Using Computational Fluid Dynamics to Predict Flow Through the West Crack Breach of the Great Salt Lake Railroad Causeway

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USING COMPUTATIONAL FLUID DYNAMICS TO PREDICT FLOW THROUGH
THE WEST CRACK BREACH OF THE GREAT SALT LAKE RAILROAD
CAUSEWAY

by

Michael Rasmussen

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Civil and Environmental Engineering

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UTAH STATE UNIVERSITY
Logan, Utah

2022
ABSTRACT

Using Computational Fluid Dynamics to Predict Flow through the West Crack Breach of the Great Salt Lake Railroad Causeway

by

Michael Rasmussen, Master of Science

Utah State University, 2022

Major Professor: Dr. Brian Mark Crookston
Department: Civil and Environmental Engineering

An east-to-west railroad causeway separates The Great Salt Lake, Utah, USA, into northern and southern sections, creating significant water surface elevation and density gradients. Conditions in the different sections of the lake are such that density-driven exchange flows form in the causeway openings; a behavior observed in other lake and ocean settings where two fluids of differing densities interact. Quantifying these exchange flows is a priority for lake managers who face the challenge of preserving numerous societal and environmental benefits the lake provides. Due to rising environmental and economic concerns associated with varied lake salinity and water surface elevation, a new 50 m-wide breach was added to the railroad causeway to enhance salt and water exchange between the northern and southern sections. To support management efforts, exchange flows through the new breach were investigated using computational fluid dynamics (CFD) modelling supplemented by a field campaign. The results of this investigation indicate exchange flows through the breach are sensitive to
changes in density and water surface elevation gradients in addition to breach geometry and bathymetry. The model accurately predicted flow velocities and discharges and was used to forecast discharge through the breach as a function of the water surface elevation and density gradients under future lake conditions.

(85 Pages)
PUBLIC ABSTRACT

Using Computational Fluid Dynamics to Predict Flow through the West Crack Breach of the Great Salt Lake Railroad Causeway

Michael Rasmussen

The Great Salt Lake in Utah, USA, is a terminal, saline lake and is divided into two primary sections (northern and southern) by an east-to-west railroad causeway. Shortly after completion of the earth-fill causeway in the late 1950s, the two sections became dramatically different with differences in water surface elevation and water density. These differences cause the formation of a unique flow behavior commonly referred to as a density-driven exchange flow or bi-directional flow; a behavior observed in other lake and ocean settings where two fluids of differing densities interact. Measuring these exchange flows is a priority for lake managers who face the challenge of preserving the numerous societal and environmental benefits the lake provides. Due to rising environmental and economic concerns associated with varied lake salinity and water surface elevation, a new 50 m-wide breach was added to the railroad causeway to enhance salt and water exchange between the northern and southern sections. To support management efforts, exchange flows through the new breach were investigated using a computer modeling technique called computational fluid dynamics (CFD) supplemented by a field campaign. The results of this investigation indicate exchange flows through the breach are sensitive to fluctuations in density and water surface elevation differences in addition to the breach geometry and bathymetry. The model accurately predicted flow
velocities and volumes and was used to forecast discharge through the breach as a function of the water surface elevation and density gradients under future lake conditions.
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My experience at the Utah Water Research Laboratory has been phenomenal. I am very grateful to have been selected among other students to research the Great Salt Lake and work under the direction of an excellent committee of professors including Dr. Brian Crookston, Dr. Som Dutta, and Dr. Beth Neilson. I cannot thank them enough for their help and guidance through my research and classwork. Special thank you to Brian Crookston, my major professor, who has spent countless hours working with and mentoring me at the lab. His example of hard work and dedication has left a permanent impression on my mind for the better. I’d like to acknowledge and thank my wife, Maddie, for her patience and support during my research and classwork. Maddie was always willing to listen and help me prepare for presentations even long after my voice began to sound like a broken record as I rambled about nerdy things. Many thanks to all who helped me in my research of the Great Salt Lake.

- Michael Rasmussen
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NOMENCLATURE

ADCP acoustic doppler current profiler

ADVM acoustic doppler velocity meter

$A_j$ fractional area of flow in a particular direction;

$\alpha$ $k-\omega$ model parameter = 0.52

$\beta$ = 0.072$f_B$;

$\beta^*$ $k-\omega$ model parameter = 0.09$f_B^*$;

$c$ Smagorinsky coefficient;

$C_1$ $k-\varepsilon$ turbulence model coefficient = 1.44;

$C_{1\varepsilon}$ $k-\omega$ turbulence model coefficient = 1.39;

$C_2$ $k-\varepsilon$ turbulence model coefficient = 1.92;

$C_{2\epsilon}$ $k-\omega$ turbulence model coefficient = 1.42;

$C_v$ $k-\varepsilon$ turbulence model coefficient = 0.09;

$C_\mu$ $k-\omega$ turbulence model coefficient = 0.085;

$\varepsilon$ rate of dissipation of $k$;

$\varepsilon'$ percent difference between USGS and CFD velocity;

$f_B^*$ $k-\omega$ turbulence model parameter;

$f_i$ viscous accelerations;

$g$ gravitational acceleration constant;

$G_i$ body accelerations;

GSL Great Salt Lake;

$h$ flow layer thickness (densimetric Froude number);
$K$ sum of molecular and turbulent diffusivity;
$k$ turbulent kinetic energy (TKE);
$k$-$\omega$ $k$-$\omega$ turbulence model;
$k$-$\varepsilon$ $k$-$\varepsilon$ turbulence model;
LES large eddy simulation turbulence scheme;
$l$ geometric mean of the grid cell dimensions;
$p$ pressure;
$P_k$ production of $k$;
$S_{ij}$ strain rate tensor;
$u_i$ mean velocity;
$V_F$ fractional volume of flow;
$x_j$ selected cartesian coordinate;
$\Delta x$ cell dimension in the $x$-direction;
$\nu_t$ turbulent kinematic viscosity;
$\mu$ dynamic viscosity;
$\mu_t$ turbulent dynamic viscosity;
$\mu_{tot}$ total dynamic viscosity;
$\rho$ fluid density;
$F'$ densimetric Froude number;
$\rho_1$ top layer fluid density (densimetric Froude number);
$\rho_2$ bottom layer fluid density (densimetric Froude number);
$g'$ modified gravitational constant (densimetric Froude number);
$\rho_S$ reference density;

$\sigma_e$ Prandtl number for turbulence = 1.3;

$\sigma_{k\varepsilon}$ Prandtl number for turbulence = 1.0;

$C_1\varepsilon C_2\varepsilon C_\mu \beta^* f_B^* \sigma_{k\omega}$ Prandtl number = 0.5;

$\sigma_\omega$ Prandtl number = 0.5;

$\tau_{b,i}$ wall shear stress $\beta$;

USGS United States Geological Survey;

N-S north to south;

S-N south to north;

$\sigma$ water specific conductance;

$\rho$ water density;

$\Delta \rho$ density gradient;

RNG k-ε; RNG k-ε turbulence model;

$U$ average bottom layer velocity (densimetric Froude number);

$V$ flow velocity;

$V_{CFD}$ CFD flow velocity (for comparison with USGS data);

$V_{USGS}$ USGS flow velocity (for comparison with CFD data)

$WSE$ water surface elevation;

$\Delta WSE$ water surface elevation gradient;

$WSE_{South}$ south section water surface elevation;
Saline lakes are found on all seven continents and comprise approximately 44% of the volume of all lakes on earth (Messager et al. 2016; Williams 2002). These include the Caspian Sea (Europe, Central Asia), the Dead Sea (Middle East), Don Juan Pond (Antarctica), Lake Assal (Africa), Lake Urmia (Middle East), Koyashskoye Salt Lake (Europe), Mono Lake (North America), Salar de Uyuni (South America) and the Great Salt Lake (North America), among others. Saline lakes were formed by special geologic and climatic conditions, including sea isolation, tectonic events, the availability of soluble salts within an endorheic drainage basin and evaporation rates that exceeds rainfall or other inflows (Hammer 1986, Waiser and Robarts 2009). These salt bodies may be classified as mesohaline or hypersaline depending upon their environment (Rich and Maier 2015).

