What is the status and future of Lake Abert?

Responses to Primary Questions motivating the Workshop on Southcentral Oregon Saline Lakes, November 2022, US Geological Survey

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Lake Abert, 9-2-2012, viewed from near Juniper Point when the lake was relatively high. Ron Larson photo.

Executive Summary

This document provides the U.S. Geological Survey (USGS) with information for their Integrated Water Availability Assessment of Lake Abert and the Chewaucan Basin. Lake Abert is a hypersaline, terminal lake of great ecological importance located in southcentral Oregon. The lake is primarily fed by the Chewaucan River, which was straightened and channelized. Numerous diversions were built between Paisley and the lake for flood-irrigation of grass-hay, but the amount of water diverted is not reported and thus unknown. However, the estimated water needs to meet annual crop ET demand totaled 37 to 68 TAF for the 2017-2022 period, which if supplied from the river, would have consumed much of the flow. Several estimates suggest, on average over recent decades, ~40-70% of the flow measured at Paisley has reached the lake, but less water likely gets to the lake more recently, such as in 2020-2021, when almost no river flow entered the lake.

The lake supports many waterbirds and nearly 80 species have been reported from the lake, with the most numerous being: Wilsons Phalaropes, Eared Grebes, and American Avocets, which have numbered >200,000, 40,000, and 20,000, respectively. The lake has provided habitat to relatively high percentages of the North American populations of the following birds: American Avocets, Snowy Plovers, Black-necked Stilts, Red-necked Phalaropes, and Wilson's Phalaropes. The primary driver of waterbird populations using the lake is considered to be food availability provided by brine shrimp and fly populations, which are affected by salinity which is controlled by water levels. Lake levels ≥4250 feet are deemed necessary to ensure that ecological conditions for birds are suitable. Since 2000, lake levels have been ≥4250 feet in October in 8 of the 23 years, and more recently, since 2010, October elevations

have been ≥4250 feet in only 2 of 13 years, and the lake was mostly dry during 4 of 13 years. Consequently, it is likely that recent low water levels and high salinities are responsible for the substantial downward trend in waterbird abundances over the past decade, going from over 200,000 to <15,000. The adverse effects of low lake elevations include: 1. Reduced habitat for algae, shrimp, flies, and birds; 2. Increased probability of the desiccation owing to the ~2 feet of annual net ET; 3. The lake ecosystem spends more time in an ecologically unproductive state; and 4. If the lake is low for long periods, it will become progressively less saline and less productive owing to loss of solutes, including plant nutrients, from the sediment surface as a result of wind erosion.

With the effects of climate change on water supplies in the Chewaucan Basin is likely to become more severe, efforts are needed to find equitable, science-based solutions that meet the water needs of both the agricultural community and the lake ecosystem. The Chewaucan watershed is thus in critical need of an integrated water-availability assessment, such as the USGS is considering. As part of that effort, research is needed on the resilience of Lake Abert's hypersaline ecosystem, including bird populations dependent on the lake.

Recommendations/Findings

1. Climate change will further exacerbate water shortages in the Chewaucan Basin; therefore, action is needed to ensure that both agriculture and the lake ecosystem are equitably sustained.
2. Lake Abert merits a high priority for conservation efforts because it is a rare and highly productive ecosystem that has supported large numbers of migratory waterbirds.
3. Future water-use decisions in the Chewaucan Basin require development of an accurate water budget. The USGS and the State of Oregon, with help from stakeholders, should undertake an Integrated Water Availability Assessment of the Chewaucan Basin to clarify how climate change is affecting and will affect both agriculture and the lake ecosystem and to help develop solutions that are equitable and feasible.
4. Unavailable data needs include measurements of: A. Net irrigation diversions; B. Groundwater withdrawal and availability; C.ET from agricultural fields and the lake; D. Precipitation amounts on the lake and agricultural fields; E. River and tributary flows below Paisley; F. Inflows to the lake from adjacent springs and seasonal creeks; and H. Predictions of future Chewaucan Basin water availability.
5. Continued monitoring of waterbird assemblages at the lake is critical to understand how the combined effects of irrigation and climate change are affecting bird abundances.
6. Monitoring of alkali fly and brine shrimp populations, as well as *Ctenocladus* algal productivity, is needed to clarify how their populations are being affected by the wide swings in salinity and reductions in lake area.
7. Research is needed on the resilience of Lake Abert's hypersaline ecosystem, including bird populations dependent on the lake.

Introduction

The U.S. Geological Survey (USGS) is developing Integrated Water Availability Assessments for areas of the U.S. that currently have, or are likely to have, problems meeting human and ecological water needs. As part of that effort, the USGS developed five primary questions focused around environmental data collection, activities, or management needs of saline and terminal western lakes, and have asked for responses to aid them in developing a strategic plan specifically for saline lakes (R. Frus, correspondence, 2022). Here, we, The Oregon Lakes Association, have responded to those questions for Lake Abert, a hypersaline, terminal lake located in Lake County, southcentral Oregon (42.65° -120.22°). We appreciate the fact that the USGS is now undertaking this assessment because saline lakes, especially hypersaline lakes, are one of our most endangered aquatic ecosystems, and thus we need to understand what impacts them and to develop solutions to prevent them from being lost.

By way of an introduction, we provide a discussion on what is a saline lake and which Oregon lakes are saline, before focusing on Lake Abert and the five specific questions posed by USGS in the rest of the document. Salt lakes are classified based on their salt content, and according to the system developed by Hammer (1986), they must have a salt concentration ≥ 0.3% (≥3 g/kg). Based on that, Oregon has six reported salt lakes: Abert, Alkali, Bluejoint, Harney, Soda, and Summer, as well as two smaller saline ponds/vernal pools: Chewaucan Narrows and North of Borax Lake (Table 1). Additionally, there likely are other small saline lakes in the larger basins where paleolakes occurred that are undetected. For example, Soda Lake in the Warner Basin, was recently found to be saline (Larson, unpub.). One potential is Stinking Lake on Malheur National Wildlife Refuge. Saline lakes are relatively rare and represent a very small proportion, perhaps <0.01% of the lakes in Oregon, according to data in the Oregon Lakes Basin Database (Portland State University, Center for Lakes and Reservoirs), and data from Larson (unpub.). All of these saline water bodies are located in Lake, Harney, and Malheur Counties in southcentral Oregon; Lake Abert is Oregon's 6th largest lake (by area) and also the most saline.

Saline Lake Type	Total Dissolved Solids		Oregon Lakes/Ponds/Vernal Pools
Hyposaline	0.3-2%	3 – 20 g/kg	Alkali, Bluejoint, Harney, and Summer Lakes, Chewaucan Narrows, and North of Borax Lake Ponds
Mesosaline	2-5%	20 – 50 g/kg	Soda Lake
Hypersaline	>5%	>50 g/kg	Lake Abert

Table 1. List of Oregon's saline lakes and their salt content based on data from Phillips and Van Denburgh (1971), Oregon Lakes Basin Database, and Larson (unpub.), using the classification system of Hammer (1986).

Primary Question 1: How much water is there and how is it used?

A. Chewaucan River Discharge Data

Lake Abert is primarily fed by the Chewaucan River, which drains ~650 sq-miles. Hydrological data for the river is found in Phillips and Van Denburgh (1971), Keister (1992), Mayer and Naman (2011), Moore (2016), Larson et al. (2016), and Larson (in press). Over the 98-year period of recorded river flows (water years 1925-2022), average daily flows measured at the Paisley gage (ID# 10384000) have varied from a low of 25 annual CFS in 1931 to a high of 350 CFS in 1956; average annual flow equals ~145 CFS, and the median flow equals 128 CFS. Total annual discharge data are shown in Figure 1, and has varied from 25 to 256 TAF (TAF =1,000-ac-ft); the median is 92 TAF. Mayer and Naman (2011) characterized the Chewaucan River as being surface-dominated and snow-melt driven, and having a flow coefficient of variation of 150% and a base-flow index of 16%. Water is diverted from the Chewaucan River for human use below Paisley, primarily for flood-irrigation of grass-hay. The amount of water diverted from the river between the Paisley gage and the lake is unknown. ***There is a clear need for measuring diversions, estimating seepage returns to the river, and measuring the river flow at the point of its entry to Lake Abert***.

