More than Meets the Eye: Managing Salinity in Great Salt Lake, Utah

James S. White, Sarah E. Null, and David Tarboton

Great Salt Lake (GSL) is a pluvial lake and a remnant of historic Lake Bonneville. It is the largest saline lake in the Western Hemisphere, and fourth-largest in the world. The only outflow of water is via evaporation, causing a very gradual accumulation of minerals. Over time, this has led to high salinity in GSL, and is responsible for the relatively simple but highly productive saline ecosystem. The lake is a critical link in the Pacific flyway, supporting millions of migratory and resident birds, which feed on invertebrates inhabiting the lake. The lake is also used commercially for mineral extraction and brine shrimp harvest. GSL is vital to the local and regional economy, contributing an estimated $1.3 billion, and supporting nearly 8,000 jobs.

In 1959, Union Pacific Railroad (UPR) constructed a rock-filled causeway across GSL, bisecting the lake from Promontory Point on the east bank, to the West Desert on the west bank (Figure 1). This caused the lake to be separated into north and south bays, Gunnison and Gilbert Bay, respectively. Upon completion, flow between the bays was restricted to the semi-porous fill material and two 4.5 m wide culverts installed during causeway construction. In 1984, an 88 m wide and 4 m deep breach was added to the causeway to increase inter-bay flow and alleviate flooding (it was later deepened to 6.4 m). Ninety-five percent of streamflow enters the south bay, causing an elevation gradient to form between the two bays (the south bay is roughly 0.3 meters higher than the north bay). Because of the hydrologic isolation and discrepancy of inflows between the bays, the causeway has become a key driver of salinity in GSL. The north bay is often at or near saturation levels, averaging 317 g/L since 1966, while the south is considerably less saline, averaging 142 g/L since 1966.