Although historically perceived by some as unimportant, saline lakes provide many societal and ecologic benefits (Williams 1993). For instance, saline lakes and their associated wetlands are recognized for their biodiversity and are highly valued habitat for many waterbirds (Pendleton et al. 2020; Zadereev et al. 2020). Many salt lakes also have thriving fishing, mineral extraction, and recreational industries (Demnati et al. 2017). Indeed, some saline lakes have been exploited for the abundant evaporitic minerals (e.g., sodium chloride, sodium carbonate, magnesium, potassium) that have a wide range of uses in medicine, manufacturing, chemical, agricultural, and construction industries (Waiser and Robarts 2009).
Anthropogenic impacts (primarily upstream diversions of water) and lack of conservation measures have caused many of the world’s saline lakes to significantly decline, and in some cases, completely desiccate (Ghalibaf and Moussavi 2014; Wurtsbaugh et al. 2017). Desiccation is further exacerbated by climate change and the increased water demands of growing human populations (Chaudhari et al. 2018; Hassani et al. 2020). Desiccation leads to often irreversible degradation of the environmental values associated with saline lakes along with declines in tourism. These include changes to the natural character and limnology, increased salinity, loss of biodiversity, changes to and loss of local habitat, and declining groundwater levels, among others (Williams 2002). Exposed lakebeds become sources of dust and toxic substances that can negatively affect air quality and human health (Griffin and Kellogg 2004; Indoitu et al. 2015; Mahowald et al. 2003).
SPECIFIC CASE: THE GREAT SALT LAKE

The Great Salt Lake (GSL) is the largest saline lake in the western hemisphere and fourth largest in the world (Fig. 1) (Arnow and Stephens 1990). As with other saline lakes, the GSL is currently under threat and requires additional conservation and management efforts. The GSL water surface elevation (WSE) has experienced a general decline over time, which is in part attributed to climate shifts, but also to irrigation demands that have reduced river inflow to the lake (Klotz and Miller 2010; Wine et al. 2019; Wurtsbaugh 2014; Wurtsbaugh et al. 2016, 2017). The GSL was below the historic low lake elevation of 1277.5 m recorded in 2016 which further declined in fall 2021 to an all-time low (Wurtsbaugh et al. 2017). Despite drought and flow diversion, the GSL has an estimated economic output of over $1.3 billion via the mineral extraction, brine shrimp (Artemia franciscana) harvesting, and recreation industries (Bink 2021, Bedford 2005, Bioeconomics, Inc. 2012). In addition to table salt and other minerals, approximately 10% of the world’s supply of magnesium is mined from the GSL (Tripp 2009). Millions of migratory birds use the GSL annually as a staging area to feed on brine shrimp and rest during their migrations (Frank 2016).
From 1956-1959, a rockfill railroad causeway (Fig. 1) was constructed East-to-West that divided GSL into north and south sections (Great Salt Lake 1980). Construction of the causeway included two 4.6 m wide x 6.1 m high (15x20 ft) culverts installed to provide a location of flow exchange; however, the two sections quickly became physically and chemically different despite the culverts and the semi-porous fill material (Madison 1970). Because 95% of freshwater flows into the GSL south of the causeway (Bear, Weber, and Jordan Rivers, see Fig. 1), the salinity of the northern section increased while the southern section became more dilute (Hahl and Handy 1969). In addition to salinity and the corresponding water density differences, a water surface gradient formed with a higher lake elevation in the southern section that has persisted even during periods of drought.
The railroad causeway has been modified several times since construction to control flows between the northern and southern sections. To reduce flooding of Salt Lake City in 1984, a 91.4 m wide breach was constructed in the causeway near GSL’s west shoreline (Gwynn and Sturm 1987) (Fig. 2). This breach does not experience flows below a lake elevation of about 1,278.5 m (Baskin 2005). Deterioration of the culverts eventually resulted in their closure and abandonment (west culvert 2012, east culvert in 2013, (Waddell et al. 2014)). A new breach and bridge, known as the West Crack Breach (WC Breach), were added and completed in December 2016 to replace the culverts (Fig. 3).

Fig. 2. GSL breach constructed in 1984 to alleviate flooding on the south section (photo taken February 2022, looking northeast). This breach is located approximately 8 km east of the WC Breach.
Due to the aforementioned differences in lake water surface elevation ($\Delta WSE$) and density ($\Delta \rho$) between the northern and southern lake sections, water flowed simultaneously in both directions (north and south) through the causeway culverts and later through the WC Breach (Wold et al. 1997). This density-stratified bi-direction flow is often referred to as a gravity-driven exchange flow; such a hydraulic feature is known to occur in similar lake and ocean settings (Turner 1973). At the WC Breach, the bi-directional flow is characterized by a plunging current of northern water beneath a surface current of less-dense southern water (Fig. 4). The less-dense surface flow travels more than a kilometer as it gradually expands laterally. The saltier north-to-south flow is mostly unmixed and connects to a deep brine layer in the southern section of the lake (Naftz 2017).
Fig. 4. Simple illustration of bi-directional flow through an opening in the GSL railroad causeway. The two lake sections are colored red and blue, respectively, consistent with the natural coloring of the GSL. The north part appears pink in color due to halophile bacteria that thrive in the hypersaline environment (Baxter 2018).

Under certain weather conditions with winds that exceed about 13 m/s, flow through the WC Breach and can become unidirectional resulting in three flow regimes for this hydraulic structure (Freeman 2014). These less-frequent unidirectional flows are either north-to-south (N-S) or south-to-north (S-N) and are brief temporal events with the reestablishment of the dominant bi-directional flow case shortly after the necessary meteorologic conditions end (Freeman 2014).

The exchange of flow and salt through the WC Breach is critical to current lake management and conservation efforts. For example, brine shrimp production is optimal for a salinity range (Barnes and Wurtsbaugh 2015) while the competing mineral industries depend on pumping flows from the deep brine layer to and the formation of evaporation ponds in the northern section (Larsen 2016). However, the WC Breach does not address low inflows to the GSL or increased lakebed exposure, both of which affect basin hydrology and wind-carried unhealthy dust deposits in nearby urban areas (Potential Costs of Declining Water Levels in Great Salt Lake 2019, Skiles et al. 2018).

