PAST ELEVATIONS AND ECOSYSTEMS OF WALKER LAKE PROVIDE A CONTEXT FOR FUTURE MANAGEMENT DECISIONS

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INTRODUCTION

Walker Lake became the southernmost embayment of Nevada's Lake Lahontan about 14,000 years ago when waters rose above 4,271 feet (1,302 m) mean sea level (msl) at the Adrian Valley sill north of Wabuska [Figure 1] (Benson and Mifflin 1986). This elevation is corrected for isostatic rebound and tilting. This high stand of Lake Lahontan occurred sometime between 14,500 and 13,000 yr B.P. (before present) and may have lasted less than 200 years (Benson 1991). Climate conditions providing greater effective moisture (precipitation minus evaporation) were responsible for high lake levels at this time.

The elevation of Walker Lake in December 2007 was 3,934 feet msl, a difference of over 337 feet between this highstand and today. Highstand Walker Lake was fresh with a total dissolved solids (TDS) possibly as low as 500 milligrams per liter (mg/L). In December 2007 Walker Lake TDS was ~ 16,000 mg/L. At times during the last 30,000 years, however, Walker Lake was shallow and much more saline than today with TDS possibly as high as 100,000 mg/L (Benson 1991, Benson et al. 1991, Bradbury et al. 1989).

Changes in river volume and, therefore, lake volume can create different river and lake ecosystems. Lopes and Smith (2007) report lake elevation has not exceeded 4,120 ft-msl during the last ~10,000 years. This finding is consistent with Adams (2007) who reports that lake elevations fluctuated about 180 feet during the last ~3,500 years and that during this time period four episodes of deep water occurred. Yuan et al. (2006a) also report deep and shallow lake stands during the last ~2,700 years. Ecosystems resulting from different lake elevations have different physical attributes, processes, and biota. What triggered these substantial fluctuations in Walker Lake's elevation? On what timescales has the lake changed? What ecosystems have resulted from changes in lake and river volume? How can this information be used to aid management decisions?

Decadal to millennial change in the elevation of Walker Lake resulted from three processes: change in climate, change in the course of the Walker River, and modification of the hydrology of the Walker Basin caused by humans. These processes affect lake and river ecology on different timescales.

Climate affects the river and lake on both short and long timescales. Periods of drought can last seasons to centuries. Pluvial (wet) periods can last tens of thousands of years during glacial climates or decades during cool and wet climate episodes within overall drier climate regimes. When climate is cool and wet relative to today precipitation is greater than evaporation and more water is available to lake and river ecosystems. When climate is warm and dry like our current climate has been for the last ~ 10,000 years, precipitation is often less than evaporation and less water is generally available.

Present-day climate at Walker Lake is arid with hot summers. The Sierra Nevada create a rain shadow to their east which decreases precipitation as storms move from west to east across the mountain range. Substantial seasonal and diurnal temperature fluctuation, common to desert environments, occurs at elevations near Walker Lake. Temperatures at Hawthorne, Nevada, (elevation 4,220 feet), range from an average maximum temperature of 71˚ F to an average minimum temperature of 41˚ F. Average annual precipitation at Hawthorne is less than 5 inches (51-year record; WRCC, 2006).

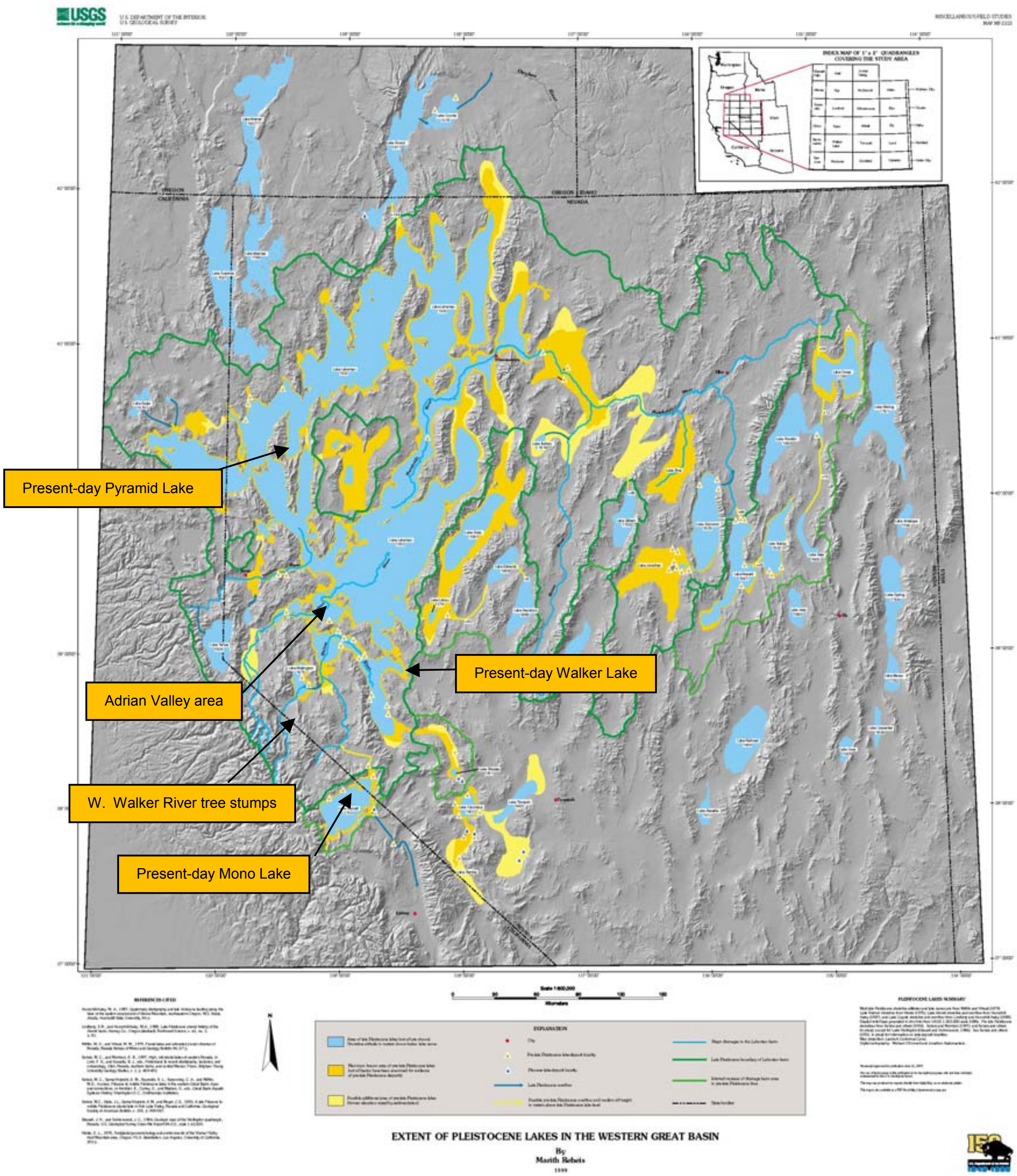

Figure 1. Pleistocene Lakes in the Western Great Basin and other localities mentioned in text (from: Reheis 1999, http://pubs.usgs.gov/mf/1999/mf-2323/mf2323.pdf).

