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Utah Division of Forestry, Fire and State Lands

Modeled changes to Great Salt Lake salinity from railroad causeway alteration

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Executive Summary

The Great Salt Lake (GSL) changed dramatically after Union Pacific Railroad (UPR) installed a railroad causeway in 1959 that divided the lake into two “arms”. The south arm (Gilbert Bay) receives all three major tributaries and 95% of incoming streamflow. Freshwater inputs to the north arm (Gunnison Bay) are limited to direct precipitation and ephemeral streams from the West Desert (Loving et al., 2000). Despite construction of two 15 ft wide culverts to allow for boat passage, and a 290 ft breach that was added in 1984, a large salinity gradient has formed between the north and south arm. The north is often at or near saturation (317 g/L), while the south is significantly less saline, averaging approximately 142 g/L. In 2012 and 2013, UPR closed both culverts and proposed to replace them with a 180-foot trapezoidal bridge. The effect this bridge would have on inter-arm flow and salinity was heretofore unknown. This report describes modeled flow and salinity changes from recent causeway modifications and the proposed trapezoidal bridge.

The naturally high salinity of Great Salt Lake is critical to its ecological, economic, and social function. Brine shrimp (*Artemia franciscana*) and brine fly (*Ephydra cinerea*) are keystone species in the lake and support millions of migratory birds (Alrich and Paul, 2002). Additionally, Artemia are commercially harvested annually, which contributes an estimated $56.7 million to the local economy (Bioeconomics, 2012). Commercial extraction of dissolved minerals via evaporation ponds are also dependent on salinity levels and contribute an estimated $1.1 billion to the local economy. GSL attracts millions of visitors annually and the recreation industry reliant on the lake contributes $135 million to the local economy (Bioeconomics, 2012). Therefore, many diverse parties are interested in salinity management for the lake.

We used a modified version of the USGS Great Salt Lake Fortran Model (Waddel and Bolke, 1973; Wold et al., 1997; Loving et al., 2000) to evaluate how the proposed causeway bridge will affect salinity in each arm of the lake. We ran a historical simulation, to replicate the dynamic condition of the causeway from 1966-2012, which was compared to measured data to assess model fit. Once the model’s ability to simulate historic conditions was established, we ran a total of seven models over the historical time period (1966-2012). The “subsided” model simulates the conditions of the causeway as of March, 2014, where the culverts are closed, the causeway subsided, the breach deepened, and the ability of the fill material to transmit water is reduced. The “proposed bridge” model run replaced the historical culverts with the bridge design proposed by UPR. Four modified bridge scenarios assessed the sensitivity of salt and water flow through the causeway to bridge design. These included a longer and shorter trapezoid bridge, as well as two rectangular designs. Finally, we evaluated a “whole lake” condition, with no causeway and uniform lake salinity. All model runs used identical climatic data (streamflow, precipitation, evaporation) and salt losses (West Desert pumping and mineral extractions).

Overall, the Great Salt Lake Fortran Model suggests that lake salinity is sensitive to causeway modification. Comparing results from historical conditions and the proposed trapezoidal bridge design, we found the bridge significantly increases flow between arms compared to historical culverts, causing a decrease in north arm salinity and an increase in south salinity (figure I). Results also show that the shape of the bridge design is as important as the size of the opening. Finally, salinity varies inversely with tributary inflows in our modeled whole lake condition, with concentrations between approximately 180 to 350 g/L.

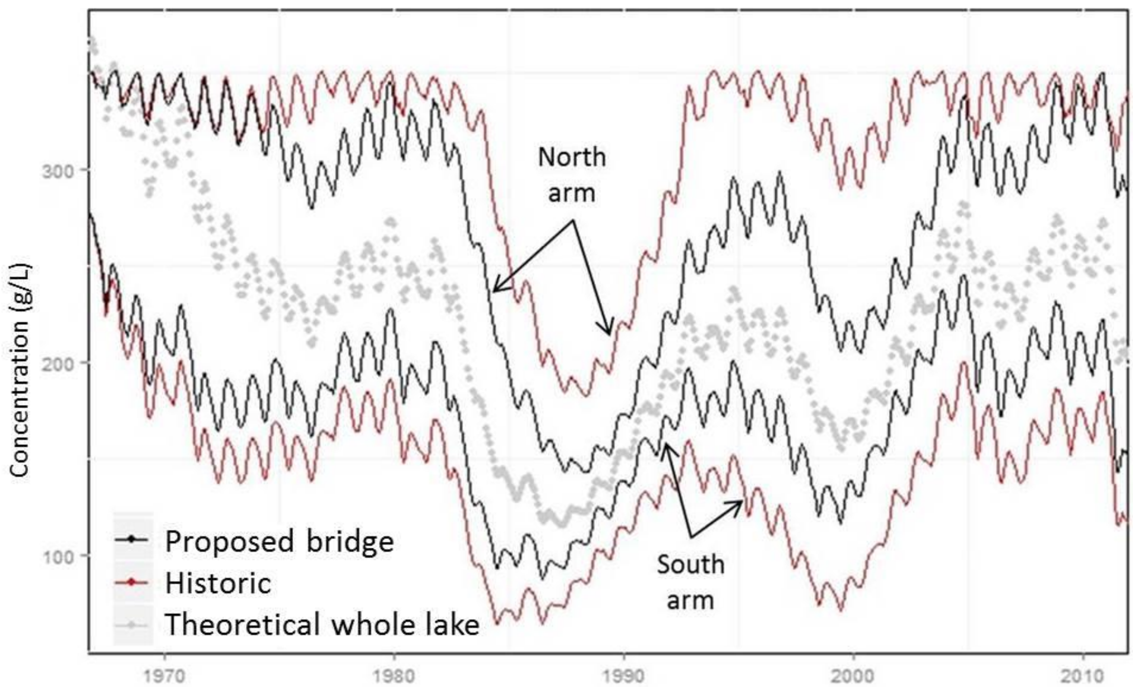


Figure I. Salinity concentrations from historical conditions, proposed bridge, and theoretical whole lake

Introduction

In 1959, Union Pacific Railroad (UPR) built a rock filled causeway across Great Salt Lake, dissecting the lake from Promontory Point on the eastern bank to the West Desert on the western bank (Figure 1). The causeway hydrologically separated the lake into two "arms" – Gilbert Bay in the south and Gunnison Bay in the north. The south arm receives approximately 95% of the incoming streamflow, thus it has become progressively more fresh, averaging approximately 142 g/l since 1966, while the north has become hypersaline, averaging 317 g/l since 1966 (Loving et al., 2000).

To allow boat passage, UPR installed two fifteen foot wide culverts in the causeway during original construction and added a 290 foot breach in 1984 to ameliorate salinity differences. However, the causeway was built on unstable lake sediments, which caused the causeway and culverts to slowly subside. This subsidence resulted in a reduction in the capacity of water to flow through the semi-porous fill material, and over time rendered the culverts structurally unstable. In 2012 and 2013, UPR closed the west and east culverts, respectively, due to their instability, and proposed to replace them with a 180 foot trapezoidal bridge.

