Winter 2-24-2016

Impacts of Water Development on Great Salt Lake and the Wasatch Front

Wayne Wurtsbaugh
Utah State University

Craig Miller
Utah Division of Water Resources

Sarah Null
Utah State University

Peter Wilcock
Utah State University

Maura Hahnenberger
Salt Lake Community College

Frank Howe
Utah Division of Wildlife Resources

Recommended Citation

Wurtsbaugh, Wayne; Miller, Craig; Null, Sarah; Wilcock, Peter; Hahnenberger, Maura; and Howe, Frank, "Impacts of Water Development on Great Salt Lake and the Wasatch Front" (2016). *Watershed Sciences Faculty Publications.* Paper 875.
http://digitalcommons.usu.edu/wats_facpub/875

White paper
February 24, 2016

Impacts of Water Development on Great Salt Lake and the Wasatch Front

Wayne Wurtsbaugh[1], Craig Miller[2], Sarah Null[1], Peter Wilcock[1], Maura Hahnenberger[3], Frank Howe[1,4]

Utah State University[1]; [2]Utah Division of Water Resources; [3]Salt Lake Community College; [4]Utah Division of Wildlife Resources

Summary

Although droughts and floods produce short-term fluctuations in the elevation of Great Salt Lake, water diversions since the arrival of 19th Century pioneers represent a persistent reduction in water supply to the lake, decreasing its elevation by 11 feet and exposing much of the lake bed. As Utah moves forward, we need to be aware of the impacts of lowered lake levels and make decisions that serve the interests of all Utahns. In particular, proposals to further develop the water supply of the Great Salt Lake should carefully consider potential impacts to the health of the lake and examine the tradeoffs. There are no water rights to protect Great Salt Lake, so water development currently focuses solely on whether there is water upstream to divert. If future water projects reduce the supply of water to the lake, its level will continue to drop.[1] Although water conservation has reduced urban per capita use by 18 percent, overall municipal water use has increased by 5 percent because of our growing population.[2] To significantly reduce water use, a balanced conservation ethic needs to consider all uses, including agriculture, which consumes 63 percent of the water in the Great Salt Lake Basin.

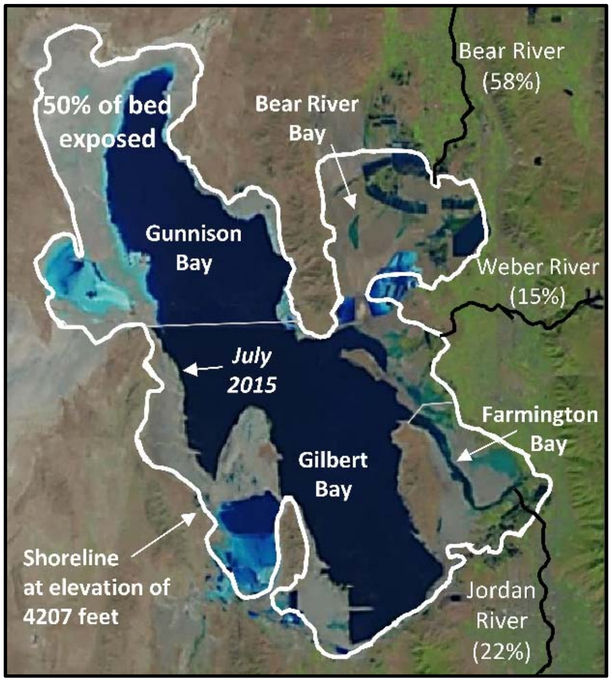

Figure 1. Great Salt Lake showing its major bays and the relative contribution (%) of each of the major river inflows. The white line shows the lake margin at its average natural elevation of 4,207 feet and the July 2015 NASA photograph shows the lake at near record-low levels, exposing half of the lake bed.

Increased awareness of how water use is lowering Great Salt Lake will help us avoid the fate of other salt lakes such as the Aral Sea in Central Asia or California's Owens Lake, both of which have been desiccated and now cause severe environmental problems. We must look beyond the next few decades and decide how we value the lake for future generations. Lower lake levels will increase dust pollution and related human health impacts, and reduce industrial and environmental function of Great Salt Lake. We must be willing to make decisions now that preserve Great Salt Lake's benefits and mitigate its negative impacts into the coming centuries.

Introduction

Utah's Great Salt Lake is immensely valuable as an environmental, cultural, and economic resource. A 2012 analysis by Bioeconomics[3] estimated the economic value of the lake at $1.32 billion per year for mineral extraction, brine shrimp cyst production, and recreation. The abundant food and wetlands of the lake attract 3 million shorebirds, as many as 1.7 million eared grebes, and hundreds of thousands of waterfowl during spring and fall migrations. Because of this, it has been designated as a Western Hemisphere Shorebird Reserve Network Site. Notably, the lake is the namesake of Utah's capital city, which underscores its cultural significance.