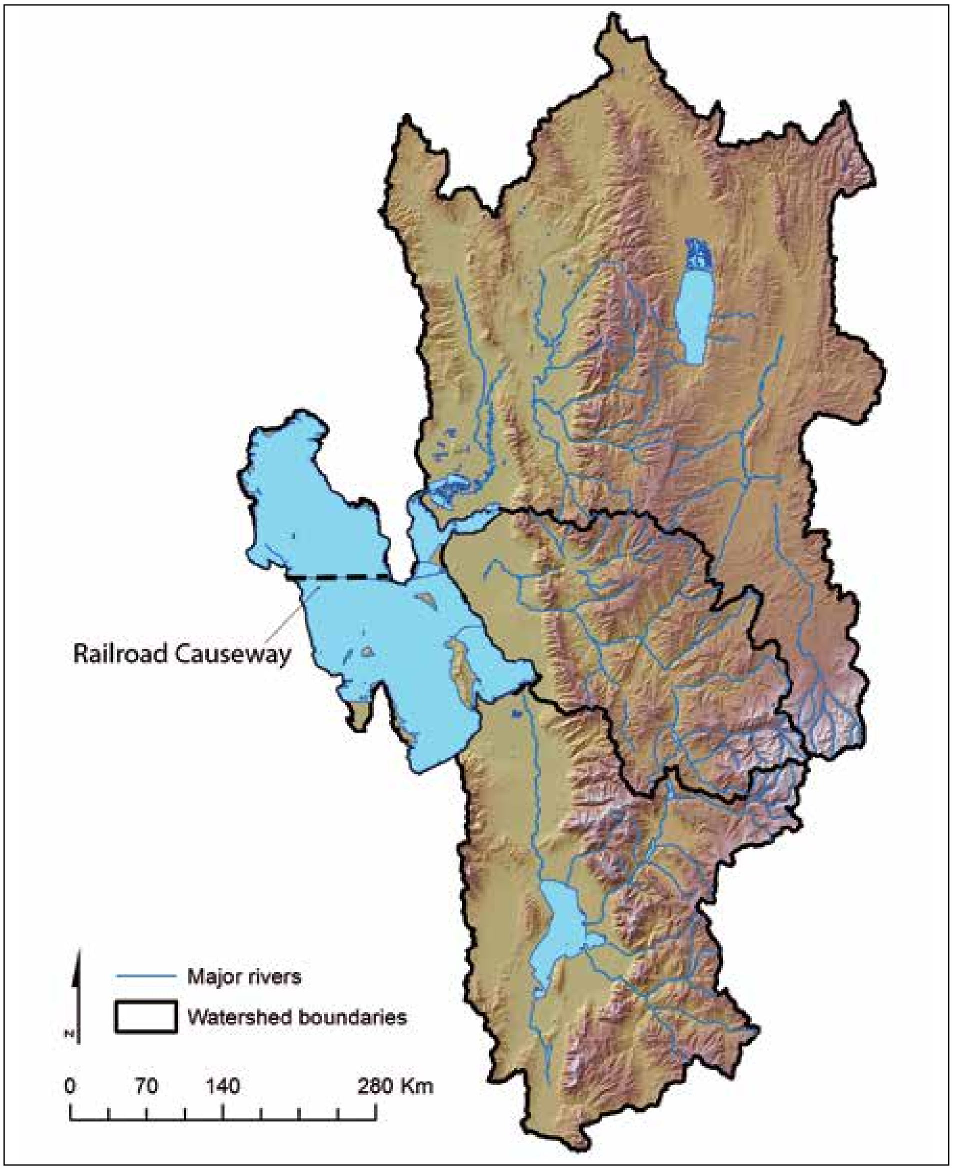


Figure 1. Major watersheds of Great Salt Lake. The West Desert contributes a very small amount of water to the lake.

The causeway was built on soft lake sediments and has slowly subsided through time. The two 4.5 m wide culverts became unstable and in 2012 through 2013 they were closed. To replace the flow provided by the culverts, UPR has proposed to build a 55 m trapezoidal bridge. However, changes to lake level and salinity from the bridge had previously not been quantified. To evaluate how the proposed bridge opening will affect the salinity of both bays of the lake, we simulated historical and proposed causeway changes with a modified version of the USGS Great Salt Lake Fortran Model (Waddel and Bolke 1973; Wold et al. 1997; Loving et al 2000).

Salinity and lake level have an inverse relationship, whereby salinity increases as lake level drops, and decreases as lake level rises. Lake level changes primarily from precipitation and surface runoff. Thus, salinity is highly variable over time, and dependent on climatic conditions. Periods of drought give rise to high salinity, whereas high precipitation periods result in dilution. While salinity varies significantly over time, total mineral (salt) load in GSL is much more consistent. Total mineral load is the mass of salts in the lake that does not change with precipitation and surface runoff. Prior to human development, salt load changed over geologic timescales, with miniscule but accumulating contributions from tributaries. In human timescales, the salt load of GSL can be thought of as constant, except for human activities like mineral extraction.

Two factors have reduced GSL mineral load over the past 50 years. The first is extracting minerals such as sodium chloride, magnesium, and potassium for commercial uses. The second is pumping Great Salt Lake water into the West Desert to protect Salt Lake City from lake flooding during consecutive wet years. Pumps were built in 1987 and mineral load was reduced by approximately 0.5 billion tons during wet years of the late 1980's. Mineral load loss from GSL over the past 50 years due to mineral extraction and pumping is approximately 1 billion tons.

Salinity differences between the bays have significant impacts on ecology, mineralogy, and commercial and recreational uses The hypersaline north bay is largely inhospitable for macroinvertebrates such as brine shrimp (*Artemia franciscana*) and brine fly (*Ephydra cinera*). Instead, it is characterized by large populations of archaea (microbes) and red-algae. This causes a discoloration that is easily visible to the naked eye and even satellite images (Figure 2). In contrast, the relatively moderate salinities of the south bay provide habitat for large populations of Artemia and Ephydra, which are vital food sources for birds. However, during periods of high precipitation, salinity drops, allowing freshwater predators such as corixids (water boatmen), usually intolerant to GSL conditions, to prey on Artemia and decimate populations (Wurtsbaugh and Berry 1998). Lake managers are concerned that if culverts remain closed and new openings are not installed, the causeway will result in water that is too salty in the north bay and too fresh in the south bay to maintain Artemia populations. Our research provides estimates for salinity, salt load, and lake level to evaluate Artemia habitat with current and proposed modifications to the causeway.