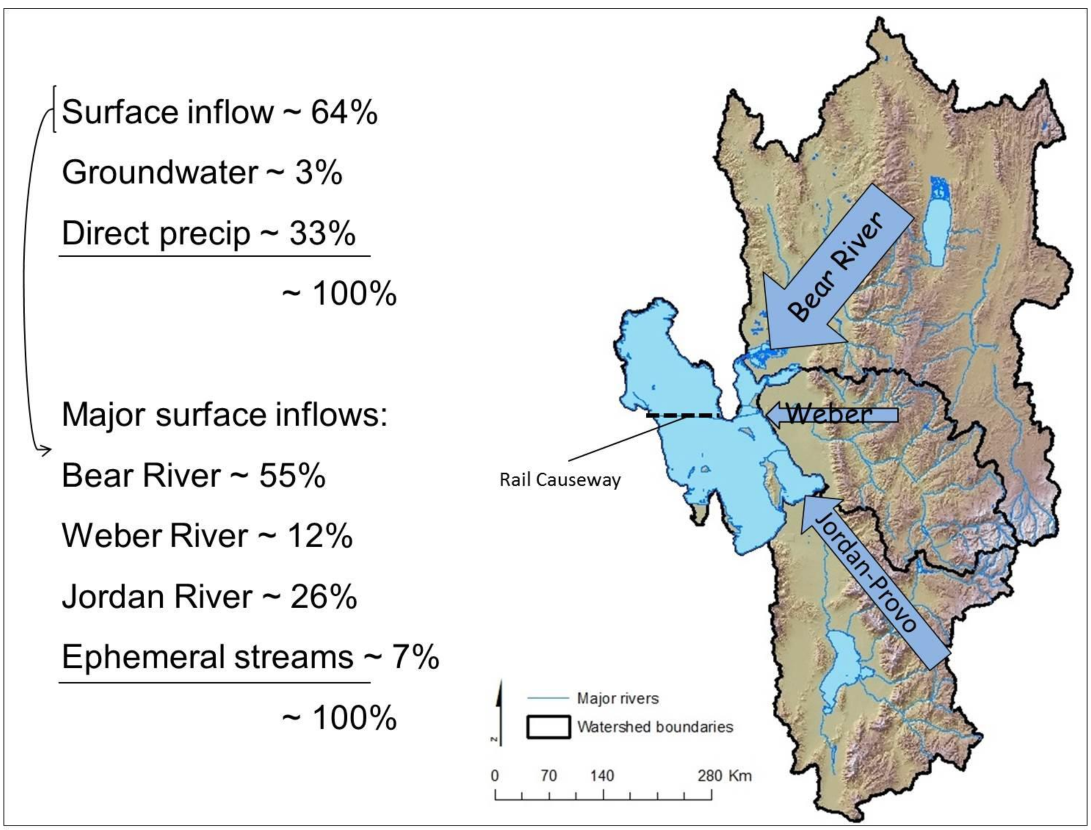


Figure 1. Schematic of Great Salt Lake and relative contributions of tributaries

Additional anthropogenic influences exist on Great Salt Lake beyond the causeway. In 1987, after a series of high precipitation years, large hydraulic pumps were installed on the northwest shoreline of the lake to pump brine into the West Desert and alleviate flooding. Pumping temporarily exports water from the north arm of the lake into the West Desert, although much of it eventually returns via a flow return system (Mohammed and Tarboton, 2012). Total salt load decreased approximately 50 million tons due to West Desert pumping (Loving et al., 2000). Pumps are still in place; however the lake has not reached an elevation requiring pumping since 1989. Additional salt is lost from commercial mineral extraction ponds. To date, total losses from both pumping and mineral extraction are estimated at approximately 1 billion tons (Figure 2) (Mohammed and Tarboton, 2012).

Many diverse parties are interested in Great Salt Lake salinity, and the economy dependent on the lake is intertwined with its ecology. Annual brine shrimp harvests are estimated to create over 500 full and part time jobs, while the mineral extraction and recreation industries produce 5400 and 1700 full and part time jobs, respectively (Bioeconomics, 2012). Overall, the lake contributes an estimated $1.3 billion to the local and regional economy. Much of this is reliant on the hypersaline nature of Great Salt Lake: brine shrimp require salinity within certain thresholds for survival; mineral extraction is commercially viable due to the high concentrations of salts, and recreation is heavily based on the millions of birds which feed on the brine shrimp and brine flies.

In this report, we describe the Great Salt Lake Fortran Model and the updates we have made to it to estimate GSL causeway modifications. We evaluated four different causeway alternatives:

- 1966 to 2012 historical conditions, where the causeway and culverts subside over time,
- 1966 to 2012 whole lake conditions, the causeway is removed and the lake exhibits single lake behavior,
- subsided (or current) conditions, with a subsided causeway, closed culverts, and historical climate and streamflow conditions, and
- proposed bridge conditions, with the proposed 180' trapezoidal bridge, closed culverts, and historical climate and streamflow conditions.

We also report the results of a sensitivity analysis on the design of the bridge. We tested four different bridge designs, two with a trapezoidal shape but varying lengths, and two rectangular bridge designs.

Methods

<u>Great Salt Lake Fortran Model</u>

We used the USGS Great Salt Lake Fortran Model developed by Waddel and Bolke (1973), with updates and calibrations by Wold et al. (1997) and Loving et al. (2000). This model uses a mass balance approach to calculate volume and mineral load for each arm of the lake. Volume is calculated at each time interval, or timestep, (every two days) by:

$$V_{aT}=V_{aT-1} + QS_{in} + QB_{in} + QC_{in} + P + Q_{wdr} – E - QC_{out} - Q_{wd}$$

where V_{aT-1} is the volume of an arm at the previous timestep, QS_{in} is the volume of streamflow into the arm, QG_{in} is the volume of groundwater inflow, QC_{in} is the total flow into the arm through the causeway, P is the volume of direct precipitation, Q_{wdr} is the return flow from West Desert (if occurring), E is volume of evaporation off the surface of the lake, Q_{wd} is the volume lost to West Desert pumping (if occurring) and QC_{out} is the volume exported through the causeway. Salt load of each arm at a timestep is calculated by

$L_{aT} = L_{aT-1} + L_T + L_{inC} + L_{rd} - L_{pp} - L_{outC} - L_{outP}$

where L_{aT-1} is the previous timestep's load, L_T is the incoming load from tributaries, L_{inC} is incoming load through the causeway, L_{rd} is redissolved load, L_{pp} is load that has precipitated, L_{outC} is load exported through the causeway, and L_{outP} is load removed when West Desert pumping is initiated. Flow through the culverts and breach were calculated using equations developed by Holley and Waddel (1976) and Loving et al. (2000). Salinity concentration is then is calculated by $C_{aT}=L_{aT}/V_{aT}$ in units of grams per liter.

