Herbst, 1994). Lower lake levels expose salt flats and limit access to such shoreline habitats. The persistence of low lake area since 2005 has eliminated access this habitat, which can now be reached only during short high stands. Lower lake areas also likely affect shorebird nesting success, but there is no data on Lake Abert nesting habitat to estimate the effect.

The monthly lake volume time series (Fig. 2b) shows the same trends/patterns as lake area, but better illustrates the water balance through time. The transformation from area to volume mutes some short-term variability (e.g., the large decreases in area in the mid-1990s and 2014–2015), but emphasizes the large changes in volume that can occur in the lake at different time scales. The largest changes are seen over a decade scale, when high lake volumes can shrink from 430 to  $740 \times 10^6$  m<sup>3</sup> (Mm<sup>3</sup>) (350–600 taf). Even at the annualmonthly scale, changes are commonly from 30 to 95 Mm<sup>3</sup> (25–75 taf) (Fig. 2c). The largest drop in volume occurred from the high stand in 1984 of nearly 863 Mm<sup>3</sup> (700 taf) to very low volumes of about 25 Mm<sup>3</sup> (20 taf) in the early-mid 1990s. Over this decade the lake lost about 840 Mm<sup>3</sup>, but over the next five years gained about 592 Mm<sup>3</sup> (480 taf) to another high stand in 2000. However, since 2000 the lake has acted very differently with much smaller highs and steady decreases in lows to the near zero values in 2014 and 2015.

#### 4.2. Salinity time series and control on aquatic insects

Salinity of Lake Abert is dominantly controlled by dilution/concentration as volume increases/decreases (Fig 3). Pre-1992, monthly salinity generally ranged from 2.5–7.5%, except for values of about 15–25% in some months in 1950–51. Post-1992, salinities reached peaks more often remained higher longer, with much higher salinities in 1992– 1996 corresponding to the very low volumes in the record during this interval. Since 2000, monthly salinity has increased steadily, reaching the highest values in the record in 2014 and 2015 of 28%. These high salinity excursions have lasted for many months or years, very unlike the salinity patterns pre-1992 which had much less variability over seasonal or multi-year time scales.

Ultimately, the productivity of Lake Abert and support for shorebirds depend on populations of aquatic insects that inhabit the lake at various life stages (alkali flies and brine shrimp) and the overlap of insect availability with shorebird use and migration patterns (Herbst, 1994) (Herbst, 1994). Salinity mainly determines the structure and complexity of these systems (Williams, 1998), controlling both biodiversity and species composition. Salt-adapted organisms, such as brine shrimp (*Artemia*) and brine flies (*Ephydra*) proliferate in certain ranges of salinity, controlled by predation and effects on physiology (Herbst, 1988; Wurtsbaugh and Berry, 1990). Different researchers have found different ranges of salinity tolerance in different lakes. These likely result from both differences in resident species and differing chemical composition of lakes.

In the Great Salt Lake, Brown (2010) suggests that both brine flies and brine shrimp can tolerate salinities as high as 20–26%, had poorer survivability above 15%, and brine shrimp had a reproduction upper threshold at salinities of 10–14%. Grimm et al. (1997) found that at low salinities of 5% predators substantially decreased brine shrimp



Fig. 2. Monthly time series for Lake Abert. (a) Area in thousands of hectares (left) and thousands of acres (right). (b) Volume in millions of cubic meters (left) and thousands of acre feet (right).