Model Methods and Validation

The USGS GSL Fortran Model uses a mass balance approach to calculate total volume and mineral load for both bays at each timestep (every two days). The model was originally developed in 1973, and was updated in 1997 and 2000. A schematic of major model inputs and outputs are illustrated in Figure 3.

Three different alternatives were modeled.

1. *Historical* – causeway with two open culverts and breach. Results from this run were compared to measured data to test model performance.
2. *Proposed bridge* – Causeway with the proposed bridge and breach. This estimates lake level and salinity with proposed railroad causeway changes (but historical climate data) and allows a direct comparison to the historical model run.
3. *Whole lake* – A whole lake condition without a causeway. The lake exhibits a single salinity behavior. Human-induced

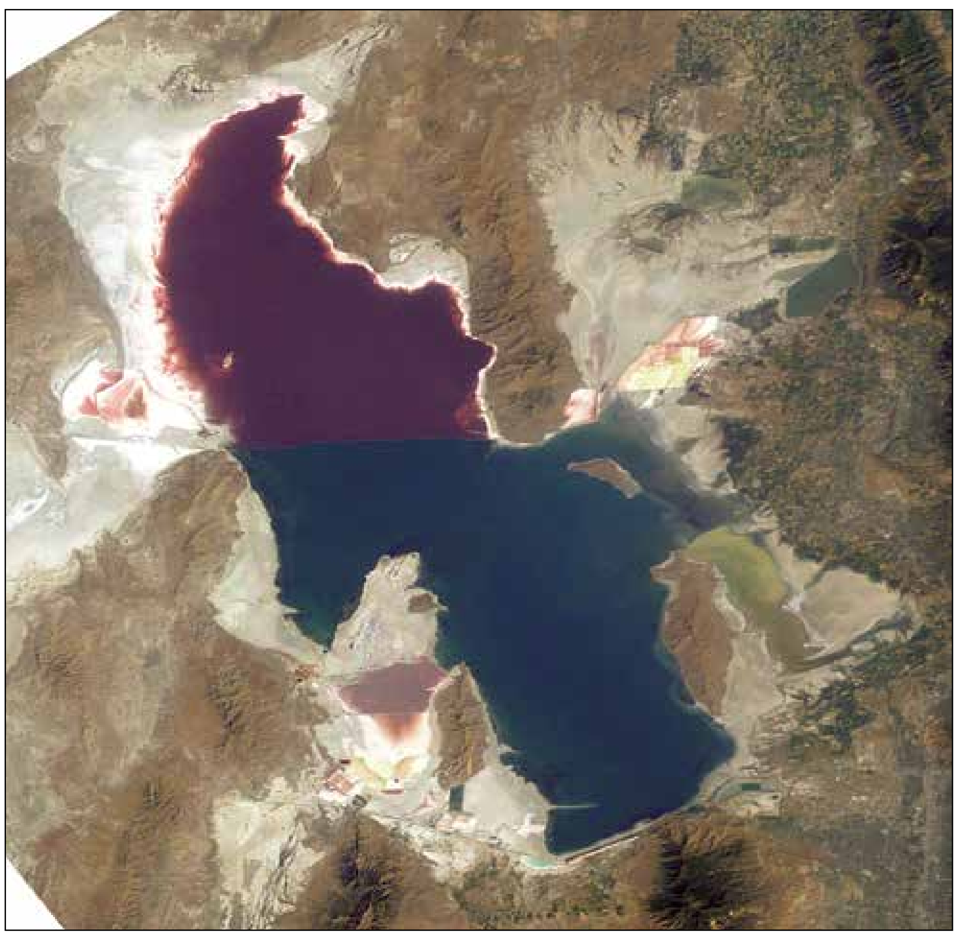


Figure 2. Aerial image of Great Sale Lake. Photo from NASA Earth Observatory.

