Great Salt Lake Past and Present: Elevation and Salinity Changes to Utah's
Great Salt Lake from Railroad Causeway Alterations

by

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ABSTRACT

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Utah State University, 2015

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Department: Watershed Science

In 1959, Union Pacific Railroad constructed a rock-filled causeway bisecting Utah’s Great Salt Lake, separating the lake into a north and south arm. Flow between the two arms was limited to two 4.6 meter wide culverts installed during original construction, an 88 meter breach opening installed in 1984, and the semi porous boulder and gravel causeway material. The south arm receives nearly all streamflows entering Great Salt Lake and a salinity gradient between the two arms developed over time. North arm salinity is often at or near saturation, averaging 317 g/L since 1966, while the south is considerably less saline, averaging 142 g/L since 1966. Ecological and industrial uses of the lake depend on salinity levels staying within physiologic and economic thresholds. Union Pacific Railroad proposed to replace aging culverts with a bridge, and provided four alternative bridge designs. Northern Utah’s variable climate complicates management of the causeway, where lake elevation and salinity are affected by wet and
dry periods. Understanding the historical duration, magnitude, and frequency of wet and dry periods can inform future management decisions. I model the effect of each proposed bridge design on Great Salt Lake salinity and elevation in both arms by updating and applying US Geological Survey’s Great Salt Lake Fortran Model. I used measured historical streamflow and a 400-year tree-ring paleo-streamflow reconstruction to understand lake elevation and salinity sensitivity to longer-term climate variability. The model accurately simulates historical lake elevation and salinity and is sensitive to proposed bridge designs. Bridge alternatives vary salinity by 20 g/L within each arm using historical 1966-2012 conditions. When the model was run with the 400-year paleo-reconstructed hydrology, I find that the 20th century had the lowest average lake level of any century since 1600, and that 20th century floods were smaller than in previous centuries, both in terms of length and magnitude. With the 400-year paleo-streamflow model, differences of south arm salinity between bridge alternatives increase considerably through time, where alternative D results in salinity up to 100 g/l less than alternative A and that the current condition of the causeway would result in a fundamental change in Great Salt Lake characteristics, with the south arm approaching freshwater conditions at times. This research demonstrates that mass balance models are useful to predict management effects on terminal lake ecosystems, and provides a unique approach to reconstruct terminal lake paleo-salinity.

(89 pages)
PUBLIC ABSTRACT

Great Salt Lake Past and Present: Elevation and Salinity Changes to Utah’s Great Salt Lake from Railroad Causeway Alterations

Utah’s Great Salt Lake contributes and estimated $1.3 billion to the local and regional economy and is a vital food-source for migratory and resident birds. In 1959, the lake was fundamentally changed with construction of an earth-filled, semi-permeable railroad causeway which splits the lake into two “arms”. The only flow interaction between these two arms is through the semi-permeable causeway material, and three openings in the causeway. In 2013, two of these causeway openings were closed, and a bridge was proposed to improve flow between arms. Four bridge designs were proposed. I modeled Great Salt Lake water and salt distribution with each bridge design using historical 1966-2012 measured streamflow and climate data. I then used tree-ring reconstructed hydrologic data to estimate lake elevation and salinity since 1604 to understand the effects of long-term climate variability and the long-term influence the causeway has on the water and salt balance on the lake. I find that Great Salt Lake is sensitive to changes in bridge designs, particularly in the south arm, where the largest bridge design increases mean salinity by almost 20% from the smallest bridge design over the 400-year modeled period. Additionally, if the causeway is left in its current state with few openings for interflow, salinity in the south arm may eventually approach freshwater levels, while the north would almost always be saturated. I also find that the 20th century had a lower average lake level than the three preceding centuries, and also
had smaller flooding events compared to the 17th and 18th centuries. These results will aid Great Salt Lake management by quantifying elevation and salinity effects of proposed causeway changes and allow managers and stakeholders to better prepare for climate-driven Great Salt Lake elevation and salinity changes not witnessed in the historical record.
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CHAPTER I
INTRODUCTION

Northern Utah’s Great Salt Lake (GSL) is a pluvial lake and a remnant of the larger, historical Lake Bonneville. GSL is the largest saline lake in the western hemisphere and the fourth largest in the world (Arnow and Stephens, 1990). GSL’s large population of macroinvertebrates supports millions of resident and migratory birds, making the lake a vital link in the Pacific Flyway (Aldrich and Paul, 2002). GSL also contributes approximately $1.3 billion annually to Utah’s economy through recreation, mineral extraction, and brine shrimp cyst harvest (Bioeconomics, 2012). Because of its ecological, social, and economic significance, lake conditions and salinity are important to local residents, lake managers, and other stakeholders.

In 1959, Union Pacific Railroad constructed a rock-filled, semi-porous railroad causeway across GSL, bisecting the lake into Gunnison Bay to the north and Gilbert Bay to the south (Figure 2.1), locally referred to as north and south “arms”. Since then, lake dynamics have changed dramatically, with substantial salinity differences between the two arms. North arm salinity is often saturated (approximately 350 g/L), while the south arm, which receives the vast majority of streamflow, averages less than half the salinity of the north. Two culverts which once allowed bi-directional flow through the causeway were closed in 2012 and 2013, and a bridge has been proposed as a replacement. The bridge design is likely to change water and salt flow between arms, with potential to significantly alter salinity levels in each arm. Quantifying such changes is important to
help managers and stakeholders identify the best design to maintain the lake’s ecological, social, and economic services.

Complicating lake conditions, and by extension bridge alternative evaluation, is the variability of northern Utah’s climate (Mann et al., 1995). Dry periods are regularly punctuated by years of high precipitation and streamflow. This is reflected in GSL surface elevation (level) and salinity, which are controlled by the balance of incoming freshwater via streamflow and precipitation, and loss from evaporation. GSL infrastructure and policy planning, including causeway modification, relies on a relatively short (less than 100-year) historical record to plan for local infrastructure and assess potential management changes. However, recent studies suggest the historical period of record is moderate in the magnitude and duration of extreme dry and wet periods when compared to ~500 year streamflow reconstructions (Allen et al., 2013; DeRose et al.; 2014). Reconstructing 400 years of tree-ring derived streamflow and precipitation data provides a range of climate conditions to evaluate proposed GSL causeway modifications on north and south arm elevation and salinity. The following research questions will be addressed in chapters 2 and 3 of this thesis:

(1) How will the water and salt balance of Utah’s Great Salt Lake change with proposed modifications to the railroad causeway using historical 1966-2012 climate and streamflow data?

(2) How do GSL elevation and streamflow of the past 100 years compare to a 400-year reconstruction of GSL, and how would causeway bridge alternatives affect water and salt balance with increased climatic variability represented in the 400 year reconstruction?
CHAPTER II
MODELING CHANGES TO SALINITY IN GREAT SALT LAKE FROM RAILROAD CAUSEWAY ALTERATIONS

2.1 INTRODUCTION

Northern Utah’s Great Salt Lake (GSL) is a pluvial lake and a remnant of the larger, historical Lake Bonneville. GSL is the largest saline lake in the western hemisphere and the fourth largest in the world (Arnow and Stephens, 1990). GSL’s large population of macroinvertebrates supports millions of resident and migratory birds, making the lake a vital link in the Pacific Flyway (Aldrich and Paul, 2002). GSL also contributes approximately $1.3 billion annually to Utah’s economy through recreation, mineral extraction, and brine shrimp cyst harvest (Bioeconomics, 2012). Because of its ecological, social, and economic significance, lake conditions and salinity are important to local residents, lake managers, and other stakeholders.

In 1959, Union Pacific Railroad constructed a rock-filled, semi-porous railroad causeway across GSL, bisecting the lake into north and south bays, locally referred to as “arms” (Figure 2.1). Since then, lake dynamics have changed dramatically, with substantial salinity differences between the two arms. The north arm is often saturated (averaging approximately 317 g/L, with saturation occurring near 350 g/L), while the south arm, which receives the vast majority of streamflow, averages less than half the salinity of the north. Two culverts were built upon causeway construction to increase flow between arms. However, due to the slow subsidence of the causeway over time, the culverts deteriorated and were in danger of collapse, prompting their closure in 2013. A
bridge was proposed as a replacement, with four design alternatives provided by Union Pacific Railroad (Waddell and Gwynn, 2014). The design of the bridge is likely to change water and salt flow, with potential to significantly alter salinity levels in each arm.

I investigated the salt and water balance between GSL’s north and south arms from anticipated railroad causeway alterations by updating and applying the United States Geological Survey’s (USGS) Great Salt Lake Fortran Model (Waddell and Bolke, 1973; Wold et al., 1997; Loving et al., 2000). My research analyzes how the causeway influences lake elevation and salinity between arms, and evaluates causeway alternatives to identify promising solutions for managing water and salt flow in GSL. It also provides an example modeling approach to aid decision-making for other terminal lakes.

Salinity is a growing problem for terminal lake management worldwide (Williams, 1999). Salinity in Mono Lake, a prominent saline lake in California, USA, decreased following decades of water diversions from streams which feed the lake. Mono Lake’s level has risen somewhat following a 1994 court case which allocates water to the lake for ecological and aesthetic uses (Hart, 1997). Lake Urmia, Iran, considered GSL’s sister lake due to shared characteristics of elevation, latitude, sediment, and a causeway (Kelts, 1986), has also faced salinity and water resources management problems from water diversions. Management strategies to reduce recent salinity increases in Mono Lake and Lake Urmia have focused on increasing freshwater inflows to the lake. Like Mono Lake and Lake Urmia, water is diverted for urban and agricultural water uses upstream of GSL; however, the railroad causeway provides another opportunity to manage salinity in GSL.
Computer models provide a tool to evaluate and simulate changes to hydrologic and environmental systems. The relative simplicity of many closed basin systems enables a mass balance approach to simulating hydrologic conditions. Mass balance models have been used to investigate lake dynamics at other terminal lake worldwide, including Mono Lake (Vorster, 1985), Argentina’s Laguna Mar Chiquita (Troin et al., 2010), Ethiopia’s Lake Tana (Kebede et al., 2005) and Kazakhstan’s Aral Sea (Benduhn and Renard, 2004). These models help inform management decisions, such as inflow quantities necessary to maintain desired salinity levels.

