Record Low Water-Surface Elevations at Great Salt Lake, Utah, 2021–2022

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ABSTRACT

The United States Geological Survey (USGS) operates two long-term water-surface elevation (WSE) gages on Great Salt Lake, Utah, one north of the Union Pacific Railroad causeway in the historic Little Valley Boat Harbor (Saline gage), and one south of the causeway in the harbor at Great Salt Lake State Park (Saltair gage). From September 28 to December 15, 2022, lake levels were too low in the harbor for the Saltair gage to operate and WSE data was measured at the South Causeway gage, a relatively new gaging station (installed in 2020) located immediately south of the causeway. Data collected at the South Causeway gage were used to estimate the daily mean WSE record for the Saltair gage for the period it was shut down, preserving the continuity of the 175-year WSE record that is associated with this gage. The long-standing historic low daily mean WSE measured at the Saltair gage on October 15, 1963 (4,191.35 feet, relative to the National Geodetic Vertical Datum of 1929 (NGVD29)) was broken on July 21, 2021. Seasonal lake-level declines from July 2021 to October 2021 and April 2022 to early November 2022 resulted in a new historic low daily mean WSE of 4,188.5 feet NGVD29, measured during several days during November 2022 at the South Causeway gage. The same value is also the new historic low daily mean WSE for the Saline gage and was measured during several days in November and December 2022 (the previous historic low of 4,188.98 feet NGVD29 was measured in September and October 2016 and was related to closure of two railroad causeway culverts). USGS also operates streamgages on major surface-water inflows including the Bear River, Weber River, Jordan River, and Surplus Canal. The combined annual discharge measured at these gages in water years 2021 and 2022 was 0.704 and 0.743 million acre-feet, respectively, which is less than half of the combined median annual discharge (1.57 million acre-feet) based on the period of record for each gage.

INTRODUCTION

The United States Geological Survey (USGS), in cooperation with the Utah Department of Natural Resources, operates two long-term water-surface elevation (WSE) gages on Great Salt Lake (GSL), Utah (figure 1). USGS station 10010000 Great Salt Lake at Saltair Boat Harbor, UT (Saltair gage) (U.S. Geological Survey, 2023), is located about 35 miles south of the Union Pacific Railroad Causeway (referred to as the causeway in the rest of this document) in the harbor at GSL State Park. This gage is associated with a WSE data record dating back to 1847. The record from 1847 to 1874 was compiled by Grove Karl Gilbert, first Chief Geologist of the USGS, and is based on oral reports from stockmen who had ridden horses across sandbars to reach Antelope and Stansbury Islands (Gilbert, 1890; Arnow and Stephens, 1990). The accuracy of the early measurements does not compare to those made with modern methods (for example, Arnow and Stephens (1990) state that water levels from 1847 to 1874 should be considered accurate only to within 1 foot (ft)); however, this does not detract from the scientific value of those early observations.

Systematic lake level measurements at GSL began in 1875 as described by Gilbert (1890):

> *"In the year 1875, Dr. John R. Park, of Salt Lake City, at the suggestion of Prof. Joseph Henry of the Smithsonian Institution and with the cooperation of other citizens, instituted a series of observations. There was erected at the water's edge at Black Rock a granite block cut in the form of an obelisk and engraved on one side with a scale of feet and inches; and Mr. John T. Mitchell was engaged to observe the water-height at intervals of a few days."*

From 1875 to 1938, the lake level was measured at staff gages by many different individuals and organizations at variable intervals ranging from weekly to monthly. Since 1939, lake levels associated with the Saltair gage have been measured continuously with various recorder devices operated by the USGS. The Saltair gage has been moved several times within GSL State Park because of storm damage, rebuilding of the harbor dikes, high lake levels, and low lake levels. From September 28 to December 15, 2022, lake levels were too low in the harbor for the Saltair gage to operate. During this period, WSEs south of the causeway were obtained from USGS station