Climate has been responsible for swings of hundreds of feet in the elevation of Walker Lake. Climate influence on Walker Lake is a product of the interplay of snowpack (river discharge) in the Sierra Nevada, and temperature, evaporation, and humidity at Walker Lake. For example, if snowpack in the Sierra Nevada were extensive (creating high river flow in spring and summer) and temperature at Walker Lake were low, lake levels would be high (assuming no agricultural use of water). If snowpack in the Sierra Nevada were moderate (creating moderate or low river flow), but temperature at Walker Lake remained very low, lake levels could remain relatively high because evaporation would be reduced. This last scenario may have occurred in Walker Lake's pre-history.

The course of the Walker River also affects the elevation of Walker Lake. The Walker River makes a 180 degree bend near Wabuska in Mason Valley. An old river channel heading in a northwesterly direction through Adrian Valley (Figure 1), however, likely carried the Walker River away from Walker Lake and into the Carson Sink at times in the past (King 1993, 1996, Yuan et al. 2006a, Adams 2003, 2007). During the time(s) that the Walker River flowed through the Adrian Valley, Walker Lake was very shallow or possibly dry.

For the purposes of this report, the exact timing of lake levels (discussed in Benson 1991, Benson et al. 1991, Bradbury et al. 1989, Adams 2003, 2007, and Yuan et al. 2004, 2006a, 2006b) is secondary to what we can learn about the Walker Lake ecosystem during times of different lake elevations. This discussion will compare what is known about taxa inhabiting low-water-saline to high-water-fresh Walker Lake ecosystems.

Humans began affecting the river and lake in 1852 when Walker River water was diverted for irrigation of agricultural lands (Horton 1996). Lands irrigated for agricultural production increased from 0 acres in 1850 to approximately 110,850 today (Pahl 1999). The operation of Topaz and Bridgeport Reservoirs allows farmers in Smith and Mason valleys to extend their growing season until late September and October which alters the natural hydrograph of the Walker River and the amount of water flowing into Walker Lake. Groundwater pumping in Smith and Mason valleys began in the 1960s and has since depressed the aquifer's water table, resulted in a net increase in recharge from the Walker River to the aquifer, and created a net decrease in stream flow passing the Wabuska stream gage located just upstream from the Walker River Paiute Reservation (Horton 1996, Sharpe et al. 2008). These modifications, not drought, have decreased the elevation of Walker Lake from approximately 4,083 feet in 1882 to 3,934 feet msl in December 2007 (Milne 1987, Beutel et al. 2001). The 149 foot elevation decrease concomitantly decreased lake volume from approximately 9.0 to 1.7 million acre-feet and increased TDS from an estimated 2,500 to approximately 15,995 mg/L.

This chapter will focus on the paleoecology of Walker Lake rather than the Walker River because little information exists on the ecology of the Walker River. The river section of this report is the first comprehensive study on the physical characteristics, biota, and health of the Walker River. Past variability and ecosystem change in Walker Lake, however, indicates that the Walker River is the lifeline for lake taxa. Therefore, a healthy Walker River is the key to long-term species survival in Walker Lake.

PREVIOUS RESEARCH

The first study to collect comprehensive physical and biological data in Walker Lake was conducted by DRI researchers between May 1975 and May 1977 (Koch et al. 1979, Cooper and Koch 1984). Numerous data sets were collected every two weeks or monthly for two years and are extremely valuable because they record Walker Lake biota and processes when the lake TDS were at ~ 10,300 mg/L. Horne et al. (1994) sampled Walker Lake between 1992 and 1994. Horne sampled one day each in July and October 1992, in March, April, July and September 1993, and in February and May 1994. These data, not taken as regularly at the previous study, record Walker Lake at ~ 12,500 mg/L. Subsequent lake studies include Beutel (2001) who sampled water quality and chlorophyll-a monthly at two locations from October 1992 to September 1993 and January 1995 to December 1996. Beutel also monitored zooplankton from 1992 to 1996 at one or more lake locations. In the summer of 1998 water profiles and undisturbed sediment-water interface samples were collected (Beutel 2001).

The Walker Lake Fishery Improvement Team (WLFIT) includes representatives from the Walker River Paiute Tribe, Nevada Department of Wildlife, and U.S. Fish and Wildlife Service. The WLFIT began a 5-year monitoring program in 2006 designed to evaluate the response of water quality, benthic invertebrates, macrophytes, the zooplankton community, tui chub, and Lahontan cutthroat trout to fluctuating lake environment and seasonal inflow to Walker Lake. The WLFIT has been monitoring benthic invertebrates in the near-shore areas quarterly since 2006 and is collecting temporal and spatial data to assess current conditions in the river and lake. Additionally, the six locations monitored and reported on in this report are also monitored monthly by the WLFIT. These studies as well as quarterly monitoring by the Nevada Division of Environmental Protection beginning in 1992, monitoring and reports compiled by the Nevada Department of Wildlife for the Walker Lake fishery beginning in 1958, and Lahontan cutthroat trout data collected by the U.S. Fish and Wildlife Service are crucial to our understanding of lake processes and changes on seasonal to decadal time scales.

Projects focusing on the ecology of the Walker River and its tributaries are few. Samples of water, bottom sediment, and biota were collected during the summers of 1994 and 1995 from sites on the Walker River to assess environmental quality (Thodal and Tuttle 1996). A study of mercury in 12 fish and 29 aquatic invertebrates and sediment from 19 sites in the Walker River Basin was conducted by Wiemeyer (2002). Leach and Benson (USGS) measured chemistry of the river at numerous locations during high and low flow periods and demonstrated the problem with irrigation return as a pollutant. In 2006 the U.S. Fish and Wildlife Service commissioned a study by Otis Bay, Reno, Nevada, to complete surveys for vegetation, avian, herpetological, and aquatic invertebrate abundance and richness and geomorphic and geologic characteristics along the Walker River.

The river and lake, however, operate on many timescales, from diurnal to seasonal to millennial. It is important to become familiar with past environments of Walker Lake and the Walker River because the past provides us with the additional knowledge to make informed management decisions.

THE GEOCHEMICAL HISTORY OF WALKER LAKE

Walker Lake provides a clear example of how solutes (ions) within a water body can change with continued evaporation and, as a result, alter lake environment and habitat. Changes in major ions [Ca, Mg, K, Na, SO_4, Cl, $HCO_3(CO_3)$] can affect the occurrence of certain taxa just like TDS and temperature. Changes in solute composition were called solute evolution by Jones (1966). Eugster and Jones (1979) provide a detailed discussion of solute evolution as a consequence of evaporation and mineral precipitation, as well as other processes. Forester (1983, 1987, 1991) discusses how solute evolution affects the distribution of ostracodes and Sharpe and Forester (2008) discuss how solute evolution affects the distribution of mollusks. Solute evolution may affect other taxa as well.