USGS’ GSL Fortran Model was developed to evaluate GSL water balance and salinity conditions. It has been updated several times (Waddell and Bolke, 1973), primarily to account for changes in causeway condition. For example, the frequent addition of fill material to prevent the lake from overtopping the causeway resulted in a change of the permeability of the causeway, necessitating new calculations (Wold et al., 1997). Additionally, an 88 meter (m) long breach was installed in the causeway in 1984, allowing more water to flow between the arms. The most recent update (Loving et al., 2000) accounted for these changes and evaluated effects of the causeway breach and West Desert pumping project, which pumps water from the lake to mitigate flooding in wet periods.

The closure of the historical culverts and a proposed new bridge warranted an update and new investigation into causeway dynamics. I updated the GSL Fortran Model to evaluate proposed causeway bridge designs affect GSL water and salt balance. The
specific alternatives examined provide information that can directly improve management of the GSL.

In the following sections of this chapter, I describe GSL geography, hydrology, anthropogenic impacts, and ecology. Next I explain the Great Salt Lake Fortran Model, its assumptions, and outline the model runs I performed. Results focus on model validation with measured data, and differences in salt content, concentration, and lake level between runs. I finish by detailing limitations of my approach and discussing major findings within the context of GSL management, as well as insights and implications for other terminal lakes.

2.1.1 Background

GSL is located in north-central Utah (Figure 1). It is bounded by the Wasatch and Uinta Ranges to the east and West Desert to the west. The climate is semi-arid. GSL averages roughly 20 cm of precipitation per year, with the majority of precipitation falling as snow in the mountains. Snowmelt runoff occurs in the spring followed by low streamflows throughout the rest of the year. Baseflow allows for major tributaries to be sustained throughout the dry summer and fall. Spring runoff and subsequent late summer baseflow is evident in GSL salinity, which fluctuates annually with spring dilution followed by concentration in summer to early winter (Price, 1985).

As a terminal lake, GSL’s only outflow of water is via evaporation. GSL surface elevation (henceforth level) is sensitive to inflows and evaporation, and fluctuates significantly through time (Mohammed and Tarboton, 2012). Streamflow from the three main tributaries (Bear, Weber and Jordan Rivers) on average account for 64% of the total
freshwater entering the lake. Direct precipitation accounts for 33% and groundwater accounts for the final 3% of inflows (Loving et al., 2000). Over the past 160 years, lake level has averaged 1280 m above sea level, and lake area increases dramatically with level. At 1280 m, GSL surface area is 4400 km², however with an increase of elevation to 1283 m, area increases to nearly 6000 km² (Arnow and Stephens, 1990). Despite its area, the mean depth of the lake is only 4.3 m at mean elevation. The south arm, averaging 12.3 x 10⁹ m³ since 1966, is roughly 80% larger than the north arm, which averages approximately 6.75 x 10⁹ m³.

Lake level (and thus volume) and salinity are inversely related and vary seasonally and decadally with climate. During wet periods, lake level and volume increase, and salinity decreases. During dry periods, lake level and volume decrease, which concentrates salinity. Total minerals, or salts, is the sum of the dissolved and precipitated salts present in the lake and is generally static. Historically, precipitated salt content on the bed of the lake has been confined to the north arm. Prior to human development, total salt content changed only on geologic timescales. The estimated annual tributary contribution of total dissolved solids (TDS) to GSL is estimated at 3.5 million metric tons per year, which is roughly 0.08% of the current 4.5 billion metric tons of salt in GSL (Hahl and Langford, 1964). Thus, in human timescales, tributary salt contributions to GSL are relatively minor. Unlike many saline lakes, which are often carbonate dominated, the chemical composition of GSL is dominated by sodium chloride, and shares an ionic composition similar to that found in oceans.
2.1.2 Anthropogenic Impacts

The total amount of salt in GSL has been reduced over the past half century by mineral extraction and export of brine from the lake for flood protection. GSL is an ideal location for mineral extraction via evaporation ponds because of the lake’s high salinity and the region’s dry climate. Four large mineral extraction companies, in addition to several smaller companies, operate on GSL. Additionally, two large hydraulic pumps stand ready to transport brine from the north arm into the adjacent West Desert to protect local highways and other infrastructure from flooding. This pumping activity, called the West Desert Pumping Project, operated in wet years from 1986 to 1989 and reduced salts by an estimated 0.45 billion metric tons (Loving et al., 2000). In total, GSL has lost approximately 1 billion metric tons of salt from anthropogenic causes over the past century.

Upon completion of the solid-fill railroad causeway in 1959, flow between the north and south arms was restricted to that moving through the semi-porous fill material and two 4.6 m-wide and approximately 6 m-deep culverts, constructed to enable boat passage through the causeway. In 1984, an 88 m wide and 4 m deep breach was added to increase inter-arm flow and alleviate flooding around the south arm. Due to this hydrologic separation, and the south arm receiving the vast majority of the total streamflow, south arm lake level is now roughly half a meter higher than the north arm, resulting in a pressure gradient which forces brine near the lake surface to flow from the south arm to the north arm. However, since the north is considerably more saline, a
Figure 2.1. Great Salt Lake and surrounding watershed. Three main tributaries are the Bear, Weber, and Jordan Rivers, which contribute roughly 95% of incoming streamflow.
density gradient exists at depth within the lake which forces brine to flow from the north arm to south arm through the lower parts of the culverts and causeway fill material (Loving et al., 2000). This deep brine forms a concentrated layer (monimolimnion) below a depth of ca. 6 m in the south arm. The GSL causeway is built on soft lake sediments and has slowly subsided over time, resulting in a loss of integrity of the culverts. In 2013, Union Pacific Railroad closed the culverts as an emergency structural safety provision and proposed to replace them with a bridge.

2.1.3 GSL Ecology

The ecologies of the two arms are now quite distinct due to salinity differences. The south arm supports large populations of brine shrimp (*Artemia franciscana*) and brine fly (*Ephydra cinerea*). The hypersaline north arm is largely inhospitable for significant populations of macroinvertebrates, such as *Artemia* or *Ephydra* to survive, and is instead characterized by several species of phytoplankton and archaea (Post, 1981). Although not the only macroinvertebrate present, *Artemia* are a keystone species because they control phytoplankton by grazing, and are also a major food source for birds (Stephens, 1990). The relatively moderate salinities of the south arm provide habitat for large populations of *Artemia*. However, during wet years with low salinity, predators such as corixids (water boatmen) colonize the south arm, which can result in a trophic cascade where *Artemia* populations fall precipitously, resulting in reduced prey availability for migratory birds and waterfowl, as well as revenue loss for the brine shrimp harvest industry (Wurtsbaugh and Berry, 1990). This was observed in the mid-1980’s when salinity levels dropped to nearly 50 g/L in the south arm. Birds also feed
extensively on the *Ephydra* (Roberts, 2013), the larvae of which grow primarily on stromatolites (biostromes) in the shallow areas of the south arm (Wurtsbaugh et al., 2011).

Research into relationships between salinity and *Artemia* and *Ephydra* is ongoing, but maximum survival and growth for both species is thought to occur around 100 g\L and decreases above 125 g\L (Barnes and Wurtsbaugh, 2015). GSL *Artemia* survive with salinity as low as 25 g\L, however at lower salinity levels, predation by salt tolerant organisms such as corixids likely limit survival (Wurtsbaugh and Berry, 1990). Although salinity is not the exclusive control on *Artemia* or *Ephydra* in GSL, it is a main driver of ecosystem productivity. Thus, I focus on salinity changes from causeway alteration and management in my modeling and analysis. Changes to salinity from causeway alterations are of keen concern to the brine shrimp harvesting industry, wildlife managers, and mineral extraction companies.

### 2.2 METHODS

To evaluate the effects of proposed causeway changes on lake elevation, total salt, and salinity, I used USGS’ Great Salt Lake Fortran Model (Waddell and Bolke, 1973; Wold et al., 1997; Loving et al., 2000) to simulate historical and modified causeway lake level and salinity. The model uses a mass balance approach to calculate water and salt flow between GSL’s bays and estimates water volume, total salt, and salinity for each arm of the lake. Water is assumed to be vertically and laterally homogenous within each arm, estimating salinity above the deep brine layer. Water volume is calculated at each time timestep (every two days) by:
\[ V_{aT} = V_{aT-1} + Q_{S_{in}} + Q_{G_{in}} + Q_{C_{in}} + P + Q_{wdr} - E - Q_{C_{out}} - Q_{wd} \]  

where \( V_{aT-1} \) is the volume of an arm at the previous timestep, \( Q_{S_{in}} \) is streamflow into the arm, \( Q_{G_{in}} \) is groundwater inflow, \( Q_{C_{in}} \) is total flow into the arm through the causeway, \( P \) is direct precipitation, \( Q_{wdr} \) is return flow from West Desert (if occurring), \( E \) is evaporation, \( Q_{wd} \) is losses to West Desert pumping (if occurring), and \( Q_{C_{out}} \) is outflow from an arm through the causeway. Rate variables have units of m\(^3\)d\(^{-1}\), while volumes have units of m\(^3\).

Mineral content of each arm for each timestep is calculated by:

\[ L_{aT} = L_{aT-1} + L_{T} + L_{inc} + L_{rd} - L_{pp} - L_{outC} - L_{outP} - L_{outE} \]  

where \( L_{aT-1} \) is the previous timestep’s salt content, \( L_{T} \) is incoming tributary content, \( L_{inc} \) is incoming content through the causeway, \( L_{rd} \) is redissolved content, \( L_{pp} \) is precipitated content, \( L_{outC} \) is content exported through the causeway, \( L_{outP} \) is content removed when West Desert pumping is initiated, and \( L_{outE} \) is content extracted from mineral extractions.