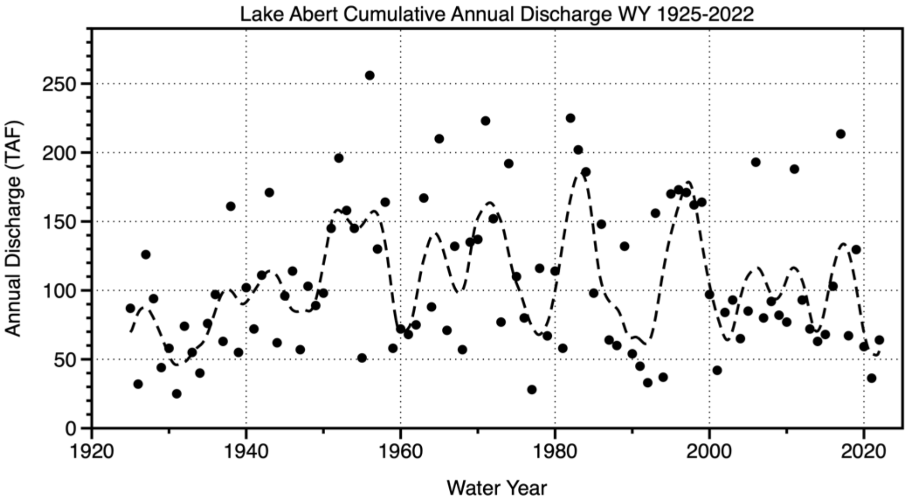

Figure 1. Plot of temporal variability of annual Chewaucan River discharge measured above Paisley, WYs 1925-2022. The dashed black line shows trends as determined by LOESS. Data from: wrd.state.or.us.

As is evident in Figure 1, flows have been highly variable. Noticeable in the record is a 25-year period of low flows extending from about 1925 to 1950, followed by higher, but variable, flows extending to 1985, and thereafter by a recent period of variable and mostly lower flows, especially after 2000. The period from 1929 to 1934 had the lowest annual flow with a mean of 68 TAF. Drought conditions in central Oregon during the 1930s were considered the most sustained in the last 500 years, based on a climate reconstruction from analyses of tree-rings (Pohl et al. 2002). Also visible in Figure 1 is a 50 year-period, from about 1950 to 2000, with obvious peaks and valleys in flows at approximately 15-year intervals, as is shown by the dashed line. The recent series of mostly declining flows and less variable low flows that started around 2000, is likely an indicator of a drying climate, as has been seen elsewhere in the Pacific Northwest and California (e.g., Dalton et al. 2021). ***A projection of likely changes in river flow into the future is needed.***

B. Contributions of Seasonal Creeks and Springs that Empty into the Lake

Three small ephemeral creeks, i.e., Cold, Juniper, and Poison (Figure 2), briefly flow directly into the lake by surface or subsurface discharge during the spring runoff period in wet years. No data exist on the volume of discharge, but total flow is likely insignificant in most years. Also present, and more important, are numerous springs/seeps located around the perimeter of the lake, especially on its eastern side (Figure 2). Most of the discharges from these springs are small, based on visual evidence made when the lake is low, but some larger ones contribute water to the lake. The largest of the springs, "Mile-Post 74 Spring" (because it is located near mile-post 74 on Highway 395), is a mile-long complex located between 42°42'20" N and 42°40'50" N (Figure 2). The significance of this spring complex is evident in satellite images made in 2014 and 2015, and in 2021 and 2022, when a very shallow, elongated pool, ranging in size from ~0.5 to 1.7 sq-mi was present near the mid-lake, eastern shore throughout the summer and fall (Figure 2).

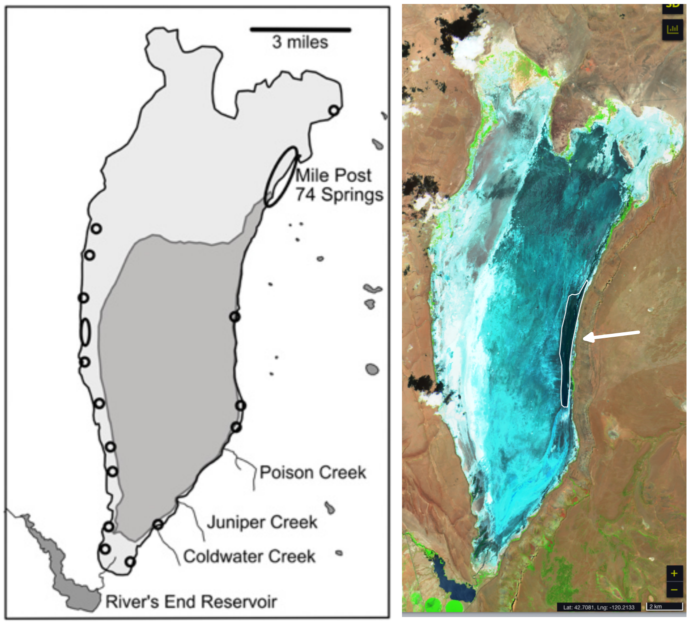

Figure 2. Left: Locations of Lake Abert's larger springs (circles), its three seasonal creeks, and River's End Reservoir. Right: Sentinel-2 satellite image of Lake Abert, 7-8-2022, showing the pool of shallow water created by discharge from the Mile-Post 74 spring complex flowing south along the eastern lakeshore. Water from the springs flows southwards to form the pool shown.

Phillips and VanDenburgh (1971) and VanDenburgh (1975) estimated that locally-derived annual surface water inflow to the lake averaged ~10 CFS when the lake was high and most of the springs were not visible. Larson et al. (2016), reported making a single discharge measurement of 11 CFS at the Mile-Post 74 Spring complex in September 2015, when the lake was low and at a time when there was evidence of additional springs and seasonal streams that emptied into the lake. Based on that, Larson et al. assumed that the locally-derived annual inflows averaged ~20 CFS. Recent satellite images of the lake, show a pool of ~600 acres created by the Mile-Post 74 spring complex from July through September 2022 (Figure 2). Using the monthly ET data from Phillips and VanDenburgh for July-September, it would require ~10 CFS to maintain this pool, which is similar to discharge reported by Larson et al. (2016). ***Accurate measurements of the inflows to the lake contributed by springs and creeks are needed.*** The ecological importance of the direct spring inputs to the lake will be discussed later in the section dealing with waterbirds.

Upstream of the lake, unaccounted-for flows also result from streams entering the river below the Paisley gage, with the largest being Crooked Creek. Most of the ungaged creeks are small and ephemeral, and discharge is unlikely to reach the river except during the spring in wet years. ***The flows and seasonalities of these tributaries should be documented as part of the water budget.***

Beginning in the 1880s, the Chewaucan River was straightened and channelized to minimize flooding near Paisley, and numerous diversions created. Now, what remains of the river is affected by an extensive network of intertied canals and drains (Figures 3, and 4).

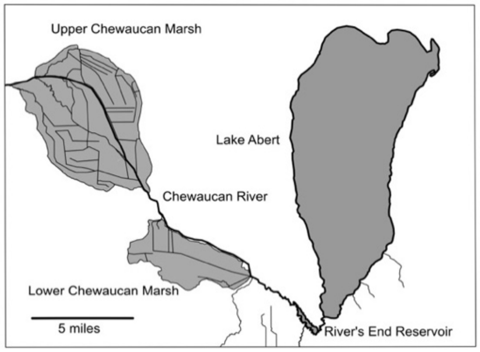

Figure 3. Map showing Lake Abert, the lower Chewaucan River, Upper and Lower Chewaucan Marshes with the larger irrigation canals and drains shown, and River's End Reservoir at the south end of Lake Abert, which has ~1,800 acre-feet of storage. Source: Larson in press.

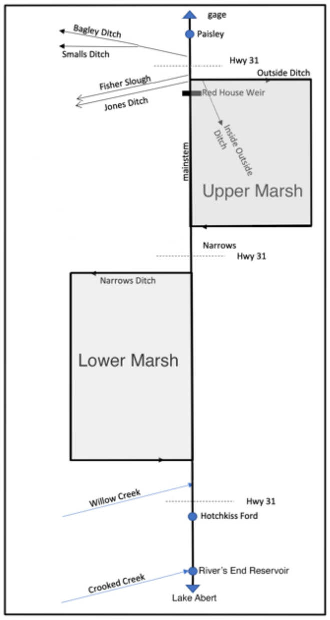

Figure 4. Schematic diagram of major canals in the Upper and Lower Chewaucan Marshes that divert water from the Chewaucan River, as well as creeks that empty into the river below Paisley. Source: T. Wood, OLA.