Input Data and Sources

Streamflow volumes are from measured USGS data in the Bear, Jordan, and Weber rivers, precipitation is from Oregon State University's PRISM dataset (PRISM Climate Group), and groundwater is assumed constant at 5410 acre-ft/ month in the south and 830 acre-ft/month in the north (Loving et al., 2000). Monthly evaporation can either be calculated directly from climate variables using the Penman equation adjusted for salinity, or closing a mass balance equation may be used. Recent research by Tarboton (unpublished data, 2011) shows that the mass balance approach better reproduced historical lake levels than the salinity-adjusted Penman equation, thus we used this approach in all scenarios.

Causeway opening geometry, including the culverts, breach and proposed bridge design are from UPR, and causeway subsidence information is from Loving et al.

Changes to USGS Great Salt Lake Fortran Model

Several changes were made to the USGS model code distributed by Loving et al. (2000). The model was previously hard-coded to simulate lake conditions from 1987-1998. We made the following code changes to improve flexibility, evaluate longer time series, and alter causeway conditions:

1. We calculated flows based on differences in elevation and brine density between each arm (measured flows through the breach and culverts were previously user specified)
2. Causeway openings (bridge, culverts, breach) and geometry (shape, dimensions, elevations) and flow through causeway fill material are now user specified with an input file.
3. Bathymetry was modified to represent changes from evaporation pond development (Tarboton, unpublished data, 2011).
4. Mineral (salt) load loss and return from pumping and mineral pond extractions are now user specified with input files.
5. Flow through submerged culverts is set to zero, instead of calculated via equations developed by Loving et al.

Model runs

Four primary model alternatives were constructed and run from 1966-2012, using identical climatic and streamflow data, as well as identical initial lake conditions (salt loads and elevations in each arm). All model runs also assume zero flow through culverts if they are submerged. Loving et al. (2000) developed equations for submerged conditions, however we found that assuming zero flow was significantly more accurate in simulating observed conditions. This is not surprising, as submerged conditions were highly variable; the culverts were often partially or entirely filled with debris, thus violating assumptions of hydraulic equations developed by Loving et al. Details of each model are as follows.

1. Historical conditions

The historical 1966 – 2012 model includes two culverts and the breach. It assumes the causeway and culverts subside through time, and flow through causeway material is reduced from subsidence and fill material changes made in 1974 (Loving et al., 2000). The breach is deepened in 1998 and 2000. The model also accounts for West Desert pumping from 1987-1989 and mineral losses from commercial mineral extraction. This model run simulates historical conditions over this period.

2. Proposed bridge conditions

We simulated UPR's proposed trapezoidal bridge opening that is 60 feet long at the base and 180 feet long at the top. To better understand bridge design influence on inter-arm flow, we also completed a sensitivity analysis using four alternatives including: increasing and decreasing bridge length by 20% (while retaining trapezoidal shape), a 180 ft rectangle design (the uppermost length of the proposed bridge), and 60ft rectangular design (the bottom length of the proposed bridge). Additionally, we applied the proposed bridge design to simulate a future lake condition by using the same climatic inputs, but initializing the model with 2012 conditions, and holding mineral extraction at similar rates 1992-2012. This provides a rough estimate of future lake conditions with the proposed bridge.

3. Subsided conditions (settled causeway, closed culverts, reduced fill flow)

The "subsided condition" model run holds current causeway conditions (as of March, 2014) consistent throughout the entire modeled period. Therefore, the causeway fill flow reduction coefficient is 0.1 (a unitless parameter), culverts are closed, the breach is open and deepened, and the causeway has subsided for the duration of the model run. We run this model under two scenarios: one using the same initial conditions, climate, and streamflow data as the historical model to allow a comparison of how it compares to the historical causeway. The second aims to evaluate the long term impacts of the current causeway conditions compared to the proposed bridge. To do this, we hold climate and streamflow inputs identical to 1966-2012 run, but initial conditions are set to those at the end of 2012, and the mineral extraction losses from the previous 20 year (1992-2012) are held constant, with the assumption that mineral industries will continue to operate similarly to recent decades. This alternative simulates current conditions if a bridge is not constructed in the railroad causeway.

4. Whole lake conditions

A whole lake (no causeway) condition is estimated by dividing the sum of north, south, and precipitated salt load by the combined volume of each arm. This was not run with the Great Salt Lake Fortran Model, but instead completed in the statistical program R using data from the historical model run. Salt losses due to pumping and mineral extractions have been included in the whole lake condition.

Results

Model Validation and Historical Conditions

We compared modeled historical conditions with observed elevation, salt load, and salinity data to assess model performance. Overall, the historical simulation represents GSL elevation and salinity conditions well, as shown in figures 2, 3, and 4. Elevation of the north arm is occasionally over predicted by up to 2 ft, while the south level is very similar to measured levels with no consistent bias (figure 3). The model also simulates load and concentration well, with a notable exception in the south arm between 1989-2000. This is attributable to the submerged culverts throughout this period. Although Loving et al. developed equations to simulate this condition, the culverts tended to become plugged with debris, thus obstructing flows. Because of this, the equations developed only held when culvert debris was removed (a relatively short period). Although some flow certainly occurred during this time, the model preforms better assuming no flow than calculating a fully open culvert. Developing more accurate equations for submerged flow were outside of the scope of this study.

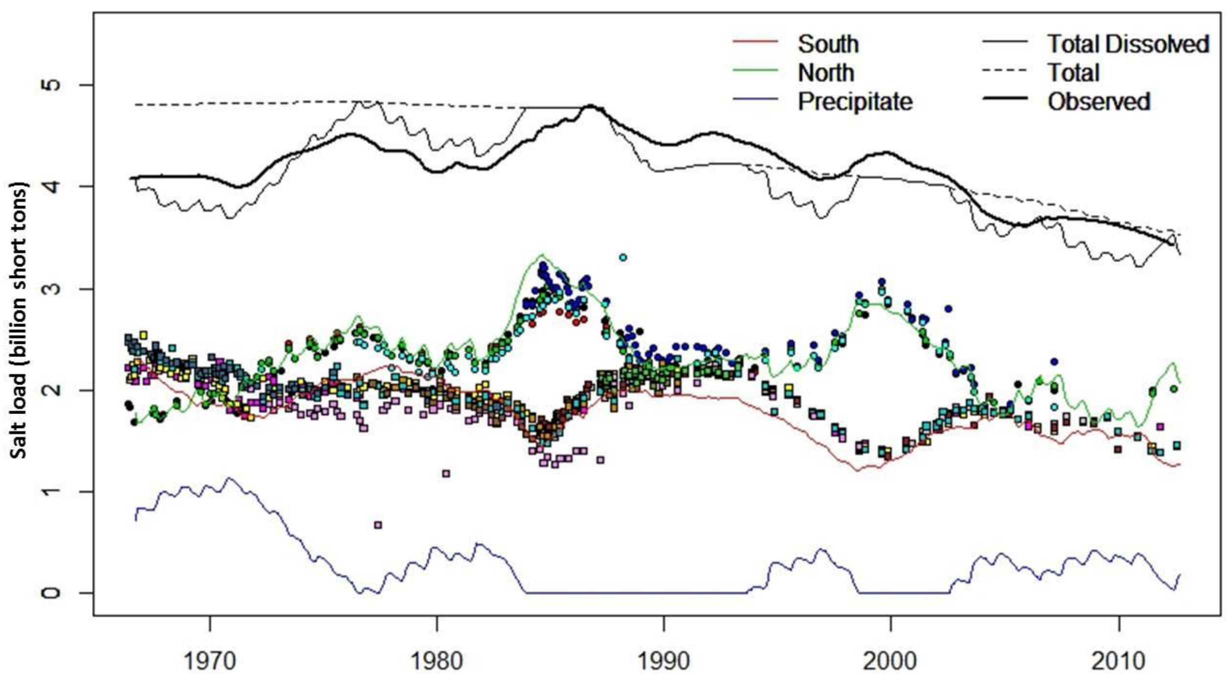


Figure 2. Observed and modeled salt loads of north, south, precipitated and total loads.