Flows through the culverts and breach were calculated using equations developed by Holley and Waddell (1976), Wold et al. (1997), and Loving et al. (2000). Details of equations are summarized in Loving et al. (2000). Salt loads are in metric tons. All salt losses/additions are in metric tons per time step, and salinity was calculated by

\[ C_{aT} = L_{aT}/V_{aT} \]  
in units of g\(\text{L}^{-1}\). Salt concentrations exceeding 350 g\(\text{L}^{-1}\) are converted to precipitated salt content in the model.
Holley and Waddell (1976) did not anticipate submersion of the culverts, and therefore did not develop equations for bi-directional flow with submerged conditions. Submerged conditions occurred prior to Wold et al.’s (1997) updating of the model. However, since the culverts often become inundated with debris when submerged, they assumed no flow occurred through culverts once submerged, and bi-directional flow occurred only through the breach and fill material. Loving et al. (2000) recognized that indeed some flow did occur with submerged culverts, and updated the original equations developed by Holley and Waddell (1976) to calculate bi-directional flow when culverts were submerged. However, flow measurements were not taken from 1987-1995 when culverts were submerged to verify the new equations. Both Wold et al. (1997) and Loving et al. (2000) agreed that flow through the culverts during this time was greatly diminished. Despite the equations developed by Loving et al. (2000) for bi-directional flow with submerged culvert conditions, comparing results between zero culvert flow under submerged conditions with flow equations developed by Loving et al. (2000), a visual comparison clearly showed that the assumption of zero flow better replicated measured lake salinity and level. Therefore, I assumed culvert flow under submerged conditions was zero.

2.2.1 Input Data and Sources

Streamflow volumes were from USGS gages on the three major rivers feeding the lake, the Bear, Jordan, and Weber Rivers, direct precipitation was from Oregon State University’s PRISM dataset (PRISM Climate Group), and groundwater was assumed constant at 10 million m$^3$/month in the south bay and 1 million m$^3$/month in the north.
bay (Loving et al., 2000). Monthly evaporation was estimated by closing a mass balance equation with changes of volume and inflows. Initial salt content and lake elevations were obtained from Utah Geological Survey and USGS, respectively. Bathymetry data, the same used in Loving et al. (2000) was from unpublished USGS data. A visual analysis clearly showed that the mass balance approach more accurately reproduced historical lake level, salt content, and salinity, compared to using a salinity-adjusted Penman equation to estimate evaporation (Penman, 1948; Mohammed and Tarboton, 2012).

Causeway opening geometry, including the culverts, breach, and proposed bridge designs, were from Union Pacific Railroad (Waddell and Gwynn, 2014), and causeway subsidence rates were from Loving et al. (2000). Validation datasets were obtained from Utah Geological Survey for salinity and total salt content, and lake elevation data was from USGS.

2.2.2 Model Runs

Seven model runs simulating 1966-2012 were conducted, using identical climate, streamflow, West Desert Pumping, mineral extraction, and initial lake condition data. Details of each run are described below and summarized in table 2.1. Climate change effects on the lake were ignored.

1. Historical conditions

The historical 1966 – 2012 run simulated salt and water balance with the following causeway changes occurring through time: causeway and culverts subsided,
flow through causeway material was reduced in the late 1970s following subsidence (Loving et al., 2000), the breach was deepened in 1998 and again in 2000 (by 4.2 m and 2.1 m, respectively). The model also included West Desert pumping from 1987-1989 and salt losses from commercial extraction. This model run simulated historical conditions to evaluate model fit and accuracy, and provided a reference comparison for other model runs.

2 – 5. Union Pacific Railroad bridge alternatives

These runs estimated water and salt flow through the causeway if a bridge replaces the closed culverts. Union Pacific Railroad proposed four trapezoidal bridge alternatives (table 2.2 and Figure. 2.2). Alternative A is the largest, spanning 55 m at the

<table>
<thead>
<tr>
<th>Model Run</th>
<th>Model Name</th>
<th>Number of culverts</th>
<th>Breach</th>
<th>Subsidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Historical</td>
<td>2</td>
<td>Opened in 1984</td>
<td>Subsides over time</td>
</tr>
<tr>
<td>2</td>
<td>Alternative A</td>
<td>0</td>
<td>Opened in 1984</td>
<td>Subsides over time</td>
</tr>
<tr>
<td>3</td>
<td>Alternative B</td>
<td>0</td>
<td>Opened in 1984</td>
<td>Subsides over time</td>
</tr>
<tr>
<td>4</td>
<td>Alternative C</td>
<td>0</td>
<td>Opened in 1984</td>
<td>Subsides over time</td>
</tr>
<tr>
<td>5</td>
<td>Alternative D</td>
<td>0</td>
<td>Opened in 1984</td>
<td>Subsides over time</td>
</tr>
<tr>
<td>6</td>
<td>Current Conditions</td>
<td>0</td>
<td>Open throughout</td>
<td>Fully subsided</td>
</tr>
<tr>
<td>7</td>
<td>Whole Lake</td>
<td>0</td>
<td>No breach</td>
<td>No causeway</td>
</tr>
</tbody>
</table>
top and 19 m at the bottom. Alternatives B, C, and D, are 10 m narrower than alternative A with identical top widths and elevations, but alternative B has the same bottom depth as alternative A, while C and D are 1.5 m and 3 m shallower, respectively (Waddell and Gwynn, 2014). The location of the bridge opening in the causeway did not change between alternatives. All bridge alternatives used identical equations (with different parameters based on design) to calculate bi-directional flow through the bridge proposals. Head and density differentials calculate flow in a trapezoidal opening. These same equations are used to calculate flow through the breach (Loving et al., 2000).

6. Current conditions

Current conditions simulated causeway conditions when culverts were closed, the causeway had subsided, and flow was reduced through causeway fill material. This run simulated lake level and salinity if a bridge is not built to replace closed causeway culverts and represents conditions subsequent to December 2013, after both culverts were filled.

7. Whole lake conditions

A whole lake (no causeway) condition was estimated by dividing the sum of north, south, and precipitated salt by the combined volume of each arm. These calculations were completed using data from the historical model run. Salt losses due to pumping and mineral extractions were included in the whole lake condition so this run is comparable to other alternatives.
**Figure 2.2.** Proposed bridge alternative designs (Waddell and Gwynn, 2014).

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Top Width (m)</th>
<th>Bottom Width (m)</th>
<th>Channel Bottom Elevation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>54.9</td>
<td>18.6</td>
<td>1273.5</td>
</tr>
<tr>
<td>B</td>
<td>45.7</td>
<td>9.4</td>
<td>1273.5</td>
</tr>
<tr>
<td>C</td>
<td>45.7</td>
<td>14.9</td>
<td>1275.0</td>
</tr>
<tr>
<td>D</td>
<td>45.7</td>
<td>20.1</td>
<td>1276.5</td>
</tr>
</tbody>
</table>

**Table 2.2.** Details of proposed bridge alternatives. Specifications obtained from Union Pacific Railroad (Waddell and Gwynn, 2014).

**2.3 RESULTS**

**2.3.1 Model Validation**

Overall, the model provides an excellent representation of GSL lake level, salt content, and salinity (Figure. 2.3). Model results track measured data (representing a depth-weighted average of measurements taken at various depths and locations) well and there is no consistent bias. However, from 1989-2000 both modeled salt content and salinity in the south arm are lower than observed data. During this time, culverts were submerged and zero flow through them is assumed. I found that no culvert flow was more accurate than the submerged culvert equations developed by Loving et al. (2000) and
assumed no flow through culverts when they were submerged. In reality, the elevation and the density gradients between the north and south arms would likely have exchanged some small and unmeasured quantity of water in both directions through the culverts, and this may account for the discrepancy during this period.

The Nash-Sutcliffe Efficiency (NSE) statistic evaluates the predictive power of models by comparing the magnitude of modeled residual variance with measured data variance (Nash and Sutcliffe, 1970; Legates and McCabe, 1999; Moriasi et al., 2007). This unitless statistic ranges from $-\infty$ (no fit) to 1 (perfect fit). Table 2.3 provides the NSE for GSL level, salt content, and salinity. As shown, lake level is modeled with near complete accuracy (0.99 for both the north and south arms). Salinity in each arm is also excellent with values of 0.94 and 0.89 in the north and south arm, respectively. Total mineral content is less accurate, with NSE of 0.78 in the north, but only 0.36 in the south. The good NSE values for lake level and poor NSE for load are due to NSE being a statistic that is normalized by variance. The intent of NSE is to quantify the model's ability to explain variability. With the exception of anthropogenic losses, changes to total salt content in the GSL are negligible. Salt movement between the arms gives rise to the small variability in total load in each arm, and the small observed variability in the denominator of NSE leads to poorer values. This effect can be seen in Figure. 2.3C where load in each does not change greatly through time and the difference between modeled and observed salt load is comparable in scale to the observed variability. On the other hand, lake level is highly variable and the model replicates this well, leading to NSE statistics with good fit.
When culverts were submerged (and bi-directional flow was assumed zero), the model is the least accurate. Additional uncertainty exists regarding estimates of salt loss from West Desert Pumping. The modeled inaccurate period begins around 1990 immediately following pumping activity. Finally, total salt content is not a direct measurement, rather a calculation based on ionic concentration and lake volume; therefore, it has the highest variability and least certainty of all modeled variables.

Total salt content was reduced by roughly 1 billion metric tons from 1985-2012 in this model (Figure. 2.3c). Roughly half (0.45 billion metric tons) of this loss is attributable to pumping in the late 1980s, when brine was pumped to the West Desert to evaporate. The remaining losses are from commercial mineral extractions. The net loss of salt manifested in north arm salinity levels when it was unsaturated and no precipitated salt was present.

2.3.2 Bridge Alternatives

Salinity differences between the proposed bridge alternatives and historical conditions were greatest from the mid-1980s through early 2000s, when culverts were submerged (Figure. 2.4). Alternative A allowed for the greatest bi-directional flow exchange (Figure. 2.5) while alternative D allowed the least. Alternatives B and C are nearly identical throughout the modeled period. The top elevation (1284 m) of all bridge alternatives was sufficiently high so that they are never submerged with 1966 -2012 conditions. Summary statistics for each model run are shown in figure 2.4.

Probability exceedance curves from the modeled period indicate that a bridge opening in the causeway increased salinity in the south arm and reduced it in the north
Figure 2.3. Measured & modeled historical A) Lake level, B Salinity, C) Total Salt in GSL north and south arms. Different colored points in B and C represent different locations on GSL where measurements were taken. Salinity at each location is calculated as a depth averaged value. Total salt in C is calculated by summing north, south, and dissolved salts.
Table 2.3. Measured versus modeled Nash-Sutcliffe efficiency for historical simulation (unitless).