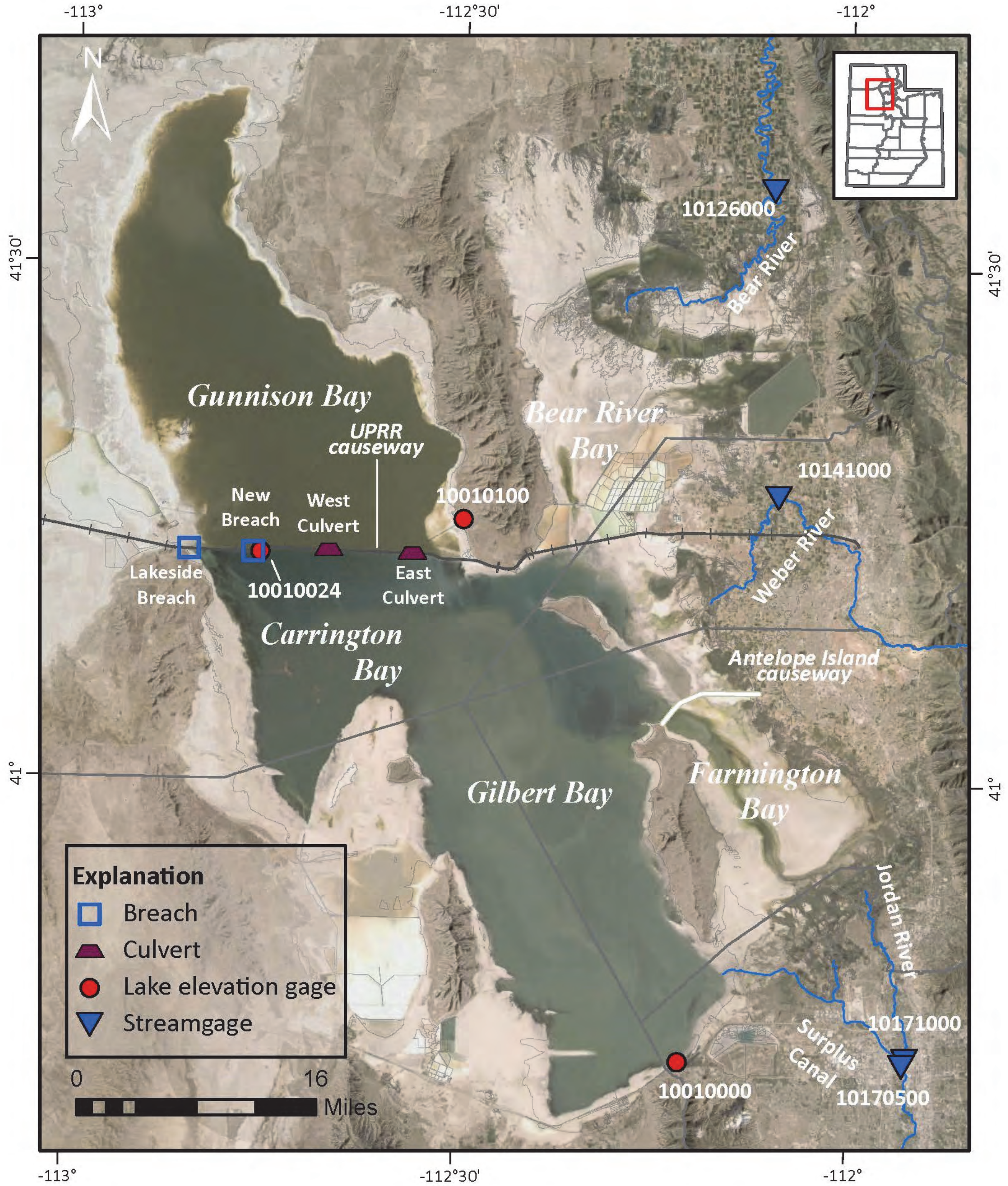

Figure 1. *Locations of selected United States Geological Survey gaging stations (U.S. Geological Survey, 2023) at and near Great Salt Lake, Utah. Base from Maxar Imagery digital data, various scales, 2019-2022. Universal Transverse Mercator projection, zone 12 N, North American Datum of 1983.*

10010024 GSL South Side of Causeway, 6 Miles East of Lakeside, Utah (referred to as the South Causeway gage in the rest of this document) (U.S. Geological Survey, 2023), a relatively new gage installed in 2020.

The second long-term WSE gage is USGS station 10010100 Great Salt Lake near Saline, UT (Saline gage) (U.S. Geological Survey, 2023), is in the historic Little Valley Boat Harbor on the west side of Promontory Point, about 2.7 miles north of the causeway. This gage was installed in 1966, about 7 years after the causeway was completed (figure 1). Water-surface elevations at this gage have been measured continuously with various recorder devices operated by the USGS. It has only been moved once within the harbor (in May 1996) so that the pier it was mounted to could be removed by the owner.

The USGS also operates four long-term streamgages on major surface-water inflow sources to the south part of GSL (collectively referred to as inflow gages in this document). While these gages do not measure all surface-water inflows to GSL (there are several unmeasured surface-water inflows), and also unmeasured losses or gains of water between the gages and GSL, they provide important insight into GSL WSE changes over time. These inflow gages are USGS stations 10126000 Bear River near Corinne, UT (Bear River gage); 10141000 Weber River near Plain City, UT (Weber River gage); 10171000 Jordan River at 1700 South at Salt Lake City, UT (Jordan River gage); and 10170500 Surplus Canal at Salt Lake City, UT (Surplus Canal gage) (U.S. Geological Survey. 2023) (figure 1). The Weber River gage is among the 10 oldest streamgages in Utah and has been active since October 1907, with some discrete-discharge measurements starting in 1904. The other inflow gages were installed in the 1940s.