Briefly, solute evolution occurs as follows. The TDS along a solute evolutionary climate or hydrologic gradient will commonly increase more or less in a linear fashion. As solutes are concentrated in the water column due to processes such as evaporation, calcium (Ca) and bicarbonate/carbonate ([$HCO_3(CO_3)$] referred to as alk, for alkalinity, hereafter) reach saturation at ~ 200-300 mg/L TDS (Figure 2) because each ion is a relatively insoluble mineral compared to halite or gypsum. Note that 200-300 mg/L TDS is the high percentage interval in the Figure 2 data array. After this interval, the Ca and alk in the water column decrease because calcite is precipitating and other ions are concentrating. When calcite precipitates, Ca and alk are removed in equal equivalents. Either Ca or alk are lost (depleted) from solution relative to the other depending on the initial alk to Ca ratio. The colored bars in Figure 2 are discussed below.

Calcium plus alk depletion commonly occurs at TDS levels between ~ 1,000 to 2,000 mg/L (Figure 2). At TDS levels greater than ~2,000 mg/L, Ca plus alk are no longer dominant, therefore higher-TDS waters are dominated by ions other Ca or alk. Note in Figure 2 that Walker Lake is shown in blue triangles and the 1882 value occurs just beyond the Ca plus alk depletion zone of ~ 1,000 to 2,000 mg/L. All other values (1937-2003) occur well after Ca plus alk depletion. These values fall into the zone where Ca plus alk are no longer dominant in the water column. The ions currently dominating Walker Lake are sodium and chloride. In 1882, and in periods of fresher water (lower TDS), Walker Lake had Ca plus alk values over 50% (Figure 2). Between 1941 to ~ 1975, with ongoing evaporation and low inflow, the Ca plus alk value drops to just below 30% and after 1975 the Ca plus alk value drops to less than 20% (Figure 2). This simplified scenario does not account for non-equilibrium processes, species of calcium precipitated, or calcium complexed to other chemical species, but it does illustrate that the ions in Walker Lake have changed over time.

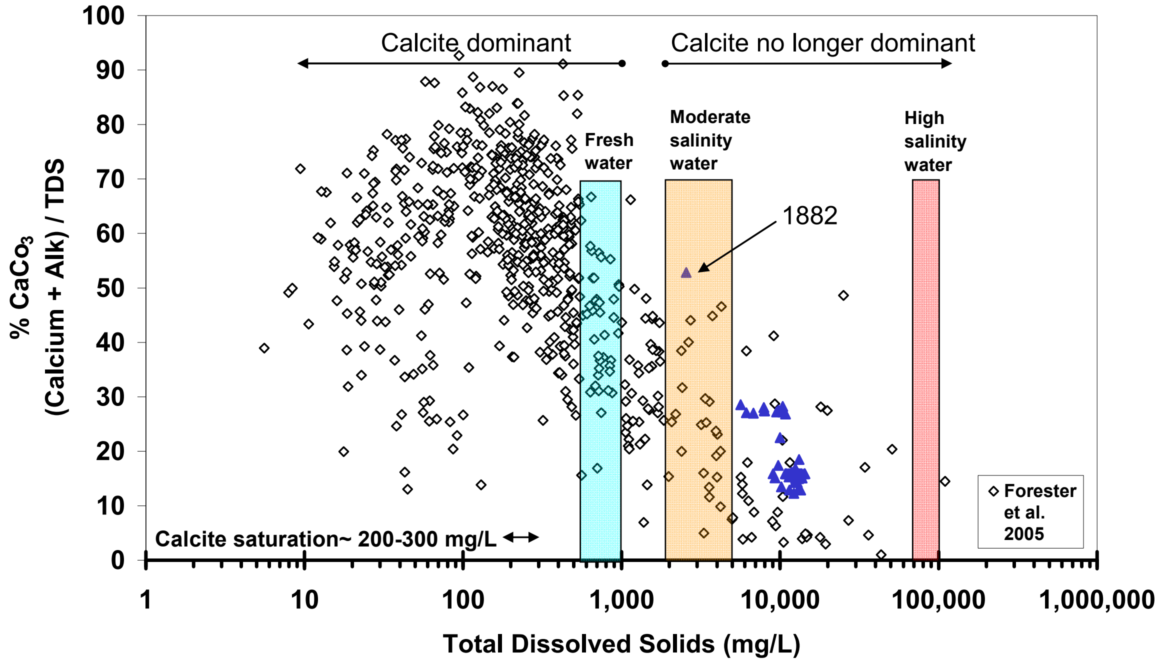

Figure 2. The solute evolution process. Diamonds show the ratio of Ca plus alk to TDS of 631 aquatic locations included in the North American Non-Marine Ostracode Database (NANODe) (Forester et al. 2005). Blue triangles show Walker Lake values. The two clusters of blue Walker Lake triangles are artifacts of the years data were collected (a data gap). Calcite saturation (the maximum percentage of Ca plus alk commonly occurs at about 200 to 300 mg/L TDS, the high-point of the curve. At saturation, Ca and alk are removed in equal equivalents while other ions remain in solution, so it is at this point that the curve begins to decline. As the percent of Ca plus alk to total ions decreases, the concentration of other ions is rising because of evaporative loss of water. Between approximately 1,000 to 2,000 mg/L TDS Ca plus alk (taken together) are no longer dominant solutes. Beyond this TDS range, the solutes are dominated by ions other than Ca or alk and, commonly, either Ca or alk is depleted from solution. Blue bar denotes fresh water, orange bar denotes moderate salinity water, and red bar denotes high salinity water. Bar widths are illustrative; they vary in width and overlap based on biota and water geochemistry specific to location.

Figure 3 tracks individual ions in Walker Lake through time. Note that alk (HCO_3) is always greater than Ca. This is because inflowing Walker River waters contain much greater alk relative to Ca (Humberstone 1999). Because alk and Ca are precipitated first, because they are precipitated in equal equivalents, and because Walker Lake initially had greater alk relative to Ca, Ca will be depleted relative to alk with continued evaporation. Figure 3 shows that over time, calcium is depleted and the remaining ions values increased. Also, the spread among all ions has increased relative to initial values. Therefore, in addition to TDS change, the ionic composition of Walker Lake today is vastly different from 1882 values. The changes noted in Figure 3 are the result of water withdrawn from the Walker River for agricultural use. This solute evolution process however, also occurs naturally with increased or decreased inflow and evaporation based on climate change or river diversion. When fresh water is input, the process reverses.

In 1882 Walker Lake was transitioning from waters dominated by alk and calcium to waters dominated by other ions. This major shift in ionic composition (not just TDS) can be one of the primary factors affecting the occurrence of taxa.

Solute evolution at these TDS concentrations creates three generalized solute fields: (1) Ca and alk in roughly equal proportions below ~ 2,000 mg/L (type 1 solutes); (2) alk enriched and Ca depleted above ~ 2,000 mg/L (type 2 solutes); and (3) alk depleted and Ca enriched above ~ 2,000 mg/L (type 3 solutes) (Figure 4). Type 1 is common to freshwater and types 2 and 3 to saline waters, although dilute waters can have solute compositions common to types 2 and 3 (see Sharpe and Forester 2008). Walker Lake is (and always will be) type 2 because its waters have greater alk relative to Ca (Figure 3). The colored bars in Figure 4 are discussed below.