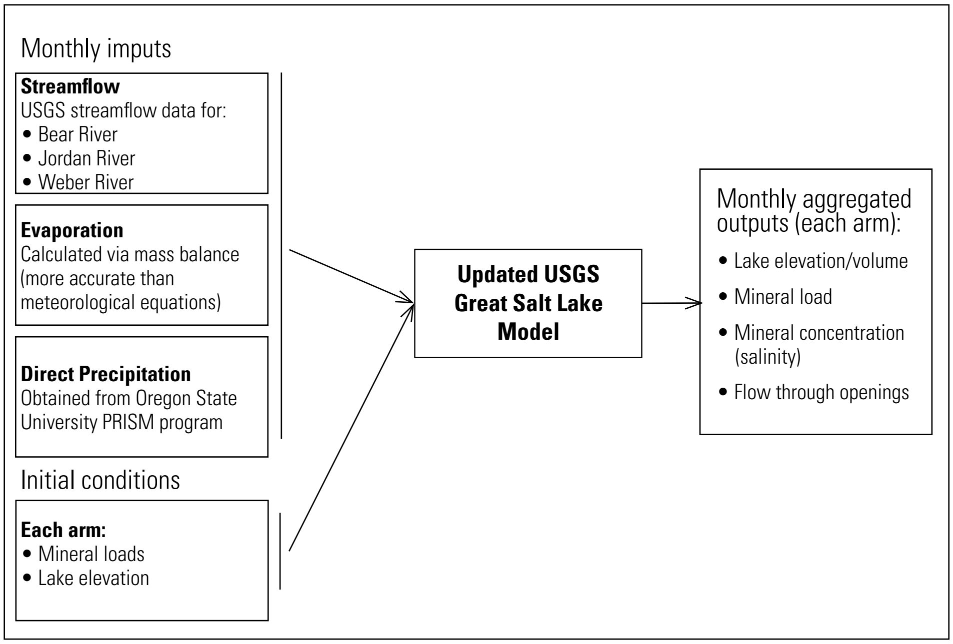


Figure 3. Schematic of major model inputs and outputs

modifications are identical to the two previous runs so that lost mineral load to pumping and extraction are included, and streamflows have been reduced from withdrawals for consumptive, agricultural and industrial use.

Results

We compared 1966 – 2012 modeled and measured data to evaluate model fit for lake level (Figure 4), salinity concentration (Figure 5) and salt load (Figure 6). The model represents past conditions well, with an exception for salinity and load in the mid through late 1990s, when salinity concentration and load is under-predicted compared to measurements. We attribute these discrepancies to a limitation of the model that assumes no flow through the culverts if they are submerged, conditions that occurred throughout much of the 1990s. In reality, a density gradient from different salinity concentrations between the two bays would have caused some flow through the culverts. Despite this limitation, we are confident in the model's ability to replicate GSL dynamics.