The primary objective of this document is to summarize selected data from the locations listed above through November 2022, which includes the lowest daily mean WSE measured at GSL. This document 1) reports how record low WSEs at GSL were measured and validated; 2) summarizes extended periods of WSE and inflow gage data; 3) compares WSEs to inflow gage data; and 4) compares WSE and inflow gage data to a standardized measure of drought severity in Utah.

The locations of USGS monitoring stations discussed in this document are shown in figure 1 and a summary of parameters used in this document, including the period of record associated with each parameter, are summarized in table 1. Data summarized in table 1 are available via the USGS National Water Information System (NWIS) (U.S. Geological Survey, 2023).

Table 1. *U.S. Geological Survey (USGS) station name, number, and available period of record for data used in this report. Data are available via the USGS National Water Information System (U.S. Geological Survey, 2023).*

Station Name	Station Number	Parameter and units	Available Period of Record
Great Salt Lake at Saltair Boat Harbor, Utah	10010000	Daily and annual mean water-surface elevation above National Geodetic Vertical Datum of 1929, in feet	10/15/1847 to current
Great Salt Lake near Saline, Utah	10010100	Daily and annual mean water-surface elevation above National Geodetic Vertical Datum of 1929, in feet	4/15/1966 to current
Great Salt Lake South Side of Causeway, 6 Miles East of Lakeside, Utah	10010024	Daily mean water- surface elevation above National Geodetic Vertical Datum of 1929, in feet	2/25/2020 to current
Bear River near Corinne, Utah	10126000	Daily and monthly mean discharge, in cubic feet per second	10/1/1949 to 9/29/1957 and 10/1/1963 to current (No data 9/30/1957 to 9/30/1963)
Weber River near Plain City, Utah	10141000	Daily and monthly mean discharge, in cubic feet per second	10/1/1907 to current
Jordan River at 1700 South at Salt Lake City, Utah	10171000	Daily and monthly mean discharge, in cubic feet per second	12/1/1942 to current
Surplus Canal at Salt Lake City, Utah	10170500	Daily and monthly mean discharge, in cubic feet per second	12/1/1942 to current

DESCRIPTION OF STUDY AREA

Great Salt Lake is a closed-basin lake bordered on the west by desert and on the east by the Wasatch Range. Its abundant food and wetlands attract nearly 2 million shorebirds, including over 1.5 million grebes (Podiscipedidae) and several million migrating waterfowl (Wurstbaugh and others, 2017). Construction of a rock-fill causeway across GSL in 1959 created two separate but connected parts of the lake with different WSEs, salinities, and densities resulting from more than 95 percent of all freshwater surface inflow entering the lake south of the causeway (Loving and others, 2000). The differences between the WSEs and densities of the south and north parts of GSL provide the potential for water (GSL water is technically brine because it contains more than 35,000 milligrams per liter of dissolved solids; however, for simplicity, the term water is used in this document) to flow in both directions through the causeway conveyances. Generally, the less-dense water from the south part flows northward through the upper part of the causeway conveyances (breaches and causeway fill) and the more-dense water from the north part flows southward through the lower part of the causeway conveyances (Loving and others, 2000). Currently, the means of conveyance include the following: a 290 ft wide breach (often referred to as the Lakeside breach) near the west end of the causeway that was completed in 1984 with a bottom elevation of 4,200 ft that was lowered to 4,193 ft relative to the National Geodetic Vertical Datum of 1929 (NGVD29) in 2000; a relatively new 150 ft wide breach about 4.5 miles from the west end of the causeway that was opened on December 1, 2016, with an adjustable berm that has a current top elevation of 4,192 ft NGVD29; and the permeability of the rock-fill material used to construct the causeway. The 150 ft wide breach completed in 2016 replaced two culverts, referred to as the east and the west culverts, that were in service from causeway completion in 1959 until closure in November 2012 (east culvert) and December 2013 (west culvert).

METHODS

Measurement of Water-Surface Elevation

Gaging stations located on GSL are used to measure WSE. The measurement of WSE at GSL follows USGS protocols outlined in Sauer and Turnipseed (2010) which details the measurement of stage. In summary, each gaging station has a network of reference points and reference marks. These reference locations are surveyed, using a variety of techniques, to establish an elevation relative to an assigned datum. Once an elevation is assigned to these reference locations, a nonrecording reference gage can be established at the gaging station. The reference gage is used to physically measure the WSE of GSL. Once the WSE is measured using the reference gage, a recording water-level instrument can be set up to measure the WSE at a set interval relative to the reference gage WSE reading. Currently, WSE recorders for GSL are set up to measure every 15 minutes. Gaging stations are visited every 1–2 months to read the WSE from the reference gage and compare those readings with the WSE recorder. If a difference is observed between the reference and recorded values because of instrument drift, a correction is applied to the recorded data so that the WSE is accurately reported. Daily and annual mean WSEs discussed in this report are available via NWIS (U.S. Geological Survey, 2023).