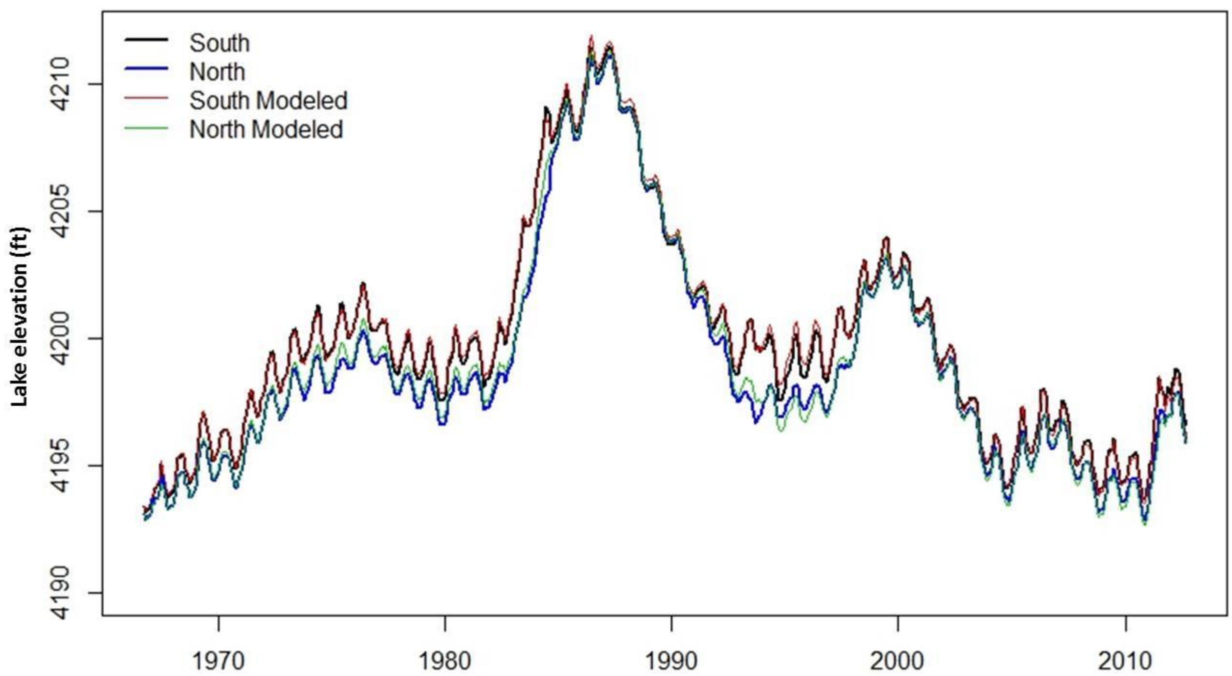


Figure 3. Modeled and observed lake elevation of north and south arm.

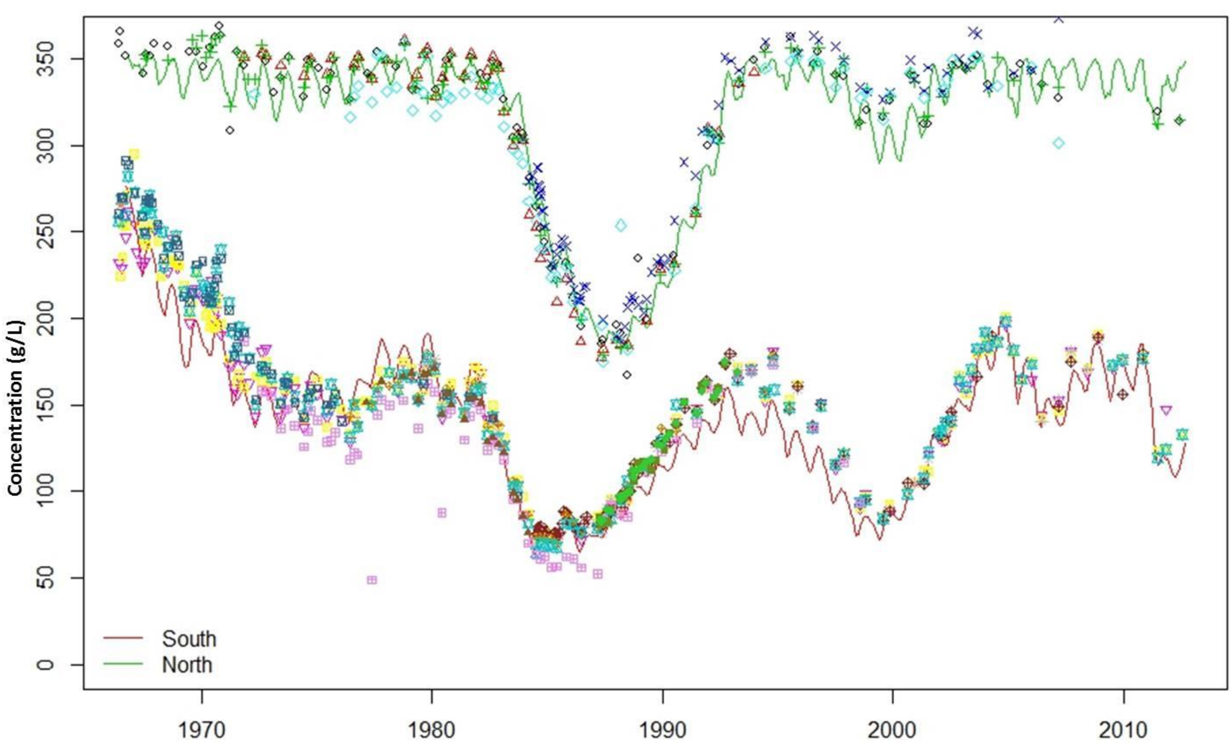


Figure 4. Modeled (solid lines) and observed (points) salt concentrations in Great Salt Lake.

Proposed Bridge Conditions

Modeling suggests the proposed causeway bridge will reduce salinity in the north and increase it in the south (figure 5). This is consistent with expectations, as the bridge increases flows in both directions compared to the much smaller culverts (figure 6). The absence of flow through the culverts from 1984-2004 is due to the culverts inundation during this time. As outlined, this was a simplification, and some amount of flow was virtually certain to have occurred. Despite this, the proposed bridge can confidently be said to increase bidirectional flow.