biomass. Barnes and Wurtsbaugh (2015), in microcosm experiments based on Great Salt Lake water chemistry, determined that brine shrimp had maximum densities between salinities of about 2.5-9%. Above a salinity of about 13% few individuals survived and above 20-22% they were nearly absent. Brine shrimp abundance decreased as salinity increased from about 8% to 15% in experiments conducted by Dana et al. (1993), on simulated Mono Lake water. In Lake Abert, Herbst (1994) showed that brine flies had good productivity in 2.5-15% salinity, with maximum abundance between 2.5 and 10%. Similarly, Keister (1992) estimated that the optimal range for aquatic biota at Lake Abert was from 3 to 8%. Conte and Conte (1988) found high biomass of brine shrimp in Lake Abert at a salinity of 8.2%, but Larson and Eilers (2014) observed that when Lake Abert reached salinities of 16-17% brine fly and brine shrimp populations were severely stressed and plummeted. At 20% salinity brine shrimp died out completely and brine flies were very rare. At 25% salinity the lake was saturated with CaCO<sub>3</sub> and aquatic insects could survive only in refuges near freshwater springs, where salinity was lower. At these high salinities, the crash of aquatic insect abundance caused shorebirds populations to decrease by two orders of magnitude (Larson and Eilers, 2014). Considering all these data, it is likely that the salinity range for adequate productivity and reproduction for both brine flies and brine shrimp is about 2.5–15%, with the optimum range from 3% to 8% (Keister, 1992). At salinities above 15%, salt toxicity (and decreased dissolved oxygen resulting from high salinity) stresses organisms and decreases populations. At salinities below 2.5%, high predation on primary producers decreases populations. Applying these ranges to the monthly salinity time series presented above can determine the effects of salinity changes on Lake Abert productivity over the last 65 years, to put recent salinity levels in a longer context.

At the highest volumes, salinities dropped to values at or below the optimal and tolerance lower limits, so that from about 1952–1992, lake productivity was likely more restricted by low salinities than by high salinities. After 1992, the situation changed dramatically, when monthly mean salinities have reached concentrations that are well above both the upper optimal productivity level (8%) and the upper tolerance limit (15%)(Fig. 3), and only briefly fell to levels near the lower limits. The large decreases in volume from about 1992–1997 caused a peak in salinity well above both limits. The lake had similar conditions for a much briefer time from about 1950–1952, but remained above the upper tolerance limit for only about three months. Since 2000, salinities



Fig. 3. Calculated Lake Abert monthly salinity (blue line). Horizontal dashed red lines are the approximate upper and lower tolerance limits for brine fly and brine shrimp (2.5% and 15%); dashed green lines are the approximate upper and lower optimal levels (3% to 8%); black dashed line is the approximate salt saturation limit. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

have steadily risen, mostly remaining above the optimal range and near or well above the upper tolerance threshold. The lake appears to have moved into a different salinity state, one with persistent salinities that would severely decrease food resources for shorebirds and hence their populations.

Salinity controls on aquatic insect productivity are extremely important as shorebirds breed and stage for migration. Shorebird populations show a small peak in May with the highest shorebird numbers in late summer to fall; numbers increase in July to a peak in August, but remain high through September (Warnock et al., 1998). Shorebird seasonal use corresponds to seasonal increases in salinity, with salinity commonly starting to increase in late spring or early summer and reaching maximum values in August-October.

#### 4.3. Drought severity and lake volume

To examine the potential effects of drought on Lake Abert, changes in lake volume were compared to the self-correcting Palmer Drought Severity Index (scPDSI). The scPDSI consolidates effects from temperature, precipitation, and soil available water (calibrated to local climate characteristics) to quantify the severity of metrological droughts (Wells et al., 2004). To smooth short-term seasonal variability, monthly scPDSI values from the Oregon Closed Basins Hydrologic Unit that encloses Lake Abert (http://www.wrcc.dri.edu/wwdt/time/) were aggregated into water year. The monthly changes in Lake Abert volume were also aggregated into water years, and then the Z-score of each water-year volume change was calculated for direct comparison to the scPDSI index. To clarify the comparison, scPDSI was normalized to the maximum Z-score of the measured change in lake volume, giving similar ranges in index values for both.