Great Salt Lake lies in a terminal basin (*Figure 1*). This means water flowing into it only leaves by evaporation. Freshwater lakes have river outflows, but not Great Salt Lake. Its tributaries bring trace amounts of salt, which is left behind when water evaporates. The concentrated salts, including sodium, chloride, potassium, sulfate, magnesium and others, provide a valuable resource for mineral extraction companies. Because most of the lake is too salty for fish to survive, millions of migratory birds are the dominant predators of the abundant brine shrimp and brine flies that can tolerate the salty waters in the main lake. Bear River Bay and Farmington Bay, which receive freshwater inflows and are less salty, harbor an even greater diversity of insects, crustaceans and fish which are also important prey for the bird community.

Since the lake is in a closed basin, it naturally rises with greater water supply during wet periods and falls during droughts. On top of this natural pattern, water supply to the lake has decreased over time as more and more of it is consumed for agricultural, industrial and urban uses. As water supply decreases, the lake level falls. There are compensating factors that can slow shrinkage of the lake when water supply is reduced. First, as the elevation declines, the size of the lake decreases, and thus, there is less evaporative surface area. Second, as the lake shrinks, salts become more concentrated, which further reduces evaporation.[4] These processes slow, but do not stop, the decrease in lake elevation when water supply decreases. The lake's elevation and salinity equilibrate to the amount of water flowing into it from rivers, rainwater and groundwater. For example, if there was a 25 percent decrease in streamflow to the lake, its elevation would slowly drop and, after 15 years, equilibrate at an elevation about 2.2 feet lower.[4]

Effects of water withdrawals on Great Salt Lake levels

Although fluctuations in rainfall and river flow cause the lake level to rise and fall, there has been no significant long-term change in precipitation[5] and water supply[6] from mountain tributaries since the pioneers arrived in 1847 (*Figure 2A*). In contrast, water development and river diversions over more than a century and a half have produced a persistent reduction in water supply to the lake (*Figure 2B*). Some of the diverted water is lost via evaporation from agricultural fields, urban landscaping, and industrial activity, including losses from salt ponds. These reduced stream flows have been offset by eight percent with imported water from the Colorado River Basin through the Central Utah Project, as well as return flows from upstream diversions. Overall, however, *consumptive water use has reduced net river inflow to the lake by 39 percent over the past 150 years*.[7] This consumptive water use causes the Great Salt Lake to shrink (*Figure 2C*, red line). Although wet periods like those in the mid-1980s and the current drought cause water supply and lake levels to fluctuate, the lake level has persistently declined since the pioneers arrived.[8] This contrasts strikingly with the constant long-term average of precipitation and river flow in the upper watersheds noted above and in *Figure 2A*.

This decline in lake level is more obvious when compared against a hydrological model[9] that estimates lake elevation if no consumptive use of water occurred (*Figure 2C*, blue line). This analysis demonstrates that *without* consumptive water use, the *long-term* trend in the lake level since 1847 would have been flat with a natural mean elevation of 4,207 feet. Put another way, the lake is now 11 feet lower than it would have been if we were not diverting water for agricultural, industrial, urban and impounded wetland uses. This 11-foot elevation drop has reduced the volume of the lake by 48 percent. Table 1 shows how much each of the various uses of water have contributed to the decrease in lake level.

Any future development of water will cause the lake to drop more. For example, the Utah Division of Water Resources estimates that water consumption associated with the proposed Bear River Development Project[10] would decrease the level of Great Salt Lake approximately 8.5 inches. This would expose about another 30 square miles of lake bed.[11] The logic is straightforward: if less water is delivered to the lake, the lake level must drop. This is an inevitable consequence of ever increasing water consumption.