Hydraulic models of the original culverts were created to estimate discharge and salt exchange to support lake management efforts (Holley et al. 1976). The WC Breach,
was designed to duplicate (as closely as possible) the transfer of water previously provided by the culverts (HDR Engineering, Inc. 2018), but the original culvert model was used for WC Breach flow prediction. The WC Breach does include a subsurface berm that can be modified to adjust mass (or deep brine) exchange, and

To improve discharge estimates through the Great Salt Lake Causeway WC Breach and gain further insights into the three flow regimes as a function of lake conditions, this study was conducted to develop a computational fluid dynamics (CFD) hydraulic model of the WC Breach. This hydraulic model will aid in the formulation of case-specific (bi-directional, north-to-south unidirectional, and south-to-north unidirectional) discharge rating curves for use in hydrologic models of the Great Salt Lake Basin and corresponding GSL management efforts.
NUMERICAL MODELING LITERATURE

Rating Curve Development and CFD Applications

Rating curves for many types of hydraulic structures have been developed to establish a unique relationship between stage or water surface elevation and discharge (Novak et al. 2007). Such a relationship is empirical, specific to the range of elevations and discharges investigated, and often includes coefficients in a curve-fit or semi-physics-based equation. These equations are generally easy to implement and can potentially provide timely and accurate estimates. The data needed for developing a rating curve primarily comes from field data, laboratory data, or from computational fluid dynamics (CFD) models.

One of the abilities of CFD models is forecasting hypothetical or future flow scenarios. Crookston et al. (2018) described the use of CFD to estimate discharge rating curves of piano key weirs. Similarly, Torres et al. (2021) presented the successful use of CFD models in free-surface flows over a weir and spillway to estimate a rating curve. Another study by Chanel and Doering (2008) compared CFD predictions with physical modeling of spillway flow with general success.

CFD modeling has also been successfully applied to complex stratified and multiphase flows. Dutta et al. (2014) used CFD models to reveal particle trapping secondary currents in sewer conduits with single and multi-phase flows. Stratified flows within the atmospheric boundary layer were studied by Koblitz et al. (2013). An et al. (2012) simulated particle-driven gravity currents that agreed well with similar laboratory
experiments. Another study by Stancanelli et al. (2018) applied CFD models to analyze the classic lock exchange experiment with good success.

Numerical Modeling of the GSL

Past efforts to predict flow dynamics in the GSL and causeway have helped managers protect the lake and guide management decisions. Some studies have aimed directly at the railroad causeway and its effects on the GSL. Madison (1970) looked at the effects of the railroad causeway on brine circulation in the lake and recommended the use of a model for future scenarios. With respect to the causeway culverts, Holley et al. (1976) presented a numerical model of stratified flows to be used for comparison with field discharge measurements. Another study by Waddell and Bolke (1973) examined the railroad causeway’s effects on the movement of brine and optimum culvert widths to achieve certain salinities throughout the lake. Waddell and Fields (1977) looked at the water and salt budgets of the GSL and how inflow, outflow, and multiple diking options affect the lake’s WSE-volume relationship.

Other studies of the GSL examined the general flow dynamics and parameters of the lake. For example, a 3D numerical model by Spall (2009) was used to simulate cyclonic gyres in the south arm of the GSL. Mohammed and Tarboton (2012) examined the sensitivity of GSL volume changes to inputs and the lake’s internal parameters. A study by Naftz et al. (2011) described the site-specific relationship of fluid $\rho$ to salinity and temperature in the GSL for use in hydrodynamic calculations. Although much field
work and numerical modeling has been performed, no study exists that specifically models the new 2016 WC breach.
METHODOLOGY

Field Campaign

To supplement available USGS data, a USU field campaign was conducted to collect data near the WC breach for CFD model calibration and comparison efforts. Field data and observations are invaluable for model parameter selection, boundary conditions, and the development of an appropriate numerical domain.

Density, determined via total dissolved solids (TDS) and specific conductance, $\sigma$, was measured monthly by USGS at the northern side of the bridge at the WC Breach. This field campaign investigated any water density $\rho$ or $\sigma$ spatial variability at numerous locations within approximately 300m south and 600 m north of the WC breach. Water samples and measurements at multiple depths were made by kayak. Samples were collected using a syringe with tubing attached to a measured cable; when the tube inlet was positioned at the desired depth, the system was manually flushed and then a water sample collected for a laboratory TDS analysis (Standard Methods 2014). The USGS converts TDS to $\rho$ in the GSL via the empirical relationship (Waddell and Bolke 1973) presented as Eq. (1). This conversion method (herein referred to as the TDS Method) was applied to all UWRL water samples including individual north and south shoreline samples collected during each visit. Additionally, $\rho$ was directly calculated by weighing a specific sample volume at 5°C (herein referred to as the Direct Method).

$$TDS = \frac{(\rho - 1)(1,000)}{0.63}$$

(1)
An In-Situ AquaTroll 600 multi-parameter water quality sonde (In-Situ 2021; reported instrument accuracy of $\pm 2\%$ and $\pm 0.1^\circ\text{C}$ at 100,000-200,000 $\mu\text{S/cm}$) was used to measure $\sigma$ (see Fig. 5). The kayaks were positioned with a GPS unit and anchored in place with flow depths measured by a field tape.

**Fig. 5.** Specific conductivity profiling of the north and south sections

In addition to a spatial TDS and $\sigma$ investigation, the AquaTroll 600 was used for continuous measurement from October 2020 to March 2022 at a 15-minute sample frequency to represent conditions on the south and north sides of the breach. In the southern section of the GSL, a sonde was placed approximately 150 m west of the WC breach and within a perforated PVC pipe mounted to a large boulder on the causeway shoreline where no northern water influences were present (except during high wind events). The sonde depth was approximately 1.6 m from the lake surface (see Fig. 6). The north side sonde was similarly installed but instead mounted to a pole approximately 7 m from the north causeway shoreline and 300 m west of the WC breach where no southern
water influences were present. The north sonde PVC casing was heavily damaged and torn from the pole in April 2021 by a storm event; it was retrieved and relocated approximately 150 m west of the WC Breach to a sizeable boulder in the same manner as the southern installation (see Fig. 6). Monthly visits allowed for cleaning, calibration, and routine maintenance.

Fig. 6. Perforated PVC casings attached to shoreline boulders for continuous SC measurement on the north (left) and south (right) sides.

Bi-directional flow interface

The two sections of GSL generally have different temperatures; therefore, the bi-directional flow interface within the WC breach can be identified via water temperature measurements. In May 2021, a temperature sensor array placed within a perforated PVC casing was installed on a middle bridge pier in the WC breach (see Fig. 7). The array consisted of 13 Hobo Pro V2 temperature sensors (Onset n.d.) at 0.3 m intervals with the lowest sensor placed 0.3 m above the channel bottom. The top of the PVC casing was surveyed by measuring the distance between the top of the casing and the water surface.
The breach WSE (as reported by USGS) provided a datum by which the individual sensor elevations could be estimated. Additional measurements were taken from the bridge deck to the top of the casing, and the casing elevation was calculated using as-built engineering drawings (HDR Engineering, Inc. 2017).

![Image](image_url)

**Fig. 7.** Temperature sensors, chain, and PVC casing (6.1 m length) with steel bracings.

**Additional Field Datasets**

The CFD modelling effort also considered water surface elevations and density data recorded by the USGS for locations throughout the GSL including at and near the WC breach. Lake elevations have been measured by USGS on the north and south sides of the causeway for more than 50 years. Additionally, the USGS installed multiple instruments at WC Breach in early 2017 for continuous data collection of WSE, surface flow velocity, a water column velocity profile within the breach, wind speed and direction, air temperature, air pressure, and water quality parameters.