The resulting plot (Fig. 4) shows that measured lake volume change corresponds to scPDSI ( $R^2 = 0.52$ , p < 0.001). This strong correlation is shown by very similar patterns between scPDSI and lake volume change. When scPDSI rises, lake volume change increases; when scPDSI falls, lake volume change decreases. This relationship exists through most of the 65-year record, until the last few years. The decrease in scPDSI from 2011 to 2012 was followed by lake volume change. But as scPDSI continued to decline into 2015, lake volume change did not continue to decrease, instead reaching zero change. This resulted simply from the lake being nearly completely desiccated during these years, so the volume could not continue to decrease as the drought deepened.

The relationships presented above bring us to the main question of this research: How would volume and salinity of Lake Abert differ from those measured under "natural" conditions, ie., without water withdrawals upstream? Answering that question requires constructing a natural water balance for Lake Abert to compare natural vs. measured conditions over the last 65 years.

#### 4.4. Water balance: natural vs. measured lake volume and salinity

A conceptual water balance for Lake Abert is depicted in Fig. 5 (refer to Section 2 and Fig. 1 for component names). Inputs to the lake consist of flow at the inlet from the Chewaucan River (QCheR<sub>Inlet</sub>), local runoff from the surround basin (R<sub>Local</sub>), precipitation times lake surface area (PLake ALake) and inflow from springs along the northeastern edge of the lake (R<sub>Sprg</sub>). Outflow consists of only evaporation from the lake surface times the area of the lake (ELake ALake). QInlet is the combination of flow in the Chewaucan River near Paisley  $(Q_{CheR})$  and flow from the main un-gaged tributaries (Q<sub>Tribs</sub>) flowing into the river/agricultural system below Paisley, minus the water removed and consumed by irrigation and crop consumption (Q<sub>Irrig</sub>) in the lower valley agricultural system. This equation (Eq. 1) depicts the Lake Abert water balance with irrigation. It is the present "measured" system-the main components of inflow and outflow including direct modification for human use. The "natural" system (Eq. 2) is exactly the same but without water withdrawals for irrigation, Q<sub>Irrig</sub>. Irrigation withdrawal upstream of the inlet is simply the results from the calculated natural water balance (volume) minus the measured change in lake volume over some standard time period, typically the water year (WY., Oct 1-Sep 30).

$$\begin{aligned} \text{Measured} : E_{\text{Lake}} & A_{\text{Lake}} = P_{\text{Lake}} A_{\text{Lake}} + R_{\text{Sprg}} + R_{\text{Local}} \\ & + \left( Q_{\text{CheR}} + Q_{\text{Tribs}} - Q_{\text{Irrig}} \right) \end{aligned}$$
 (1)

Natural : 
$$E_{Lake} A_{Lake} = P_{Lake} A_{Lake} + R_{Sprg} + R_{Local} + (Q_{CheR} + Q_{Tribs}).$$
 (2)

To construct the water balance all monthly data were aggregated into water year to minimize variability and effects from lag times between inputs/outputs and responses (see Section 3.4). This produces an annual (WY) balance from WY1951 through WY2015. Similarly, the measured monthly time series of lake volume and lake volume change was aggregated into water years as the comparison to the calculated water balance (Fig. 6).

Calculated flow into and out of the lake is summarized in Fig. 7. Total river flow into the lake includes only the natural flow available at the inlet into the lake ( $Q_{inlet}$ ), i.e. the sum of the flow in the Chewaucan River measured at Paisley ( $Q_{CheR}$ ) and the flow estimated for ungaged tributaries ( $Q_{tribs}$ ), assuming no water consumption by irrigation (Fig. 7a). The local water balance for Lake Abert is the balance between inflows and outflows without these flows from the Chewaucan R. watershed. Local inputs to the lake are from excess runoff above precipitation from the surrounding basin ( $R_{Local}$ ), average annual inflow from local springs ( $R_{Sprg} = 8.9 \text{ Mm}^3$ /year or 7.23 taf/year, Phillips and Van Denburgh, 1971), and precipitation onto the lake's surface ( $P_{Lake} A_{Lake}$ ) (Fig. 7b). Outflow is simply the salinity-adjusted evaporation from the lake's surface ( $E_{Lake} A_{lake}$ ), because there is no ground-water or surface-water flow leaving the lake (Phillips and Van Denburgh, 1971). Contrasting these inflows and outflows shows that the lake is