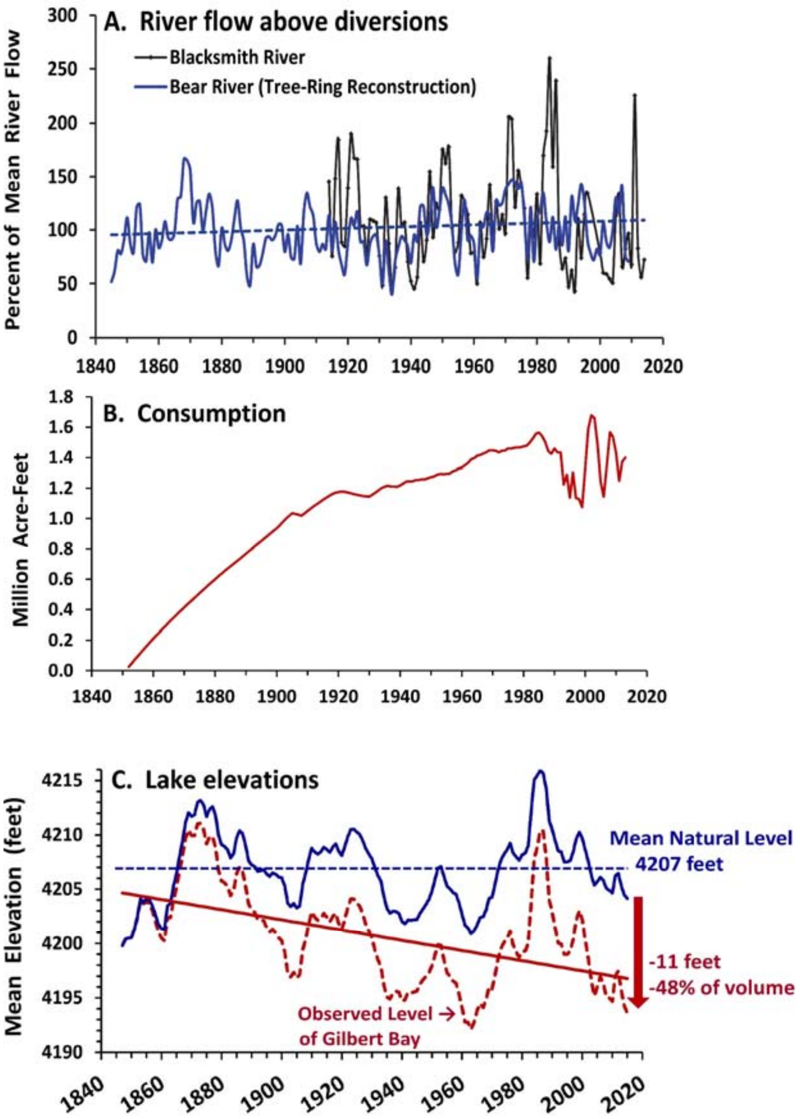

Figure 2. A. Water flow in headwater streams (Blacksmith River gage data; Bear River flow based on tree-ring reconstructions[6]). **B.** Estimated consumptive use of water for agriculture, salt ponds, wetlands and cities. **C.** Observed level of Great Salt Lake (dashed red line). The solid blue line shows a model of lake elevation in the absence of consumptive water uses. Averaged over the last 10 years, water use has lowered the lake 11 feet and decreased its volume by 48 percent.

Impacts of lowered lake levels

Dust & health—Water diversions and drought have reduced lake area from around 1,600 square miles when the pioneers arrived to 1,050 square miles in 2015. The exposed 550 square miles of lake bed increases the potential for locally severe dust storms. *Figure 1* shows lake area at an elevation of 4,207 feet, the 1847-2015 average estimated lake level if there had been no diversions (*Figure 2C*), and the level in July 2015 as the lake approached its lowest recorded level. At the current lake elevation, 48% of the lake bed is exposed compared to when the lake is at 4,207 feet.

Decreased lake elevation, however, affects various bays of the lake differently. Shallow Bear River and Farmington Bays are particularly impacted, and at the current lake level, more than three-quarters of their lake beds are exposed, making them potential sources of dust that influence Wasatch Front communities.

Table 1. Types of human water consumption (depletions) and their influence on decreasing the level of the Great Salt Lake (Source, Utah Division of Water Resources, 2016).

Source and percent of water use	**Median estimated decrease in lake level (Total = 11.1 ft)**
Agricultural (63%)	7.0 feet
Mineral extraction—salt ponds (13%)	1.4 feet
Municipal & industrial (11%)	1.3 feet
Impounded wetlands (10%)	1.1 feet
Reservoir evaporation (3%)	0.3 feet