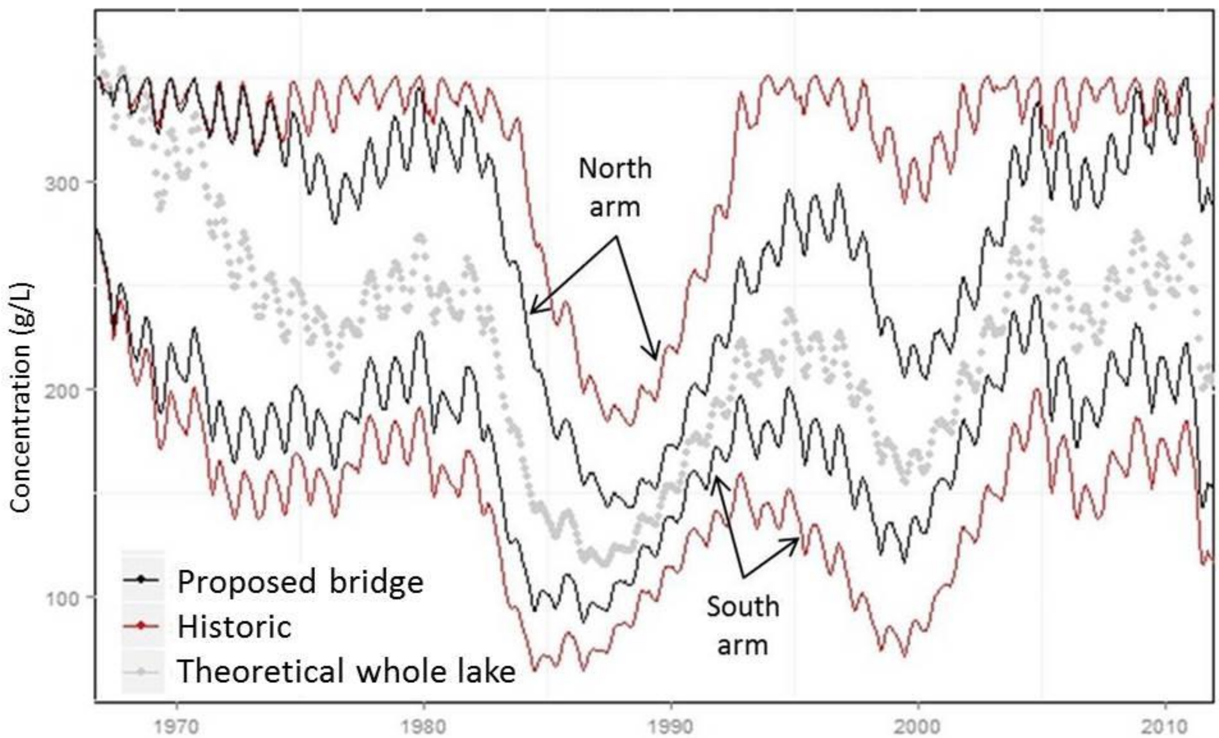
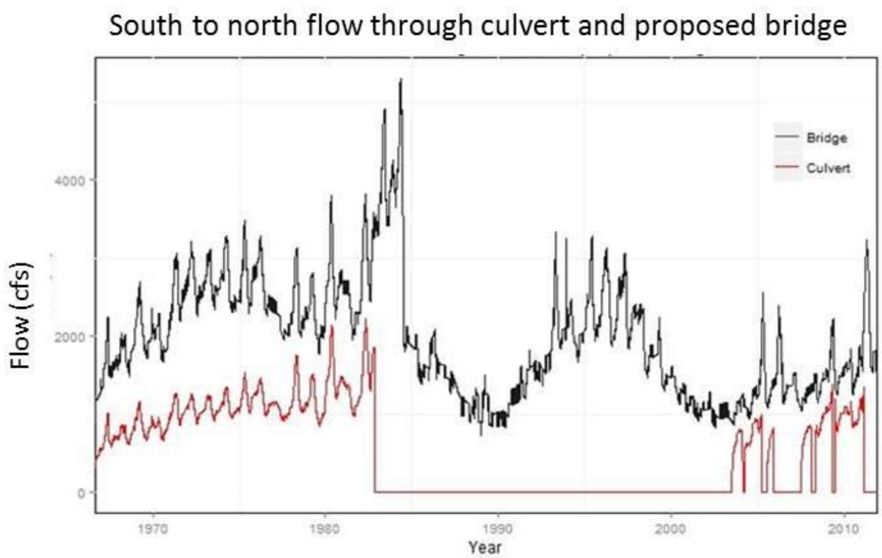


Figure 5. Salinity concentrations from historical condition, proposed bridge, and theoretical whole lake.



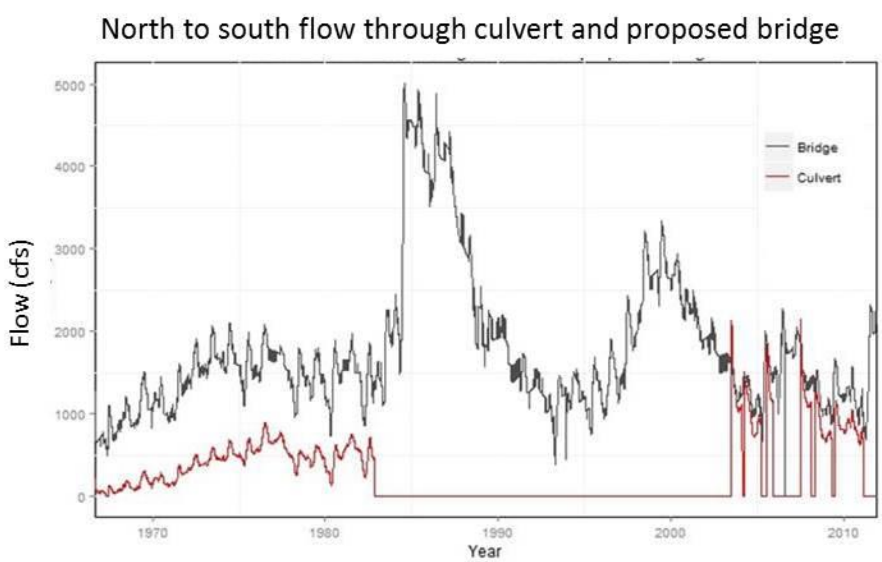


Figure 6. Flows south to north (top) and north to south (bottom) through culverts (red) and proposed bridge (black)