The USGS collects monthly water samples from WC Breach for lab analysis of water quality parameters including density (USGS 2021). Some USGS monitoring sites
contain records for $\sigma$, TDS, and $\rho$ measured over several years prior to WC Breach construction (Fig. 8). Further WC breach water quality data were recorded by a private consultancy (HDR Engineering, Inc.) involved in the project since 2017 and made publicly available by the Utah Department of Environmental Quality. Plots of these water quality data provided initial estimates for density in the model boundary conditions. Once the model was calibrated, densities were assigned based on USGS water samples collected at the breach during the flow event being modeled.

Fig. 8. Map showing USGS monitoring locations with historical water quality datasets. Point colors are consistent with data plots in the results section.

The USGS records a 1D streamwise velocity profile within the WC Breach via an acoustic doppler velocimeter (ADVM) placed at the channel bottom immediately north of the bridge. The ADVM measures velocities over 0.4 m vertical sections of the water column beginning about 1.8 m above the channel bottom (Fig. 9). USGS has not estimated measurement accuracies or uncertainties, but velocity estimate errors could
exceed 50% (Ryan Rowland, Personal Correspondence, October 20, 2021) due to the difficulties associated with acoustic measurement of bi-directional flow.

**Fig. 9.** Illustration of USGS ADV measurement elevations.

Monthly northward and/or southward discharge calculations through the WC Breach have been made by USGS using an acoustic doppler current profiler (ADCP) that provides a cross-sectional view of streamwise velocity. These USGS discharge calculations assume a fixed channel cross section and an approximated log-curve velocity profile outside of ADCP measurement range (i.e., the instrument’s blanking distance near the bed). The majority of USGS ADCP measurements taken since year 2017 were given a ‘poor’ rating due in part to the wide scatter in the data and also due to instrument limitations linked to site conditions; however, the USGS ADV and ADCP data are the only field-measured velocity data currently available for the WC Breach. USGS processes these data to obtain the velocity profiles (Michael Freeman, Personal Correspondence, Feb. 15, 2022) used for comparison with CFD results. For individual
ADV velocity profiles, the data are automatically processed by the instrument to give a single velocity measurement at each cell elevation (see Fig. 9). Conversely, ADCP data are manually processed/filtered to obtain a velocity profile by which USGS can calculate discharge.

CFD Modeling

In this study, FLOW-3D™ by Flow Science, Inc.© was utilized to numerically simulate flow in the WC Breach (Flow Science Inc. 2022). The CFD software uses numerical methods to approximate the Reynold-averaged Navier-Stokes (RANS) equations that are solved with the Boussinesq assumption to simplify the compressible form of the RANS equations.

Bathymetry data for CFD model geometry were compiled from multiple sources (Fig. 10). HDR Engineering Inc. (HDR Engineering, Inc. 2017) provided data for the entire excavated section of the WC breach (minimum elevation ~1273 m) and around 518 m of causeway (minimum elevation of ~1279 m at base of causeway) in both the east and west directions. Bathymetry north and south of the causeway were missing from this dataset, but were provided by the USGS (Baskin 2005). Any additional necessary bathymetric data was derived from topographic maps. The specific geometry of the bridge was created using bridge structural drawings (HDR Engineering, Inc. 2016).
Phase 1 – Sectional Model

The CFD modeling in this study had 1) a sectional model phase and 2) a full-width model phase. Phase 1 was of a single-cell width through the center of WC Breach (Fig. 11) and allowed for an efficient initial study of mesh size, governing equations, boundary conditions, numerical methods, etc. for consideration in Phase 2. The Sectional mesh boundaries were assigned as symmetry and pressure types for the E/W and N/S bounds, respectively. Pressure boundaries required input for both fluid elevation and $\rho$. 

**Fig. 10.** As-built bathymetry for WC breach (a) and additional USGS GSL bathymetry map (b) (Adapted from Baskin 2005).
Grid convergence with 8 different cell sizes was performed and focused on minimal changes in the velocity profile at the USGS measurement locations with numerical velocity probes assigned at locations identical to the USGS ADV measurements (see Fig. 9).

**Fig. 11.** Single mesh configuration for the Sectional model initialized with differing densities (red and blue for the north and south, respectively).

In this study, four turbulence schemes provided by FLOW-3D were considered: \( k-\varepsilon \), *Renormalized Group k-\( \varepsilon \)* (RNG-\( k-\varepsilon \)), \( k-\omega \), and *Large Eddy Simulation (LES)* (Flow Science, 2008). The four turbulence schemes were tested in Phase 1 considering different model coefficients, and the results indicated best performance by the LES and \( k-\omega \), which were then considered in Phase 2.

The following density evaluation options by the FLOW-3D solver considered herein include: 1) density as a function of hydraulic parameters (i.e., temperature, etc.), 2)
a first-order approximation, and 3) a second-order monotonicity preserving approximation. Although a fourth option was available (a constant uniform density) it was not considered appropriate for this study.

Phase 2 - Full 3-dimensional Domain

For Phase 2, the computational mesh was expanded in the east and west directions. In order to continue the grid convergence study, a nested block approach was adopted with two primary or main mesh blocks to represent the north and south sections of the lake with a symmetry boundary condition within the WC Breach. Similar to Phase 1, additional boundary conditions were assigned pressure conditions with \( WSE \) and \( \rho \) inputs (Fig. 12). Nested blocks with refined cell size were centered at the WC Breach due to the primary focus of discharge estimation and available velocity data.

![Fig. 12. Initial 3D mesh domain. P and S represent pressure and symmetry boundary types, respectively.](image)

Probe velocities were compared between subsequent simulations to determine the effect of mesh block extent (north, south, east, and west directions) for the full 3D
domain. During field visits, a north flowing plume with a radial pattern was observed at the WC breach that similarly developed in the CFD model (Fig. 13). The domain and grid resolution was sufficient to include plume formation.

![Fig. 13](image_url). Aerial photo taken directly above the WC breach bridge. The variation in watercolor shows the radial flow pattern at the surface which appears similar in 3D CFD simulations.

The total number of computational cells was limited to a maximum of around 25 million due to computing power limitations (four very well-equipped desktop machines). To obtain mesh independence in the 3D domain, three mesh configurations were tested with a 2:1 cell size ratio between blocks: 1) 0.3 m cells without a nested mesh block, 2) with a nested 0.15 m mesh block around the breach, and 3) with both a 0.15m mesh block around the breach and a smaller 0.08 m mesh block.

In the case of unidirectional flow events caused by high winds that create wave action, a lake seiche occurs which can reverse the WSE difference from being south
dominated to north dominated. Unidirectional flow events were selected from November 2020 field data for the N-S and S-N cases. An identical 3D mesh domain was used for these events as was used for the bi-directional flow event but with differing boundary conditions. Wind-induced shear, though a contributor to unidirectional flow events, was not explicitly added to the CFD model to test the hypothesis that local effects of wind are unnecessary for the formation of unidirectional flow.