The amount of water diverted from the river between the Paisley gage and the lake is not regularly measured and reported; however, water rights records show there are numerous diversions from the river for domestic, livestock, irrigation, and wildlife/fisheries use, according to the Oregon Water Resources Department (WRD), Point of Diversion (POD) database (https://apps.wrd.state.or.us/apps/). Additionally, there are numerous small storage reservoirs for livestock. The first water rights in the basin date back to the mid-1870s, and allocations have grown substantially since then.

It is unknown how much water is diverted from the river. However, there are several estimates of the diversion rates as a percentage of river flow, based on water budgets or on assumptions of crop water needs (e.g., Phillips and VanDenburgh 1971, Keister 1992, Larson et al. 2016, and Moore 2016). Phillips and VanDenburgh (1971) and Keister (1992) estimated that over the 1926-1963 and 1926-1990 periods, ~50% and 70% respectively, of the annual river flow reached the lake, on average. Over water years (WY) 2007-2014, Larson et al. (2016) stated that on average only ~40% of the flow measured at Paisley reached the lake. Also, Moore (2016) presented graphs showing that without diversions, Lake Abert would have been substantially higher during the 2014 desiccation event. Based on these estimates, it appears that a smaller percentage of the river flow is currently reaching the lake, and in fact in 2021 and 2022, very little river water entered the lake because of the low flows in the lower river and the low elevation of River's End Reservoir prevented water from reaching the lake. ***There is an urgent need for accurate water availability data to be publicly available for future water-use decisions***.

Recently, the OpenET website (https://explore.etdata.org), began providing annual estimates of crop evapotranspiration (ET), at the level of a farm field. Crop ET is the amount of water needed by each crop. For ~28,000 acres of the estimated 30,000 acres of irrigated land in the three major agricultural areas above the lake (Figures 3 and 6), the estimated water needs to meet annual crop ET demand totaled 37 to 68 TAF (Table 2) for the 2017-2022 period, which are the only years with available data. If all of these fields were irrigated using river water over that same time period, diversions would have consumed most of the river flow in all but 2 years (Table 2). Note that irrigated crop ET is met both by water diversions and from soil moisture created by direct precipitation. Furthermore, ET estimates do not include water that is diverted from the tributaries, is lost during transport to the fields, evaporates directly from flooded areas, enters the groundwater system, or is returned back to the river as overflow. Thus, the actual amount of Chewaucan River water that is lost to the river system as a result of irrigation is different than the calculated crop ET. ***Thus, while satellite-based measurements, such as those provided by OpenET, provide valuable estimates for understanding the hydrology of the Chewaucan basin, we need accurate discharge and ET measurements to construct a correct water budget.***

Table 2. Estimated annual ET for agricultural fields in the Upper and Lower Chewaucan Marshes, and in the Willow Creek and Lower Crooked Creek areas, and annual river flow measured above Paisley for 2017-2022. Note that annual crop ET is partially met by direct precipitation. Data sources: https://openetdata.org, https://apps.wrd.state.or.us.

Year	Upper Marsh Area Annual ET (TAF)	Lower Marsh Area Annual ET (TAF)	Willow and Lower Crooked Creeks Area Annual ET (TAF)	Combined Area Annual ET (TAF)	Annual River Discharge at Paisley Gage (TAF)
2017	48.5	13.5	5.7	67.7	214
2018	47.7	11.2	5.0	63.9	67.1
2019	44.7	11.8	5.7	62.2	130
2020	43.4	6.0	2.2	51.6	59.2
2021	33.2	2.5	1.7	37.4	36.3
2022	41.5	8.3	2.0	51.8	64.5

In addition to diversions from the river, there are numerous wells supplying water for center- pivot irrigation systems located near Paisley and Valley Falls (Figure 6). OpenET shows at least 28 such systems totaling >3,000 acres and having a total average annual ET consumption of ~8 TAF. The effect that groundwater extraction has on the river and lake is unknown, but this consumption rate is likely greater than what is supplied to the groundwater by precipitation, as is indicated by the downward trends in the water levels in two wells located in the Chewaucan Basin (Figure 5). ***Measurements of groundwater resources and usage are needed.***

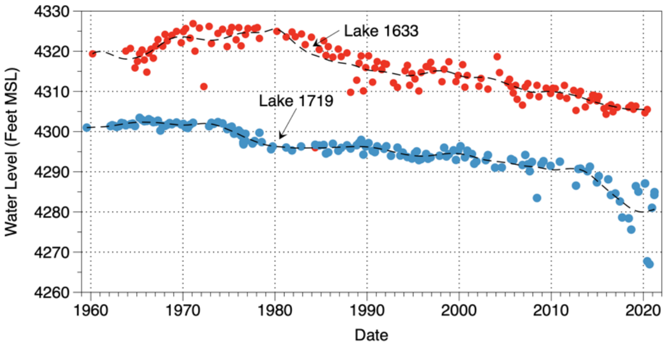

Figure 5. Temporal changes in the groundwater levels in two wells located in the Chewaucan Basin. Source: OWRD groundwater hydrographs. (https://apps.wrd.state.or.us/apps/gw/gw_info/gw_hydrograph/).

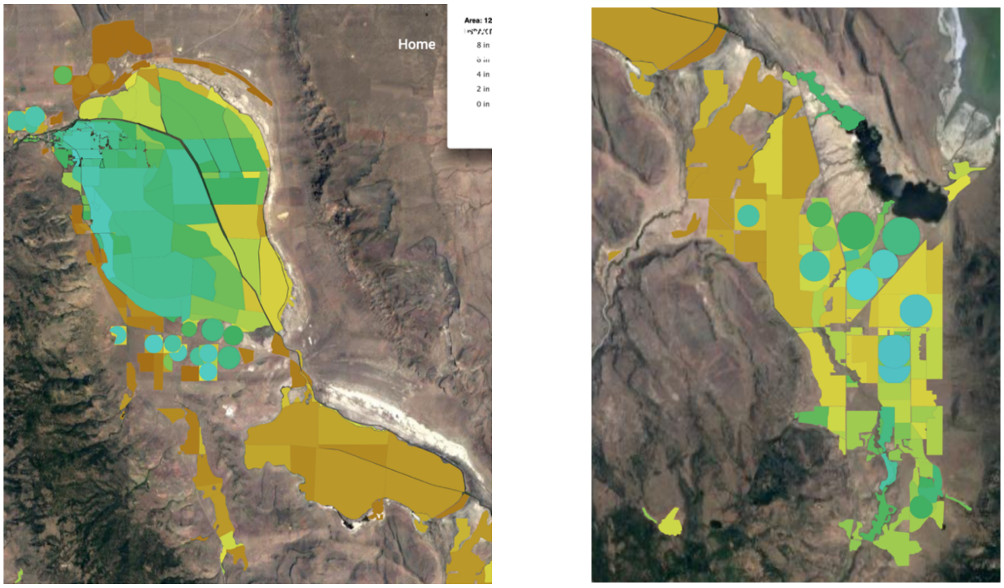

Figure 6. Primary agricultural areas of the Chewaucan Basin with annual field ET rates identified based on color: green and blue indicate higher ET and yellow and browns lower ET. Left: Upper and Lower Chewaucan Marsh agricultural areas. Right: Willow Creek and Lower Crooked Creek agricultural areas. Circles are center-pivot irrigation fields. Lake Abert at top right, River's End Reservoir in black. Source: OpenET (https://openetdata.org).

C. Regional Precipitation

No continuous weather stations are located near Lake Abert. ***USGS in Corvallis installed a remote, automated weather station at the south end of the lake at the River's End Ranch ca. 2010, but we have been unable to access the data and we recommend that this station be reactivated***. The nearest operational weather stations to Lake Abert are at Summer Lake (30 miles northwest), and Lakeview (25 miles south). Neither of these stations is likely to have exactly the same climate as Lake Abert or the lower Chewaucan watershed because of differences caused by nearby terrain and rain-shadow effects, and etc.; however, they probably show similar annual trends. Here, we selected Lakeview for accessing climate data to show temporal changes, because it has both a NOAA cooperative station providing a very long record and a US Bureau of Reclamation (USBR) AgriMet station that collects physical data for estimating ET. Annual variations in precipitation at Lakeview are shown in Figure 7. From WYs 1989-2022, annual totals have varied from 5 to 16 inches, with an annual mean of 10 inches. Precipitation was the lowest during WY 1999 and highest in WY 2017. Peaks in precipitation occurred in WYs 1996-1997, 2005-2006, 2010-2011 and 2017, while troughs occurred in 1990-1991, 1997, 2007-2008, and 2020-2022. There was an increasing trend in precipitation between 1989 and 2019, but more recently, annual totals have been lower than average. Note that this picture is different from that of river flows and lake elevations that have been declining since 2000 or before (Figure 1).