Water-Surface Elevation Reported Datum

Reference marks, reference gages and recording gages are all referenced to NGVD29. NGVD29 is similar in elevation to dynamic heights reported by the National Geodetic Survey (NGS). Dynamic height values are defined by an equipotential surface allowing for accurate representation of hydrologic gradient when measuring WSEs over a large geographic area (Meyer and others, 2006). The reporting of vertical datums using dynamic heights to accurately measure water gradients is best documented in the establishment of the International Great Lakes Datum of 1985 (Meyer and others, 2006). The equipotential surface applied to dynamic heights provides a WSE that flows downhill as expected. Dynamic heights for the GSL region are most accurately reported when referencing WSE to NGVD29. In contrast, the more commonly used North American Vertical Datum 1988 (NAVD88) is influenced by gravitational models that can cause WSEs that suggest water flowing in an upstream direction when a downstream gradient is known and expected. Because of the causeway and the dividing of GSL, it is important to accurately represent hydraulic gradient across the causeway and, therefore, elevation should always be reported with respect to an equipotential surface so that hydraulic gradient can accurately be measured.

To accurately report WSEs of GSL, the stability of the gaging station's reference to NGVD29 is verified using a variety of survey methods. The survey method used to verify vertical datum is determined by the location of the three lake gaging stations. The Saltair and South Causeway gaging stations are located on earthen-fill material and have shown vertical movement in previous years related to the rising and falling WSE of the GSL. As WSE of GSL increases, the earthen material rises with increasing water level, whereas when the WSE of the GSL decreases the earthen material subsides within the lake substrate. To maintain accurate reporting of WSE at these locations, the two sites are surveyed at the peak and the trough of the annual hydrograph. By surveying at the peak and the trough, WSE data are corrected based on the annual fluctuations of GSL. In contrast, the Saline gage has demonstrated vertical stability and is surveyed annually to ensure the gage is reporting WSE accurately. Because of the complex surveying techniques required to verify vertical datum at GSL gaging stations, WSE reported by the USGS GSL gages are considered to be accurate to within +/-0.10 ft of the datum in use (Loving, 2002).

USGS Station 10010000 Great Salt Lake at Saltair Boat Harbor, UT

To verify that this gaging station is reporting accurately to NGVD29, trigonometric and differential leveling techniques are used to carry vertical datum from NGS vertical control point C-174 (table 2) to the gaging station. Starting from NGS Reference Mark C-174, a double-run spur traverse (DRST) using trigonometric leveling techniques documented in Noll and Rydlund (2020) is used to carry datum approximately 0.5 miles from the reference mark near Kennecott Smelter to the harbor at Great Salt Lake State Park. The level line from the DRST establishes an elevation relative to NGVD29 to a reference mark closer to the Saltair gaging station where differential leveling techniques can be used to verify the datum of the reference gage (Kenney, 2010). If the reference gage has moved (+/-0.05 ft) a datum correction is applied to the WSE record of the gage to correct for movement of the reference gage.

USGS Station 10010024 GSL South Side of Causeway, 6 Miles East of Lakeside, UT

To verify that this gaging station is reporting accurately to NGVD29, Survey-Grade Global Navigational Satellite Systems (GNSS), trigonometric, and differential leveling techniques are used to verify vertical datum. To begin datum verification, GNSS static survey techniques outlined in Rydlund and others (2012) are performed on four independent benchmarks near the causeway. The four independent benchmarks, documented in table 2, are occupied for a minimum of 2 hours with all four static surveys overlapping in time for a minimum of 1 hour. Once the static survey is complete, a NGS Online Positioning User Service (OPUS) Project is performed to verify that the four independent benchmarks are stable and to determine the elevation of the reference mark (RM4) at the causeway bridge. Once the elevation of RM4 is verified, the NAVD88 elevation from the OPUS Project is converted to NGVD29 using NGS Vertcon (National Oceanic and Atmospheric Administration, 2023a). A DRST is then performed to carry the datum approximately 0.3 miles to an established reference mark near the South Causeway gaging station. The level line from the DRST establishes an elevation relative to NGVD29 to a reference mark closer to the South Causeway gaging station where differential leveling techniques can be used to verify the datum of the reference gage. If the reference gage has moved (+/-0.05 ft) a datum correction is applied to the WSE record of the gage to correct for movement of the reference gage.

USGS Station 10010100 Great Salt Lake near Saline, UT

In 2009, differential leveling techniques were used to carry NGVD29 vertical datum from NGS Benchmark FMK-77 (table 2) to this gaging station. The level loop was approximately 1.0 mile long and predated the trigonometric leveling techniques used at other GSL gaging stations. Differential levels carried NGVD29 vertical datum to three independent benchmarks near the Saline gaging station which have remained stable as referenced in Kenney (2010). Differential levels are run annually to verify the reference gage at the Saline gaging station. If the reference gage has moved (+/-0.05 ft) a datum correction is applied to the WSE record of the gage to correct for movement of the reference gage.