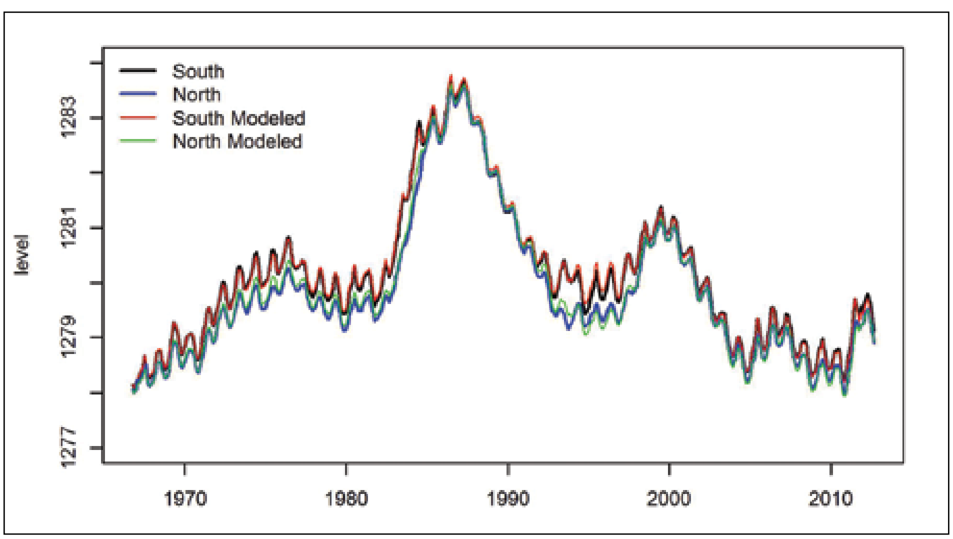


Figure 4. Measured (black and blue) and modeled (red and green) lake level since 1966. South bay (black and red) averages roughly 0.3 m higher than north bay.

Results from the historical proposed bridge model show that the proposed bridge would ameliorate salinity differences between the north and south bays, returning lake level and salinity to more natural conditions (Figure 7). On average, north arm salinity is reduced 41 g/l, and south arm salinity is increased 34 g/l (Table 1). While the north bay still reaches saturation approximately 10 percent of time period, it is closer to the whole lake model simulation, where the average salinity is 222 g/l.

Implications for Ecology and Management

We focus attention on Artemia, as they are a primary food source for migratory birds and a reasonable proxy for other salt-tolerant organisms such as Ephydra. Although Artemia growth and fitness are dependent on more than just salinity, such as temperature, food abundance, and predation, salinity levels are a key driver for growth and survival. Ongoing research into salinity tolerances for Artemia suggests an upper salinity threshold of 225 g/l. While specimens can be observed in higher salinities, fitness is greatly reduced and populations are likely small and isolated. Establishing a low salinity threshold for Artemia is more difficult because predation, not physiology, likely controls survival. While lab experiments show Artemia survive to 10 g/l, we used 60 g/l as a low threshold, as this was the salinity in the 1980's, where Artemia populations began to collapse. Below 60 g/l, predators such as corixids begin to populate the lake and prey on Artemia in significant numbers.

Overlaying these thresholds on our results (Figure 7), results show that in both the historical and proposed bridge models the south arm nearly always provides habitat with suitable salinities, while the north is almost always too saline. As shown in Figure 7, conditions in the late 1980s and late 1990s were inhospitable to Artemia. This is validated by several studies showing significant loss of Artemia populations during these periods (Wurtsbaugh 1998). Our proposed bridge results suggest that had the bridge been in place instead of culverts, salinity in the south bay would have been saline enough so that Artemia were not threatened. Furthermore, the north arm