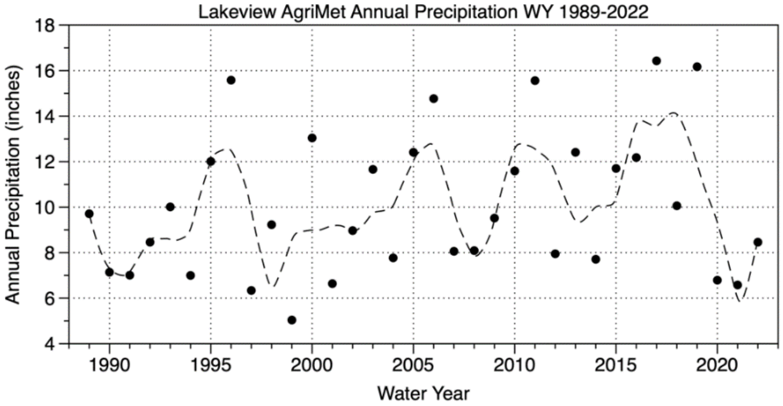

Figure 7. Scatterplot of annual precipitation at Lakeview for water years 1989-2022. The dashed line is a smoothed LOESS curve showing trends. Data are from USBR AgriMet. (https://www.usbr.gov/pn/agrimet).

D. Lake Evapotranspiration (ET)

Because Lake Abert is a terminal lake and has fine-grained sediments that impede seepage, ET is the major source of water loss (Phillips and VanDenburgh 1971). Lake ET can be measured in various ways but the most accurate estimates use eddy covariance, mass transfer, or energy-balance techniques, that require specific meteorological instrumentation that is generally not available at weather stations. Thus, no ET measurements have been made at the lake using these techniques. Recently, the energy-budget method was used to measure ET from a shallow saline lake by Riveros-Iregui et al. (2017), and that study could serve to inform a similar future study at Lake Abert. Additionally, Stannard et al. (2017) measured ET from open water and wetlands in the Klamath Basin using both eddy-covariance and energy-balance methods, so those data could be useful for further studies at the lake.

Phillips and VanDenburgh (1971) measured ET from the lake based on a simple mass-transfer model developed by Harbeck et al. (1962). Meteorological data were obtained between April and October 1962 using a floating weather station. Based on those data and corrected for salinity, seasonal ET equaled 31 inches (32.5 inches uncorrected for salinity) for the May-October period and would equal ~39 inches annually. ET also has been measured at Summer Lake Wildlife Area since 1961 using a Class-A pan. It has averaged 46 inches for a 6-month spring-summer season. Pan-based ET measurements are known to over-estimate ET of open water and a correction factor of is needed (Jensen, 2010; Linacre, no date). Stannard et al. (2013), using the Bowen-ratio, energy-balance method, determined that open-water ET at Upper Klamath Lake, June-September, equaled ~27 inches, and because of its proximity to Lake Abert, this value might be closer to what is occurring at Abert.

Additionally, annual ET values have been measured in Lakeview by the USBR AgriMet station, using the Kimberly-Penman model, and using alfalfa as the reference crop (Figure 8). The data show ET has increased by ~20% from WY 1989 to 2021. Crop ET estimates are not equivalent to open water ET, but the values are likely correlated, as is indicated by data in Stannard et al. (2013). Stannard et al. estimated annual alfalfa and pasture ET for the Klamath Basin to be 39 inches and 32 inches, respectively, which are higher than their open-water ET estimate. ***There is a strong need for a meteorological station that can measure ET to be placed as close as possible to Lake Abert, so that direct measurements can inform our understanding of the lake's hydrology and ongoing trends related to climate change.***

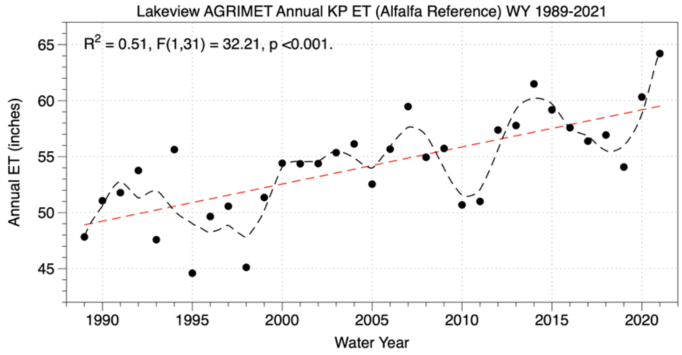

Figure 8. Plot of annual alfalfa-reference ET measured at the Lakeview AgriMet station located south of Lake Abert. The dashed line is a smoothed LOESS curve showing short-term trends, whereas the dashed red line shows the long-term trend, as determined by a least-squares regression. Data from: (https://www.usbr.gov/pn/agrimet).

The above information was presented in an effort to answer the question: how much water is there and how is it used? Based on this, if our intent is to apply science-based management to water availability and use in the basin, it’s clear that we have an inadequate understanding of the hydrology of the Chewaucan River-Lake Abert system. The gage located above Paisley provides an acceptable picture of the hydrology of the river in the upper basin. However, critically, much less is known about the hydrology of the basin between Paisley and the lake, where a substantial fraction of the river flow is diverted for irrigation, and without quantification, it’s impossible to accurately model the lake’s hydrology. Finally, at the lake there are no continuous data on lake elevations and volumes, but annual changes in surface area and lake elevation have been documented, based mostly on satellite imagery and infrequent staff-gage readings, and from those data lake volume is estimated using relationships of lake area and elevation vs. volume in Phillips and VanDenburgh (1971). Those data on the lake have helped record annual and seasonal events, but an understanding of causal factors is elementary, primarily because of a lack of data on lower river flows and lake ET. Climate change is already affecting the watershed through recent wildfires, uses of water within it, and water yield from it. Further drying of the climate is very likely to present even greater challenges for meeting the water needs of Chewaucan Basin agriculture and lake ecosystem in future years. ***In this over-appropriated system, it behooves us to develop the needed hydrological and climatological data to manage the system and ensure that both agriculture and the lake ecosystem are sustainable***.

Primary Question 2: What are the hydrologic vulnerabilities of each saline lake?

Lake Abert has a large surface area with a net annual ET ~2 feet, is quite shallow, averaging only a meter or so in depth, and inflows to the lake have been impacted by upstream water diversions, normal climate cycles, and more recently by climate change. Thus, the lake ecosystem is vulnerable and at risk of its productivity being reduced and its ecosystem altered (Larson et al. 2016, Moore 2016, Senner et al. 2018, Larson, in press). ET will likely be further elevated by climate change, as is indicated by Figure 8. These factors make the lake very susceptible to desiccation.

The volume of Lake Abert in any given year is an integration of precipitation and inflows accumulated over several prior years minus cumulative ET losses, and consequently the lake grows and shrinks on ~10-15-year cycles. This feature is common to terminal lakes with shallow bathymetry. The correlation of lake elevation with flow is maximized (Spearman ρ correlation coefficient 0.86) when the flow is accumulated over 8 prior years, as shown in Figure 9.