The calibrated 3D domain developed in Phase 2 was used to simulate multiple bidirectional and unidirectional flow events selected from 2020 and 2021. The simulated bidirectional flow events include the following dates: November 2020, July 2021, September 2021, and November 2021. The November 2020 event was selected to illustrate the general behavior of bidirectional flow in WC Breach. Bidirectional events were selected based on stable lake elevations and the availability of necessary field data including USGS ADCP measurements for both discharge and velocity. Model physics options and schemes were identical for all flow event simulations. CFD velocity results for individual flow events were directly compared to field velocity data recorded during the specific event. The difference ($\epsilon'$) between USGS velocity and CFD velocity was calculated using Equation (3). The densimetric Froude number for flow within the WC Breach was calculated according to Equations (2), (3) and (4).

$$\epsilon' = \frac{(V_{CFD} - V_{USGS})}{\text{abs}(V_{USGS})} \times 100\%$$ (2)

$$F' = \frac{U}{\sqrt{g' h}}$$ (3)

$$g' = \frac{(\rho_2 - \rho_1)}{\rho_2} g$$ (4)
Rating Curve Development

An accurate discharge rating curve for the WC Breach should consider both \( \Delta WSE \) and \( \Delta \rho \) parameters. To simplify the rating curve, constant \( \Delta WSE \) and constant \( \Delta \rho \) values were assumed. Due to higher variability of \( \Delta \rho \) over time, multiple \( \Delta \rho \) values were simulated. Beginning at a south WSE of 1277.85 m, the WSE was raised and lowered in 0.3 and 1.0 m increments on both sides assuming constant \( \Delta WSE \) of 0.07 m and 0.15 m. Four \( \Delta \rho \) values were modeled to measure the effect of \( \Delta \rho \) on discharge. These \( \Delta \rho \) values were selected from an appropriate range observed in field data. Discharge for both directions (N-S and S-N) was calculated in FLOW-3D using a flux surface tool. In CFD modeling, a flux surface calculates the volume flow rate passing through an imaginary vertical plane placed in a user-specified location of the domain. This required the model to reach a steady state flow condition after which the bidirectional flow interface elevation could be identified for the installation of separate flux surfaces in the model (separate flux surfaces for each flow layer). The simulation was restarted at the steady condition to record several seconds of flow passing through the flux surface. Several seconds was deemed sufficient as no significant changes in flow occurred after this time.
The equations solved include the following:

\[
\frac{\partial u_i}{\partial t} + \frac{1}{V_F} \left( u_j A_j \frac{\partial u_i}{\partial x_j} \right) = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{(\rho - \rho_S)}{\rho_S} G_i + f_i \tag{5}
\]

\[
\frac{\partial}{\partial x_i} (u_i A_i) = 0 \tag{6}
\]

\[
\frac{\partial \rho}{\partial t} + \frac{1}{V_F} \left( A_i \frac{\partial \rho u_i}{\partial x_i} \right) = \frac{1}{V_F} \frac{\partial}{\partial x_i} \left( K A_i \frac{\partial \rho}{\partial x_i} \right) \tag{7}
\]

Where \( u_i \) is mean velocity, \( V_F \) is the fractional volume of flow, \( A_j \) is the fractional area of flow in a particular direction, \( x_i \) is the selected cartesian coordinate, \( p \) is the pressure, \( \rho_S \) is the reference density, \( \rho \) is the density of the fluid, \( K \) is the sum of molecular and turbulent diffusivity, and \( G_i \) and \( f_i \) are the body and viscous accelerations, respectively. In Equation (5), \( f_i \) is defined as:

\[
\rho V_F f_i = \tau_{b,i} - \frac{\partial A_j S_{ij}}{\partial x_j} \tag{8}
\]

\[
S_{il} = -2\mu_{tot} \left[ \frac{\partial u_i}{\partial x_l} \right], S_{ij} = -2\mu_{tot} \left[ \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right] \tag{9}
\]

where \( \tau_{b,i} \) is the wall shear stress, \( S_{ij} \) is the strain rate tensor, and \( \mu_{tot} \) is the total dynamic viscosity. Turbulence in the CFD model can be approximated by multiple turbulence schemes including the following: \( k-\epsilon \), \( k-\omega \), Renormalized Group \( k-\epsilon \) (RNG- \( k-\epsilon \)), and Large Eddy Simulation (LES). For the standard \( k-\epsilon \) model, Equations (10)-(12) are used to calculate \( k \) and \( \epsilon \):
\[
\frac{\partial k}{\partial t} + u_i \frac{\partial k}{\partial x_i} = \frac{\partial}{\partial x_i} \left( \nu_t \frac{\partial k}{\partial x_i} \right) + \nu_t \left( \frac{\partial u_i}{\partial x_i} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_i}{\partial x_j} - \varepsilon
\] (10)

\[
\frac{\partial \varepsilon}{\partial t} + u_i \frac{\partial \varepsilon}{\partial x_i} = \frac{\partial}{\partial x_i} \left( \nu_t \frac{\partial \varepsilon}{\partial x_i} \right) + C_1 \varepsilon \nu_t \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_i}{\partial x_j} - C_2 \frac{\varepsilon^2}{k}
\] (11)

\[
\nu_t = C_v \frac{k^2}{\varepsilon}
\] (12)

where \( C_1, C_2, \) and \( C_v \) are 1.44, 1.92, and 0.09, respectively. The Prandtl numbers for turbulence \( \sigma_{k\varepsilon} \) and \( \sigma_\varepsilon \) are 1.0 and 1.3, respectively, and \( \nu_t \) is the turbulent kinematic viscosity. The \( RNG-k-\varepsilon \) model is defined by equations (13) and (14) with the turbulent viscosity calculated by Equation (15).

\[
\frac{\partial k}{\partial \varepsilon} (\rho k) + \frac{\partial}{\partial x_i} (\rho k u_i) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \mu_t \right) \frac{\partial k}{\partial x_j} \right] + P_k - \rho \varepsilon
\] (13)

\[
\frac{\partial}{\partial t} (\rho \varepsilon) + \frac{\partial}{\partial x_j} (\rho \varepsilon u_i) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \mu_t \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_1 \varepsilon \frac{\nu_t}{k} P_k - C_2 \rho \frac{\varepsilon^2}{k}
\] (14)

\[
\mu_t = \rho C_u \frac{k^2}{\varepsilon}
\] (15)

where \( \mu \) is the dynamic viscosity, \( \mu_t \) is the turbulent dynamic viscosity, \( k \) is the turbulent kinetic energy (TKE), \( \varepsilon \) is the rate of dissipation of \( k \), \( P_k \) is the production of \( k \), \( C_{1\varepsilon} = 1.39, C_{2\varepsilon} = 1.42, \) and \( C_\mu = 0.085 \). The \( k-\omega \) model is defined by Equations (16)-(18):

\[
\frac{\partial k}{\partial t} + u_i \frac{\partial k}{\partial x_i} = \tau_{ij} \frac{\partial u_i}{\partial x_j} + \frac{\partial}{\partial x_i} \left[ \left( \nu + \nu_t \right) \frac{\partial k}{\partial x_i} \right] + \beta k \omega
\] (16)