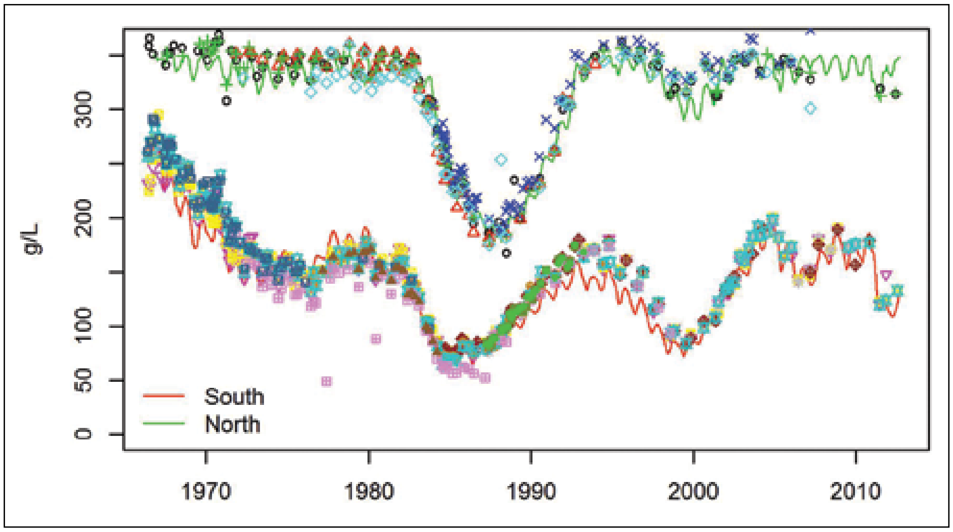


Figure 5. Measured (points) and modeled (lines) salinity over time. Different colored points represent different locations where salinity was measured.

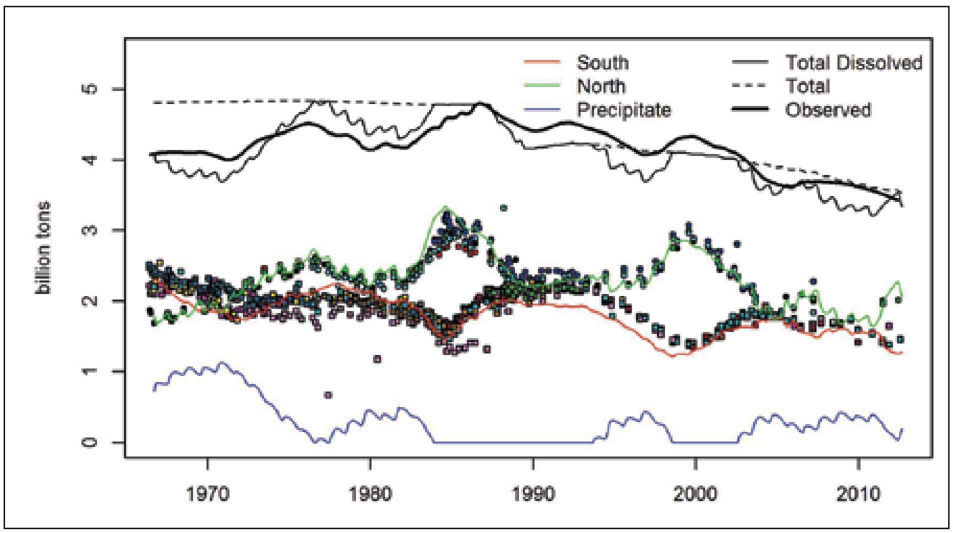


Figure 6. Measured (points) and modeled (lines) total salt load over time. Different colored points represent different locations of measurements. Blue line represents modeled precipitated salt load.

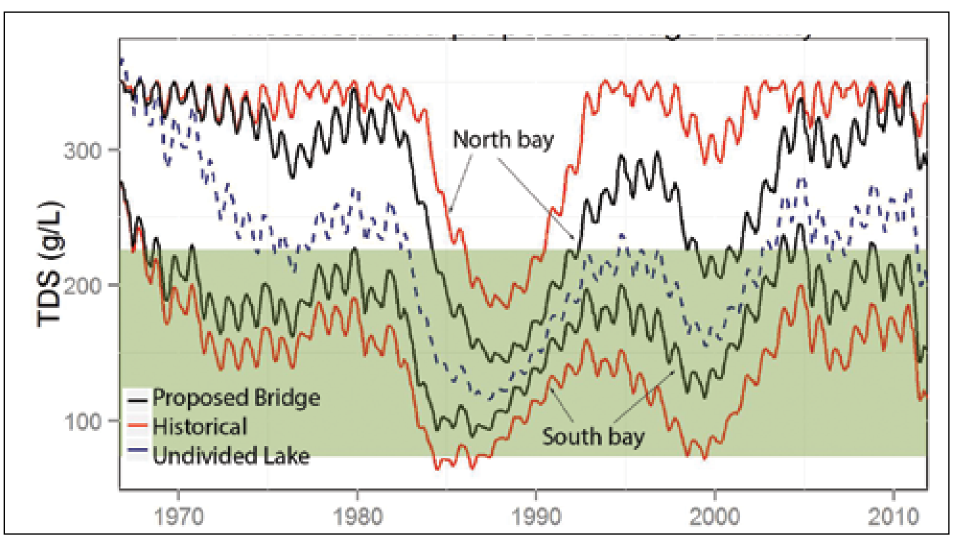


Figure 7. Historical, proposed, and undivided lake model run. Proposed bridge is consistently closer to undivided lake condition than historical.