The increase in exposed lake bed from water withdrawals and drought can have important consequences for human health. Airborne mineral dust increases hospital visits for respiratory and cardiovascular diseases[12], and increases rates of death[13]. Dust exposure also increases the prevalence of asthma, inhibits immune response, and results in cellular and DNA damage, lung infection, and respiratory disease. Additionally, the dust can transport bacteria and microorganisms that negatively impact human and ecosystem health.[14] When Great Salt Lake is at its mean natural elevation (4,207 feet), it produces only small amounts of dust due to the limited area of exposed dry lake bed. However, as exposed lake bed increases, more dust is produced from this area, causing dust storms such as seen in *Figure 3.*[15] Increased dust production following lake desiccation has occurred in numerous other closed basins nationally and internationally, including Owens Lake in California[16], Lake Urmia in Iran, and the Aral Sea in Kazakhstan and Uzbekistan. In each case the primary cause of rapid desiccation has been increased water withdrawals for agriculture and other consumptive uses. For example, diversions from the Owens River for the city of Los Angeles desiccated Owens Lake by 1926, causing it to become one of the largest sources of particulate matter (PM10) pollution in the country.[17] This dust affects about 40,000 permanent residents in the region, causing asthma and other health problems. As a consequence, since 2000, the City of Los Angeles has spent $1.3 billion for dust mitigation[18] and by 2018 will have spent more than $2.1 billion[19]. Because most of Utah's population is located near Great Salt Lake, health impacts from exposed lake bed could potentially affect even more people. Ongoing studies are estimating the magnitude of the dust impact from the exposed Great Salt Lake shoreline on Wasatch Front communities.[20] Other researchers are investigating how dust increases snowmelt rates and decreases water runoff from high-elevation mountains.[21]

Figure 3. Dust storm coming off the Great Salt Lake viewed from Olympus Cove looking NW towards Salt Lake City. This August 5, 2015 dust storm was caused by a large thunderstorm with 40-50 mph winds at the north end of the Great Salt Lake which lifted dust off the dry lake shore. Webcam image, 6:35 PM.

Mineral Extraction Industry—The exposed lake bed also creates problems for the mineral extraction industry located around the periphery of the lake. Low lake levels have a positive effect of concentrating minerals, which facilitates their extraction. However, as lake level drops, it becomes increasingly difficult and expensive to deliver brine from the lake to the salt ponds and processing plants. For example, in 2014 Morton Salt was required to dig a five-mile long canal to access the lake's water, and some companies in Gunnison Bay find that it is now cost-prohibitive to pump brine to their distant facilities.

Recreation—Similar problems are experienced by the Great Salt Lake boating community. At the current low lake level, the marina on Antelope Island is not functional for most boats, and the larger Great Salt Lake Marina is currently being dredged at a cost of more than $1.5 million to allow access to the lake. Additional water losses would cause even more severe problems. Recreational use for hunting in Bear River and Farmington Bays is also limited by a shrinking and saltier water body. Altogether, recreation in and around Great Salt Lake contributes about $135 million to Utah's economy.[3]

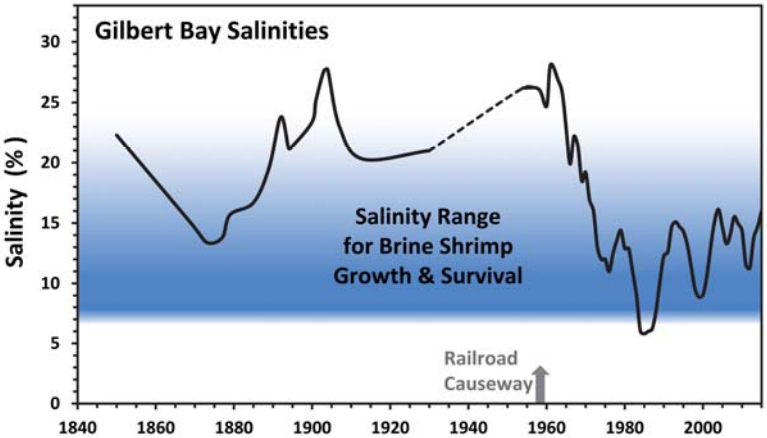

Figure 4. Changes in salinity of Great Salt Lake's southern arm and the range of salinities for growth and survival of brine shrimp. After the railroad causeway was constructed salts concentrated in the north arm, with lower salinities in the south. Dark blue indicates optimal salinities (8-12%) for brine shrimp. For reference, seawater salinity is 3.5%.

Environmental health and the brine shrimp industry—Reducing freshwater inflows to Great Salt Lake increases its salinity, which has important consequences for brine shrimp and other invertebrates (*Figure 4*). Brine shrimp rely on intermediate salinities to grow and reproduce. If salinity levels are too low, as they were in the mid-1980s, predatory insects can proliferate and obliterate the brine shrimp.[22] Conversely, when salinities are too high, the shrimp become stressed and eventually, reproduction fails.[23] The salinity level in Gilbert Bay is currently 16 percent, considerably above the optimum for brine shrimp. Nevertheless, the commercial harvest of brine shrimp cysts is still profitable. However, if diversions and drought continue and salinities rise above 20 percent, brine shrimp production is estimated to be reduced to less than 10 percent of optimal.[23] This will severely reduce the $57 million commercial brine shrimp harvest and provide less forage for birds.