\[
\frac{\partial \omega}{\partial t} + u_i \frac{\partial \omega}{\partial x_i} = \frac{\partial}{\partial x_i} \left[ \left( \nu + \nu_t \right) \frac{\partial \omega}{\partial x_i} \right] - \beta^* \omega^2 + \alpha \frac{\omega}{k} \nu_t \left( \tau_{ij} \frac{\partial u_i}{\partial x_j} \right)
\] (17)

\[
\nu_t = \frac{k}{\alpha}
\] (18)
Where $\beta^* = 0.09f_B^*$, $\alpha = 0.52$, $\sigma_{k\omega} = 0.5$, $\sigma_{\omega} = 0.5$, and $\beta = 0.072f_B$. The final turbulence scheme, LES, computes all turbulent flow structures resolved by the computational grid and approximates features too small to be resolved. Sub-grid turbulence effects are accounted for in the turbulent eddy viscosity ($\nu_T$) defined by Equations (19)-(21):

$$\nu_T = (cl)^2 \sqrt{2S_{ij}S_{ji}}$$  \hspace{1cm} (19)

$$l = (\Delta x \Delta y \Delta z)^{\frac{1}{3}}$$  \hspace{1cm} (20)

$$S_{ij} = \frac{1}{2} \left[ \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right]$$  \hspace{1cm} (21)

Where $c$ is the Smagorinsky coefficient equal to 0.1, $l$ is the geometric mean of the grid cell dimensions, $S_{ij}$ denotes the strain rate tensor components, and $\Delta x$ is the cell dimension in the x-direction. In this study, a total of 95 simulations were performed including simulations for CFD verification and validation. Details of the numerical simulation matrix are presented in Table 1.

**Table 1. Complete CFD simulation matrix.**

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**Notes:**

- The values are presented in a tabular format with columns for k-ω, 4192.5, 4192.3, 0.2, and 192,400.
- The values range from 0.23 to 5.77 for k-ω and from 0.12 to 4192.5 for the other columns.
- The table contains 60 rows, each representing a different k-ω value.

**Additional Information:**

- The values seem to be related to some form of scientific or engineering data, possibly involving frequency or acoustic properties.
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Mesh set-up

The beginning cell size for the Sectional model was set to 0.3 m and was gradually decreased to 0.03 m in a total of eight subsequent simulations (Table 2). In general, plots of velocity vs. cell size show change in velocity below the 0.3 m cell size until a cell size near 0.15 m (Fig. 14 a-e). Further mesh refinement below 0.15 m did not cause significant change in velocity. Instead, the computational mesh appeared to be over-resolved, and the velocities diverged from the steady value reached by the 0.15 m cell size. For this reason, convergence was assumed to have been met at the 0.15 m cell size.

Table 2. Cell size sensitivity simulations for the k-ω turbulence scheme.

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Fig. 14. Sectional mesh cell size convergence plots at probe elevations 1274.5 m (a), 1275.7 m (b), 1276.9 m (c), and 1277.7 m (d) with error bars to visualize the velocity range of each probe. A comparison of all nine probes and their respective steady state velocities at each cell size for the $k$-$\omega$ and LES turbulence schemes (e).
In the 3D model, domain extent was decreased to the smallest possible size to help reduce cell count and consequent simulation runtimes. The resulting flow velocities within the breach were nearly identical between the smallest and largest tested domains. Based on the Sectional model results, it was expected that optimum cell size for the full 3D domain was below 0.3 m and likely around 0.15 m. Further mesh refinement below 0.3 m was achieved by adding nested mesh blocks to resolve the more complicated geometry and flow within the breach. Probe velocity results from the full 3D domain showed solution independence was achieved with a nested mesh cell size of 0.15 m (Fig. 15a). The final 3D domain was 295 m by 275 m centered around the breach with two outer 0.3 m cell size meshes (one each for the north and south sides) and one 0.15 m mesh to contain most of the breach and the bridge piers (Fig. 15b). A 0.08 m mesh around the bridge piers was excluded after it was determined to have minimal effect on breach velocities, but significant effect on simulation runtime.

![3D mesh cell size convergence results](a) ![Mesh configuration with three blocks of decreasing size with a 2:1 ratio between subsequent sizes](b)

**Fig. 15.** 3D mesh cell size convergence results (a) and mesh configuration with three blocks of decreasing size with a 2:1 ratio between subsequent sizes (b) (Rasmussen et al).
Turbulence Closure Scheme

A macroscopic density profile for each case shows the CFD result after 3500 seconds of simulation runtime (Fig. 16). The $k-\omega$ and LES schemes produced similar bi-directional flow results at a decent level of agreement with field data and observations. Unsatisfactory results (relative to field data) were produced by the $k-\varepsilon$ and RNG-$k-\varepsilon$ schemes. Due to a reduction in simulation runtime with the LES scheme in comparison with $k-\omega$, LES was chosen for all subsequent simulations.

Density Evaluation

Velocity results were plotted and compared for the density evaluation options (Fig. 17). Although the first and second order options produced similar results, the second-order option was chosen to increase the precision of density calculation within the simulation. Calculation of density as function of other quantities produced erroneous results and was not considered a practical option.
Fig. 17. Density evaluation options velocity results for probe elevation 1274.5 m. Remaining probe elevations excluded to simplify the plot. Other quantities option only simulated for 500s once the result was observed to be erroneous.

The CFD model results were compared to ADVM field velocity data. The ADVM measurement elevations (Fig. 9) provided by USGS were assumed accurate, but the exact location of the ADV instrument within the WC breach was unknown. The general location was described by USGS (as in between the center and west rows of piers and directly below the north bridge parapet). Due to the non-uniform velocity profiles observed in bi-directional flow simulations and the uncertain ADV location, multiple velocity probe columns were place in the CFD model. The probe columns were labeled $a$ through $j$ to delineate CFD results for comparison (Fig. 18).
Fig. 18. CFD probe columns a through j placed to account for uncertainty in the ADV location.
RESULTS

USGS Field Data

The USGS WSE data provide insight into the GSL’s behavior before and after completion of the WC breach. For example, the completion of WC Breach in late 2016 caused the north section to rise 1.5 m over a four-month period (Fig. 19). After the lake WSE reached a quasi-equilibrium state in the summer of 2017, the south WSE remained approximately 0.15 m above the north; a pattern that has persisted to the present day.

![Fig. 19](image)

**Fig. 19.** Great Salt Lake north and south water surface elevations since 2016. Notice the convergence of north and south shortly after the railroad causeway was breached at the WC location in late 2016 (USGS 2021).
Water quality parameters including $TDS$, $\sigma$, and $\rho$ measured at the USGS stations shown in Fig. 8 follow a mostly linear relationship, but the linearity degrades with increased salt concentration (Fig. 20). The data show it may be possible to determine a simple linear relationship between $\rho$ and $\sigma$ for values < 200 mS/cm, but higher salt concentrations require a better $\rho$ calculation such as by means of TDS or direct $\rho$ measurement.