Within recorded history, the lake reached a maximum elevation of approximately 4,260.5 feet in 1958, and covered 64 square miles, contained an estimated volume of 500 TAF, had a maximum estimated depth of 15 feet, and was Oregon's 6th largest lake (Phillips and Van Denburgh 1971). During the Dust Bowl era of the 1920s and 1930s, the lake desiccated during six non-consecutive years (Phillips and VanDenburgh 1971), and it was almost totally desiccated in 2014-2015 and in 2021-2022 (Figure 9). The earlier desiccation events during the Dust-Bowl era were caused by low precipitation and consequent

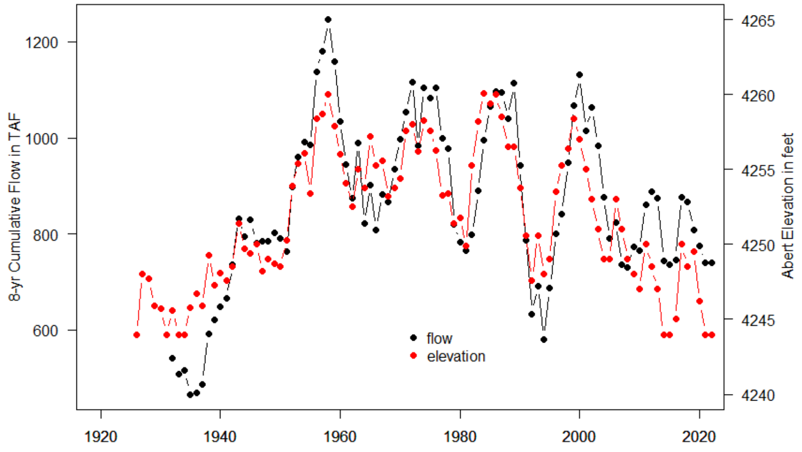

Figure 9. Plot of October 1 Lake Abert elevations, water years (WYs) 1926-2022. Elevation data are from Phillips and Van Denburgh (1971), Keister (1992), Larson et al. (2016), and Larson unpublished. At an elevation of ~4244 feet the lake is nearly dry except for very shallow, spring-fed pools. Also shown is the accumulation of flow past the Paisley gage over 8 previous water years, in thousands of acre-feet (TAF). Discharge data from Data from: wrd.state.or.us.

low inflows, compounded by irrigation diversions. The more recent desiccation events appear to have been caused by irrigation diversions coupled with elevated ET and below-average river flows and precipitation.

Low flows in the Chewaucan River were a contributing factor to the recent near-desiccations of Lake Abert, but how do they compare with historical flows? During the Dust Bowl era of the 1920s and 1930s, annual flows were exceptionally low, with annual means ranging from 34 CFS to 102 CFS, for an extended period of time. As a result, the lowest distribution of 8-year cumulative flow in the Paisley gage record occurred during the 15-year period 1933—1947. Following that period, were 60 years during which the 8-year cumulative flows were mostly much greater than 1933-1947, and Lake Abert elevations were greater as well. In the most recent 15 years, the 8-year cumulative flows decreased, but mostly overlapped the inner quartile range of flows between 1978 and 2007, and there were no flows below the median of 1933-1947 flows (Figure 10). The distribution of Lake Abert elevations over the most recent 15 years, in contrast, completely overlaps the distribution of elevation 1933—1947 and, in fact, the percentiles are all lower than the corresponding percentile in 1933-1947. Thus, although, recent flows were low, especially 2021 when the annual mean flow was 50 CFS, and which ranked 94th-lowest out of 98 years of record, on average recent flows were not remarkably low when viewed over the 98-year-long period of record. The corresponding Lake Abert elevation, however, has been disproportionately low compared to the elevations observed during the very dry period 1933-1947. ***These considerations point to important roles for increased ET and ongoing diversions in driving recent desiccation of Lake Abert. Direct hydrological measurements are therefore needed to understand the quantitative contributions of the various factors to lake desiccation.***

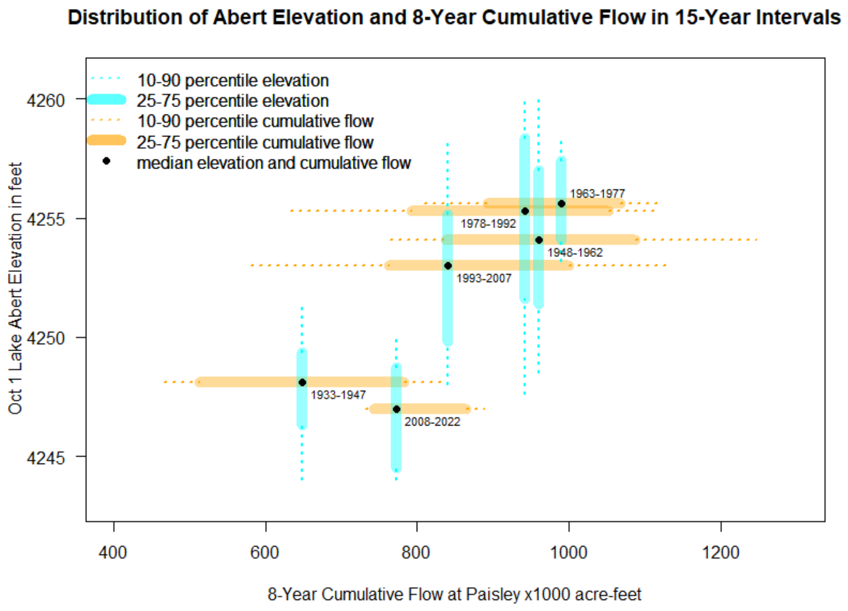

Figure 10. Distribution of October 1 Lake Abert elevations, water years (WYs) 1933-2022, in 15-year intervals. Also shown is the distribution of the cumulative flow past the Paisley gage over 8 previous water years, during the same 15-year intervals. Data from: wrd.state.or.us.

Other factors may have recently contributed to reduced inflows into the lake besides agricultural diversions from the river and increased ET. For example, since about 1990, groundwater usage has increased in the basin, as evidenced by the proliferation of center-pivot irrigation systems for alfalfa production (Figure 6), which now use an estimated 8 TAF annually. Alfalfa is a water-intensive crop that has an annual ET of ~39 inches, and pumping of groundwater for alfalfa production is lowering the water table (Figure 5). Additionally, habitat enhancement projects upstream of the lake intended for waterfowl and trout, such as the construction of the River's End Reservoir in the 1990s, could have increased upstream water diversion and use, and consequently reduced inflows to the lake.

Primary Question 3: What are the primary ecological resources used at each lake and how do these resources change over time?

Lake Abert is the only large hypersaline lake in the Pacific Northwest and is one of only three large hypersaline lakes in the western U.S. Its salinity has varied from ~2 to 25% (Phillips and VanDenburgh 1971, Herbst 1988, Keister 1992, Larson et al. 2016, Larson, in press). The dissolved salts in the lake are primarily sodium carbonate and bicarbonate and consequently it has a pH ~10, making it alkaline (Phillips and VanDenburgh 1971 and VanDenburgh 1975). Although there were early proposals to mine the salt from the lake, there is no evidence that was done. No water is removed from the lake by human activities, although there was a Federal Energy Regulatory (FERC) application in the past for a pumped-storage hydroelectric project that would use lake water; however, no facility was built. Recently, PacifiCorp has applied for a FERC permit for a pumped storage facility that would use water from Crooked Creek.

Because of its outstanding natural resources, the lake has been given special status as an Area of Critical Environmental Concern by the BLM, and the nearby 23,000-acre Abert Rim is a Wilderness Study Area under BLM management (BLM 1995). In addition, Lake Abert exists within the Northern Basin and Range Ecoregion in the Oregon Conservation Strategy (Oregon Department of Fish and Wildlife 2005), and is included in its entirety in a Conservation Opportunity Area (unit NBR-13). The purpose of the state's conservation strategy is to maintain healthy fish and wildlife populations by maintaining and restoring functioning habitats, prevent declines of at-risk species, and reverse any declines in these resources. But neither of these designations has resulted in more water getting to the lake.

Every summer when the lake is productive large numbers of waterbirds, numbering up to several hundred thousand, migrate to the lake when conditions are good (Boula 1986, BLM unpub., Larson et al. 2016, Senner et al. 2018, Larson in press). They are attracted to the lake because of the high biomass of alkali flies (Boula 1986, Herbst 1986, 1988) and brine shrimp (Conte and Conte 1988), and the need to replace lost fat reserves and grow new flight feathers prior to the birds' southward migrations.

Nearly 80 waterbird species have been reported from the lake (Larson, in press). The most numerous are: Wilsons Phalaropes, Eared Grebes, and American Avocets, which have numbered >200,000, 40,000, and 20,000, respectively. Gulls and waterfowl can also be abundant, reaching 15,000-20,000. The lake has supported the following percentages of the North American populations of American Avocets - 8, Snowy Plovers -1.3, Black-necked Stilts -2.9, Red-necked Phalaropes – 2.1, and Wilson's Phalaropes – 20. Based on these abundances, Lake Abert should be included in the Western Hemisphere Shorebird Reserve Network. Furthermore, for conservation purposes, the lake should be viewed as an integral part of a mosaic of regional Great Basin saline lakes and wetlands that includes most of southcentral Oregon and adjacent lakes and wetlands in California and Nevada. Notable waterbird nesting at Lake Abert has included approximately 100 pairs of Snowy Plovers, which are listed by Oregon as threatened, and 1,000 American Avocets (Kristensen et al. 1991); this represents a substantial portion of Oregon's population of both species.