<table>
<thead>
<tr>
<th>Level</th>
<th>Salinity</th>
<th>Total salt</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td>South</td>
<td>North</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.99</td>
</tr>
</tbody>
</table>

The 50th percentile salinity in the south arm increased from 150 g\L historically, to 180 g\L with bridge alternative A, and 167 g\L, 165 g\L, and 157 g\L for alternatives B, C, and D, respectively. Similarly, salinity decreased in the north arm, where the 50th percentile drops from 335 g\L historically to 290 g\L with bridge alternative A, and 315 g\L, 316 g\L, and 321 g\L for alternatives B, C, and D, respectively.

Among the four proposed bridge designs, alternative A is the largest and allows for salinities in the north and south arms to be most alike (in other words, the most moderate) of any proposed designs. This suggests that the width of causeway opening near the lakebed is important for increasing bi-directional flow. Although bridge alternative B is nearly 1.5 m shallower than alternative C, they produce nearly identical salinities in both the north and south arm throughout the modeled period (Figure. 2.5). Results from alternative D, the alternative with the shallowest bridge bottom, are similar to those of the historical model run. An exception occurs from 1987-2003, when the culverts were inundated. This is reflected in the exceedance curves (Figure. 2.6) which show that despite close alignment of flow throughout much of the period, there is a
systematic shift to more moderate salinities in each arm with alternative D, compared to historical conditions.

2.3.3 Current Conditions

The current conditions model run simulated lake conditions with closed culverts and subsided conditions throughout the 45-year modeled period (Figure 2.7). North arm salinity between the current conditions model run and historical model run show little difference throughout the modeled period. South arm salinity, however, varied significantly more through time. The largest differences occurred from 1973-1984 when fill material provided the only flow exchange for the current conditions simulation. During that time, in the historical conditions run, culverts were not submerged and causeway fill was more permeable since it has not yet subsided. A similar divergence was observed from 2004 – 2012 when culverts were not submerged in the historical conditions run but were closed in the current conditions run. When the breach was installed in 1984 in each model, salinity began to converge between the two runs, compounded by no bi-directional flow through submerged culverts in the historical conditions run. Although the salinity difference between the historical and current conditions models are variable over time, the comparison of the two shows that the culverts were important to bi-directional flow exchange when they were not submerged. In other words, the culverts helped to equalize salinities in both arms at lower lake elevations.
Figure 2.4. Modeled salinity concentrations of each bridge design and historical conditions in GSL north arm (A) and south arm (B).
Figure 2.5. Bi-directional flow from (A) north to south, and (B) south to north, with bridge alternatives and historical conditions. Historical culvert flow was assumed to be zero when culverts were submerged (1984-2004). Bridge alternatives are never submerged.
Table 2.4. Lake characteristics under each model run. Includes mean, maximum, and minimum salinity in the north and south arm for all model runs for the period 1966-2012. Historical is baseline simulation for comparison of alternatives.

<table>
<thead>
<tr>
<th>Model Run</th>
<th>North Arm</th>
<th>South Arm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean salinity (g/L)</td>
<td>Max salinity (g/L)</td>
</tr>
<tr>
<td>Historical</td>
<td>317</td>
<td>351</td>
</tr>
<tr>
<td>Current Condition</td>
<td>320</td>
<td>351</td>
</tr>
<tr>
<td>Alternative A</td>
<td>282</td>
<td>351</td>
</tr>
<tr>
<td>Alternative B</td>
<td>297</td>
<td>351</td>
</tr>
<tr>
<td>Alternative C</td>
<td>297</td>
<td>351</td>
</tr>
<tr>
<td>Alternative D</td>
<td>301</td>
<td>351</td>
</tr>
<tr>
<td>Whole Lake</td>
<td>222 (mean)</td>
<td>115 (min)</td>
</tr>
</tbody>
</table>

2.3.4 Whole Lake

Estimated whole-lake salinity (assuming a causeway was never built) is shown in figure 2.8 and compared to the historical conditions simulation. Modeled whole lake salinity remains between that of the north and south arms, but trends slightly toward south arm salinity because the south arm is roughly twice the volume of the north arm. These results are consistent with previous research on modeled whole lake GSL conditions (Loving et al., 2000; Null et al., 2013).

2.3.5 Limitations

This study focuses solely on changes to salinity and water balance from modifications to the causeway bisecting GSL. Although these changes are likely to have significant effects on the economic and ecological uses of GSL, the quantification of such effects are beyond the scope of this study.
Figure 2.6. Probability of exceedance curves for north arm (A) and south arm (B) for simulated historical conditions and each bridge alternative.
Figure 2.7. Comparison of historical model and current condition model salinity

My modeling assumes historical hydroclimate conditions for precipitation, evaporation, streamflow and water diversions. Increased variability from climate change was not considered, although alterations to hydrology and land use are expected over the coming century. Additionally, growing population along the Wasatch front may increase water demand and climate change has the potential to fundamentally alter the hydrology of the GSL watershed (Garfin et al., 2013).

All model runs are affected by the high precipitation years of 1984-1988, when high lake levels caused culverts to be submerged. As discussed above, historical inter-arm flow through the culverts during this period was greatly reduced due to culverts inundation with debris, but likely not zero. This is a limitation of this model and a potential improvement to make for future modeling studies.
Figure 2.8. Historical north and south arm salinity, and theoretical whole lake salinity. The whole lake simulation represents a lake undivided by a causeway.

Flow through causeway fill material is considered to be identical along the entire length of the causeway. Wold et al. (1997) found that flow conveyance is lowest at each end of the causeway, and slowly increases towards the middle. Despite this spatial variability, Wold et al. (1997) and Loving et al. (2000) used homogenous causeway permeability with sufficient accuracy to replicate lake behavior.

The model assumes that each arm is perfectly mixed. In reality, spatial variability exists within each arm. The most obvious and important example of this is the monimolimnion, or vertically-stratified deep brine layer in the south arm, which exhibits salinity close to that of the north arm. This layer is quite dense and it is estimated that 25% is mixed into the upper layer each year (Jones and Wurtsbaugh, 2014). Variable
salinities within the south arm also exist at the bays (estuaries) where tributary streams flow into GSL. Although horizontal spatial variability occurs, the consistency of measured salinities at various locations within each arm support the assumption that water is reasonably well mixed within each arm when the monimolimnion is ignored.

Finally, the Great Salt Lake Fortran model is a water and salt balance model. It is outside the scope of this research to update the complex hydrodynamic equations of interflow through openings in the causeway to account for relatively small model errors. Regardless, my modeling and analysis provides direct and useful comparisons of alternative causeway modifications and designs.

2.4 DISCUSSION AND MANAGEMENT IMPLICATIONS

With construction of a railroad causeway in 1959, GSL hydrology was dramatically changed, which altered salinity, as well as the ecological, social, and economic uses of GSL. Lake managers and stakeholders are interested in the future condition of GSL following culvert closures in 2012 and 2013, and a proposed bridge opening in the railroad causeway. My modified USGS GSL Fortran Model simulates Great Salt Lake water and salt balance with sufficient accuracy to enable comparisons and estimations of future causeway conditions.

Like most terminal lakes, GSL has multiple and competing uses. Even for the same user groups, causeway modification may have non-uniform consequences. Commercial mineral extraction, for example, occurs in the north and south arms. Thus, companies operating in the south would welcome the increase of salinity provided by larger bridge designs, while those in the north would lament the loss minerals available
for extraction. Similarly, increasing south arm salinity through a larger bridge opening would favor brine shrimp survival (and brine shrimp cyst harvest) during high lake level periods. However, larger bridge openings could also result in the south arm being too salty for brine shrimp at lower lake levels. GSL management decisions will be difficult and modeling analyses such as this one help to inform decision-making and eliminate poor alternatives.

GSL’s current conditions, with closed culverts that reduce interflow through a subsided causeway, will increase salinity differences between north and south arms. Average predicted salinities from 1966-2012 for the south arm and north arm with current conditions are \(125 \text{ g}\ell^{-1}\) and \(320 \text{ g}\ell^{-1}\), respectively - a decrease of roughly 11% in the south and increase of 1% in the north from historical causeway conditions. The south arm will become increasingly fresh with most of the streamflow contributions, and the north arm will become increasingly saline with precipitation as the only inflow of freshwater and reduced inter-flow from the south arm. Thus, the poor macroinvertebrate habitat in the north arm is unlikely to improve. The decrease of south arm salinity increases the vulnerability to infrequent but severe loss of macroinvertebrates due to salt tolerant corixids during times of high streamflows and low salinity.

The four proposed bridge designs create different salinity conditions in the north and south arms. If replication of culvert flow is the primary objective, alternative D is best (Figure 2.4). In fact, alternative D will improve upon the culvert design because the top elevation is higher so it is less vulnerable to inundation and potential clogging. However, the culverts were designed for boat passage between the bays, without specific
flow or salinity conditions considered. Therefore, replicating flow through culverts may not result in preferred conditions for lake ecology, mineral extraction industries, or brine shrimp harvesters. If maximizing inter-arm flow exchange is the goal, alternative A is best (Figure. 2.5). With this alternative, average salinity is reduced by 35 g/L in the north arm and is increased by 31 g/L in the south arm. This alternative achieves salinities closest to an undivided lake.

A bridge opening design that is adaptive to changing future conditions or objectives would be useful. Adaptive management strategies, such as controllable gates or adjustable depths between bays, have been informally discussed amongst interests groups on GSL (Null et al., 2013). These options allow for salinity control depending on conditions and needs. However, modeling such systems was outside the scope of this study.

My results show that causeways, or other divisions in terminal lakes, can significantly change salt balance. The magnitude of these changes can be partially controlled with causeway management. Such a strategy may be useful for other terminal lakes worldwide, particularly those facing desiccation and increasing salinity. Strategic isolation of parts of terminal lakes may provide an opportunity to maintain lower (and presumably preferred) salinity levels in other portions of the lake. Using a relatively simple mass balance model, such as the one described here, provides a tool to evaluate such opportunities.