![Fig. 20. USGS and HDR water quality data. These plots provided initial estimates of $\rho$ for use in the CFD model (HDR Engineering, Inc. 2020; USGS 2021).](image)

By inspection of USGS field data, high wind events (> 50 kph) that cause unidirectional flow are typically short (< 2 hours) but velocity magnitudes exceed 1 m/s. The lake quickly returns to a steadier condition after the wind subsides (Fig. 21). During a monthly visit to the breach, a N-S unidirectional flow event was observed and characterized by an obvious surface current moving in the southward direction. This event was later corroborated by USGS field velocity data.
The variability of an ADCP measurement through a breach transect can be seen in Fig. 22. Because of ADCP instrument limitations, a blanking distance exists near the channel bottom and just below the water surface wherein no velocities are measured. USGS approximates the velocity in the bottom blank region using a simple log-curve velocity profile (see Fig. 22). A cross-sectional view of these velocity data after manual processing is shown in Fig. 23. The data, recorded Nov. 2020, show a typical bi-directional flow behavior in WC Breach. Notice some areas of the velocity cross-section appear better resolved than others.
Fig. 22. Velocity data normalized by depth through the entire cross-section profile (Freeman 2022).

Fig. 23. Water velocity resolution of an ADCP discharge measurement through a cross-section of the WC Breach during November 2020. ADCP data are processed to compute discharge in both flow directions (Michael Freeman, Personal Correspondence, Apr. 4, 2022) (Freeman 2022).
Field Campaign

Numerous locations were profiled via watercraft for $\sigma$ and temperature to assess any spatial variability in salinity (Fig. 24a). These measurements indicated that in the northern section, the south-to-north flow layer became considerably thinner with increased distance from the breach. Measurements immediately south of the bridge showed a slow increase of $\sigma$ with increased depth followed by a sharp increase of $\sigma$ at an approximate 3 m depth (Fig. 24b). In the northern section, measurements indicated little spatial variability of $\sigma$ in a given flow layer, and it was possible to estimate layer thickness with the south-to-north layer (7 to 13 cm) as a relatively fast-moving top current.
Fig. 24. WC Breach with white hollow points showing $\sigma$ measurement locations near during Fall 2020 (a) and $\sigma$ related to depth on the north and south sides of the causeway. Note the uniformity of $\sigma$ through depth on the north except near the water surface within the extent of the S-N plume (b).

Results from the two $\rho$ calculations methods (TDS Method and Direct Method) for the USU grab samples were compared with corresponding USGS reported values. Most south section USU samples were consistent with USGS data with a less than 1%
difference between the TDS Method and Direct Method values (Fig. 25). North USU samples differed by about 3% from USGS data during winter months. It was observed during these visits that high amounts of mirabilite precipitation had occurred likely decreasing north water density, though this does not fully explain the discrepancy between USGS and USU data. Sampling techniques differed where USGS typically acquires samples within WC Breach, whereas USU samples were collected from the causeway shoreline near the breach. However, USU water samples were only considered supplementary to USGS data and analysis methods are likely to differ.

![Graph](image-url)

**Fig. 25.** USU and USGS field $\rho$ measurements. The USU measurements include the Direct and TDS methods for calculating $\rho$.

A sample timeseries plot of continuous USU data shows low variation in $\sigma$ over time in both the north and south sections except during high wind speed events (Fig. 26). High wind speeds appear only to have affected $\sigma$ on the south, but this was not
unexpected as both the north and south sondes were installed to be completely submerged during deployment, so less-dense south arm water would not easily show on north arm measurements, even with an increased level of mixing. Extremely high salt concentration in the north section may also make any influx of less-saline water difficult to notice in $\sigma$ measurements.

![Graph showing water conductivity and wind speed](image)

**Fig. 26.** UWRL $\sigma$ plotted with USGS wind data where the red and blue colors represent the north and south sides, respectively. Wind speed is denoted by hollow grey scatter points (USGS 2021).

The temperature array data show clear stratification through the water column (Fig. 27). A relatively large difference in temperature between two sensors indicates the likely presence of the bi-directional flow interface (+- 0.3 m). Much less vertical variation occurred during storm events which often shifted the flow from a bidirectional to a
unidirectional case with a more uniform temperature profile.

**Fig. 27.** Period of temperature array data showing temperature stratification over a 24-hr period in July 2021. By inspection of the plot, the approximate interface elevation was between 1275.9 m and 1276.2 m during the measured period.

**CFD Modeling**

**Bidirectional Flow**

Based on field observations and field data, the general behavior of bidirectional flow in WC Breach is distinct; hypersaline water moves in the N-S direction and plunges (within the breach) below a less saline flow layer that moves in the S-N direction. The S-N flow spreads laterally into a thin plume on the north side, but the N-S flow maintains much of its thickness as it travels through the excavated breach section (Fig. 28). The hypersaline bottom later is understood to connect with the deep brine layer (DBL) in the south section of GSL (Naftz 2017).
Within the breach, the CFD results show the N-S current accelerates as it approaches and plunges near a submerged berm (Fig. 29). The berm was specifically created during construction of the breach to be a flow control structure (Waddell et al. 2016). The N-S current experiences its highest streamwise velocities at and immediately downstream of the berm where the densimetric Froude number is about 0.7 and is subcritical (for the November 2020 simulation). The effect of berm height and width is beyond the scope of this paper was not studied, but the berm appears to cause local changes in flow dynamics that may affect mixing within the breach. More information on mixing between bidirectional flows over a submerged berm can be found in Cuthbertson et al. (Cuthbertson et al. 2018). The CFD model can be modified in the future to study the effect of breach and berm geometry for greater control over WC Breach exchange flows.
Fig. 29. Velocity cross-section through the breach center showing bidirectional flow.

To observe the general evolution of the bidirectional currents, cross-sectional data were taken every 15 m through the breach (Fig. 30). Beginning in the north, the flow layers are horizontal and mostly uniform in the x-direction. The S-N current has accelerated to a velocity of 1.4 m/s on the surface, and the bottom N-S current approaches the breach with a velocity of 0.15 m/s. At the sill, flow converges into the narrowest portion of the breach where the N-S current reaches its highest velocity of approximately 0.5 m/s. Within the breach, the currents are non-uniform in the x- and z-directions, especially with respect to the N-S current (Fig. 31). Although the streamwise velocity of each current varies within the breach, density profiles show the currents remain highly stratified with a sharp horizontal flow interface (Fig. 32). This suggests that turbulence within the breach does not necessarily cause considerable mixing between the two currents even where the flow encounters the bridge piers. The effect of the bridge piers was considered during analysis and determined to be a minor contributor to overall flow dynamics. However, the piers were ultimately kept within the CFD model for completeness.
Fig. 30. WC Breach cross-section locations for Figs 31, 32, and 36.

Fig. 31. Streamwise velocity profiles (facing north) for the November 2020 bi-directional flow event.
For all bidirectional events, and with respect to the reported field data, the model tended to overestimate the S-N current and underestimate the N-S current (Fig. 33 and 34). This implies a difference in the location of the flow interface which the model projected to be lower than measured in field data, though the ADV data have a confidence interval of 0.4 m. The temperature array provided a direct measurement of the interface location with a confidence interval of 0.3 m illustrated with grey dashed lines in Fig. 33 and Fig. 34.

Higher $\varepsilon'$ values near the flow interface are not unexpected, as the sudden change in velocity and density is challenging to numerically simulate. In field data, turbulence near the interface is likely to increase the uncertainty of the measurement. It must also be noted that a 0-50% difference in velocity is a much smaller range for a velocity near zero compared to a velocity of 0.5-1 m/s, so velocity measurements near the bidirectional flow interface exceed the maximum plotted $\varepsilon$ value for all four cases (Fig. 33 and Fig. 34). All
four bidirectional simulation results were within 10% of field data near the top portion of the S-N flow layer. Higher model performance near the water surface is expected in CFD modeling as opposed to the fluid-fluid interface.