Within Oregon, Lake Abert is ranked very high, and in some cases, either first or second, in terms of peak abundances for the following 11 waterbirds: American Avocet, Black-necked Stilt, California Gull, Eared Grebe, Least Sandpiper, Northern Shoveler, Red-necked Phalarope, Ring-billed Gull, Western Sandpiper, Western Willet, and Wilson's Phalarope. ***Thus, Lake Abert merits a high priority for conservation efforts.***

Primary Question 4: What drives changes in the population dynamics of birds using saline lakes?

The short answer to the above question for Lake Abert is very likely food availability, which is determined by the productivity of the ecosystem, salinity, and the amount of suitable habitat. When alkali flies (*Ephydra hians*) and brine shrimp (*Artemia franciscana*) are abundant at the lake, so are the birds, with abundances of birds peaking in July and August when shrimp and fly populations are greatest (Senner et al. 2018, Larson, in press). Most waterbirds come to the lake after breeding, at a time when they need to replace fat reserves and replace worn feathers prior to their southward migration (Jehl 1988, 1994, 1997, 1999). For example, Jehl (1997) found that Wilson's Phalaropes can double their body weight while feeding at salt lakes for several weeks, in what has been described as hyperphagia. They will also molt and grow new flight feathers to help them make their long journey south, which also is dependent on adequate food being available.

Lake levels and salinity can have a major effect on the productivity of Lake Abert, and the effects on the lake ecosystem can be complex and are not fully understood. For example, very high water levels and low salinity could have multiple effects, including: 1. Nutrients would be diluted, potentially reducing algal growth; 2. Cladocerans might be present and compete with *Artemia* for bacteria and phytoplankton; 3. Predatory aquatic insects such as water boatmen (Corixidae) and back swimmers (Notonectidae) might prey on shrimp and larval flies and thus reduce their numbers; and 4. Waterbirds might have difficulty finding food that is in water too deep for them to reach or when the prey is widely dispersed and in low concentrations. Very low water levels and high salinity could also have multiple effects on productivity, including: 1. Greater energy is required by the biota to maintain optimal internal osmotic balance; and 2. Less habitat is available and, if the lake desiccates, suitable habitat is severely limited to the pool mentioned above created by springs. Fortunately, at least in the past, water levels and salinity change in response to inflows and ET, and a range of conditions are created over time, some of which allows for high productivity. However, it remains to be seen how climate change and water diversions will affect this, and if the biota is sufficiently resilient to adjust to those changes.

Based on observations over the past decade at the lake, the dominant macro-alga and probably the major primary producer in the lake over that time was *Ctenocladus circinnatus*, a green, filamentous alga. It is eaten by alkali fly larvae (Herbst 1994, Herbst and Castenholtz 1994), and its decay products are likely consumed by microbes that are eaten by shrimp and flies. Thus, *Ctenocladus* likely plays a crucial key ecological role in the lake. Growth of benthic algae in salt lakes is optimal between salinities of 2.5 and 7.5 % and is severely reduced at 15% (Herbst 1994). Additionally, Herbst and Bradley (1989) found that overall benthic algae diversity was reduced in the laboratory at salinities >10%.

Ctenocladus was especially abundant in the lake in 2011-2012 and in 2017-2018, when salinities were relatively low as a result of higher water levels owing to inflows from the river. By August and September of those years, dense masses of *Ctenocladus* covered the lake bed and floated inshore, apparently providing an abundant food resource for alkali fly larvae and adults, which became very numerous (Figures 11 and 14).

Figure 11. *Ctenocladus* concentrations at Lake Abert, 9-2-2011. Left: A dense mat of *Ctenocladus* covers the substrate along the eastern shore. Right: *Ctenocladus* “balls” floated inshore in the same area. The dark objects in both photos are masses of alkali fly adults and pupae.

Alkali flies occur within a broad salinity range of ~2-15% (20-150 g/kg, Herbst 1994). This occurs at Lake Abert between elevations of ~4248 and 4252 feet (Figure 12). According to Herbst (1994), optimal conditions, however, are within a range of ~4251-4258 feet.

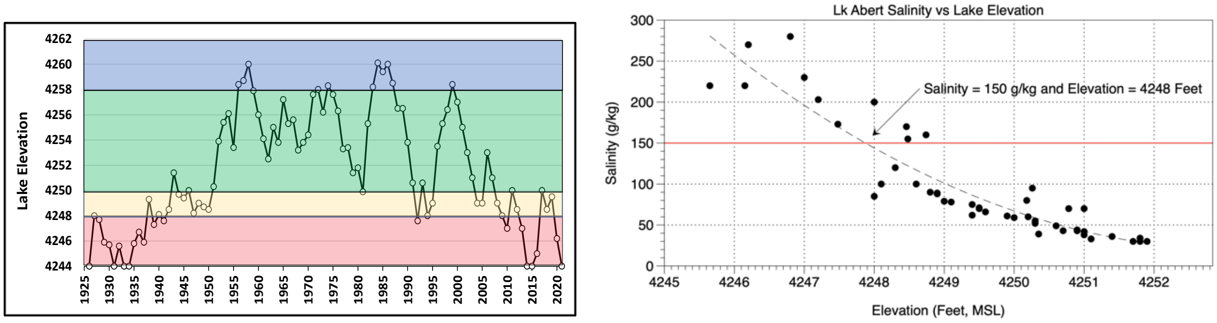

Figure 12. Left: Approximate Lake Abert elevations that affect shrimp and fly populations. At elevations of ~4250-4258 feet, salinities are optimal for the biota, shown in green (Herbst 1994). However, when the water levels drop below 4250 feet and salinity increases, the biota can become stressed, as shown in red, and that could lead to lower productivity and death. Diagram source: David Herbst. Right: Relationship between Lake Abert elevation and salinity. The 15% salinity maximum for productivity is shown as a red line. Data from Phillips and VanDenburgh (1971), and Herbst, Kreuz, and Larson pers. com.

In situ observations at the lake made between 2009-2022, suggest that adult alkali flies were most abundant when lake elevations were >4250 feet and were lowest at elevations <4248 feet and those conditions occurred in 2011-2012, 2017 and in 2019 (Figure 13), thus confirming conclusions of Herbst (1994) that high lake levels are needed by flies. However, even when the lake was nearly fully desiccated, some adult flies were always present in localized areas where spring discharges reduced salinities.

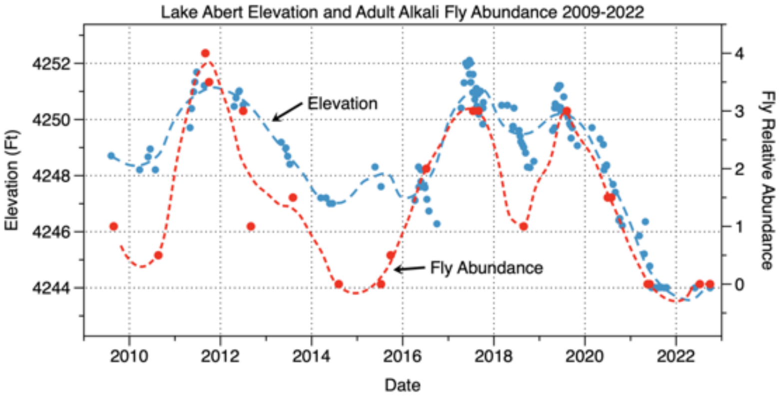

Figure 13. Lake Abert elevations and relative adult alkali fly abundance, 2009-2022, on a scale of 0-4, with 4 being highest, based on visual observations and photographs. Data from Larson, unpublished. A zero-value indicated adult flies were mostly absent except where there were spring discharges.

As mentioned above, adult alkali flies were especially abundant in 2011, 2017, and 2019, as a result of higher water levels and the presence of a large biomass of *Ctenocladus* (Figures 11 and 14). During that time, adult flies formed conspicuous black mats covering much of the shore and extended far out into the lake in all directions (Larson, in press; Figure 14). However, in 2014 and 2015, when lake levels were lower, both *Ctenocladus* and *Ephydra* were noticeably very scarce.