**Fig. 4.** Time series of the water-year averaged self-correcting Palmer Drought Severity Index (scPDSI, grey bars) compared to the Z-score of the water-year averaged measured monthly change in volume (blue). To clarify the comparison, scPDSI is normalized to the maximum measured change in lake volume, so the plotted values are 0.6 of the actual scPDSI values. The scPDSI values are for the Oregon Closed Basins Hydrologic Unit, generated from "The West Wide Drought Tracker" (http://www.wrcc.dri.edu/wwdt/time/). Measured lake volume change is significantly correlated to scPDSI with a  $R^2 = 0.52$ , at p < 0.001. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



**Fig. 5.** Schematic of water balance for Lake Abert under present-day conditions with irrigation withdrawals upstream from the lake. See text and Eq. (1) for terminology.

under strong water deficit if only local inputs are considered (Fig. 7b), however, has a water surplus most water years if the all upstream flow ( $Q_{Inlet}$ ) were added to the lake (Fig. 7c). In fact, during the last decade when lake volume has been under steep decline (Fig. 6a), inflows exceeded outflow for all but one year when they were equal (Fig. 7c) indicating that actual/measured lake volume does not match predicted natural conditions.

Comparing the calculated annual water balance to the measured change in lake volume illustrates this difference between measured and natural conditions (Fig. 8a) and allows the construction of a natural lake volume time series from WY195WY2015 (Fig. 8b). This comparison shows that the lake would be very different without upstream withdrawals, having substantially more water (higher volume) through most of the record. Fig. 9 shows two Landsat images of Lake Abert at volumes and areas equivalent to measured and natural water-year conditions. These volumes did not occur for the entire water year, but are illustrative of how different average conditions for the lake are between natural and measured conditions. In the left image (Fig. 9a), the lake has

a volume of 19.5  $Mm^3$  and an area of 5625 ha (15.8 taf/13.9 ta), the average for 2015 when the lake was nearly dry in October-this represents the average measured conditions for WY2015. The lake is concentrated into a small region (dark blue), with minimal contact with the rocky shoreline environment (shown by the maximum outline of the lake as shown in the supplemental material). The right image (Fig. 9b) is the lake at the calculated WY2015 average volume of 113.7 Mm<sup>3</sup> and an area of 11,736 ha (92.2 taf/29.0 ta). The lake occupies a large proportion of the lake basin and is in contact with the rocky shoreline in all but the northern edges of the lake. Contact with the rocky shoreline habitat can have significant effects on productivity of the lake. Larvae and pupae of alkali flies especially require shoreline boulders/cobbles/vegetation for attachment and growth. These habitats protect the growing pupae from wave action and provide hideouts from predators. Lower lake levels expose salt flats and limit access to these habitats (Herbst, 1994) so can have a deleterious effect fly production. However, the most important aspect of measured and natural conditions is driven by the potentially different salinity in each scenario.

Because volume controls salinity, and salinity is the primary driver of brine shrimp and alkali fly productivity, determining the difference between salinity under natural and measured conditions shows the effects of water withdrawals on the ecologic viability of Lake Abert. Using the salinity limits presented in Section 4.1 shows that under natural conditions the lake would have had very different salinity controls on productivity (Fig. 9c). Even after aggregating to water year, which decreases the extremes seen in the monthly data, salinity under measured conditions are well above optimal salinity limits for many years and above the upper tolerance limit in the last few years. Under natural conditions salinity is substantially lower, never reaching the upper tolerance limit for the entire record and only hitting the upper optimal limit in the last two years. Without upstream water withdrawal and use, the lake would have not have seen any of the severe die-off events due to excess salinity reported in the media (Davis, 2014). In fact, the lake would have maintained salinities at 2.5% to 6% through most of the record. These are close to the optimal range of growth for Lake Abert of 3-8% (Herbst, 1994), and if anything at the low end. At this lower limit of tolerance for brine shrimp and alkali flies, a more complex ecosystem could have been supported under natural conditions, even including some fish species presently not seen in the lake (Stickney, 1986). The next step is to



Fig. 6. Time series of water year (WY) measured volume (a) and volume change (b) in Lake Abert, aggregated from monthly data plotted in Fig. 2b.