Table 2. *Benchmarks used to maintain vertical datum at U.S. Geological Survey Great Salt Lake gaging stations (U.S. Geological Survey, 2023).*

Benchmark Name	Latitude	Longitude	NGVD29 (ft)	NAVD88 (ft)	USGS Gage
C-174	40° 43' 34.00"	112° 12' 19.00"	4230.63	4233.87	10010000
77-FMK	41° 14' 33.21"	112° 29' 28.95"	4231.16	4234.20	10010100 and 10010024
MOORE	41° 14' 50.06"	112° 15' 33.03"	4237.63	4240.60	10010024
120-FMK	41° 13' 10.04"	112° 51' 07.35"	4223.31	4226.23	10010024
RM4	41° 13' 15.49"	112° 45' 56.49"	4216.02	4218.95	10010024

Estimating Water-Surface Elevations for the Saltair Gage

From September 2022 to December 2022 the harbor at Great Salt Lake State Park was mostly dry and the USGS Saltair gaging station could not measure WSE of GSL. As a result, the elevation record was estimated for the Saltair gaging station by comparing hydrographs with the South Causeway gage. The two gaging stations have a nearly identical hydrograph during calm conditions. Because of the location of the gages in the south part of GSL, the two gages can exhibit inverse hydrographs during wind-driven lake seiches. With the South Causeway gage located on the north end of the south part, and the Saltair gage being located on the southern tip of the south part, when a lake seiche occurs, one gage will have an elevated WSE whereas the opposing gage will have a suppressed WSE. Figure 2 provides a time-series comparison of the two gages and the inverse WSE observed during higher lake levels in May 2021. Considering the inverted relationship, when estimating the WSE for the Saltair gage, the WSEs associated with seiche events were estimated to account for the high and low water levels that most likely occurred during the storm events.

Measurement of Discharge

A streamgage is a structure that contains equipment that measures and records the water level of a stream. The water level of a stream is often referred to as gage height or stage, reported in feet, and is measured using methods outlined in Sauer and Turnipseed (2010). Stage is typically recorded by an instrument at a set interval ranging from 5 to 15 minutes. The continuous record of stage is then used as a surrogate to compute discharge in cubic feet per second (cfs). To compute and report discharge at a given stage, discharge measurements are made at a variety of stages to cover low, medium, and high flow conditions. Discharge measurements at all stages follow methods outlined in Turnipseed and Sauer (2010). Once a range of stage and discharge measurements have been made, a stage-discharge rating curve can be developed. A rating curve is a graphical representation of the relationship between stage and discharge, with the assumption that for every stage, there is a unique discharge. Once a stage-discharge rating curve is established for a streamgage station, the continuously recorded stage at the streamgage can be used to compute a continuous discharge record. The stage-discharge method for computing discharge is applicable to gaging stations 10141000 (Weber River gage) and 10126000 (Bear River gage) (U.S. Geological Survey, 2023).

The stage-discharge relationship becomes inaccurate when backwater conditions occur. Backwater conditions cause the stage-discharge relationship to fail because the same discharge can occur at a range in stage values due to the backwater conditions. If backwater conditions exist at a streamgage, discharge can be computed using an index velocity method (Levesque and Oberg, 2012). Index velocity methods require that, in addition to continuously measured