Avian usage—Reduced lake levels influence the enormous bird populations that rely on Great Salt Lake for migration and reproduction; species as diverse as American avocets, mallards, swans, and pelicans are all negatively impacted by low lake levels.[24] Most important, critical nesting sites in the shallow areas of Farmington and Bear River Bays nearly disappear at low lake levels (*Figure 1*). These bays are essentially fresh-water estuaries that produce abundant food resources, and support a high density and diversity of birds.[25] When these estuaries shrink, this premier waterfowl production area and its associated $70 million waterfowl hunting industry is threatened.[26] Secondly, increases in salinity in Gilbert Bay, the largest portion of the lake, will decrease food available for those birds, such as grebes, shorebirds, and gulls that feed on brine shrimp and brine flies (*Figure 4*). Additionally, further water diversions could result in more frequent water shortages for the vital freshwater bird sanctuaries such as the Bear River Migratory Bird Refuge that line much of the eastern shore of the lake.[27] The problem of decreasing habitat for birds at Great Salt Lake is exacerbated because many other western saline lakes that host birds are similarly affected by water diversions and drought: California's Salton Sea[28], Mono Lake[29], and Owens Lake[30], as well as Oregon's Abert Lake[31] are stark examples of environmental harm to saline lakes when water is depleted by consumptive uses.

Conclusion

Figure 5 summarizes how water use and climatic fluctuations influence Great Salt Lake. Climate fluctuations, such as the flooding in the mid-1980s and the current drought, cause flooding and drying cycles with 5-30 year intervals[6]. Consumptive water uses, however, produce a persistent decrease in water supply to the lake and thus, lake levels (*Figure 2*). Since the pioneers arrived in 1847, there has been no significant long-term trend in precipitation or streamflow out of the mountains (*Figure 2A*). Consumptive uses, however, have reduced the lake level by 11 feet, decreased its volume by 48%, increased lake salinity, and exposed approximately 50% of the lake bed. This has increased wind-blown dust, impaired the use of marinas, and caused costly logistical constraints for the mineral extraction industry. Shallow Bear River Bay and Farmington Bay have been particularly impacted by desiccation, thus reducing wetland habitat and their use by waterfowl and shorebirds. Additional water development in the basin, exacerbated by long-term climate variability, may further reduce the lake's level unless conservation efforts are increased for urban, industrial, and especially agricultural uses. Utah needs to be aware of how water developments in the past, and those proposed for the future, affect the lake and the important resources it provides, as well as human health and the economic stability.

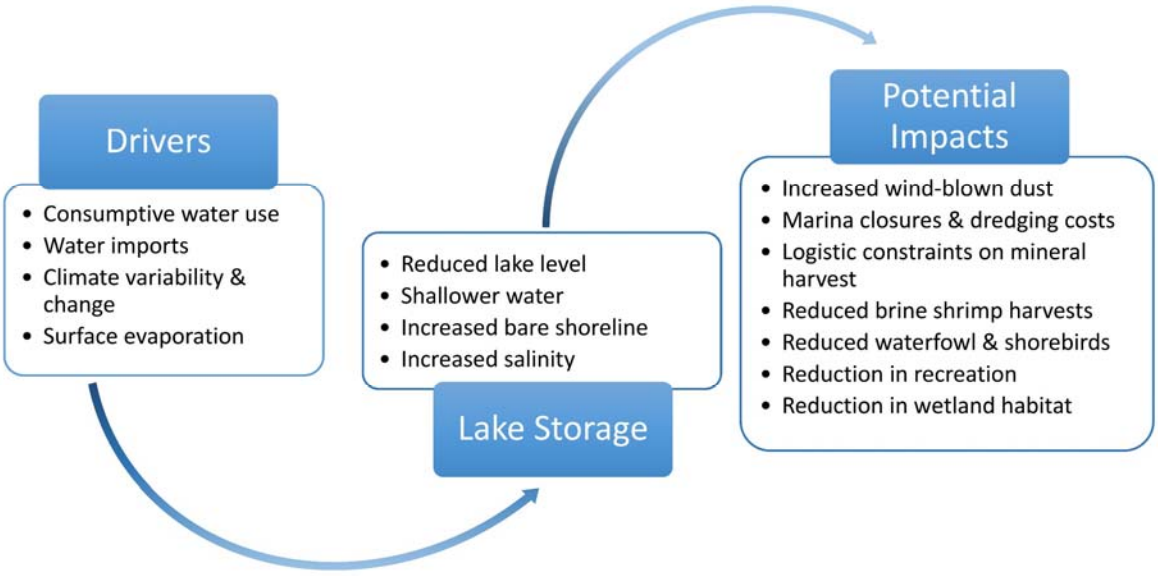

Figure 5. Summary of external forces influencing lake area and volume, and the effects of these changes on Great Salt Lake's natural resources.

Acknowledgements.