Fig. 33. ADV and CFD flow velocities plotted against depth for the July 2021 (a) and Nov. 2020 (b) flow events. Note the Nov. 2020 event occurred prior to installation of the temperature array, so no grey dashed lines appear on the plot.
Fig. 34. ADV and CFD flow velocities plotted against depth for the Sept. 2021 (a), and Nov. 2021 (b) flow events.

Unidirectional Flow

The CFD results agreed well with field data for both unidirectional flow events (Fig. 35). The majority of the CFD velocity profiles were within 10% of field measurement which is within field data measurement uncertainty. However, near the channel bottom and below about El 1,275.0, the CFD velocity profile diverges from the field measurement for the N-S and S-N unidirectional events. This discrepancy may be due to a limitation with the terrain used for the CFD model. The channel bottom is
expected to change over time with the movement of sediment and rock, yet the only bathymetry provided was at completion of construction. A second source of discrepancy is that the resolution of bathymetry data provided was based upon construction needs and did not consider resolutions needed for CFD modeling, therefore data resolution and the presence of riprap or debris at the breach influences CFD results in connection with the specification of the no-slip boundary condition and corresponding representation of bed roughness.
Fig. 35. CFD output vs USGS field data for the unidirectional flow N-S case (a) and the S-N case (b).

The effect of the submerged sill can be easily observed in cross-sections of the streamwise (Y-direction) velocity for the unidirectional cases. The sill acts as an impediment to the N-S flow layer as can be seen in (Fig. 36a and 37) where the S-N current dominates the breach until the sill is reached. Similarly, the N-S unidirectional simulation showed the sill decreases the N-S velocity and causes the bidirectional currents (very low magnitude S-N current) to become more entrained (Fig. 36b).
Fig. 36. Streamwise velocity cross-sections for the S-N (a) and N-S (b) unidirectional flow simulations.
Fig. 37. Effect of sill on the N-S current during a S-N unidirectional flow event.

Rating Curve

Based on CFD results, discharge through the WC Breach is dependent on the available upstream hydraulic head (caused by a \( \Delta WSE \)), buoyant forces resulting from \( \Delta \rho \) between the north and south sides, and the breach geometry. The \( \Delta WSE \) averaged 0.15 m from July 2017 (with seasonal variability) until Dec. 2021, and \( \Delta \rho \) trended downward toward 80-90 kg/m³ over the same period as the average GSL WSE decreased and caused the south section \( \rho \) to increase (Fig. 38). Field data appear to show that wet months in combination with spring snowmelt increase inflows to the south section which increases the \( \Delta WSE \). At the beginning of summer months, inflows to GSL decrease below the S-N discharge through WC breach, evaporation increases, and \( \Delta WSE \) decreases. This pattern is illustrated in the sinusoidal-like \( \Delta WSE \) curve (Fig. 38).
Fig. 38. $\Delta WSE$ and $\Delta \rho$ between the north and south section of GSL over time since the WC breach was opened (USGS 2021).

CFD discharge results followed the general trend observed in USGS ADCP discharge calculations (Fig. 39a). Comparing Figs. 39a and 39b, the dominant flow direction appears mainly dependent on $\Delta WSE$. As lake elevation increases, N-S flow increases at a higher rate than S-N discharge. This seems to indicate the control berm within the channel impedes the N-S flow until a threshold $WSE$ is reached. The elevation at which discharge is equal in both flow directions is shown to increase with increased $\Delta WSE$. When $\Delta WSE = 0.15$ m (most often observed in field data), N-S discharge becomes negligible in comparison to S-N discharge below south section $WSE$ ($WSE_{South} = 1277.5$ m (Fig. 39a). Both flow directions decrease below 10 cms when $\Delta WSE = 0.07$ m at $WSE_{South} = 1277.5$ m.
Fig. 39. WC breach rating curve for bi-directional flow scenario with N-S (red) and S-N (blue) discharge in m$^3$/s (cms) as a function of south section WSE with a constant $\Delta WSE$ of 0.07 m (a) and 0.15 m (b). Scatter points in (a) are all USGS monthly ADCP discharge calculations since Year 2017 with $\Delta WSE = 0.15$ m (USGS 2021).
DISCUSSION

The results of this study provide insight into the complex hydraulics of the WC Breach that can support GSL management efforts. First, the CFD model is able to estimate the movement of water and salt through the WC breach for existing hypothetical scenarios, and the CFD results from this study included the development of a simple discharge rating curve as a function of WSE, $\rho$, and breach geometry to help approximate WC Breach discharge. Secondly, the CFD model results highlight the lake’s sensitivity to conditions in the lake and specifically at the breach. This is also illustrated in field measurements recorded before and after closure of the causeway culverts.

The best available field data was selected for developing and testing the model, but even the selected field data may not accurately reflect actual conditions. The current spatial and temporal field data resolution is simply not sufficient for reliable rating curve development. This underscores the need for improved and increased field data collection especially flow velocity measurements which are currently measured by USGS instrumentation only at a single location within the breach and via monthly ADCP measurements. Flow velocities within the breach are known to vary by location, so additional instrumentation inside the breach will be required. This sensitivity is an important consideration in lake management efforts as accurate, quality data is needed for accurate flow predictions. Slight differences in water surface elevation, density, etc. can result in an appreciable deviation in prediction.

Furthermore, the CFD model can be used as a design tool to alter flows through the breach to achieve desired results. For example, the CFD model can be used to
simulate a modified submerged berm and the effects for typical hydrologic years or years of drought or intense rainfall. Although the CFD model of the WC Breach is viable for simulating complex bidirectional flows, caution is always prudent when using a model to predict hypothetical lake conditions and discharge estimates.

Another important model parameter for which up to date, high-resolution data is needed is the breach bathymetry to account for changes in and near the channel that occur with the movement of sediment and rock. A recent bathymetric survey was conducted in August 2021 for the WC Breach, and a comparison between the new survey and the As-built survey (used for this study) showed the breach bathymetry has changed by as much as 1.5 m or more in the vertical direction at some locations. The new bathymetry resulted in improved CFD velocity profiles (with respect to USGS field velocity data) for the four bidirectional flow events modeled in this study.
CONCLUSIONS

This project was undertaken to support the management and understanding of flow through the WC Breach of the GSL railroad causeway. Management of the breach is focused on addressing the rising economic and environmental concerns associated with salt and water exchange between the north and south sections of the GSL. To obtain insight into the hydraulics of the WC breach, a field campaign coupled with CFD modeling was undertaken. From the results:

- Discharge through the WC Breach is sensitive to both density and water surface elevation differences between the north and south sections.
- The CFD model is capable of approximating the bidirectional velocity profile within the breach.
- The CFD model produced discharge results similar to field ADCP measurements for discharge during the same lake conditions.

As drought and large freshwater diversions upstream of the GSL continue, the GSL’s ecological and economic resources will be increasingly strained. The desiccation of the GSL could be catastrophic and irreversible, as has been the downfall of other saline lakes around the world. The CFD model results will provide valuable insight into flow behavior in WC Breach. These results may aid in the design process of alterations to WC Breach geometry to attain desired discharge results.
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