**Fig. 7.** Water balance components for Lake Abert. a) Discharge in streams above Lake Abert inlet: tn-gaged streams (green line); Chewaucan River near Paisley (blue); total combined flow (black). b) Local water balance at Lake Abert without upstream runoff: evaporation from lake surface (red); precipitation directly onto the lake surface (blue); runoff from the immediately surrounding basin plus spring flow into the lake (green). c) Summary water balance for all inflows (blue) and outflows (red) in a and b. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



Fig. 8. Natural (i.e., without upstream water withdrawals) versus measured conditions for Lake Abert. a) Calculated water balance for natural conditions (blue) and measured water balance (red). b) Resulting lake volume based on natural (blue) and measured (red) water balances. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



**Fig. 9.** Measured vs. natural extent of Lake Abert for WY2015. The dark blue in the images is open/deeper water, light blue is patches of very shallow water on salt, grey is wet exposed salt, and white is dry salts. The open water boundary is outlined in white for clarity. a) Left panel is a Landsat image of Lake Abert taken on 2015-07-20 at an equivalent volume and area to the mean of measured monthly values for WY2015, a volume of 19.5 Mm<sup>3</sup> and an area of 5625 ha (15.8 taf/13.9 ta. b) Right panel is an image taken on 2012-08-03 at the calculated equivalent natural volume/area for WY2015, 113.7 Mm<sup>3</sup>/11,736 ha (92.2 taf/29.0 ta), i.e., what the lake would look like if no water was extracted upstream; black lines are missing data artifacts in the Landsat image. c) Resulting water-year average salinity (wt.%) for natural salinity (blue line) and measured salinity (red line). Horizontal dashed red lines mark the approximate tolerance limits for brine fly and brine shrimp productivity and green lines mark the approximate optimal levels (as in Fig. 3). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

determine the amount of water has been removed from the system for agricultural use upstream and how much would be needed to keep Lake Abert in a range of volumes and salinity for a viable and productive ecosystem.

# 4.5. Estimating upstream water use and the amount needed for lake management

The amount of water used in upstream of Lake Abert is not measured directly, however water rights records show the amount allocated to water users. There are 255 points of diversion for surface water use in the Chewaucan River and its tributaries upstream of Lake Abert; 153 from the main stem of the river alone. This does not include water rights for ground water withdrawal or storage in ponds/reservoirs. Water rights for mostly agricultural use were first established in the basin in the 1870s and grew substantially through the turn of the 20th century (Fig. 10). By 1910 the amount of water allocated was 270 Mm<sup>3</sup>/year (220 taf/year), or about two times the mean annual discharge of the Chewaucan River. Allocations grew slightly until 1990 when allocation increased dramatically to about 380 Mm<sup>3</sup>/year (310 taf/year) (Fig. 10), above the maximum annual discharge in the Chewaucan River and greater than the mean annual volume of Lake Abert. While nearly all the pre-1990 water rights were for agricultural use and so likely consumptive, the 1990 additions were for "wildlife" and "anadromous and resident fish", so are possibly less consumptive than previous agricultural allocations. In any case, the Chewaucan River is a highly over-allocated system with rights to much more water than most flows that occur annually in the river. Essentially all the surface water can be legally extracted from the river leaving nothing to flow into Lake Abert. The amount of water actually used, rather than that allocated, can be estimated by calculating the volume difference between natural and measured lake volumes.