Determining how to manage terminal lake elevation and salinity are emerging branches of ecological management and water resources management (Williams, 1999).
Many terminal lakes are threatened worldwide. Some terminal lakes have similar causeways, such as Iran’s Lake Urmia and central Asia’s Aral Sea. Others, like GSL, have inflow and salinity alterations from upstream water diversions, such as California’s Mono Lake, Nevada’s Walker Lake, and Central Asia’s Aral Sea. This study contributes to the body of knowledge on terminal lake management by quantitatively assessing water and salt flow for a specific terminal lake. This research illustrates that flow alterations and flow modifications within lakes cannot be separated from lake salinity, ecology, management, and economics.
CHAPTER III

CLIMATE VARIABILITY EFFECTS FOR UTAH’S GREAT SALT LAKE LEVEL
AND SALINITY WITH PROPOSED CAUSEWAY MODIFICATIONS

3.1 INTRODUCTION

Terminal lakes are indicators of local climate variability (Wang et al., 2012). Since the only source of outflow in closed basins is evaporation, terminal lakes, such as Utah’s Great Salt Lake (GSL), are sensitive to the balance between inflows (incoming streams and direct precipitation) and evaporation (Mohammed and Tarboton, 2012). GSL has a variable lake surface elevation (henceforth level), where drought causes declining lake levels and high precipitation causes level to rise. The relatively short-term cycles of variable GSL level are well documented (e.g., Mann et al.; 1998; Rajagopalan and Lall, 1998; Zhang and Mann, 2005), and studies have found lake level is strongly correlated to decadal and quasi-decadal Pacific oscillations (Wang et al.; 2012, Wang et al., 2010 respectively). Indeed, relatively accurate forecasting of GSL level is now possible up to 6 years in advance due to strong teleconnection to atmospheric conditions in the southeast Pacific Ocean (Gillies et al., 2011).

However, while several recent studies have investigated long-term hydroclimatic variability (100+ years) within the Great Salt Lake watershed (Allen et al., 2013; Bekker et al., 2014; DeRose et al., 2014; DeRose et al., 2015), none have investigated long-term hydroclimate effects on lake level and salinity with the railroad causeway. Recent paleo-streamflow analyses suggest that the past century had fewer and shorter droughts and smaller floods than previous centuries (Allen et al., 2013; Bekker et al., 2014). Further
tree-ring correlations to GSL level suggest that recent fluctuations of drought/flood conditions are on a shorter 10-15 year cycle compared to reconstructed records of 60-70 years (DeRose et al., 2014). Longer records of reconstructed streamflow data are vital for capturing rare but important events. Extending the record by proxy reconstructions increases the likelihood that extremely wet and dry years are quantified. Tree-ring analysis provides a method to extend hydrologic records centuries prior to measured gage data (Meko et al., 2012) and can be used to reconstruct precipitation and streamflow, although these data are specific to the local regions near the trees used for dendrochronology.

Union Pacific Railroad constructed a causeway in 1959, which bisects the lake into north and south bays, locally referred to as “arms”. Since that time, substantial salinity differences between the two arms have developed because all three major tributaries (Bear, Weber, and Jordan Rivers) enter the south arm. Streamflow to the south arm makes up approximately 64% of total incoming freshwater, with approximately 33% from direct precipitation and the remainder from groundwater seeps (Loving et al., 2000). The north arm is often saturated with salt (averaging approximately 317 g/l), while the south arm averages less than half the salinity of the north. Flow between north and south arms were historically provided by two 4.5 m culverts, an 88 m wide “breach”, and through the semi-porous causeway fill material. Culverts, which historically allowed for bi-directional flow through the causeway, subsided into the soft lakebed sediment and were filled in 2013 amid structural safety concerns. A bridge has been proposed as a replacement, with four different designs presented (Waddell and Gwynn, 2014).
design of the bridge is likely to change water and salt flow, with potential to significantly alter salinity in each arm.

This study uses a 400 year (1604-2004) paleo-streamflow and precipitation reconstruction as input data for a water and salt balance model simulating lake elevation and salinity in each arm of GSL, as well as flow between arms. I use these inputs to evaluate how proposed railroad causeway changes would influence lake elevations and salinities with long-term climate variability that includes longer, more frequent, and higher magnitude droughts and floods. No other research has evaluated potential causeway modifications on GSL level, salinity, and inter-arm flow with long-term climate variability. Although the effect that proposed bridge designs would have on inter-arm flow and salinity was previously described in chapter II of this thesis for historical 1966 – 2012 climate conditions, incorporating a longer climate record is important to improve understanding of GSL salinity and level dynamics, and to provide managers and stakeholders of GSL with a broader depiction of possible GSL conditions.

Paleo-limnologic reconstructions, particularly in endorheic basins, rely on a bevy of tools and approaches to reconstruct salinity and water level over time. Approaches to reconstruct lake level can vary from geologic interpretation of past lake land features, such as Lake Bonneville (Gilbert, 1890) or Lake Malheur (Dugas, 1997) shorelines, to isotopic analysis of sediments, as was done in Mono Lake (Li et al., 1997). Still others have used tree-ring analysis to correlate annual tree growth to lake level fluctuation, as was done recently for GSL (DeRose et al., 2015). Salinity reconstructions typically use isotopic analysis, as was done in San Francisco Bay (Ingram and DePaolo, 1993), or
fossilized diatoms in sediments, which was done for a series of terminal lakes in northeastern Canada (Wilson et al., 1994). Each approach offers unique benefits. For example, isotopic analysis provides data for thousands of years, though at relatively low temporal resolution, sometimes as low as one data point per century. Tree-ring analysis on the other hand provides an annual time series, though it is limited in duration to the age of appropriate tree-species within the watershed.

My study estimates both lake level and salinity over a 400 year period by using tree-ring reconstructed paleo-streamflow, paleo-precipitation, and paleo-lake level in the watershed. Further, I evaluate GSL salt and water balance effects of proposed causeway design changes with the 400 year reconstructed hydrology. This allows for a much longer period to evaluate lake response to changes than previously possible.

3.2 METHODS

To create an annual time series of lake level, load, and salinity from 1604-2004, I combined several tree-ring reconstructions of paleo-streamflows in the GSL basin, a tree-ring reconstruction of paleo precipitation at GSL, and a tree-ring reconstruction of GSL level to calculate evaporation. I then used these hydrologic parameters as inputs to the USGS Great Salt Lake Fortran Model (GSLFM) to evaluate how proposed management changes to the GSL causeway would change the water and salt balance of the lake over a much longer period than previously possible. A visual summary of model flow with inputs and outputs is displayed in figure. 3.1.
3.2.1 Paleo-Reconstructed Streamflow

Paleo-streamflows were developed for the Weber River by Allen et al. (2013), the Bear River by DeRose et al. (2015), and the Logan River by Bekker et al. (2014) (Figure 3.2). However, paleo-streamflows were estimated for the Weber and Bear Rivers high in the watersheds and well above respective confluences with GSL. Therefore, I regressed stream gages where paleo-streamflows were reconstructed with downstream gages near the mouth of GSL, using mean annual flows from the Bear River (USGS gage 10126000, near Corrine) and Weber River (USGS gage 10141000, near Plain City). The period of available data for the Bear River was 1950-2014, while the Weber River was 1949-2014.

Figure 3.1. Primary inputs and outputs used in GSL paleo model.
The upper Bear River and its largest tributary, the Logan River, were summed before correlation. No streamflow reconstruction was available for the Jordan River. Consequently, flow was estimated by regressing recent (1950-2014) Bear and Jordan River discharge. Flow from several small and ephemeral tributaries which enter GSL in Davis County, were accounted for by correlating summed annual flows, with Weber River streamflow. The flows at all gages are subject to varying degrees of upstream withdrawals. Therefore, the model simulates the modern hydrology of the watershed, where dams and withdrawals are present. Because of this, paleo simulations do not represent natural flow conditions.

Figure 3.2. Observed and reconstructed streamflows for the Weber (Allen et al. 2013), Bear (DeRose et al. 2015), and Logan Rivers (Bekker et al. 2014).
Reconstructed streamflows were compared to measured 1966-2014 data (Figure 3.3) to assess accuracy. Total reconstructed paleo-streamflows generally capture the historical range of streamflow conditions ($R^2 = 0.44$), although paleo flows significantly underestimated measured flows (Figure 3.3). Another regression, relating summed model streamflow and summed measured streamflow was developed to account for under-predicted streamflow, and bring the measured to modeled relationship closer to 1:1. Although the second regression, correlating summed modeled data to summed measured data, improved overall fit, high and low streamflows were not well represented. For example, the highest flow years of 1984 and 1985 were underestimated, while particularly dry years (1979) were over estimated.

Figure 3.3. Measured versus modeled streamflow entering Great Salt Lake. Summed reconstructed streamflow data is shown in blue, while transformed streamflow data is in red, with 1:1 line plotted.
3.2.2 Paleo-Reconstructed Precipitation

Tree-ring reconstructed precipitation was developed by DeRose (unpublished data, 2015) using identical methods to streamflow reconstructions, whereby total measured historical precipitation was correlated to annual tree-ring growth, and was evaluated using several statistical techniques (table 3.1). Results of this reconstruction had an adjusted $R^2$ of 0.46 and a root mean square error (RMSE) of 1.33 cm. Figure 3.4 displays measured vs. modeled data for precipitation data.

The same tree-rings were used to estimate precipitation and streamflow (DeRose, unpublished data, 2015). Also, the GSL elevation reconstruction (DeRose et al., 2014) shares one predictor with the Logan and Weber Rivers. Because of this, there is potential for compounding errors in the precipitation reconstructed and the GSL reconstruction.

Table 3.1. Validation statistics for precipitation reconstruction. Includes model fit statistics and calibration-verification results for GSL annual reconstruction.

<table>
<thead>
<tr>
<th></th>
<th>$R^2$</th>
<th>adj. $R^2$</th>
<th>RE</th>
<th>CE</th>
<th>Sign test (hit/miss)</th>
<th>RMSE (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibrate (1919-1964)</td>
<td>0.41</td>
<td>0.32</td>
<td>0.50</td>
<td>0.40</td>
<td>36/10</td>
<td>1.16</td>
</tr>
<tr>
<td>Calibrate (1965-2009)</td>
<td>0.55</td>
<td>0.48</td>
<td>0.41</td>
<td>0.15</td>
<td>36/9</td>
<td>1.50</td>
</tr>
<tr>
<td>Full model</td>
<td>0.50</td>
<td>0.46</td>
<td></td>
<td></td>
<td>71/20$^a$</td>
<td>1.33</td>
</tr>
</tbody>
</table>

($R^2$) – coefficient of determination, (adj. $R^2$) coefficient of determination adjusted for degrees of freedom, RE – reduction of error statistic, CE – coefficient of efficiency statistic, RMSE – root mean-squared error.