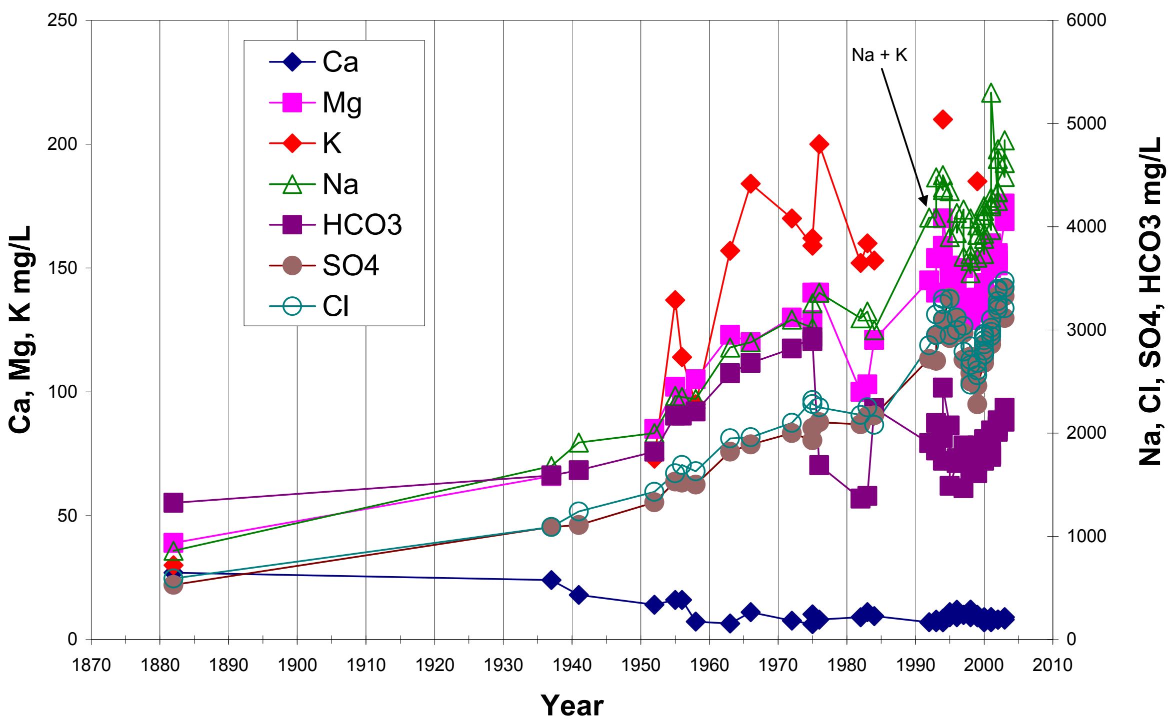

Figure 3. Walker Lake Solute Change 1882-2003. The 1882 HCO_3 and K values are estimated from Russell 1885 (see Rush 1974). Other measurements are taken from Rush (1974), Boyle Engineering (1976), Benson and Spencer (1983), Nevada Department of Wildlife, and Nevada Department of Environmental Protection. Na and K are graphed together beginning in 1992. These data are not collected after 2003. Water samples were taken at different seasons of the year and in different areas of the lake, yet trends are apparent.

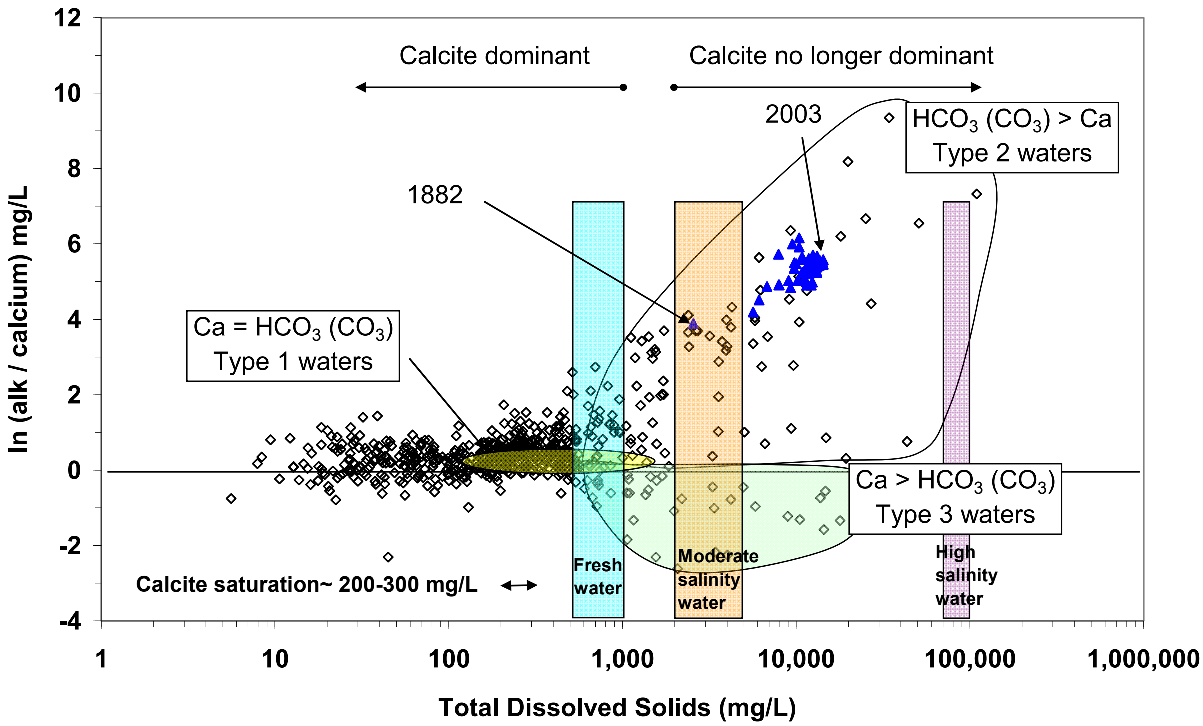

Figure 4. Walker Lake Alkalinity to Calcium Ratio 1882-2003. Diamonds, triangles, calcite saturation, and bars are shown as in Figure 2. These data are not collected after 2003. Three hydrochemical fields result from solute evolution: the alk [$HCO_3(CO_3)$ = Ca] field with a TDS below ~ 2,000 mg/L (type 1 water, yellow); the alk [$HCO_3(CO_3)$ = Ca] > Ca field with a TDS greater than ~ 2,000 mg/L (type 2 water, pink); and the alk [$HCO_3(CO_3)$ = Ca] < Ca field with a TDS greater than ~ 2,000 mg/L (type 3 water, green). Additional hydrochemical fields occur in the solute evolution process at higher TDS levels (Jones, 1966; Eugster and Jones, 1979) but they are not discussed here.