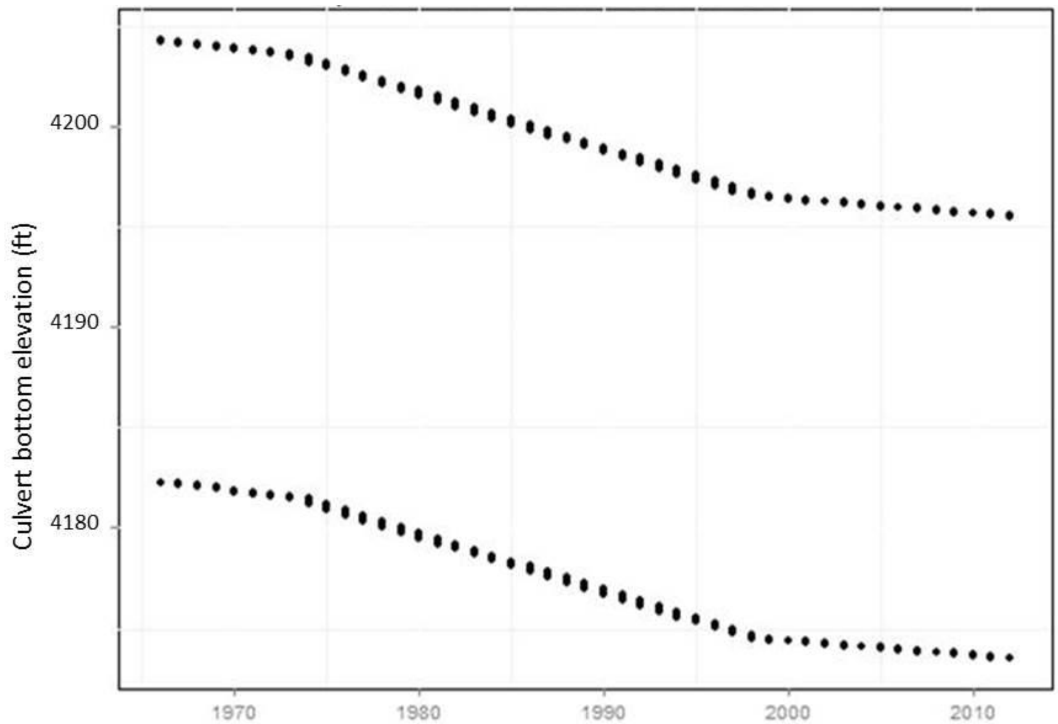


Figure 7. Elevation change from subsidence of culvert top and bottom through time

Subsided Conditions

We ran two different subsided causeway simulations. The first represents the historical time (1966 initial lake elevation and salinity condition) series using identical climate inputs and initial conditions, but with a fully subsided causeway and closed culverts to enable comparison to historical conditions (figure 8). This provides an estimate of GSL conditions had the culverts never been installed. Results show that salinity could be reduced in the north arm when it is not saturated, however this is misleading. The subsided model uses current causeway conditions for the whole simulation, thus the breach is open for the entire period and is larger (due to later deepening) than much of the historical period. Because of this, there is more flow through the breach throughout much of the subsided model compared to the historical model. This results in the decreased north arm salinity observed in figure 8. The south arm is also affected by the breach condition. The historical condition south arm salinity is higher initially; however during the high precipitation years of the 1980s, the subsided causeway conditions become more saline. This holds until the relatively dry years from 2005-2012.

We extrapolated these results to investigate how the current causeway condition and the proposed bridge might affect future lake conditions, by starting the model with lake elevation and salinity conditions using 2012 levels. We kept mineral load extraction the same as the most recent period, 1992-2012. This gives insight into what the next 45 years (2012-2057) would look like if precipitation, evaporation, and streamflow are identical from the past 45 years (figure 9). As shown, the proposed bridge results in lower salinity in the north arm and higher salinity in the south arm than the current subsided causeway condition.

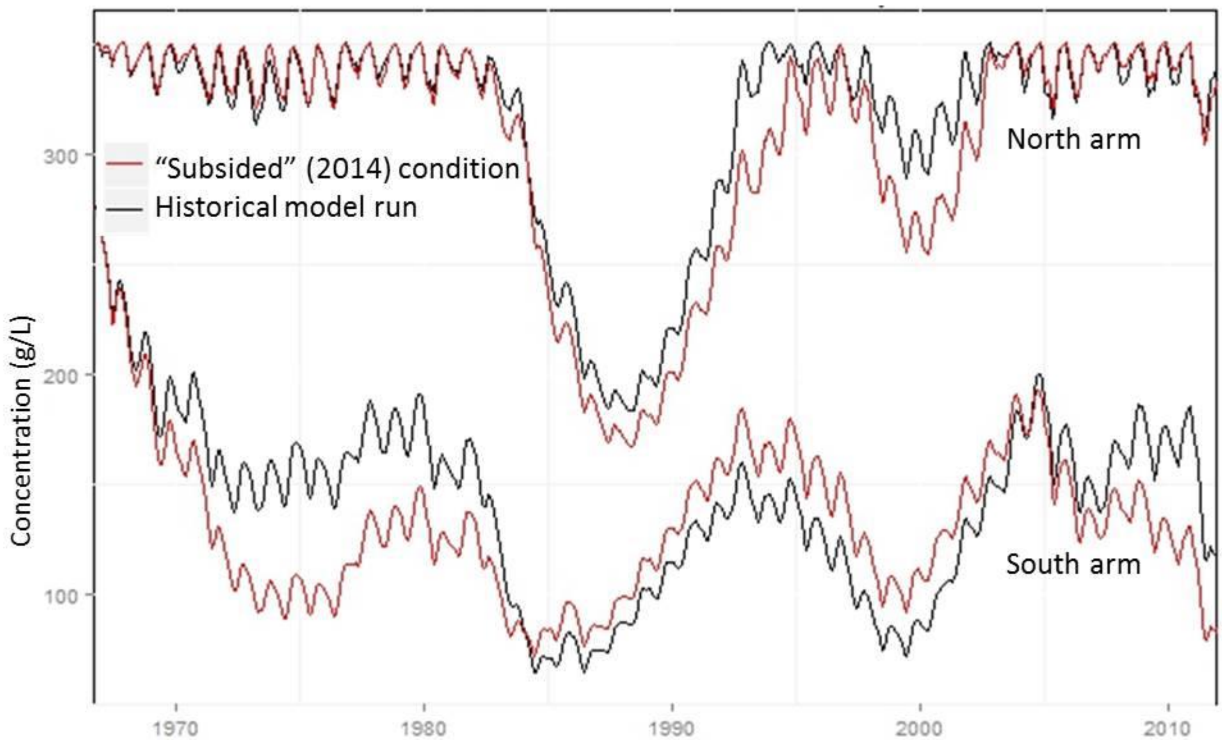


Figure 8. Historical (black) causeway conditions and subsided causeway conditions (red).