Justin DeRose from the U.S. Forest Service provided important tree-ring reconstructions of precipitation and river discharge and contributed to other aspects of the paper. David Tarboton of Utah State University contributed substantially to some of the concepts presented here. Mary-Ann Muffoletto from Utah State University edited the paper. Todd Adams, Eric Klotz, Marisa Egbert, David Cole and Josh Palmer of the Utah Division of Water Resources, and Mike Collins, Bryan Dixon and Lynn de Freitas provided comments on earlier drafts of the paper. The final document does not necessarily represent their views or the views of their organizations.

Footnotes

[1] Fornataro, E.A. 2008. The last untapped river in Utah: An argument against the development of the Bear River. J. Land, Resources and Environmental Law 28: 141-162. http://epubs.utah.edu/index.php/jlrel/article/viewFile/103/93.

[2] Although per-capita urban water use has decreased 18% in the watershed, overall urban use has increased from 131,400 acre-feet in the 1989-2000 period, to 138,800 acre-feet in the 2010-2014 period, a 5.6% increment (Utah Division of Water Resources data).

[3] Bioeconomics. 2012. Economic significance of the Great Salt Lake to the State of Utah. Prepared for the State of Utah Great Salt Lake Advisory Council, Salt Lake City, Utah. 50 p. http://www.gslcouncil.utah.gov/docs/2012/Jan/GSL_FINAL_REPORT-1-26-12.PDF, accessed 8 February 2014.

[4] Mohammed, I.N., and Tarboton, D.G. 2012. An examination of the sensitivity of the Great Salt Lake to changes in inputs. Water Resources Research 48. 1-17, DOI 10.1029/2012wr011908.

[5] Rainfall for the Wasatch Front was derived from a composite rain gage available from the National Oceanographic and Atmospheric Administration, http://w2.weather.gov/climate/xmacis.php?wfo=slc. Despite droughts and wet cycles, there has been no significant ($p = 0.52$) long-term change from 1875-2015. Regression; inches = 24.67 - 0.00465 *year; $p = 0.52$, not significant.

[6] River flow in the upper tributaries was based on the 100-year continuous record from the Blacksmith Fork (USGS gage # 10113500), a tributary to the Logan River, and on tree-ring estimates of precipitation. In high precipitation years, trees form thicker growth rings, such that the widths of these rings can be correlated with measured flows in rivers for the years when flow data are available. The tree ring widths in years prior to documented river flows can then be used to estimate flows in those years. Here, we've presented flow estimates for the Bear River at a site high in the watershed and above any water diversion structures (USGS gage # 10011500; DeRose, R.J. et al. 2015, A millennium-length reconstruction of Bear River stream flow, Utah. J. of Hydrology, doi: 10.1016/j.jhydrol.2015.01.014). Similar reconstructions for the Weber River and Logan Rivers also demonstrate that there has been no long-term decrease in river flow in upper basins (Bekker, M.F. et al. 2014. A 576-Year Weber River streamflow reconstruction from tree rings for water resource risk assessment in the Wasatch Front, Utah. JAWRA J. of the Am. Wat. Resources Assoc. 50, 1338–1348. doi:10.1111/jawr.12191, Allen, E.B. et al. 2013. A tree-ring based reconstruction of Logan River streamflow, northern Utah. Water Resources Res. 49, 8579–8588. doi:10.1002/2013WR014273). Also see DeRose, R.J., et al. 2014. Tree-ring reconstruction of the level of Great Salt Lake, USA. The Holocene 24, 805–813. doi:10.1177/0959683614530441. These reconstructions document long-term droughts and wet cycles more severe than have been documented since 1847. During these cycles the lake dried significantly more than our current situation and at other times expanded beyond even the flooding seen in the mid-1980s.

The regression line in Figure 2A is a composite of the Blacksmith River flow and the tree-ring estimated flow for the Bear River, and shows no significant trend ($n = 267$, $p = 0.085$). Similarly, there were no significant trends when the Blacksmith River ($n = 98$, $p = 0.349$) and the Bear River tree-ring data ($n = 165$, $p = 0.078$) were analyzed separately.

[7] Estimates of agricultural and reservoir consumptive use (called depletions by hydrologists) for the last 30 years were computed from net crop evapotranspiration less winter carryover soil moisture storage on a per-acre basis. Reservoir depletions were calculated as net average annual evaporation times 80% of maximum surface area (Hill, R. W. 1994.

Consumptive use of irrigated crops in Utah, Utah Agr. Exp. Station. Res. Report #145; Water Rights web site, http://www.waterrights.utah.gov/cgi-bin/damview.exe). Bear Lake and Utah Lake were not included in this calculation, meaning that the actual evapotranspiration depletions may be somewhat larger than shown.