THE TAXA OF WALKER LAKE

Sediment cores taken from Walker Lake by the U.S. Geological Survey during the 1970s and 1980s provide valuable biotic (diatom, ostracode, brine shrimp, and pollen) and abiotic (sediment structure, composition, pore water, stable isotope, and geochemical) data used to reconstruct the past environments of Walker Lake (Benson 1988, Benson 1991, Benson et al. 1991, Bradbury 1987, Bradbury et al. 1989) for the last ~ 30,000 years. Mixing of sediments may have occurred in part of one core and hiatuses in sediment deposition were noted, so the exact timing of certain events is not precisely known. Another set of cores taken in 2000 record the last ~ 2,700 years (Yuan et al. 2004, Yuan et al. 2006a, Yuan et al. 2006b). All in all, these sediment cores provide a relatively robust record for Walker Lake and clearly show that the lake can change relatively rapidly in volume and, thus, from one ecosystem to another.

Changes in inflow to Walker Lake affected the occurrence and abundance of Walker Lake taxa through both geochemical and physical processes. Geochemical processes such as lake water composition (ionic constituents) and concentration (TDS) and physical processes such as temperature, stratification, dissolved oxygen, light penetration and nutrients directly affected the occurrence and distribution of phytoplankton (algae and diatoms), zooplankton, ostracodes, brine shrimp, mollusks, and fishes. Biologic and geochemical evidence from the USGS Walker Lake sediment cores indicate that the lake TDS ranged from ~ 500 to possibly as high as 100,000 mg/L in the past and taxa moved in and out of this system as TDS and lake processes changed.

A listing of selected taxa from published literature is shown in Table 1. If a genus drops from the record in this table, it could mean that (1) it occurred but was not abundant, therefore, not recorded; (2) it was extirpated (no longer exists) in Walker Lake; (3) it was not preserved in the record; or (4) the sampling design was not intended to collect that particular taxon. Therefore, when a particular genus drops out of the record, we cannot be sure of its absence. The taxa in Table 1 are from published peer-reviewed literature only, so this table does not represent other times in the lake's history or other studies. Additionally, the large time blocks (e.g., ~5,000 to historic time) encompass taxa that may have existed during either high or very low lake levels. Taxa within these large time blocks did not all exist at once in the lake. They are included so that a general presence-absence comparison may be made.

Table 1. Selected Walker Lake taxa through time.

TIME PERIOD	**~30,000-25,000 yr B.P.*[1]**	**~25,000-10,000 yr B.P.*[1]**	**~ 10,000-5,000 yr B.P.*[1]**	**~5,000 yr B.P. to historic time*[1,2]**	**Pre-1963[3]**	**1975-1978[4]**	**1992-1996[5]**	**THIS STUDY**
Phytoplankton								
Bluegreen Algae								
Amphithrix janthina						X		
Anabaena inaequalis						X		
Anabaena sp.						X	X	
Anacystis sp.						X		
Calothrix parietina						X		
Calothrix sp.						X		
Chroococcus sp.						X		
Dermacapsa sp.						X		
Entophysalis sp.						X		
Gomphosphaeria sp.						X		
Lyngbya sp.						X		
Microcystis aeruginosa						X		
Microcoleus lynagbyaceus						X		
Nodularia (spumigena) crassa						**X**	**X**	**X**
Nodularia sp.					X			**X**
Schizothrix calcicola						X		

Table 1. Selected Walker Lake taxa through time (continued).

TIME PERIOD	~30,000-25,000 yr B.P.*[1]	~25,000-10,000 yr B.P.*[1]	~ 10,000-5,000 yr B.P.*[1]	~5,000 yr B.P. to historic time*[1,2]	Pre-1963[3]	1975-1978[4]	1992-1996[5]	THIS STUDY
Schizothrix						X		
Spirulina subsalsa						X		
Spirulina						X		
Synechococcus aeruginosa						X		
Synechococcaceae								X
Green Algae								
Botryococcus braunii						**X**		
Botryococcus sp.	X	X	X	X				
Cladophora glomerata						**X**	X	X
Cladophora sp.					X			
Dunalliella sp.						X		
Elakatothrix gelatinosa						X		
Gongrosira						X		
Oocystis sp.						X		X
Planktospheria sp.						X		
Spermatozopsis sp.								X
Ulothrix aequalis						X		
Ulothrix cf. *aequalis*						X		
Ulothrix cylindricum						X		
Diatoms								
Achnanthes sp.						X		
Amphora ovalis						X		
Anomoeoneis costata	X	**X**						
Anomeoneis sphaerophora						X		
Caloneis schumanniana						X		
Ceratoneis (Hannaea) arcus						**X**		
Chaetoceros elmorei				X		**X**		
Chaetoceros sp.					X			X
Cocconeis placentula						**X**		
Coscinodiscus sp.						X		
Cyclotella kutzingiana						**X**		
Cyclotella meneghiniana	X	X	X	X				
Cyclotella quillensis	X		X	X				
Cyclotella ocellata			X	X				
Cymatopleura sp.						X		
Cymbella spp.						**X**		
Diatoma vulgare						**X**		
Diploneis sp.						X		

Table 1. Selected Walker Lake taxa through time (continued).

TIME PERIOD	~30,000-25,000 yr B.P.*[1]	~25,000-10,000 yr B.P.*[1]	~ 10,000-5,000 yr B.P.*[1]	~5,000 yr B.P. to historic time*[1,2]	Pre-1963[3]	1975-1978[4]	1992-1996[5]	THIS STUDY
Entomoneis sp.						X		
Epithemia turgida						X		
Fragilaria vaucheriae						X		
Frustulia rhomboides						X		
Gomphonema lanceolata						X		
Melosira distans						X		
Meridion circulare						X		
Navicula subinflatoides		**X**		X				
Navicula spp.				X		**X**		
Nitzschia sp.						**X**		
Rhoicosphenia curvata						X		
Rhopalodia musculus						X		
Stephanodiscus excentricus	**X**		**X**	**X**				
Stephanodiscus niagarae		X	X	X				
Stephanodiscus rotula	X		X	X				
Surirella nevadensis	**X**	X	X	X				
Surirella striatula						X		
Synedra ulna						X		
Tabellaria sp.						X		
Zooplankton								
Copepods								
Acanthocyclops (Cyclops)					X	X		X
Ceriodaphnia quadrangular					X			
Diaphanosoma					X			
Leptodiaptomus (Diaptomus)					X	**X**	X	X
Rotifers								
Brachionus spp.							X	
Hexarthra fennica							**X**	
Hexarthra spp.								X
Lucane spp.								X
Cladocera								
Alona guttata							X	X
Moina hutchinsoni					X	**X**	X	X
Ostracodes								
Candona caudata			X	X				
Candona sp.	X	X	X	X				
Limnocythere bradburyi	**X**	X						
Limnocythere ceriotuberosa	**X**	X	**X**	**X**		X		

Table 1. Selected Walker Lake taxa through time (continued).