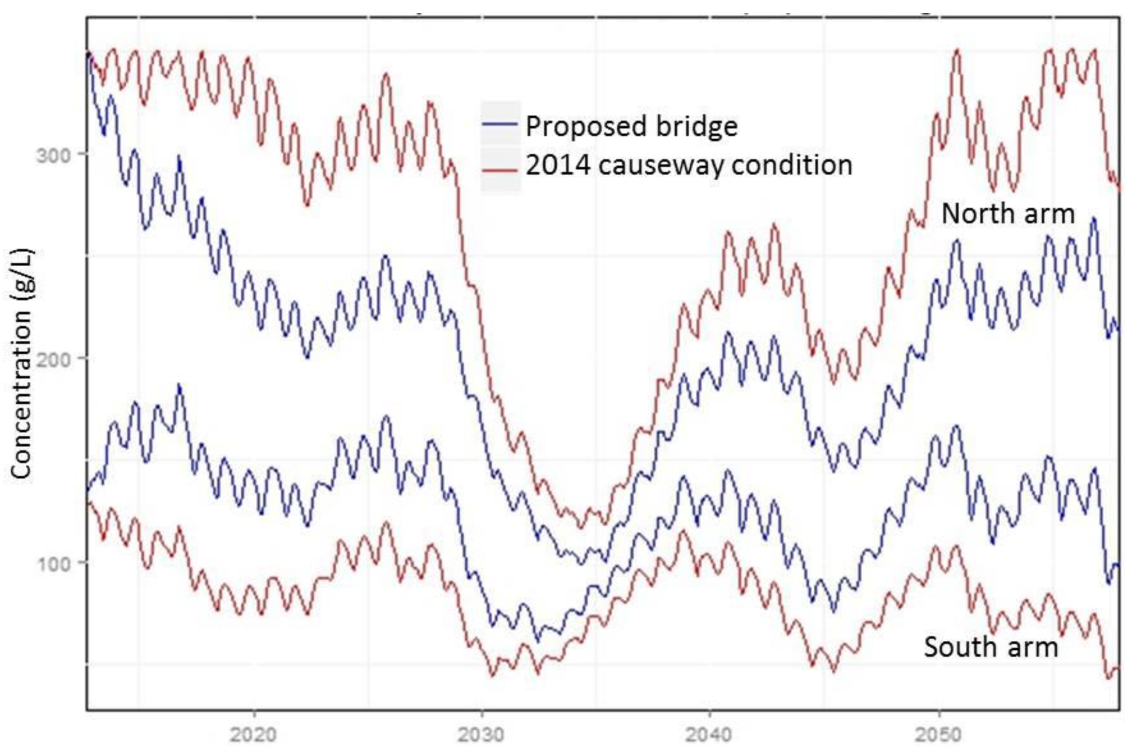


Figure 9. Proposed bridge (blue) and subsided causeway conditions (red) initializing with 2012 conditions. Both simulations use identical historical climate data.

Bridge design sensitivity analysis

Results from the sensitivity analysis of bridge design are shown in figure 10. These runs use historical climate and 1966 initial conditions. There are only slight differences from increasing or decreasing bridge length by 20%, as well as using a rectangular 60 ft bridge design. The only result that is substantially different is the 180 ft rectangular bridge, which results in reduced salinity in the north arm, and increased salinity in the south arm. This finding is discussed further in the discussion section below.

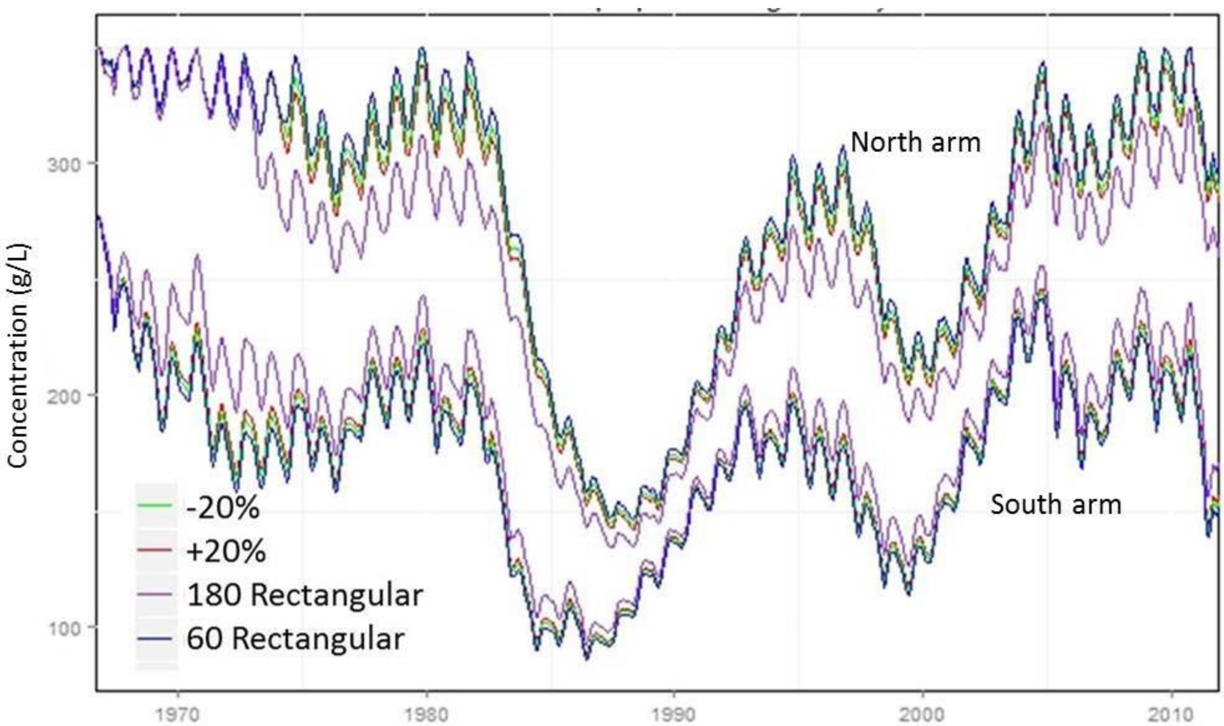


Figure 10. Sensitivity analysis of several alternative bridge designs. Only the 180 ft rectangular bridge shows significant differences between other designs.

Whole Lake Conditions

The whole lake salinity represents a lake without a causeway (figure 5); however it does have a reduction of salt load over time due to mineral extraction and West Desert pumping. The modeled salinity is consistently closer to south arm salinity than north arm. Results are consistent with those found in Loving et al., but are significantly lower than those reported in Null et al. (2013) because mineral extraction losses were not accounted for in their calculations.

Finally, average, maximum, and minimum salt concentrations for each model run are provided in Table 1 for quick comparison between model runs.

Table 1. Mean, max, and minimum salinity for each model run

	Model Run	Mean salinity North (g/l)	Max salinity North (g/l)	Min salinity North (g/l)	Mean salinity South (g/l)	Max salinity South (g/l)	Min Salinity South (g/l)
	Historical	317	351	183	142	276	64
	Subsided	307	351	168	132	276	72
	Proposed Bridge	276	351	143	176	277	88
	Whole Lake	222 (mean)		351 (max)		115 (min)	
sensitivity analysis	**Bridge + 20% length**	275	351	142	177	277	88
	Bridge -20% length	278	351	144	175	277	87
	60ft rectangular bridge	282	351	147	172	277	86
	120ft rectangular bridge	257	350	134	189	278	93
Future simulations	**Proposed Bridge**	205	350	98	124	189	60
	Subsided	264	351	116	83	129	42

Discussion

All model runs are significantly affected by the high precipitation years of 1984-1988, shown as increasing lake elevation and reductions in salinity (figures 2 and 4). This is apparent in the future modeled conditions as well (figure 9). The high lake levels during this period drive the lack of flow in either direction through the culverts from 1984 until 2004. During these years, the culverts were mostly or entirely inundated (figure 7), restricting inter-arm flow in the model to the breach and fill material. As discussed above, historical flow during this period was diminished, but not 0, and is a limitation of this model.