To obtain weather inputs for these calculations, 30-year (1971-2000) average weather data were extracted from PRISM (http://www.prism.oregonstate.edu/). Municipal depletions were calculated by subtracting estimated impervious surface runoff from municipal -calculated consumptive use. Evapotranspiration from impounded open water wetlands was estimated using an area of 56,000 acres (Emerson, R. and T. Hooker. 2011. Utah wetland functional classification and Landscape profile generation within Bear River Bay, Great Salt Lake, Utah. USGS, https://www.mendeley.com/profiles/richard-emerson1/) multiplied by the net average annual evaporation (GridET program; author Clay Lewis, 2015, https://github.com/claytonscottlewis/GridETURL). Mineral extraction depletion was calculated as 75% of lake withdrawals (Compass Minerals, personal communication). Depletions due to evaporative losses in the basin were then lowered by the amount of water imported from the Colorado River Basin.

The 39% decrease in river inflow to the lake is based on a 10-year average (2003-2012). This calculation accounts for the importation of Colorado River water into the basin. The 39% decrease due to depletions is calculated based on total depletions (corrected for Colorado R. imports) of 1,451,000 acre-feet (Utah DWR) and current river inflow to the lake of 2,303,000 acre-feet (Mohammed, I.N. and D.G. Tarboton, 2012).

The data use for the depletion estimates are a composite of early data analyses in the Utah Division of Water Resources, and more detailed data after 1989. Depletions prior to 1970 were taken from estimates of R. Palmer and G.L. Whittaker (Unpublished data, Utah Division of Water Resources). The post-1989 data shows short-term responses to droughts and wet cycles, and is thus irregular. Consequently, the data in Figure 2B were smoothed with a 5-point running average.

Estimates of water depletions are imprecise. Consequently, additional analyses of the effects of depletions on the lake's level are warranted and may change the results somewhat. Nevertheless, the absence of a long-term trend in rainfall[5] and mountain runoff over the past 170 years (Fig. 2A), when compared to the persistent decrease in lake level (Fig. 2C), indicates that water use and consumption is having a major impact on the lake. Additional analyses of water use on the lake are ongoing as part of the Great Salt Lake Integrated Water Resource Model being developed by the Division of Forestry, Fire and State Lands.

[8] Linear regression for red line in Fig. 2C, Lake Elevation (feet) = $4291.3 - 0.0469 * \text{year}$; $p < 0.0001$. Highly significant decline.

[9] To estimate what the elevation of the lake would be if water was not used for consumption we added the difference between past and current depletions as an annual input to the Great Salt Lake. The influence of lake area and salt concentration on the evaporation rate from the lake surface were included in the model.

[10] Bear River Development Project. Utah Division of Natural Resources. http://www.gslcouncil.utah.gov/docs/2014/10Oct/BearRiverPipelineProject.pdf.

[11] The Utah Division of Water Resources estimates that the proposed diversion of 220,000 acre-feet of Bear Water will result in a depletion of 85,670 acre-feet of water delivery to Great Salt Lake. They estimate that this will cause the lake to decrease a mean of 8.5 inches and a maximum of 14 inches in elevation (C. Miller, personal communication). Assuming a mean decrease of 8.5 inches from the current lake level (4193.1 feet), an additional 30 square miles of lake bed would be exposed. If the decrease was 14 inches, 45 square miles would be exposed. The areas of exposure were calculated from the bathymetric data provided by David Tarboton (Utah State Univ.) and does not include the areas in salt ponds.

[12] Grineski, S.E., Staniswalis, J.G., Bulathsinhala, P., Peng, Y, Gill, T.E., 2011. Hospital admissions for asthma and acute bronchitis in El Paso, Texas: do age, sex, and insurance status modify the effects of dust and low wind events? Environ. Res. 111, 1148-55. DOI: 10.1016/j.envres.2100.06.007.

[13] Giannadaki, D., Pozzer, A., Lelieveld, J. 2014. Modeled global effects of airborne desert dust on air quality and premature mortality. Atmos. Chem. Phys. 14, 957-968. http://dx.DOI: 10.5194/acp-14-957-2014.

[14] Griffin, D.W., Kellog, C.A., 2004. Dust storms and their impact on ocean and human health: dust in the earth's atmosphere. EcoHealth 1, 284-295. http://dx.DOI.org/10.1007/s10393-004-0120-8.

[15] Dust events from Great Salt Lake and other areas in Utah are described in Hahnenberger, M., Nicoll, K., 2012. Meteorological characteristics of dust storm events in the eastern Great Basin of Utah, U.S.A. Atmospheric Environment, 60, 601-612, ISSN 1352-2310, http://dx.doi.org/10.1016/j.atmosenv.2.