$^a$ Sign test significant at the alpha < 0.01 level (Fritts, 1976).
3.2.3 Paleo-Reconstructed Evaporation

Evaporation was estimated by closing a mass balance equation of inflows and lake volume. A time series of lake volume was generated for 1604-2004 using annual paleo lake level estimates from DeRose et al. (2014), which correlated tree ring growth to GSL surface elevation using lake bathymetry (Loving et al., 2000). Evaporation was calculated as the difference of total inputs (precipitation + streamflow + groundwater) and change in lake volume. Change in volume and evaporation can be represented as:

$$\Delta V = V(t) - V(t - 1)$$

$$E = P + Q_s + Q_G - \Delta V$$
where $\Delta V$ is change in volume, $V(t)$ is volume at a specific timestep, $E$ is evaporation, $P$ is total precipitation, $Q_S$ is streamflow, and $Q_G$ is groundwater. Groundwater inflows are from Loving et al. (2000).

Because this approach relies on multiple variables, each with their own uncertainty, there is potential for compounding errors. To check if evaporation rates estimates are reasonable, paleo evaporation was compared to estimated historical evaporation calculated via adjusted Penman equation (Mohammed and Tarboton, 2012) (Figure 3.4).

Results showed that paleo-reconstructed evaporation was considerably lower than historical evaporation calculated using an adjusted Penman equation. Further, historical data suggests a bi-model distribution in each arm, potentially attributable to the cycle of wet and dry periods. The paleo model does not contain this bi-modality, and instead, both arms exhibit fairly normal distributions. An empirical approach, such as the Penman equation, was not feasible for the paleo record, because many input variables are not available, such as temperature and wind speed.

3.2.4 Great Salt Lake Fortran Model

I modified USGS’ Great Salt Lake Fortran Model (GSLFM; Waddell and Bolke, 1973; Wold et al., 1997; Loving et al., 2000) to simulate paleo GSL lake level and salinity with the railroad causeway separating GSL’s north and south arms. The model uses a mass balance approach to calculate water and salt flow between GSL’s two major bays and estimates water volume, total salt, and salinity for each arm of the lake. Water was assumed to be perfectly mixed within each arm above the deep brine layer, which is
Figure 3.5. Histograms of evaporation distributions in GSL north (A) and south (B) arms. Historical values estimate evaporation from 1966-2012 using a modified Penman equation (Mohammed and Tarboton, 2012) and paleo-evaporation calculated from mass balance equation. Bins separated by paleo evaporation mean, +/- 1 standard deviation, and +/- 2 standard deviations.
ignored in my model. Water volume was calculated at each time timestep (every two
days) by:

$$V_{aT} = V_{aT-1} + QS_{in} + QG_{in} + QC_{in} + P - E - QC_{out}$$  \hspace{1cm} (1)

where $V_{aT-1}$ is the volume of an arm at the previous timestep, $QS_{in}$ is streamflow into the
arm, $QG_{in}$ is groundwater inflow (obtained from Loving, et al. 2000), $QC_{in}$ is total flow
into the arm through the causeway, $P$ is direct precipitation, $E$ is evaporation, and $QC_{out}$ is
outflow from an arm through the causeway. All volumes ($P$, $E$, $V_{aT}$, $V_{aT-1}$) are in cubic
meters ($m^3$), while rates ($QS_{in}$, $QG_{in}$, $QC_{in}$, $QC_{out}$) have units of $m^3 \text{ d}^{-1}$.

Salt content of each arm for each timestep was calculated by:

$$L_{aT} = L_{aT-1} + LT + LinC + L_{rd} - L_{pp} - L_{outC}$$  \hspace{1cm} (2)

where $L_{aT-1}$ is the previous timestep’s salt content, $LT$ is incoming tributary content, $LinC$
is incoming content through the causeway, $L_{rd}$ is redissolved content, and $L_{pp}$ is
precipitated content, $L_{outC}$ is content exported through the causeway. All salt
losses/additions are in metric tons, and salinity was calculated by $C_{aT} = L_{aT}/V_{aT}$ in units of
g/l. Salt concentrations exceeding 350 g/l are converted to precipitated salt content in the
model. The relationship between lake level and volume, or lake bathymetry
(hypsographic curve), used identical tables as Loving et al. (2000), which relied on USGS
derived data which was never formally published.

Two anthropogenic influences exist in the paleo simulation. One is the influence
of consumptive water use in streamflow regression equations. Paleo reconstructions by
(Allen et al., 2013; Bekker et al.; 2014, DeRose et al.; 2015) were in locations with minimal upstream withdrawals; however, the downstream gages used to correlate inflows to GSL had numerous known water withdrawals. The regressions developed here underestimate natural streamflow conditions which existed prior to western water development. The second anthropogenic influence on GSL in this simulation was the causeway, although current mineral extraction and West Desert pumping to manage flooding were ignored here. Flows through the bridge and breach were calculated using equations developed by Holley and Waddell (1976), Wold et al. (1997), and Loving et al. (2000). Details of equations are summarized in Loving et al. (2000). A schematic of model inputs and output is shown in figure 3.1.

Although not included in this study, the total amount of salt in GSL has been reduced approximately 20% over the past half century from mineral extraction and water export from the lake for flood protection. Four large mineral extraction companies and several smaller companies operate on GSL. Additionally, two large hydraulic pumps transport brine from the north arm into the adjacent West Desert to protect local highways and other infrastructure in times of flooding. This pumping activity, called the West Desert Pumping Project, operated in wet years from 1986 to 1989 and reduced salts by an estimated 0.45 billion metric tons (Loving et al., 2000). In total, GSL has lost approximately 1 billion metric tons of salt from anthropogenic causes over the past century.
3.2.5. Input Formats and Initialization

All streamflow, precipitation, and evaporation input data were estimated as annual means; however, the GSLFM is sensitive to large changes in volume, and bi-directional flow calculations were not developed for annual volumes. Further, GSL exhibits strong seasonal fluctuations in level and salinity which are not captured in annual data. To account for this, I calculated the mean monthly percentage contributions of streamflow, precipitation, and evaporation from historical data obtained from USGS (lake level), Oregon State University PRISM (precipitation), and Tarboton and Mohammed (evaporation). These monthly contributions were then applied to estimate seasonally-adjusted data (Figure 3.6).

The model was initialized with estimated total mineral content and lake level for 1604. Mineral content for 1604 was $2.77 \times 10^9$ metric tons and was calculated by

![Figure 3.6. Monthly distribution of streamflow, precipitation and evaporation.](image)
subtracting the annual loading rate of 3.17 million tons per year (Hahl and Langford, 1964) from total salt content observed in 1963 prior to West Desert pumping and mineral extractions in the late 20th century. Lake level was estimated to be 1281.7 m in 1604 by subtracting annual paleo lake level time series calculated by DeRose et al (2014) from the final year of the model inputs (2004).

3.2.6 Sensitivity Analysis

The paleo GSL model was evaluated by comparing modeled lake elevation in the south arm to measured data from 1900-2004. A total of seven models were run to elucidate paleo lake characteristics and responses to causeway and climatic changes. Bridge alternative A and D (Figure 3.7 and table 3.2), the largest and smallest proposed alternatives, respectively, were modeled to establish a range of lake level and salinity conditions in each arm with proposed bridges. Models were run from 1604-2004, the period in which paleo-streamflow and precipitation data were available. Alternative D was chosen as the baseline model for sensitivity analysis, due to its similar characteristics to historical causeway conditions (see Chapter 2).

Figure 3.7. Proposed bridge alternatives A and D. Historic low and high water included for reference (Waddell and Gwynn, 2014).
Figure 2.2. Geometry for bridge designs A and D.

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Top Width (m)</th>
<th>Bottom Width (m)</th>
<th>Channel Bottom Elevation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>54.9</td>
<td>18.6</td>
<td>1273.5</td>
</tr>
<tr>
<td>D</td>
<td>45.7</td>
<td>20.1</td>
<td>1276.5</td>
</tr>
</tbody>
</table>

The initial lake level of 1281.7 m is relatively high compared to observed historical conditions, so a sensitivity analysis was conducted on model sensitivity to initial lake level. The model was run with identical climate inputs, but initialized with starting elevations of 1281.7 m (a relatively high level), 1280.2 m (historical mean level), and 1278.6 m (a relatively low level). A sensitivity analysis of inflows was also conducted, whereby total streamflow was increased and decreased 15%. These runs help quantify uncertainty associated with errors in the various hydrologic tree-ring reconstructions. Detailed analysis of GSL level response to inflow changes was conducted by Mohammed and Tarboton (2012).

3.2.7 Model Testing

A direct comparison of paleo salinity to historical conditions was not possible because the causeway was modeled for the entire 400 year study duration to better understand long-term effects of the causeway with a variable climate. In actuality, the causeway was constructed in 1959. For example, in the paleo model, a significant precipitated load formed in the 1940s and continued throughout the rest of the century, due to the net export of salt from south to north. Such export did not occur in the 7 year
period between causeway construction (1959) and 1966, when reliable salinity data was collected on GSL.

To compare the paleo model’s ability to replicate salinity conditions, I ran a model from 1966-2004 using historical causeway and initial lake conditions (see Chapter 2) but with paleo climate variables. This allowed a comparison of measured and paleo modeled data. Salinity results are shown in figure 3.8.

3.3 RESULTS

3.3.1 Model Testing Results

Raw and transformed reconstructed streamflows were compared with measured streamflow to assess regression model fit (Figure 3.3). Despite relatively strong relationships between modeled and observed data ($R^2=0.44$), the model significantly underestimated streamflow to GSL. Although the linearly transformed regression improves streamflow estimates by bringing the relationship closer to 1:1, it still underestimates high magnitude flows and overestimates low magnitude flows.