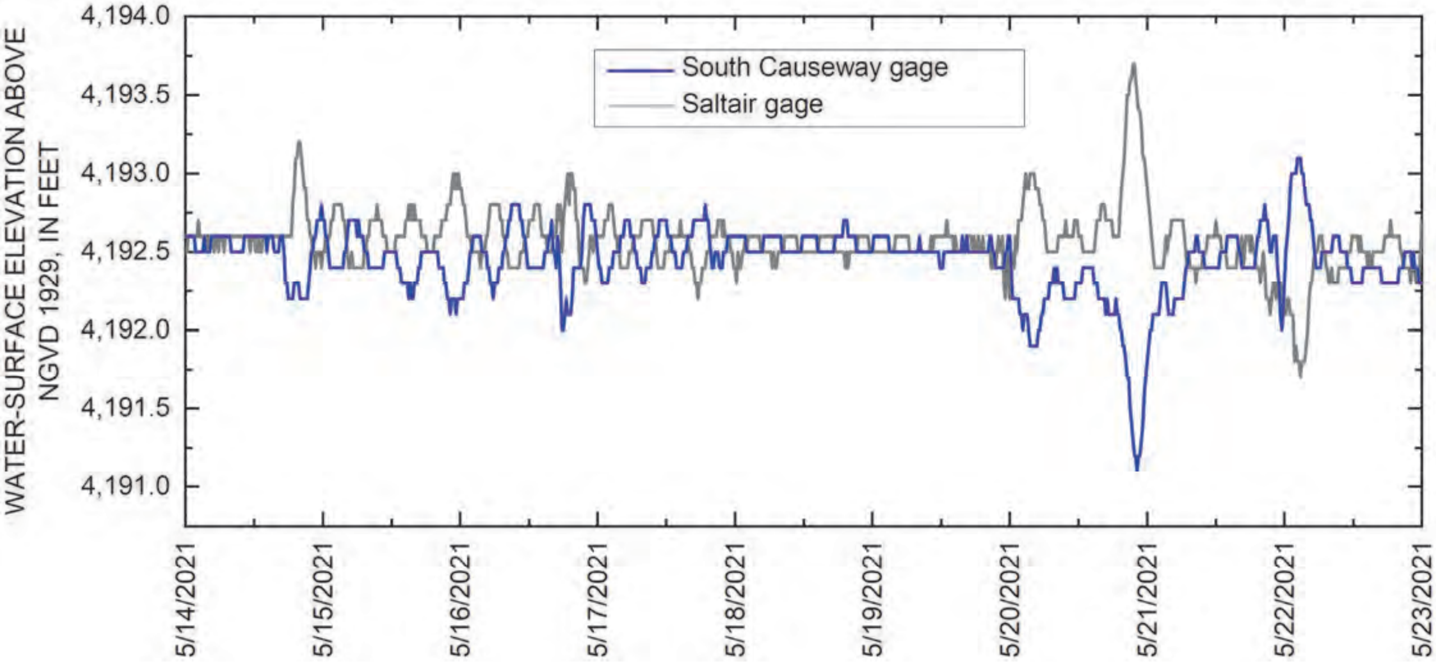

Figure 2. *Example of seiche event impact on 15-minute interval water-surface elevations measured at USGS station 10010000 Great Salt Lake at Saltair Boat Harbor, Utah (Saltair gage), and USGS station 10010024 GSL South Side of Causeway, 6 Miles East of Lakeside, Utah (South Causeway gage) (U.S. Geological Survey, 2023).*

stage, a velocity sensor is installed at the stream to continuously measure water velocity at the same measurement interval as the stage sensor (5 to 15 minutes). Discharge measurements are made over a range in stage and velocity to develop a mathematical relationship between measured indexed velocity and the mean channel velocity at the streamgage. Once this relationship is established, the measured index velocity is used to compute a mean velocity for the channel. The velocity is multiplied by a known cross-sectional area (computed from the stage value and documented channel geometry) to compute a continuous discharge at the streamgage. The index velocity method for continuous discharge is applicable to gaging stations 10171000 (Jordan River gage) and 10170500 (Surplus Canal gage) (U.S. Geological Survey, 2023).

Most streamgage stations are located on natural channels which are subject to changes over time. These changes can be seasonally influenced or occur over several years. Streamgage stations are visited routinely throughout the year to verify accurate stage data and to maintain an accurate stage-discharge or index velocity relationship.

Annual discharge values discussed in this report are in units millions of acre-feet (maf). These values were computed for each inflow gage by downloading daily mean discharge values, in cfs, from NWIS and converting these values to daily discharge, in acre-feet per day, followed by summing these values for each water year of interest. Monthly mean discharge values, in cfs, also are discussed in this report and are available via NWIS (U.S. Geological Survey, 2023).

DATA PRESENTATION AND DISCUSSION

Water-Surface Elevations

Figures 3 shows the complete period of record of daily mean WSE for the Saltair gage (a daily mean value is the average of the recorder values logged each day; periodic WSE observations made by individuals at GSL prior to installation of recorders are considered daily mean values). For detailed descriptions of the early record before June 1986, see Arnow (1984) and Arnow and Stephens (1990); it is briefly summarized below. The high stands in the 1870s and 1980s are prominent features of the early Saltair gage record along with a succession of low stands in the early 1900s, 1930s, and early 1960s. Seasonal variation, where lake levels increase from approximately late autumn to late spring and decrease from approximately early summer to mid-autumn, becomes more apparent in the record after systematic measurements began in 1875. Seasonal variation is driven by the balance between inflows and evaporation where lake levels increase when inflow exceeds evaporation and decrease when evaporation exceeds inflow (Arnow and Stephens, 1990). Until July 2021, the record low mean daily WSE was 4,191.35 ft, measured at the Saltair gage on October 15, 1963. At the time of the record low in 1963, many people thought the lake was going to become dry and roads, railroads, wildfowl management areas, recreational facilities, and industrial installations were established on the exposed