---

[16] Larsen, R. 2014. The half-life of a lake. Virginia Quarterly Review 90, 24-25. DOI: 10.1353/vqr.2014.0068.

[17] Great Basin Unified Air Pollution Control District (GBUAPCD). Owens Lake Dust Mitigation. http://www.gbuapcd.org/owenslake.htm.

[18] Smith, D. 2014. Settlement reached over dust control measures at Owens Lake. Los Angeles Daily News, November 14, 2014. http://www.dailynews.com/general-news/20141114/settlement-reached-over-dust-control-measures-at-owens-lake.

[19] Phillip Kiddoo, personal communication, Great Basin Unified Air Pollution Control District, Air Pollution Control Officer. January 28, 2016.

[20] Utah Division of Forestry, Fire & State Lands grant. http://www.ffsl.utah.gov/index.php/grant-programs/state-lands-research-grants?showall=&start=1.

[21] Dust increases sunlight absorption and hastens snowmelt, particularly in areas above tree line. See: Maurer, G.E. and D.R. Bowling. 2015. Dust effects on snowpack melt and related ecosystem processes are secondary to those of forest canopy structure and interannual snowpack variability. Ecohydrology 8:1005-1023.

[22] Wurtsbaugh, W.A. 1992. Food-web modification by an invertebrate predator in the Great Salt Lake (USA). Oecologia 89:168-175.

[23] Barnes, B.D. and W.A. Wurtsbaugh. 2015. The effects of salinity on plankton and benthic communities in the Great Salt Lake, Utah, USA: a microcosm experiment. Can. J. Fish. Aquatic Sci. DOI: 10.1139/cjfas-2014-0396. Null, S., W. Wurtsbaugh and C. Miller. 2013. Can the causeway in the Great Salt Lake be used to manage salinity? Friends of Great Salt Lake Newsletter Vol. 19 No. 1 & 2: 14-15. http://www.fogsl.org/images/stories/2013/2MayNewsletterreduced.pdf.

[24] Frank Howe, Utah Division of Wildlife Resources, personal communication, 15 January 2016.

[25] Paul, D.S., and A.E. Manning. Great Salt Lake waterbird survey five-year report (1997-2001). 1 Oct. 2008. Great Salt Lake Ecosystem Program and Utah Division of Wildlife Resources. Accessed Jan. 19, 2016. http://www.wildlife.utah.gov/gsl/waterbirdsurvey/. https://www.census.gov/prod/2012pubs/fhw11-nat.pdf.

[26] U.S. Fish and Wildlife Service. 2014. 2011 National Survey of fishing, hunting, and wildlife-associated recreation: Utah. U.S. Department of the Interior, U.S. Fish and Wildlife Service, and U.S. Department of Commerce, U.S. Census Bureau.

[27] Welsh, LW, Endter-Wada J, Downard R, and Kettenring KM. 2013. Developing adaptive capacity to droughts: the rationality of locality. Ecology and Society 18: 7. http://dx.doi.org/10.5751/ES-05484-180207.

[28] Case, HLI, Boles J, Delgado A, et al. 2013. Salton Sea ecosystem monitoring and assessment plan. U.S. Geological Survey Open-File Report: 2013-1133. (http://pubs.er.usgs.gov/publication/ofr20131133).

[29] Patten, D.T., F.P. Conte, W.E. Cooper, J. Dracup, S. Dreiss, K. Harper, G.L. Hunt, P. Kilham, H.E. Klieforth, J.M. Melack and S.A. Temple. The Mono Basin ecosystem—effects of changing lake level. National Academy Press, Washington, D.C. 272p. http://www.nap.edu/read/1007/chapter/1.

[30] Reheis, M.C., 1997, Dust deposition downwind of Owens (Dry) Lake, 1991-1994—Preliminary findings: Journal of Geophysical Research (Atmospheres), v. 102, no. D22, p. 25,999-26,008.

[31] The Oregonian. Oregon's only saltwater lake is disappearing, and scientists don't know why. http://www.oregonlive.com/lake-abert/; Moore, J.N. In press. Recent desiccation of western Great Basin saline lakes: Lessons from Lake Abert, Oregon, U.S.A. Sci. of the Total Environment.

THE AUTHORS ARE NATIONAL AND INTERNATIONAL EXPERTS IN SALINE LAKE LIMNOLOGY AND ECOLOGY AND IN MODELING OF LAKE AND WATER RESOURCE SYSTEMS. THE AUTHORS HAVE PUBLISHED WIDELY ON THE GREAT SALT LAKE IN MANY RESPECTED SCIENTIFIC JOURNAL.

Document is available at: https://works.bepress.com/wayne_wurtsbaugh/171/