TIME PERIOD	~30,000-25,000 yr B.P.*[1]	~25,000-10,000 yr B.P.*[1]	~ 10,000-5,000 yr B.P.*[1]	~5,000 yr B.P. to historic time*[1,2]	Pre-1963[3]	1975-1978[4]	1992-1996[5]	THIS STUDY
Limnocythere sappaensis		X		X				
Brine Shrimp								
Artemia		X		X				
Amphipods								
Hyallela azteca						X		
Chironomids								X
Chironomus						X		
Pelopia								
Damselflies/Dragonflies							X	X
Enallazma sp.						X		
Mollusks								
Anodonta sp.				X				
Gyraulus parvus				X				
Helisoma newberryi				X				
Helisoma trivolvus				X				
Physella sp.				X				
Pisidium sp.				X				
Pyrgulopsis nevadensis				X				
Aquatic Grass								
Ruppia sp.				X			X	
Fish				(1885-1910)[6]				
Cyprinus carpio (common carp)**				X				
Archoplites interruptus (Sac.				X				
Oncorhynchus clarki henshawi				X***		stocked	stocked	stocked
Catostomus tahoensis (Tahoe				X		X		
Siphatales (Gila) bicolor (tui chub)				X		X	X	X
Rhinichthys osculus (speckled dace)				X				

X indicates taxa recovered from lake at that time. Bold X indicates taxon was abundant.
*not all species present consistently through entire time period. Time periods encompass many different lake environments.
**introduced.
***native strain extirpated in lake; current LCT are stocked.
1 Bradbury et al. 1989.
2 S.E. Sharpe, unpublished data.
3 Cooper and Koch 1984, Koch et al. 1979, Ting, unpublished data (see Koch et al. 1979).
4Cooper and Koch 1984, Koch et al. 1979, Osborne et al. 1982.
5Horne et al. 1994, Beutel et al. 2001.
6 Brussard et al. 1996.

It is important to remember that the record of taxa recovered in cores is incomplete and not representative of all the taxa in the lake because of differential preservation and sampling techniques. The sediment record favors those taxa with resistant coverings such as diatoms and ostracodes. It is also possible that some taxa recovered from lake cores were transported to the lake from the river and then incorporated into lake sediments. However, Bradbury et al. (1989) compare different climate and environmental proxy data such as geochemical measurements from the same core intervals and climate and hydrology records near Walker Lake to support the conclusion that the taxa listed were living in the lake at that particular time.

No-analog situations between past and present may exist. A no analog situation is one where an assemblage of taxa found in the past is not known to occur together today. For example, the ostracode, *Limnocythere bradburyi*, was recovered in two different intervals in the Walker Lake record. Today this ostracode occurs primarily in central Mexico and is found in the U.S. only in southernmost Arizona (Forester et al. 2005). Climatic, hydrologic, and limnologic conditions very different than today existed for periods allowing this ostracode to live in Walker Lake. Some taxa may be able to recolonize Walker Lake after extirpation but others may not if past physical and geochemical conditions are not recreated.

High Salinity Alkaline Waters

Periods of very high salinity with alkaline (alk relative to Ca) water occurred at ~2,100 and >4,650 ^{14}C age B.P. (Benson 1991, Benson et al. 1991, Bradbury et al. 1989). Diatoms *Anomoeoneis costata* and *Navicula subinflatoides*, ostracode *Limnocythere sappaensis* and pellets of brine shrimp (*Artemia* sp.) were recovered at these same core depths in Walker Lake sediments indicating shallow, saline water (Bradbury et al. 1989). All these taxa are tolerant of high salinity waters and *N. subinflatoides* and *Artemia monica* currently inhabit Mono Lake where TDS can exceed 100,000 mg/L. Walker Lake was likely surrounded by marshes and salt flats during these time periods evidenced by the pollen of Cyperaceae (sedge) and *Sarcobatus* (greasewood) recovered from these same core depths. This shallow, saline lake ecosystem may have experienced rapid fluctuations in depth and in area of open water because of its small volume. The lake, between ~ 2,500 and 2,150 years B.P., may have been less than three feet deep and reduced in volume by 98% and areally by 93% from the 1968 size (see Bradbury et al. 1989). TDS during these low stands may have been as high as 60,000 or 100,000 mg/L, similar to Mono Lake in salinity and ionic composition.

High salinity alkaline Walker Lake waters can result from climate or diversion of the river. The climate scenario for high salinity alkaline waters is nominal snowpack in the Sierra Nevada and low river flow. Nominal precipitation and moderate temperature at Walker Lake likely occurred or alternately, moderate precipitation and high temperature at Walker Lake occurred, resulting in low effective moisture at the lake. The river diversion scenario for these saline waters is extensive snowpack in the Sierra Nevada. Adams (2003) calculates that the inflow to Carson Lake would have to increase by a factor of at least four to produce late Holocene Carson Lake levels even when the Walker River was flowing to Carson Sink. High to moderate precipitation would likely occur at Walker Lake associated with the Sierra storm tracks. Taxa capable of moving upriver as lake conditions became inhospitable likely did so. Taxa living in the river recolonized the lake when inflow once again reduced lake TDS levels.

Figures 2 and 4 (red bar) show the area of high salinity alkaline waters. If Walker Lake were to continue to evaporate it would fall below 10% Ca plus alk and move toward the red bar in Figure 2. With increased TDS the Walker Lake alk to Ca ratio would further increase the amount of alk relative to calcium, thus moving Walker Lake values toward the top right corner of Figure 4.

Moderate Salinity Alkaline Waters

Periods of moderate salinity occurred during transitions from low to high water or vice versa. Diatoms *Stephanodiscus excentricus*, *Surirella nevadensis*, *Cyclotella meneghiniana*, *Chaetoceros elmorei*, and *Cyclotella quillensis* and ostracode *Limnocythere ceriotuberosa* are representative of a moderate-salinity eutrophic lake and inhabited Walker Lake at different intervals from about 4,650 (Bradbury et al. 1989) prior to historic lake drawdown. *Botryococcus*, often common in this type of environment, was recorded by Bradbury et al. (1989) between ~ 4,300 and ~900 ^{14}C age B.P. *Botryococcus* was recorded in 1975-1977 by Cooper and Koch (1984) but is absent or rare in Walker Lake today.

The taxa *S. excentricus*, *S. nevadensis*, and *C. quillensis* occurred in Pyramid Lake in the 1920s when it had a salinity of ~ 3,500 mg/L (see Bradbury et al. 1989). *C. elmorei* was the predominant diatom collected by Koch et al. (1979). They state that *C. elmorei* TDS range is large: from ~ 400-30,000 mg/L. The presence of *L. ceriotuberosa* implies that the lake bottom was at least seasonally oxygenated. *L. ceriotuberosa* is the only abundant ostracode living in Walker Lake sediment today (Bradbury et al. 1989).

The diatom and ostracode taxa suggest that the lake fluctuated between ~ 2,000-5,000 mg/L TDS during this time period (Forester et al. 2005). The high-end range of moderate salinity alkaline waters is greater than 10,000 mg/L TDS and would contain a different assemblage of taxa than the lower TDS value. Based on salinity, geochemistry, and taxa, Walker Lake today is transitioning from a moderately salinity alkaline water (on the high end) to a high salinity alkaline water (on the low end).