would have provided habitat from 1984-1992, whereas with culverts, the north bay supported Artemia from 1986-1989 (Figure 8).

Our research shows that causeway opening design (e.g., culverts, bridge, breach) affects salinities in GSL's north and south bays. Results indicate that of the alternatives we evaluated, the proposed bridge will best ameliorate salinity differences between the north and south bays and benefit lake ecology, although additional research is needed to evaluate hydrodynamic changes from modified causeway openings. We anticipate that the proposed bridge would support brine shrimp in 95 percent of the years of the 1966-2012 model runs we completed; whereas, current conditions with the breach and closed culverts would support brine shrimp for only 85 percent of the 46-year model period (Figure 9). We recommend the proposed bridge design for the GSL railroad causeway instead of maintaining the causeway with closed culverts for sustainable management of GSL salinity and ecology (Figure 10).

References

Loving, B.L., K.M. Waddell and C.W. Miller. 2000. Water and salt balance of Great Salt Lake, Utah, and simulation of water and salt movement through the causeway, 1987-98, *U.S. Geol. Surv. Water Resour. Invest. Rep.*, 2000-4221.

Waddell, K.M. and E.L. Bolke. 1973. The effects of restricted circulation on the salt balance of Great Salt Lake, Utah. *Water Resour. Bull. Rep. 18, Utah Geol. and Mineral Survey*, Salt Lake City.

Wold, S.R., B.E. Thomas and K.M. Waddell. 1997. Water and salt balance of Great Salt Lake, Utah, and simulation of water and salt movement through the causeway. *U.S. Geol. Survey Water Supply Pap.*, 2450.

Wurtsbaugh, W.A. and T. Smith Berry. 1998. Cascading effects of decreased salinity on the plankton, chemistry, and physics of the Great Salt Lake (Utah). *Can J Fish Aquatic Sci*, 47:100-109.

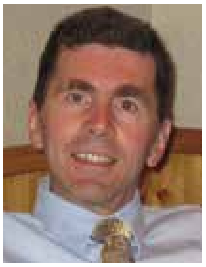
Table 1. Mean, Minimum, and Maximum Salinity by Model Run.

Model Run	North			South		
	Mean salinity (g/l)	Max salinity (g/l)	Min salinity (g/l)	Mean salinity (g/l)	Max salinity (g/l)	Min Salinity (g/l)
Historical	317	351	183	142	276	64
Proposed bridge	276	351	143	176	277	88
Whole Lake	222 (mean)		351 (max)		115 (min)	

Figure 8. View from Union Pacific Railroad Causeway looking east. Note red color of north bay on left. Photo courtesy of Wayne Wurtsbaugh.

James S. White is a graduate student in the Watershed Science Department at Utah State University. His research includes modeling changes to Great Salt Lake and reconstructing historical lake conditions.

Sarah E. Null is an assistant professor in the Watershed Science Department Utah State University. Her research includes modeling changes to ecosystems and water supply from climate change and Great Salt Lake hydrology.



David Tarboton is a professor in the Civil and Environmental Engineering Department at Utah State University. His research includes hydrologic predictions using geographic information systems and digital elevation models and has done extensive research on the hydrology of Great Salt Lake.

Figure 9. Commercial brine shrimp harvesting. Brine shrimp cysts (eggs) visible in foreground appear similar to an oil slick. Photo courtesy of Wayne Wurtsbaugh.

Figure 10. Tundra Swans on Great Salt Lake. Photo courtesy of Chris Luecke.