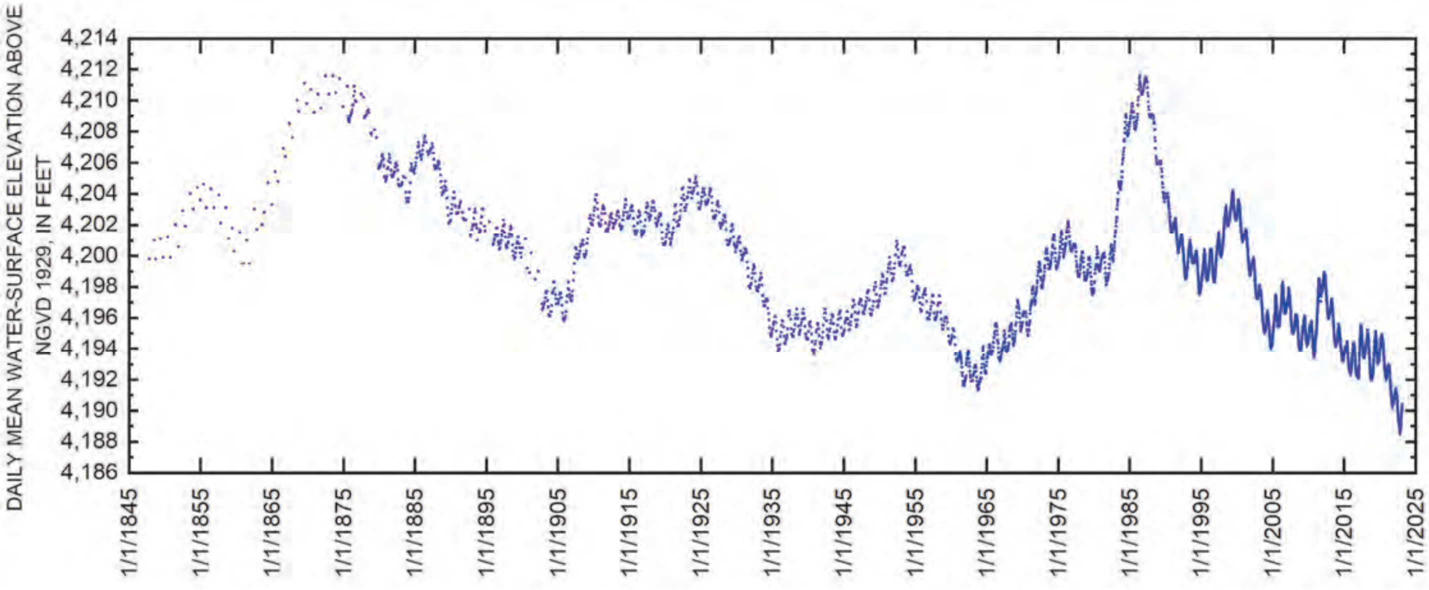

Figure 3. *Daily mean water-surface elevation at USGS station 10010000 Great Salt Lake at Saltair Boat Harbor, Utah (Saltair gage), 1847-2022 (U.S. Geological Survey, 2023).*

lakebed (Arnow, 1984). From the low in 1963 to 1976 lake levels increased about 11 ft leading to discussions about pumping water from the lake into the undeveloped desert west of GSL, but in 1977 lake levels began to decline ending concerns about high water (Arnow, 1984). From September 1982 to its historic peak on June 3, 1986 (4,211.60 ft NGVD29), lake levels had a net rise of about 12 ft. This period of rapid rise culminated in $240 million in flood damages and prompted completion of the Lakeside breach in the causeway in August 1984 to help decrease the approximate +3.5 ft WSE difference between the south and north parts of the lake. It also prompted completion of the West Desert Pumping Project in June 1987. The pumps associated with that project were shut down on June 30, 1989, after pumping 2.2 million acre-feet of water from GSL into the West Desert Pond, which reduced GSL's WSE by about 2.2 feet (Austin, 2002).

A plot of daily mean WSEs for the Saltair and Saline gages from June 1986 to November 2022 is shown in figure 4. The difference between the WSEs for the two gages depends on factors such as inflows, densities of the south and north parts of GSL (which provides the potential for GSL water to flow in both directions through the causeway conveyances), evaporation, and modifications to causeway conveyances. It is beyond the scope of this paper to discuss each of these factors in detail; however, modifications were made to the causeway conveyances during the periods that are associated with observed WSE differences (figure 4). Because almost all surface-water inflow is to the south part of the lake, WSEs at Saltair are usually higher than Saline (median value for period shown in plot is +0.7 ft). The increased difference in WSE between Saltair and Saline from November 1991 through January 1998 occurred during an extended period when the culverts were frequently plugged with debris (Loving, 2002). The effective depth of the Lakeside breach was deepened from about 4,200 ft to 4,198 ft NGVD29 in August 1996 (Loving, 2002), which likely contributed to the subsequent reduction in WSE difference between Saltair and Saline from 1996 to 1998. The increased WSE difference from September 2014 to February 2017 is associated with closure of the east (November 2012) and west (December 2013) culverts. The rapid decrease in WSE difference from December 2016 to June 2017 is associated with the opening of the new breach on December 1, 2016. This breach has an adjustable berm on the north side of the causeway. To help manage the salinity in the southern half of the lake the top of the berm was raised from 4,183 to 4,187 ft NGVD29 (completed July 27, 2022) and from 4,187 to 4,192 ft NGVD29 (completed February 9, 2023). The latter modification raised the top of the berm above the WSE of the south part of the lake at the time and contributed to the increased WSE difference after February 9, 2023.