Figure 14. Examples of extremely dense, black mats of adult alkali flies covering shoreline areas and far out onto the lake. Left: 9-2-2011 and right: 8-16-2019. In both cases, the flies were associated with an abundance of decomposing *Ctenocladus* algae that had drifted inshore. Photos: R. Larson.

In addition to lower productivity of alkali flies and benthic algae at high salinities, low lake levels reduce the availability of rock substrates used by the flies for pupal attachment (Herbst 1994). Eventually, as water levels drop and salinities increase, salts begin precipitating from solution. The first recent evidence of that happening was in early September 2013 when trona crystals formed along the shore. At that time the salinity was ~18%. At elevations near 4245 feet, the lake becomes so saline, ~25%, that sodium chloride precipitates, and as a result only hypersaline archaea and bacteria can survive. This was first observed in the summer of 2014 when what remained of the lake turned red (Figure 15). ***An understanding of these dynamics can help identify periods when diversions have lowest impact on the lake's ability to support migratory birds.***

Figure 15. An aerial view of Lake Abert taken in October 2014vwhen it was red as a result of a “bloom” of hypersaline archaea that developed owing to the high salinities that were present because of low lake levels.

Artemia were first reported at Lake Abert in 1882 (Russell 1884), and there was an artisanal brine-shrimp fishery in the lake from 1980 to 2013. Shrimp harvesting ended because increased salinities had impacted them by 2013, and then in 2014, the lake was nearly fully desiccated and no harvesting could be done (Kreuz pers. com.). *Artemia franciscana*, the brine shrimp species in the lake, is known to survive salinities >20% in the laboratory (Castro-Mejia et al. 2011). However, at salinities >15%, in situ productivity and survival of *Artemia* substantially declined owing to the increased energy demands of osmoregulation, effects of reduced dissolved oxygen concentrations, and lower food availability (Gajardo and Beadmore 2012). Observations at Lake Abert also indicate that *Artemia* are sometimes killed by hypoxic events, such as the one that occurred in August 2010, when masses of dying shrimp floated inshore (Larson, in press). The shrimp were blood-red, indicating that hemoglobin was produced in response to low dissolved oxygen concentrations (Figure 16). High temperatures and lack of wind mixing likely contributed to this hypoxic event, but dissolved oxygen concentrations are also reduced by salinity.

Figure 16. Masses of dying brine shrimp drifted ashore along the eastern side of Lake Abert in August 2010. The red coloration of the shrimp is due to hemoglobin, which is produced by the shrimp in response to low dissolved oxygen concentrations. Photo: R. Larson.

Primary Question 5: How much water is needed to sustain quality habitat for birds now and into the future?

This question is difficult to answer with certainty because a number of poorly-known factors are likely involved, e.g., habitat conditions at the lake and elsewhere in the Great Basin affecting birds, including salinity and water levels, and food availability. Nevertheless, by ensuring the lake frequently is in the green zone, with water levels >4250 feet, as shown in Figure 11, it should provide suitable habitat and that should lead to viable numbers of birds using the lake, if other conditions for the birds are good, including those in breeding and wintering habitats. If the lake cannot be maintained within the green zone, just how low could the lake go, how frequently could it go low, and for how long could it remain low, and still provide adequate habitat conditions for algae, shrimp, flies, and birds? That question is impossible to answer with existing data. Furthermore, it's important to understand that waterbirds using Lake Abert are part of larger Great Basin populations, and the conservation of those birds is dependent on having a network of salt lakes and other wetlands capable of supporting them (e.g., Haig and Oring 1998; Haig et al. 1998, 2002; Plissner et al. 1999, 2000; Donnelly et al. 2020; Larson in press). As a corollary of these considerations, if there is not enough water quantity data to answer the question of a sustained waterfowl population, is there sufficient water quantity data to predict the future viability of agriculture in the basin?

Waterbird surveys, which included shorebirds, wading birds, and waterfowl, have been conducted at the lake since the early 1980s, but not continuously, and were mostly done during the June-September period when bird abundance peaks (Figure 17). Several patterns are evident in the data. First, most of the maximum counts for the year fall into the range of 10,000 to 100,000 birds, however in 2012, 2013, and 2018, the maximums were >100,000. Secondly, there is a declining recent trend in maximum abundance from highs in 2012 and 2013 to the lowest in 2021. In 2014, there was an order of magnitude decline going from ~200,000 in 2012 and 2013 to ~20,000 in 2014 and 2015. In 2018, after the lake level rose, there was a brief increase in abundance to 100,000 birds, but numbers fell afterwards, and were especially low in 2021 and 2022.

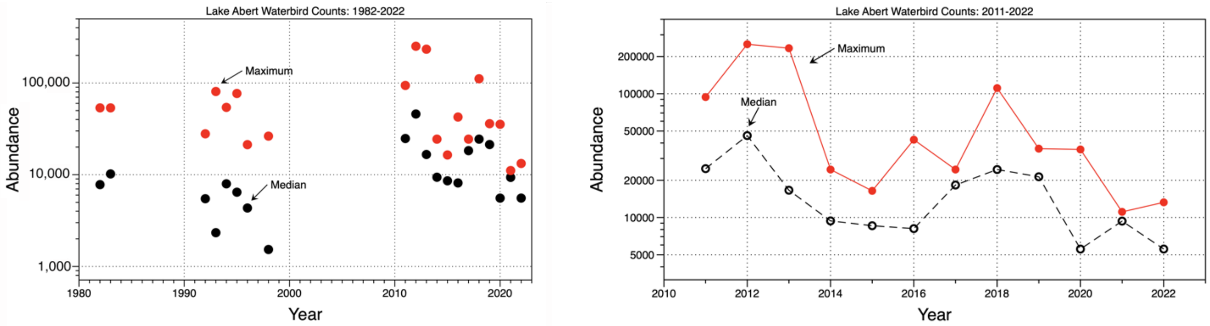

Figure 17. Lake Abert annual waterbird abundances. Left: Plot of all data, 1982-2022. Right: Plot of 2011-2022 data. Data source: Boula (1986), BLM (unpub.), and J. Reuland, East Cascades Audubon Society (unpub.). Red = annual maximum counts and black = annual median counts.

To determine if the changes in waterbird abundance were related to changes in lake elevation, these variables were plotted in Figure 18. Those data showed highest waterbird abundance occurred in 2012 and 2013, when lake elevations were relatively high and ranged from 4248-4251 feet in elevation (Figure 18). Then in 2014, when the lake level fell below 4248 feet bird numbers declined substantially and they stayed relatively low until 2018 when they temporarily increased during a period when lake levels were mostly above 4250 feet. Based on this it appears that birds are responding to changes in lake elevation, perhaps as it affects salinity and food availability.

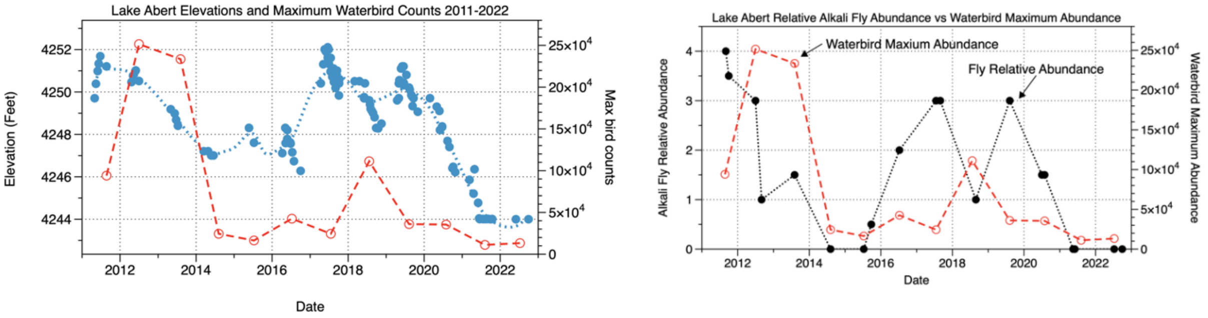

Figure 18. Left: Plot of waterbird maximum abundance (blue points) vs. Lake Abert elevations, 2011-2022. Right: Plot of waterbirds abundance vs alkali fly relative abundance, 2011-2022. The relative abundance of alkali fly adults was measured on a scale of 0-4, with 4 being highest and 0 being the lowest. A zero-value indicated that adult flies were very scarce, but they were likely always present in seeps where springs kept the mud moist. Data sources: J. Reuland, East Cascades Audubon Society, and Ron Larson, OLA.