<u>Proposed Bridge model (Figure 5)</u>
The proposed bridge significantly increases flow in both the north and south directions (Figure 6). Differences between salinities are generally greatest from 1985-2004, coinciding with a particularly wet climatic period. This is a result of the proposed bridge top elevation (4216) being sufficiently high to

allow for flow during high water years compared to relatively low culverts. Results from the bridge design sensitivity analysis suggest even relatively large changes in trapezoidal bridge length (+/- 20%, or +/- 36ft) make little difference to salt concentration (Table 1). Changing bridge shape from trapezoid to rectangular made a larger difference. Results from the he 60 ft rectangular bridge run show only slightly less flow exchange compared to the 180 ft trapezoidal bridge run, while the 180 ft rectangular design shows notable changes in both the north and south arm. Under the 180 ft rectangular bridge, salinity in the north arm is reduced by an average of 19 g/l compared to the 180 ft trapezoidal bridge, while the south is increased by an average of 13 g/l. The breach depth sensitivity analysis performed by Loving et al. (2000) may provide an explanation for these results. Their results showed that significantly more flow was enabled by deepening the breach, instead of widening it. Thus, the 60 ft rectangle preserves the deepest section of the proposed bridge, and only higher elevation flow is lost. This is reflected in a slight loss of salt exchange between the arms compared to the proposed bridge, but only by approximately 2%. The 180 ft rectangle substantially increases deeper area for flow, which leads to a significant change of salinity compared to the proposed bridge.

Subsided model (Figure 8)

Results from subsided causeway (or current condition) show surprising results in the north and south arms. When not saturated, the “subsided condition” simulation has lower salinity than historical conditions in the north arm. This initially appears counterintuitive, since there are less openings for water to flow, thus one may expect higher salinity under the subsided condition. However, since opening in 1984, the bottom of the breach was deepened 7 ft, from an elevation of 4200 ft to 4193 ft. This depth of 4193 ft is held constant through the subsided run, thus providing significantly more area for brine to flow through. Furthermore, since the culverts were submerged for nearly 20 years, their influence in the model is substantially less during those years, thus the subsided condition allows more north to south flow throughout much of the simulation compared to historic.

Salinity levels in the south arm in this comparison vary. From 1970-1984, the subsided condition salinity is lower than historical levels. This is a result of the breach being open throughout the entire modeled subsided condition, whereas its opening in 1984 for the historical run. Since the breach is much larger than the culverts, it allows for significantly more bidirectional flow. From 1984-2004, the subsided condition has higher salinity. This again may appear counterintuitive, but is likely explained by two factors. The culverts are inundated throughout this period, limiting their contribution to inter-arm flow. In addition, the breach reaches its final elevation of 4193 ft in 2001 in the historical model; however this is the bottom elevation throughout the subsided condition model, thus allowing for a larger opening in which brine can flow. Once the culverts are not inundated in 2004 and the breach elevations are equal, the effect on flow and salinity is clearly seen, as the historical condition’s salinity is well above the subsided.

Subsided and proposed bridge models under future condition (Figure 9)

Our simulation of two hypothetical future scenarios, one with the proposed bridge and the other with subsided causeway conditions, shows that installation of the bridge reduces the salinity differences between both arms (figure 9). The difference between the two scenarios is greatest when lake elevation is low and least when elevation is high. Both scenarios show salt load is reduced from continued mineral extraction and identical West Desert pumping conditions as occurred in the 1980's. During wet years, the north arm drops to 98 g/l in the proposed bridge alternative and 116 g/l in the subsided condition alternative. The south reaches a minimum of 60 g/l and 42 g/l for the bridge and subsided condition simulations, respectively. On average, salinity with the proposed bridge scenario averages 124 g/l in the south, and 205 g/l in the north. Compared to the historical averages, 141 g/l in the south and 316 g/l in the north, an estimated average drop of 17 g/l in the south and 111 g/l in the north occurs with the proposed trapezoidal bridge. The current condition scenario has a larger change in the south arm, averaging 83 g/l, while the north reduces less, to an average 264 g/l (table 1).

Conclusions and Management Implications

With the construction of a railroad causeway in 1959, the hydrology of Great Salt Lake changed dramatically. Many parties are interested in the future condition of Great Salt Lake following the closures of culverts in 2012 and 2013, and proposed trapezoidal bridge in the railroad causeway. Our modified USGS GSL Fortran model simulates Great Salt Lake dynamics with sufficient accuracy to enable comparisons and estimations of theoretical causeway designs.

The bridge design proposed by UPR significantly increases interarm flow compared to historical and current conditions, and creates conditions more similar to an undivided lake. However, we see in the historical proposed bridge model that salinity in the south arm still drops well below 100 g/l during high precipitation periods. While this is 24 g/l higher than historic conditions, it may not be enough to prevent the trophic cascade witnessed in the lake during the late 1980's attributed to the drop of salinity, causing a collapse in brine shrimp populations (Wurtsbaugh and Berry, 1998). Greater understanding of ecosystem responses is needed to evaluate the ecological response to causeway modification.

The diverse parties interested in GSL conditions create difficult questions for lake management. Some interests may welcome the export of salinity from north to south shown by the proposed bridge condition. This would create a lake more like historic conditions without a causeway, and could support brine shrimp during high precipitation years. Others, however, may lament the loss of resources provided by the brine in the north arm. Indeed, it could be the north arm provides refugia for salt dependent organisms in years of high precipitation. UPR, meanwhile, needs a reliable form of transportation across the lake. Evaluating the merit of these competing demands is not the purpose of this study, and will be a question for managers and politicians for the foreseeable future.

Future Research Needed

A notable model limitation discussed in this report is the lack of flow through culverts when they are submerged with water. This likely accounts for the inaccuracy of modeled to measured loads and salinity observed from 1990-2000. Since the culverts are now closed, submerged flow will not be needed to model future scenarios; however improving flow estimations during this period would increase confidence in the model.

Our future scenarios are based on an identical climate as the past 45 years. While the model provides a rough idea of future conditions, it is very crude. There are two major factors that will affect Great Salt Lake conditions that were not considered in this study. The first is the anticipated change of climate over the coming century. Current estimates expect temperatures in Utah to increase between 2^{o} and 9^{o} F by 2100, and a decrease in winter snowpack of up to 40% (Garfin et al., 2013). Additionally, with anticipated population growth along the Wasatch Front, water demand is expected to increase, potentially at the expense of inflows to GSL. Effects of climate change and water demand increases on Great Salt Lake are not well understood. Incorporating these factors into the model would significantly increase the accuracy and usefulness of modeling future conditions.

The response of organisms to changes of salinity in GSL is currently not well understood. Efforts in other saline lakes have been made to estimate salinity needs and tolerances for brine shrimp, however less attention has been paid to brine flies, and even less attention to algae and bacteria. A better understanding of how the GSL ecosystem will respond to changes in salinity would provide greater context to efforts to model future lake behavior.

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