The difference between the natural and measured lake volume curves (Fig. 8b) is a direct estimate of the "missing" water withdrawn for upstream use during each water year for the last 65 years (Fig. 10c). The resulting time series has a median value  $108 \text{ Mm}^3/\text{year}$ (88 taf/year) and 25th and 75th percentile values of 79 and 139  $Mm^3/$ year (64-113 taf/year). The calculated median withdrawal amounts are about 30% of the total allocations pre-1990, but the values over the last 65 years range from 0 to 75% of allocation, showing the high variability of the calculated water withdrawal. As a check, we can compare these values to those estimated by the amount and type of cropland in the basin. The lower Chewaucan River basin above Lake Abert has about 17,000 ha (42,000 ac) of surface-water irrigated lands where mostly alfalfa and other hay is grown (OWRD data, digitized on Google Earth images). In the arid regions of the Intermountain West these crops require from 0.6–1.2 m of water per year (2–4 ft/year; Putnam et al., 2007). Growing these crops would require about 108–207 Mm<sup>3</sup> (84– 168 taf) of water annually, very similar to the somewhat lower water balance calculation of 79–139 Mm<sup>3</sup>.

#### 4.6. Management strategies defined

Using the water balance calculation as a reasonable estimate of water used upstream, management strategies can be determined for Lake Abert. The amount of water needed annually to keep the lake below the optimal salinity limit of 8%, or the upper tolerance limit of 15% is, surprisingly, relatively small (Fig. 11a). Only 12–60 Mm<sup>3</sup> (10– 50 taf) in 3 of the last 65 years would be needed to keep the lake below the upper tolerance limit. Even to keep the lake below the upper optimal limit would require only 12-120 Mm<sup>3</sup> (10-100 taf/ year) in 13 of 65 years, with all but four years requiring <60 Mm<sup>3</sup> (<50 taf). To put these values in perspective, the total water rights in the basin are about 370 Mm<sup>3</sup> (300 taf), more than three times the maximum water needed (and that for only one year), and more than six times the typical amount of water needed. Therefore, the amount of water to maintain Lake Abert at a volume that would preserve brine shrimp and alkali fly productivity is at the low end of the amount legally-available water upstream. In theory, water could be purchased from willing sellers and reallocated to Lake Abert. However, remembering that water is highly over-allocated, there may be other physical limitations (not considering the social and political constraints).

To examine those limitations we need to compare the water needed with what is actually physically available each year. Fig. 11b compares that total available discharge  $(Q_{CheR} + Q_{Tribs})$  from the water balance with the water needed to maintain lake productivity (as a percent of the total available flow). Previous to 1992, there is no or very minimal constraints to reallocating water to the lake-all years zero except for WY1951 which would require only 20% of the available water. However, from 1992 to the present, water allocation would be more challenging to maintain optimal conditions. In some years the amount of water needed is a large fraction of, or exceeds, the available water. This is especially true in 2014 and 2015 when Lake Abert nearly completely dried up in the late summer and flows in the Chewaucan River were extremely low. In these two years, to keep salinity below the upper optimal limit (8%) would require 110-120% of upstream flow, and 50% of upstream flow to keep the lake below the upper tolerance limit (15%). However, with advanced planning even these demands could be met by banking water during wet years by transferring it through the water diversion system into Lake Abert.



**Fig. 10.** Water rights for the Chewaucan River basin from the Oregon Water Resources Department (http://www.oregon.gov/OWRD/pages/index.aspx). a) Start year and total water-year amount for water rights on record for each year. b) Cumulative amount of water rights per each consecutive water year; green dashed lines mark the maximum (upper) and mean (lower) water-year flows in the Chewaucan River; dashed black line marks the mean water-year volume of Lake Abert. c) Calculated irrigation withdrawals upstream of Lake Abert (the difference between measured and natural volumes), where, the heavy dashed black line marks the median water year withdrawal (108 Mm<sup>3</sup>/year or 88 taf/year), and the lower light dashed black line marks the 25th percentile value (179 Mm<sup>3</sup>/year or taf/year) and the upper light black dashed line marks the 75th percentile value (139 Mm<sup>3</sup>/year or 113 taf/year). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



**Fig. 11.** a) Total upstream flows (black line) compared to flows needed to keep the salinity in Lake Abert below the upper optimal (blue, 8%) and upper tolerance (red, 15%) limits for brine shrimp and brine fly productivity. b) Fraction of the total upstream flows (%) for each water year needed to keep Lake Abert below the salinity limits (colors as for a); dashed black line is 100% of total available upstream flow. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Such transfers at times of water surplus would buffer water deficits during extended/extreme droughts in following years.