To assess the possible effects of food ability on waterbird abundance, maximum waterbird numbers were plotted against relative abundance of alkali fly adults, based on notes and photos (Figure 18, Larson, unpub.). Flies were relatively numerous in 2011-2012, during and just prior to the highest numbers of waterbirds in 2012 and 2013. Then fly abundance declined sharply in 2014 and remained low until 2017, after which fly numbers declined slightly in 2018 to increase again in 2019, and then declined again and were especially low in 2021 and 2022 (Figure 13). Thus, based on changes in elevations and numbers of flies, there is an indication that water levels are affecting both fly populations and birds. Birds are likely affected by the abundance of flies because birds feed on them, and this is indicated by the fact that when fly numbers were very low, such as in 2014-2016 and in 2021-2022, bird abundance was also very low. However, there were years when despite relatively high numbers of flies, numbers of birds were not equally numerous, such as in 2017 and 2019, thus suggesting other factors are likely involved. Perhaps with more years of data, a more complete understanding of the effects of water levels and fly abundance on bird numbers will become clearer.

The above discussion indicates that the abundance of waterbirds is very likely affected by water levels, and concomitant reductions in lake area, and the abundance of flies. Is it also possible that those effects were felt differently among the waterbirds? Effects of diminished prey availability for migratory waterbirds using Lake Abert as a result of habitat loss and high salinities has likely had a substantial adverse effect on several waterbird species, especially Eared Grebes and phalaropes, whose numbers declined the most (Figure 19).

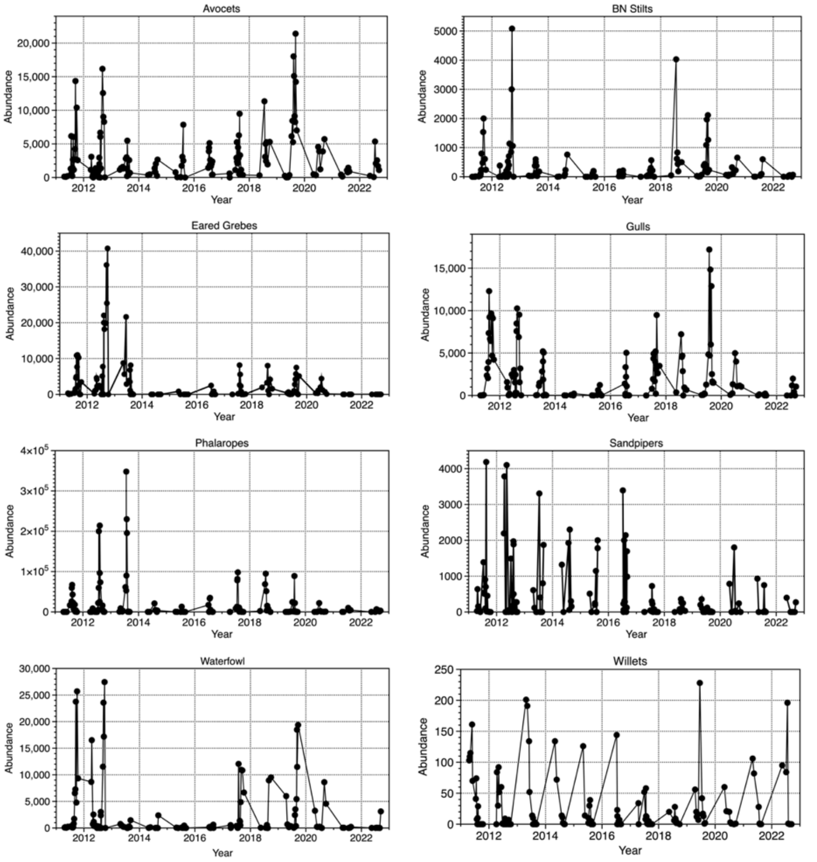

Figure 19. Abundance of major groups of waterbirds at Lake Abert, 2011-2022. Data from J. Reuland, East Cascades Audubon Society. Note that vertical axes are different for each graph.

These two groups of birds are known to feed in open water (Boula 1986, Jehl 1988, Roberts 2013, Larson in press). Under conditions when alkali flies are numerous, fly larvae and pupae are also present at or near the lake surface and thus are likely eaten by the birds. Eared Grebes can dive, so they are not dependent on prey being near the water surface. Fly larvae and pupae are larger than brine shrimp and have a higher energy content, so they are probably the desired prey. Eared Grebes have not been seen at the lake since 2020, indicating that habitat conditions for them was likely missing. This is not surprising, given that the only water present was just inches deep (Figure 2). Other waterbirds, especially Willets but also American Avocets and Black-necked Stilts, appeared less affected than the three groups mentioned above. This is possibly due to their ability to forage on benthic prey, especially fly larvae and pupae, present in the shallow pool created by the Mile-Post 74 Springs and at shoreline seeps and smaller springs where habitat consists of a watery film and wet mud. Western and Least Sandpipers were relatively abundant from 2011-2016, but thereafter, for unknown reasons, were mostly present in low numbers (Figure 18). The fact that some waterbirds still utilized Lake Abert under the adverse habitat conditions that were present in 2014 and 2015 and again in 2021 and 2022 attests to their adaptability, but their numbers were much less than in 2011-2013, and it remains to be seen what the overall effect of lower abundances is on these birds' long-term population viability, especially given that terminal lakes throughout the Great Basin are shrinking (Haig et al. 2019, Donnelly et al. 2020).

To answer the question: how much water is needed to sustain quality habitat for birds, seems best answered by focusing on lake levels because it affects the lake's productivity through changes in salinity and surface area. If the lake is ≥4250 feet in elevation frequently and for extended periods, then the lake is likely to be more productive and therefore be able to support healthy bird populations. Based on lake conditions during the past decade and on projections of a future climate being even drier than it is today, it seems inevitable that the Lake Abert ecosystem and the Chewaucan Basin as a whole will face extreme water-availability challenges. Thus, the basin would benefit from an Integrated Water Availability Assessment such as the USGS is proposing for saline lakes.

Conclusions

Lake Abert is a critically important saline ecosystem, and in fact, this author believes it is ecologically the most important water body in the northern Great Basin. The lake has sustained a large biomass of algae, alkali flies, and brine shrimp, and in turn, these species have supported substantial numbers of migratory waterbirds at a time when the bird's energy needs are great. However, the lake is being impacted by water diversions and climate change, and the abundance of birds has recently shown large declines, going from >250,000 in 2012 to 11,000 in 2021. Thus, concerns have been raised about the lake's future and it is incumbent upon us to ensure the ecosystem is viable. If our intent is to apply science-based management to water use in the basin, it's clear from the information presented above that we have an inadequate understanding of the hydrology of the Chewaucan River-Lake Abert system, especially of the reach below Paisley and at the lake. Additionally, we have limited knowledge of how climate and water diversions are affecting the lake's ecosystem, especially how productivity will be affected by frequent and prolonged drought, and how the birds will respond to that. At the same time, climate change will also impact the availability of water for agriculture. ***Thus, the Chewaucan Basin***

could greatly benefit from an Integrated Water Availability Assessment such as what the USGS is considering.

Findings/Recommendations

1. The Chewaucan River is over appropriated and climate change will exacerbate water shortages unless actions are taken to ensure that both agriculture and the lake ecosystem are sustainable.
2. Future water-use decisions in the Chewaucan Basin requires development of an accurate water budget and that should be based on the best available science. Data needs include measurements of: A. irrigation diversion rates; B. seepage returns from diversions to the river; C. ET from fields and from the lake; D. tributary flows to the river below Paisley; E. precipitation on the lake and agricultural fields; and F. inflows to the lake contributed by springs and seasonal creeks.
3. The USGS, with assistance of the State of Oregon and stakeholders, should undertake an Integrated Water Availability Assessment of the Chewaucan Basin to clarify how climate change is affecting both agriculture and the lake ecosystem and to help develop solutions.
4. Lake Abert merits a high priority for conservation efforts because it is a rare and productive ecosystem that can support large numbers of waterbirds.
5. Continued monitoring of waterbirds at the lake is critical to understand how the combined effects of irrigation and climate change are affecting bird abundances.
6. Getting data on alkali fly and brine shrimp populations, as well as on *Ctenocladus* productivity, is needed to clarify how they are being affected by climate change and irrigation diversions.

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