Bridge alternative D was chosen for the baseline model to test against measured data due to its similarities to historical causeway conditions (e.g. with open culverts). The GSLFM generally replicated lake levels from 1900-2004 well (Figure 3.7). There was no consistent bias, and higher and lower lake levels followed measured data. South arm levels were modeled with an NSE of 0.35 and a PBIAS of 5%. The proximity to zero for PBIAS value suggests there is little systemic bias of the model. However, the model under-predicted high lake levels observed in the mid 1980’s by over 3 m.
Salinity was compared by initializing the paleo model at 1966 with lake levels and salt content recorded in 1966. This created a like for like comparison, where historical model results from Chapter 2 could be used to test paleo-salinity levels. Salinity in the south arm is represented well, while north arm salinity is overestimated throughout much of the model. NSE values of 0.72 and -0.23 were obtained for the south and north, respectively. However, because south arm lake level is under predicted for much of the 1966-2004 period (figure 3.9), salinity should be over-predicted during the same period. Despite these inaccurate results, if comparing a whole lake salinity condition (no causeway), and the only change in salt content is the annual loading rate (Hahl and Langford, 1964), lake level can be used as a proxy for salinity, which suggests that salinity from 1900-1966 is reasonably well modeled.

**Figure 3.8.** Measured and modeled paleo-reconstructed lake level with bridge alternative D (baseline scenario). The causeway was installed in 1959, thus north arm data do not exist prior to that date.
3.3.2. GSL Paleo Lake Level and Salinity

The largest wet period of 1604-2004 reached a maximum lake level of 1285 m in 1620 (Figure 3.10). This unprecedented wet period lasted for over 20 years, and lake levels dwarfed the recorded high of the 1980s by over a meter. Modeled lake level reached its lowest point of 1278.1 in 1961 and 1979; however, these low estimates are roughly 0.75 m higher than the measured lake levels.

**Figure 3.9.** Comparison of paleo lake salinity model and measured historical condition. Paleo salinity model run was initialized with historical lake conditions observed in 1966, and causeway conditions were identical to the historical model described in Chapter 2, while climate inputs were from the paleo model.
Lake salinity generally has an inverse trend with level, where salinity levels plummet to 37 g/l in the south arm and 103 g/l in the north arm in 1620 (Figure 3.11). These values are 58 g/l and 75 g/l lower than lowest historical measured salinities in the south and north arms, respectively. Another wet period in the early 18th century also produced very low salinity levels of 112 g/l in the north arm and 96 g/l in the south arm. The north arm does not reach saturation in the first 150 years of the modeled period, with the exception of a very short period in the 1670s. This highlights the relatively wet conditions of the 16th and 17th centuries. After 1760, the north became saturated more regularly, and is saturated throughout the majority of the 20th century.

Dissolved, precipitated, and total salt content (sum of dissolved and precipitated content) for each arm over the 400 year period is displayed in Figure 3.12. Total salt
Figure 3.11. 400 year reconstruction of Great Salt Lake salinity in north and south arms. Modeled using bridge design D.

Figure 3.12. 400 year reconstruction of Great Salt Lake total salt content. Lines show estimates of total salt content and distribution in the south arm, north arm, and the precipitated salt in the north arm of GSL from 1604-2004 with bridge alternative D.
content increases at a rate of $3.17 \times 10^6$ metric tons per year Hahl and Langford, 1964.

There is no precipitated salt load in the first 150 years because the north arm is unsaturated. Until 1920 there is a strong inverse relationship between north and south arm salt load, indicating salt exchange between the arms. However, this relationship broke down once precipitated load formed in the middle of the 20th century. Precipitated load occurred in both arms for roughly 15 years from 1965-1980.

### 3.3.3. Comparison of Causeway Bridge Alternatives

A comparison of salinity between bridge alternative A (largest bridge), D (smallest bridge), and current causeway condition (no culverts) shows that constructing either bridge will result in notably different lake salinity than the current causeway condition (Figure 3.13). Alternative A provides conditions most like an undivided lake. Salinity under alternatives A and D have similar trends; however, the north arm is generally more saline and the south arm is generally less saline under alternative D. The salinity of the current condition model run varies from both of these, as it results in much lower south arm salinity. Remarkably, it reached 6 g/l in 1985, while the north arm is saturated throughout the vast majority of the modeled period.

The salinity difference between alternatives A and D becomes more pronounced through time in the south arm (Figure. 3.14). Because the north is often saturated in with both bridge designs, there is generally less variability in salinities in the north arm.

The GSLFM is not sensitive to initial starting lake level (figure 3.15). Both elevation and salinity in each arm take roughly 30 years to converge, at which point they remain identical throughout the rest of the modeled period.
Sensitivity analyses suggest that a 15% increase or decrease in streamflows varies lake elevation roughly 1.5 m (figure 3.16a). The exception is at the beginning of the modeled period, when there is little variation for the first 50 years. A similar comparison for salinity sensitivity to streamflow shows that salinity in the north arm is more sensitive to streamflow changes, while the south is relatively resilient to such changes (figure 3.16b). These results of GSL sensitivity to changes of inputs are similar to those of Mohammed and Tarboton (2012).

Exceedance probability graphs demonstrate how lake salinity and level change with causeway design (figures 3.17a, and 3.17b). Salinity in the south arm was systematically lower with alternative A than alternative D, though the two share a similar shape. Comparatively, the current condition causeway had the lowest salinity and even approached freshwater levels. The observed south arm salinity (1966-2012) was consistently less saline than either proposed bridge. In the north arm, the two bridge alternatives display only slightly different salinity distributions. However in the north, both the historical conditions and current condition causeway were more alike, exceeding 300 g/l nearly 80% of the time.

The 1966-2012 (historical record, Chapter 2) and 100 year measured record have a similar exceedance probability for lake level (figure 3.18). Both exceed an elevation of 1281 m about 20% of the time. The 400 year paleo model however suggests the lake level exceeded 1281 m 30% of the time. Further, neither recent dataset exceeded an elevation of 1284 m, while the full paleo record does almost 10% of the time. North arm lake levels were omitted for clarity, but generally mirror south arm levels.
Figure 3.13. Comparison of salinity under bridge alternatives A, D, and current condition.

Figure 3.14. Salinity difference between bridge alternatives A and D in the north and south arm.
Figure 3.15. Lake salinity and level sensitivity to initial elevation. Modeled north and south arm salinity (top) and south arm lake level (bottom) sensitivity to initial lake elevation (north arm level omitted for clarity).
Figure 3.16. GSL south arm level (A) and salinity (B) sensitivity to a 15% increase or decrease in streamflow.
Figure 3.17. Probability exceedance curves for GSL salinity in the north arm (A) and south arm (B), for each bridge alternative and historical recorded data. Current condition represents causeway conditions as of 2014, with closed culverts and a subsided causeway.
3.4 DISCUSSION

Wet and dry years are defined by comparing the current year’s runoff with the historical average of measured runoff (Null and Viers, 2013). However, this approach inherently assumes climate stationarity. Wet periods in the early 17th and 18th centuries exceeded the historical high lake level observed for GSL (1283.7 m, 1986) by over one meter. Also, in the paleo model, wet periods could last over 50 years. The highest modeled level reached 1285 m in 1622. Such a level would overtop any of the proposed bridge designs if the West Desert Pumping Project was not used. The modeled lake level reaches two nearly identical lows of 1278.5 m in 1961 and 1979. 1961 was the lowest measured elevation of GSL, when the lake reached 1277.5 m. Interestingly, between 1940 -1980, the three lowest levels of the entire 400 year period were modeled. The next lowest lake level is over 1 m higher than those modeled in the late 20th century. The 20th
century had the lowest mean lake level (1279.9 m) of all modeled centuries, with mean level 0.3 m, 1 m, and 1.8 m lower than the 19th (1280.1 m), 18th (1280.9 m), and 17th (1281.7 m) centuries, respectively. For reference, measured mean lake level in the 20th century was 1280 m (the recorded mean lake level), suggesting that the inability of GSLFM to replicate the 1980s wet period does not significantly affect centennial mean level.

Unsurprisingly, these results support streamflow results from other regional GSL studies, from which this studied relied on (Allen et al., 2013; Bekker et al., 2014; DeRose et al., 2015). The timing of the largest pluvial coincides with the Little Ice Age observed throughout much of the northern hemisphere (Houghton et al., 1990). This is at odds with regional streamflow reconstruction in the Upper Green River and Upper Wind River, which suggests that the 20th century was generally wetter than preceding centuries (Barnet et al., 2010; Watson et al., 2009). Regional differences may account for part of these changes. Also, those studies focused on individual events, rather than longer periods. My results suggest that total stream and precipitation entering GSL were lower in the 20th century than the preceding three centuries, despite the two strong pluvial events of 1920 and 1985. The lower average lake levels of the 20th century are also likely related to the length of these pluvials, which were considerably shorter than those from the 17th and 18th centuries. However, because inputs are uncertain, this warrants future study.

Overall, GSLFM predicts observed lake levels over the roughly 100 year period of measured data well, with an NSE of 0.35. Underestimating wet periods, like the 1980s
pluvial, is an important source of error and more frequent or higher magnitude wet periods with high lake elevations may have been more common than is portrayed here. Several factors likely contribute to this error. First, all three published tree-ring streamflow studies (Allen et al., 2013; Bekker et al., 2014; DeRose et al., 2015) and the precipitation reconstruction, underestimate peak flows. This suggests that there were regional factors limiting tree growth beyond water availability, such as precipitation timing or available sunlight. Additionally, regressions for correlating upstream streamflow to flows entering GSL considerably underestimate the highest recorded streamflow from the period on record (1950-2014). Thus, even with perfectly reconstructed streamflow at upstream gages, total flows entering GSL would still be underestimated. The model results suggest that my approach is able to represent long duration wet periods, such as those seen at the beginning of the 17th and 18th century. However, it is possible that additional shorter-term wet periods occurred, such as those of the 1980s, which were not captured by the tree-ring reconstructions.