#### 5. Conclusion

Lessons learned at Lake Abert apply to the worldwide desiccation of endorheic lakes under continuing human actions and increasing drought (Cook et al., 2014; Gutzler and Robbins, 2011; Williams, 1996, 2000, 2001; Jellison et al., 2008; Zhao and Dai, 2015). Drought drives landscape and waterscape change in arid regions (e.g., Dai, 2011) and drought clearly has a strong control on Lake Abert (Fig. 3). However, change in climate is not the only factor controlling lake area and salinity, and by itself would not produce the recent low lake volumes and high salinities that have decreased shorebird use at Lake Abert. Human water use has become a defining aspect of endorheic lakes survivability in a warming world. The contraction and salinization of Lake Urima (Iran) and the Aral Sea (central Asia) result primarily from upstream water withdrawals, not from climate change (Micklin, 2007; Lotfi and Moser, 2012). Increased salinity and reduced area have dramatically diminished the ecosystem services of these once highly productive lakes. These ecosystem services have been exchanged for agriculture production on upstream lands. Wetland habitats throughout the world are now so endangered from over allocation of upstream water that wildlife conservation is in conflict with agricultural use at a global scale (Lemly et al., 2000). It is extremely important to accurately attribute the causes of such change in order to understand how best to manage these systems.

Recognizing the importance of agriculture in arid/semi-arid regions to local communities and the economy as a whole, other ecosystem values are also important. Large-scale withdrawal of water for direct human use increases the imbalance between natural runoff and evaporation during periods of drought. As shown in Lake Abert, those humancaused changes can far outweigh the natural responses to drought. Without upstream withdrawals, the Lake Abert ecosystem would have been stressed in recent droughts, but not decimated as it has been in the last two years, when high salinities nearly destroyed the brine shrimp populations with a concomitant decline in shorebird use. These avian declines extend well beyond Lake Abert. Although trends in North American shorebird populations are poorly constrained by lack of continuous and local data, assessments have shown statistically significant declines in a majority of species (e.g., Morrison et al., 2001, Morrison et al., 2006; Thomas et al., 2006; Bart et al., 2007; Andres et al., 2012). Similar declines are occurring across the Great Basin, where all endorheic lakes designated as critical shorebird habitat by the Intermountain West Joint Venture (http://iwjv.org/shorebirdsintermountain-west) were completely dry or at their lowest recorded stands in summer 2014 and 2015, including the Great Salt Lake at the far-eastern edge of the Great Basin (Wurtsbaugh, 2014). If the trends in increasing water use and drought continue, even the Great Salt Lake may go the way of Lake Urima and the Aral Sea, severely impacting western hemisphere shorebird populations.

Because large numbers of shorebirds depend on saline lakes worldwide during migration, untangling natural fluctuations from those due to direct human actions is critical to preserving shorebird populations. Using available information and approaches presented above, an "environmental water budget" could be determined for all such lakes, to lay a foundation for sustainable conservation among continued threats from development and climate change (Mount and Gray, 2015). This tool could lead to development of innovative solutions, such as inviting consortiums of local water users, stakeholders, and wildlife management agencies to develop plans to allocate water to the lake and to create a "water right", as suggested for the drought-ravaged California environment to protect endangered fish species (Mount et al., 2015) and the Great Salt Lake (Wurtsbaugh, 2014). Possessing an accurate picture of past and current water uses based on factual data is foundational to saving the endorheic saline lakes worldwide.

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#### Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx. doi.org/10.1016/j.scitotenv.2016.02.161.

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