The climate scenario for moderate salinity alkaline waters is moderate to low snowpack in the Sierra Nevada, moderate to low river flow, and moderate to low precipitation at Walker Lake. Alternatively, if moderate precipitation occurred in the mountains but temperature at Walker Lake was high, evaporation would increase. These waters could also occur if diversion of the Walker River was not rapid or diversion was partial (as suggested by Yuan et al 2006a), allowing some water to flow into the lake. These waters would also occur on a transition from very saline to fresh water.

Walker Lake currently contains moderate salinity alkaline waters resulting from agricultural diversions. Figure 2 shows moderate salinity alkaline waters to the right of the depletion zone (~1,000-2,000 mg/L) where alk plus calcium are no longer dominant (orange bar). Figure 4 shows moderate salinity alkaline waters (orange bar). Note that the 1882 Walker Lake value is within the orange bar in Figs 2 and 4. Subsequent Walker Lake values are to the right of the orange bar. Geochemically, moderate salinity alkaline waters can encompass much greater TDS values than contained within the orange bars.

The TDS of the orange bars is based on the modern requirements of taxa recovered from Walker Lake core sediments.

Fresh Waters

When Walker Lake is deep and fresh, the diatom *Cyclotella ocellata* and ostracode *Candona caudata* occur. *C. ocellata* is found in Lake Tahoe and in the epilimnion of other cool oligotrophic freshwater lakes. The presence of *C. caudata* implies that TDS was below 2,000 mg/L (Forester et al. 2005). Stable isotope values of unrecrystallized carbonates (Benson et al. 1991) indicate Walker Lake was rising when *C. ocellata* first appeared in the record (~ 4,800 ^{14}C age B.P.), and approached and reached a steady state condition when *C. caudata* entered the record (~ 4,700 ^{14}C age B.P.). Walker Lake TDS was probably below 1,000 mg/L at times during the last 5,000 years (late Holocene highstands) and it may have averaged as low as 500 mg/L during these highstands (R.M. Forester, personal communication). Two diatoms, *Stephanodiscus niagarae* and *Stephanodiscus rotula* occurred in Walker Lake when the lake was slightly more saline, but still considered relatively fresh.

The climate scenario for fresh waters is high snowpack in the Sierra Nevada and high river flow. High to moderate precipitation at Walker Lake would likely occur and evaporation on the lake surface would be offset by inflow. Walker Lake waters have not been fresh during the historic period. Figs. 2 and 4 show where fresh waters occur (blue bar). This area is just after Ca and alk saturation (200-300 mg/L) but before Ca or alk depletion.

Historic Change in Taxa

Blue-green algae and diatoms comprised over 99% of the total phytoplankton numbers sampled in 1975-1977 and blue-green algae alone made up 97% of this sample (Cooper and Koch, 1984). The blue-green algae, *Nodularia (spumigena) crassa*, has dominated the blue-green algae assemblage for more than the last 30 years (Table 1). The green algae, *Cladophora glomerata*, was dominant in the 1975-1977 study and was collected in the 1990s and in the present study. *Chaetoceros* sp. was found in the lake prior to 1963 and was collected in this study. *C. elmorei* was living in Walker Lake during at least seven intervals of moderate salinity water during the last ~ 5,000 years (Bradbury et al. 1989). It was the dominant diatom during the 1970s.

Two species of copepods, *Ceriodaphnia quadrangular* and *Diaphanosoma leuchtenbergianum* no longer live in the lake because of the elevated TDS (Dickerson and Vinyard 1999). *Leptodiaptomus (Diaptomus) sicilis* and *Acanthocyclops (Cyclops) vernalis* have been recorded in the lake prior to 1963 and are recorded in this study. *L. sicilis* declined 50-70% in abundance between 1977 and 1994 (Horne et al. 1994). The rotifer *Hexarthra fennica* was first recovered in the 1990s and was a dominant species at that time. It was also recovered in this study. Cladoceran *Moina hutchinsoni* has lived in the lake for at least the last 45 years and was also recovered in this study. Amphipods were not recovered from the lake in 2003 or 2004 (NDOW, 2005) nor in this study.

Historically, four native species of fish inhabited Walker Lake: Lahontan cutthroat trout, LCT (*Oncorhynchus clarki henshawi*), tui chub (*Gila bicolor*), speckled dace (*Rhinichthys osculus*), and Tahoe sucker (*Catostomus tahoensis*) (Sigler and Sigler

1987, LaRivers 1962, Brussard et al. 1996). Speckled dace have not been collected since before 1963 and Tahoe sucker have not been collected since the mid 1970s. Tui chub is the only native fish (defined as the strain that evolved in Walker Lake) remaining in Walker Lake. LCT are native to Walker Lake, however, the stocked fish are not the original Walker Lake native strain and, so, are considered by many not native. Two introduced fish species, the common carp (*Cyprinus carpio*) and the Sacramento perch (*Archoplites interruptus*) were extirpated from the lake by about 1963 (Cooper and Koch 1984).

DROUGHT CONDITIONS AT WALKER LAKE

Two intervals of low Walker Lake levels are documented during the last 2,000 years (Benson et al. 1991, Yuan et al. 2004, Adams 2003). Bradbury et al. (1989) report two intervals in the last ~2,100 years that contain the saline-tolerant ostracode *Limnocythere sappaensis.* The interval at ~ 2,100 years ago also contains brine shrimp. Bradbury et al. (1989) report an older saline episode containing brine shrimp at slightly greater than 4,700 ^{14}C age B.P. The modern physical tolerances of the other taxa recovered suggest high salinity waters during all three of these intervals.

Low levels and high salinity of Walker Lake have been attributed to both drought conditions and the diversion of the Walker River through the Adrian Valley (Figure 1). Benson et al. (1991) report that Walker Lake was shallow and saline at ~ 2,000 and ~ 1,000 yr B.P. and that desiccations of Walker Lake since 21,000 yr B.P. resulted from the diversion of the Walker River. Adams (2003) reports lowering of Walker Lake levels at ~ 1500-1000 and 500-300 cal yr B.P. associated with the diversion of the Walker River (Adams 2007).

Bradbury et al. (1989) argue that drought conditions, not diversion, caused shallow, saline Walker Lake conditions between ~2,400 and 2,000 yr B.P. They do not report a later low stand. Yuan et al. (2004) report that substantial multicentury droughts occurred between AD 900 and 1100 (1038 and 838 cal yr B.P.) and AD 1200 and 1350 (740 and 550 cal yr B.P). They argue that the Walker River was not diverted from Walker Lake during the last 1,200 years so these droughts were climate controlled. Mensing et al. (2008) report two extended droughts at Pyramid Lake ending at 800 and 550 cal yr B.P. Graham et al. (2007) report generally arid conditions with episodes of severe centennial-scale drought in the western and central U.S. between 500 and 1350 A.D. Although dates of drought from these various climate proxy records are not consistent, they do indicate that severe, long-term drought episodes existed in the past.