Extreme low lake levels are also underestimated in the model, though by a much smaller extent compared to extreme high levels. This could be from proportionally larger anthropogenic diversions from streams in dry years compared to normal and wet periods, causing reduced streamflows in measured data. The paleo-streamflow approach used here was intended to replicate unregulated streamflow conditions, not to replicate water withdrawals. Regardless, the model represents increasing and decreasing lake level trends well. Further investigation of tree-ring growth dynamics during this period is outside the scope of this study, but could further refine model inputs.
Salinity was generally not well modeled from 1966-2004 (the period available for comparison). Trends tracked well, but salinity was overestimated because the paleo model did not capture the magnitude of the 1980’s pluvial. Results are consistent with lake level errors since salinity is inversely related to level. Because of this, if comparing a whole lake salinity condition (no causeway), and the only change in salt content is the annual loading rate (Hahl and Langford, 1964), lake level can be used as a proxy for salinity, which suggests that salinity from 1900-1966 is reasonably well modeled. Thus, despite the poor performance of the model during much of the period of reliable records, paleo salinity results can still provide useful results.

Salinity slowly increases through time in all model runs. This coincides with a slow decrease in lake level over time, as well as a slow increase of salt loading from tributaries. Although this is observed visually and statistically, it is possible this is a statistical artifact of the extremely high level the lake in the early 1600s.

3.4.1 Streamflow sensitivity

Streamflow was increased and decreased by 15% to evaluate uncertainty effects on lake level and salinity (Figure 3.16). Lake level is sensitive to changing inflows, and error in streamflow reconstructions and regressions could influence model results, leading to average salinity differences of 2.5m. Lake levels are least sensitive during periods of rapid level changes, such as the beginning of the 17th century, explaining the small differences of lake level during the early 17th century pluvial. This is a stark contrast the next pluvial, roughly 100 years later in the 18th century, where there are large variations in lake level, as GSL slowly rose and receded.
Salinity response to changes of streamflow varies considerably between the north and south arm. In the south arm, salinity was resilient to changes in streamflow, with 15% changes to streamflow altering salinity by 4.3 g/l. Salinity in the north arm however was sensitive to streamflow, with changes up to 100 g/l at times. This occurred because volume of the north arm is roughly 75% smaller than the south arm. Also, when lake level rises in the south arm, south to north flow increases through causeway fill and openings, delivering relatively fresh water to the north. Salinity in the north arm is sensitive to inflow from the south arm, particularly during periods of low and moderate salinity.

3.4.2 Comparison of bridge alternatives

Comparing bridge alternatives A and D reinforce findings from Chapter 2. Alternative A results in more moderate salinity conditions compared to alternative D. The salinity difference between the two alternatives fluctuates through time, and slowly increases through time (Figure 3.13). This reinforces the salinity gradient that have developed from construction of the rock-filled causeway, where smaller or fewer causeway openings result in a growing salinity gradient between the north and south arms (Null et al., 2013).

The model provides a bleak representation of GSL level and salinity under the current conditions model run. With this alternative, the lake approaches freshwater conditions in the south, while salinity is consistently saturated in the north arm. Such conditions would likely be catastrophic to the existing food web, particularly in the south
arm, where lab research suggests *Artemia* prefer salinities near 100 g/l (Barnes and Wurtsbaugh, 2015).

### 3.4.3 Limitations

Results of this modeling quantify long-term climate variability effects on GSL level and salinity, and assess causeway alternatives over a longer period than previously possible. However, caution should be heeded when extrapolating results to future conditions. Climate change is expected to fundamentally alter the hydrology and climate of Utah and the American west (Garfin et al., 2013). My approach did not capture non-stationarity of changing future conditions from anthropogenic climate change (Milly et al., 2008). Further, demands for water are likely to increase with a projected population increase of 2.5 million people by 2050 (Utah Foundation, 2014). Proposed water development, including new surface reservoirs on the Bear River, may further alter GSL streamflow contributions in coming decades (Cache County Water Master Plan, 2014). These factors combine for an uncertain future of GSL level and salinity.

The GSLFM was originally developed to model periods of less than 30 years and assumed salt losses occurred only via mineral extraction and West Desert pumping. However, salt loss through aerosolization of exposed lake bed may have occurred over a 400 year period. No studies have investigated such losses for exposed GSL lakebed, but aerosolization of sediments is thought to occur in other desiccated lakes in the region (e.g. Sevier Lake and Owens Lake) (Steenburgh et al., 2012; Reheis, 1997). Detailed investigation of this potential salt loss is outside the scope of this study, but should be considered for future studies.
As discussed, each model input has uncertainty. When calculating results from these inputs, there is potential to exacerbate errors. Highlighting this is the underestimation of lake levels in the 1980s, in which input data underestimated the amount of precipitation and streamflows, resulting in a large discrepancy between modeled versus observed data. Improving this input data will reduce uncertainty, leading to more certain results.

The GSLFM assumes homogenous salinity within each arm of the lake, and acts as a one-dimensional representation of lake conditions. In reality, salinity variations occur with depth and spatial location. Examples include the south arm’s deep brine layer, and the less saline areas where tributaries enter the lake.

3.5 CONCLUSION

Despite the roughly 3 m error in high modeled lake levels of the 1980s, this is the first study to estimate GSL level and salinity with the railroad causeway using long-term climate variability. The 20\textsuperscript{th} century had, on average, the lowest lake level and highest salinity of any century modeled. Furthermore, the four lowest GSL levels all occurred in the 20\textsuperscript{th} century. Generally dry conditions have extended into the 21\textsuperscript{st} century (not modeled past 2004). As of 2015, GSL level is at a record low, per USGS gage 10010000. However, individual drought events of the 17\textsuperscript{th}, 18\textsuperscript{th}, and 19\textsuperscript{th} centuries were larger in magnitude than those of the 20\textsuperscript{th} century. The period of high lake levels witnessed in the mid-1980s was also shorter in length than previous pluvials, but was considerably smaller in magnitude compared to the early 1600s pluvial. If a similar multi-decadal pluvial were to occur again, the West Desert Pumping Project would be needed, and may be
challenged to match the rate of inflows. Further, high lake levels would lead to
inundation of any of the proposed bridge alternatives. When this occurred to the historical
culverts, they often became plugged with debris, reducing interflow between arms and
requiring additional maintenance.

Causeway bridge design will be important for future lake level and salinity.
Salinity and lake level with alternative A provide for conditions in each arm to be most
alike (e.g. lower north arm salinity and higher south arm salinity). Differences of salinity
between alternatives A and D, particularly in the south arm, are likely to increase over
time, particularly if lake levels remain low. Leaving the causeway as is, without bridge
replacement, could drastically change lake conditions. Results indicate salinity in GSL’s
south arm may fall as low as 6 g/l. Such conditions would likely be inhospitable for the
salt dependent organisms currently occupying GSL, but would likely allow for mesohaline fish and other organisms. The selection of bridge design is complicated by the
many diverse stakeholders on GSL. Other management variables, such as mineral
extraction and reduced streamflow contributions from water withdrawals and
development, were not investigated in this study, but are likely to play important roles in
future conditions of GSL and warrant additional research. This approach could be
adapted to more explicitly include future changes to the lake. Such analysis would further
refine decision-making regarding the best bridge alternative.

Reconstructing lake level and salinity over a 400 year period with estimated
streamflow, precipitation, and evaporation is a novel approach to better understand
climate variability on a managed terminal lake. Results will help managers and
stakeholders better evaluate likely future outcomes for GSL elevation and salinity given the highly variable climate of Northern Utah and may ultimately better inform causeway modification decisions.
Utah’s Great Salt Lake (GSL) provides refuge for millions of resident and migratory birds, and contributes $1.3 billion to the regional and local economy (Bioeconomics, 2012). Despite the relative abundance of saline lakes worldwide, GSL provides a unique and important ecosystem in North America. Construction of the Union Pacific Railroad causeway in 1959 fundamentally altered the hydrology of GSL by essentially creating two lakes connected by the semi-permeable fill material and three separate openings in the causeway itself. With the closure of the two openings (culverts) in 2013, concern grew over limited interflow between the north and south arms of GSL. Four different bridge designs were proposed to replace, and potentially increase, interflow provided by the historical culverts (Waddell and Gwynn, 2014). How these changes affect the water and salt balance of GSL is of keen concern to the many stakeholders, managers, and interest groups on the lake.

The variable nature of northern Utah’s climate causes lake level and salinity to fluctuate on decadal and multi-decadal cycles (Mann et al., 1995). Because of climate variability, consequences of proposed bridge designs are best evaluated over long periods of time to increase the likelihood that important, but rare, events are captured and quantified. Accurately establishing the extent of these historic events on GSL allows for a better comparison of proposed bridge alternatives and allows managers to better plan for rare but historically re-occurring events.
In my first chapter, I established that the updated Great Salt Lake Fortran Model accurately reconstructs historical lake events between 1966 - 2012. I compared five different causeway scenarios, each of the four proposed bridge alternatives and a no action alternative. Bridge alternative A, the largest proposed design, allows for the most bi-directional flow, and in turn a lake condition most like an undivided lake. Bridge alternative D allows for conditions which mimic those of the historical culverts. Alternatives B and C are similar and roughly split the difference between alternatives A and D.

In my second chapter, I used paleo-streamflow reconstructions, a precipitation reconstruction, and a GSL level reconstruction to evaluate bridge alternatives over a 400 year time period and investigated if the historical record accurately captures GSL variability. I found that the 20th century has had the lowest lake level and highest salinity of any century since 1600. I also found that extremely high lake levels (and low salinities) were significantly shorter in the 20th century compared to historical events, especially in the early 17th and 18th centuries. Differences in south arm salinity driven by bridge design may increase over time, resulting in nearly 100 g/l difference by the end of the modeled period. Long-term GSL conditions are sensitive to bridge causeway design.

The mass balance modeling approach is a useful and practical approach to evaluating changes to a large endorheic basin. This approach can be applied to terminal lakes worldwide to evaluate climate change, climate variability, or future management options, and can help identify promising solutions to challenges such as desiccation and salinity management.
I expect my research to aid understanding of GSL dynamics by evaluating lake response to alternative causeway designs. I also provide the first known continuous paleo reconstruction of salinity at an annual scale in a terminal lake. My results provide valuable information for managers and stakeholders, and provide a novel approach to studying terminal lake dynamics and history.
References


Waddell KM, Bolke EL (1973) The Effects of Restricted Circulation on the Salt Balance of Great Salt Lake, Utah. Salt Lake City, Utah. Utah Department of Natural Resources.