Stine (1994, 2004) provides evidence for climate controlled low lake stands in the central Sierra Nevada. Upright and rooted stumps in and adjacent to the West Walker River, Mono Lake (Figure 1), Owens Lake (south of Bishop, California) and Tenaya Lake, Fallen Leaf Lake, Independence Lake, and Osgood Swamp (all located in the central Sierra Nevada) were once trees growing in sites that today are too wet to support their growth. For example, under natural conditions (excluding human drawdown of lake elevation) stumps at Mono Lake would be submerged under 50 feet and stumps at Walker Lake would be submerged under 140 feet of water. Tenaya Lake currently has rooted stumps beneath 70 feet of water and Fallen Leaf Lake has rooted stumps under tens of feet of water. Radiometric dates (Stine 1994, 2004) from these localities are grouped in two intervals in Medieval time: more than 200 years prior to ~ AD 1100 (~ 1038 to 838 cal yr B.P.) and more than 140 years prior to ~ AD 1350 (~ 740 to 550 cal yr B.P.).

Stine documented 104 rooted stumps in the West Walker River Canyon approximately three miles north of the junction of Highway 395 and Highway 108 (Sonora Pass road, Figure 1). These trees date to either of the two medieval drought intervals. Stream flow must have been much less than present to allow these trees to grow in the lowest areas of the narrow canyon floor. Stine ruled out piracy of the West Walker River, so the Walker River likely flowed in near these trees toward Walker Lake during these time periods. It is possible that the Walker River was diverted through Adrian Valley during these low-flow periods. It is also possible that the Walker River flowed into Walker Lake and that inflow was not sufficient to exceed evaporation during these drought periods.

Relatively good concurrence exists for a climate-induced severe, century-scale drought between ~ 1,038-838 and ~ 740-550 cal yr B.P. (Yuan et al. 2004, Stine 1994, Mensing et al. 2008) supporting the hypothesis that low Walker Lake levels at these times were climate controlled. Evidence also exists for drought conditions at ~ 2,000 years ago (Mensing et al. 2008) indicating that this earlier Walker Lake low stand may also have been climate controlled.

The widespread distribution of stumps dating from these two drought periods, as well as other drought proxy data, suggest drought conditions on at least a regional scale. The magnitude of these droughts exceeded both the Dust Bowl and recent drought periods; these droughts lasted from decades to centuries (Stine 1994, Mensing et al. 2008). The evidence for past century-duration drought in the Great Basin suggests that climate-induced, severe, long-term drought will undoubtedly affect future Walker Lake levels and salinity. Given this probability, it is critical that Walker Lake taxa are allowed to move upriver when drought conditions occur or they may be extirpated, even if TDS levels have been lowered relative to current measurements.

RIVER CONDITIONS

The record over the last 30,000 years suggests that many species enter and leave the lake ecosystem depending on their ecological tolerances to the physical conditions of the lake. The taxonomic record indicates that species of phytoplankton, diatoms, zooplankton, ostracodes, brine shrimp, and fishes have been able to move back into a system where they have previously been rare or extirpated. Recolonization mechanisms for these taxa include transport by wind or waterfowl, persisting in refugia such as at a groundwater discharge site within the lake or leaving the lake to live in appropriate reaches of the Walker River.

The Walker River once provided a stable refugium for taxa. Lahontan cutthroat trout and tui chub could inhabit and reproduce in river waters when lake conditions were unfavorable. They could migrate back to the lake when hospitable conditions returned. The river, however, has been modified from its prehistoric conditions by the construction of dams (e.g., introducing barriers, changing the seasonal river hydrograph, and increased water temperature in certain reaches), introduction of non-native fish (competition and predation), introduction of plant species, removal of water for irrigation, and decrease in water quality resulting from agriculture. The river is no longer a healthy, natural ecosystem available to host taxa that must leave the lake or die when conditions are unfavorable. Until the river can again act as a refugium, many taxa, particularly fish, requiring less saline lake conditions will likely not be able to naturally recolonize the lake when salinity decreases.

CONCLUSION

Knowledge of the long-term record of Walker Lake ecosystems can aid current management decisions. The paleoecological record shows:

1. The depth and salinity of Walker Lake naturally fluctuated from fresh and deep to very shallow and saline. Lake elevation fluctuated as much as 180 feet during the last 5,000 years (Adams 2007). The TDS in Walker Lake may have been as high as 100,000 mg/L when brine shrimp inhabited the lake to as low as 500 mg/L when the lake was deep (Bradbury et al. 1989). Currently Walker Lake is 149 feet below its historic high elevation with a salinity of ~16,000 mg/L. The lake environment and many of its taxa are adapted to substantial variation in depth and salinity. This is good news for management because large lake fluctuations resulting from acquisitions should not pose problems to taxa. The natural system, however contained a healthy, unobstructed river which served as an escape route and habitat for many taxa when the lake became inhospitable. Management of the Walker Lake ecosystem must include restoration of the river so that taxa can move upriver when lake conditions deteriorate or they will likely be extirpated from the lake.
2. The geochemistry of Walker Lake changed over time not only in TDS, but also in the relative abundance of ions. This affected the distribution and occurrence of certain taxa. The good news for management is that with increased water flowing to the lake, or greatly decreased evaporation or both, this process will reverse and TDS and ionic strength will decrease. Increased inflow from the Walker River relative to today is needed to help reverse the solute evolution process.
3. Past fluctuation in lake elevation and salinity occurred rapidly, particularly when the Walker River changed course and diverted flow from or returned flow to the lake. Bradbury et al. (1989) suggest that the lake transitioned from low and saline to high and dilute within several decades. This information suggests that if water acquisitions result in substantial inflow in short periods of time, it would not be uncommon to the Walker Lake environment. This is helpful for management and water release decisions because the time frame for acquisitions could be within a short time frame, from years to decades.
4. Certain taxa quickly colonized the lake, evidenced by the sudden occurrence or transition of ostracode and diatom taxa in the sediment record. This suggests that the taxa found in Walker Lake are adapted to rapid recolonization when conditions are favorable. However, it is essential that particular taxa are able to migrate up and live in a healthy Walker River so that they can return to the lake when conditions are favorable. This finding is significant because it underscores

the value of a healthy, passable (e.g., temperature, depth, obstacle, and cover) river that taxa can use as a conduit to provide suitable habitat.

5. Long-term decadal to centennial drought in the future is likely because droughts of this magnitude and duration occurred in the past. The Walker Lake ecosystem will again be compromised if severe, long-term drought conditions occur. The Walker River should be restored to provide a usable escape route and healthy habitat for species until drought conditions abate.

It is ironic that this chapter and almost all previous work have focused on the lake ecosystem because so many different aspects of the past record imply that the Walker River is the key to species survival in Walker Lake. The river, not the lake, is the stable ecosystem that many taxa require in a highly variable environment such as Walker Lake and the river should be the focus of restoration efforts. As river health is restored, lake health will follow. The Walker River currently appears to be considered only a pipeline to deliver more water to Walker Lake. Instead, the river is the lifeline Walker Lake taxa need to survive unfavorable lake conditions and it has served as such for many tens of thousands of years. Little information is available and few studies have been conducted on the Walker River most likely because its tremendous value in sustaining Walker Lake taxa has not been fully recognized.

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