The magnitude of seasonal fluctuations in the daily mean WSE record from 1986 to 2022 are shown in figure 5. At Saltair, the average seasonal increase is 1.8 ft and the average seasonal decrease is 2.4 ft. The largest seasonal lake level increase (5.1 ft) occurred from autumn 2010 to late spring 2011. The largest seasonal lake level decrease (3.2 ft) occurred during

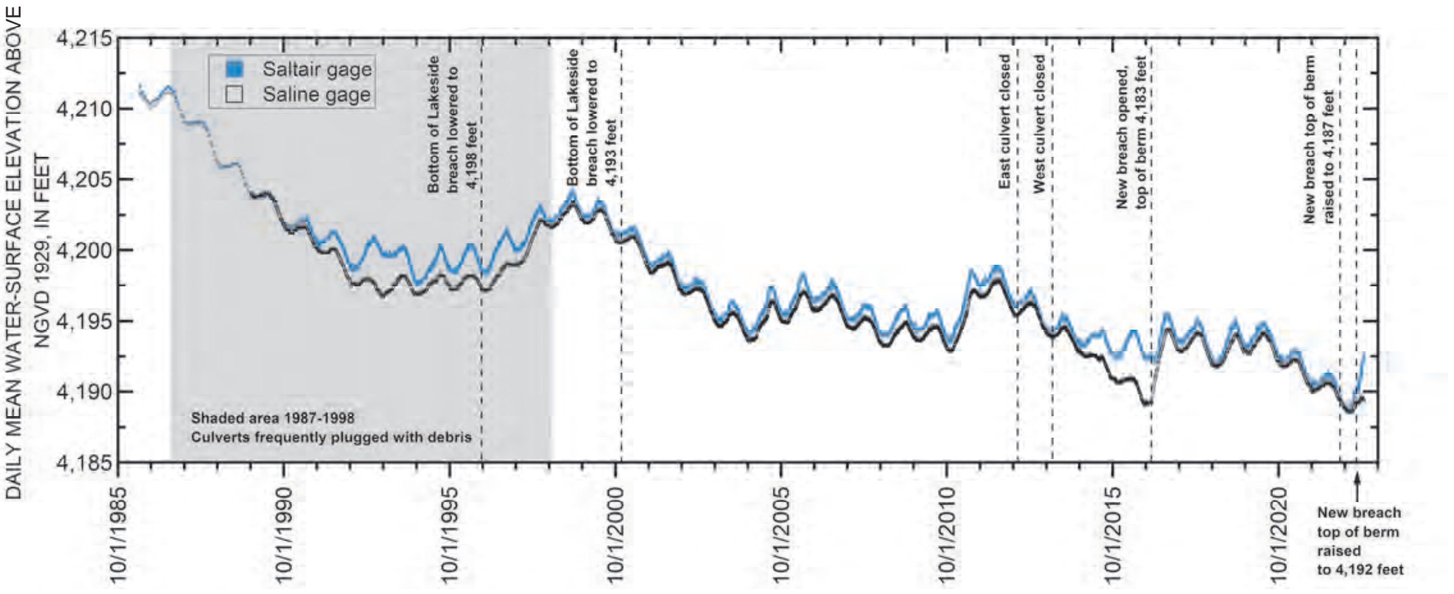

Figure 4. *Daily mean water-surface elevation at USGS station 10010000 Great Salt Lake at Saltair Boat Harbor, Utah (Saltair gage), and USGS station 10010100 Great Salt Lake near Saline, Utah (Saline gage), 1985-2022 (U.S. Geological Survey, 2023).*

spring and summer 1988 and 2018. Lake level decreases exceeded increases in 25 of the 36 seasonal cycles shown. At the Saline gage, the average seasonal increase is 1.5 ft and the average seasonal decrease is 2.1 ft. The largest seasonal lake level increase (5.5 ft) occurred from December 2016 to May 2017, after the new 150 ft wide breach was opened restoring open channel connection between the south and north parts of the lake that was previously associated with the east and west culverts. The largest seasonal lake level decrease (3.3 ft) occurred during spring and summer 1988. Lake level decreases exceeded increases in 22 of the 36 seasonal cycles shown in figure 5.

With seasonal decreases exceeding increases for most years following the record high WSE in June 1986, both the north and south parts of the lake had net WSE drops that resulted in record low WSEs in November 2022 (figure 4). The long-standing historic

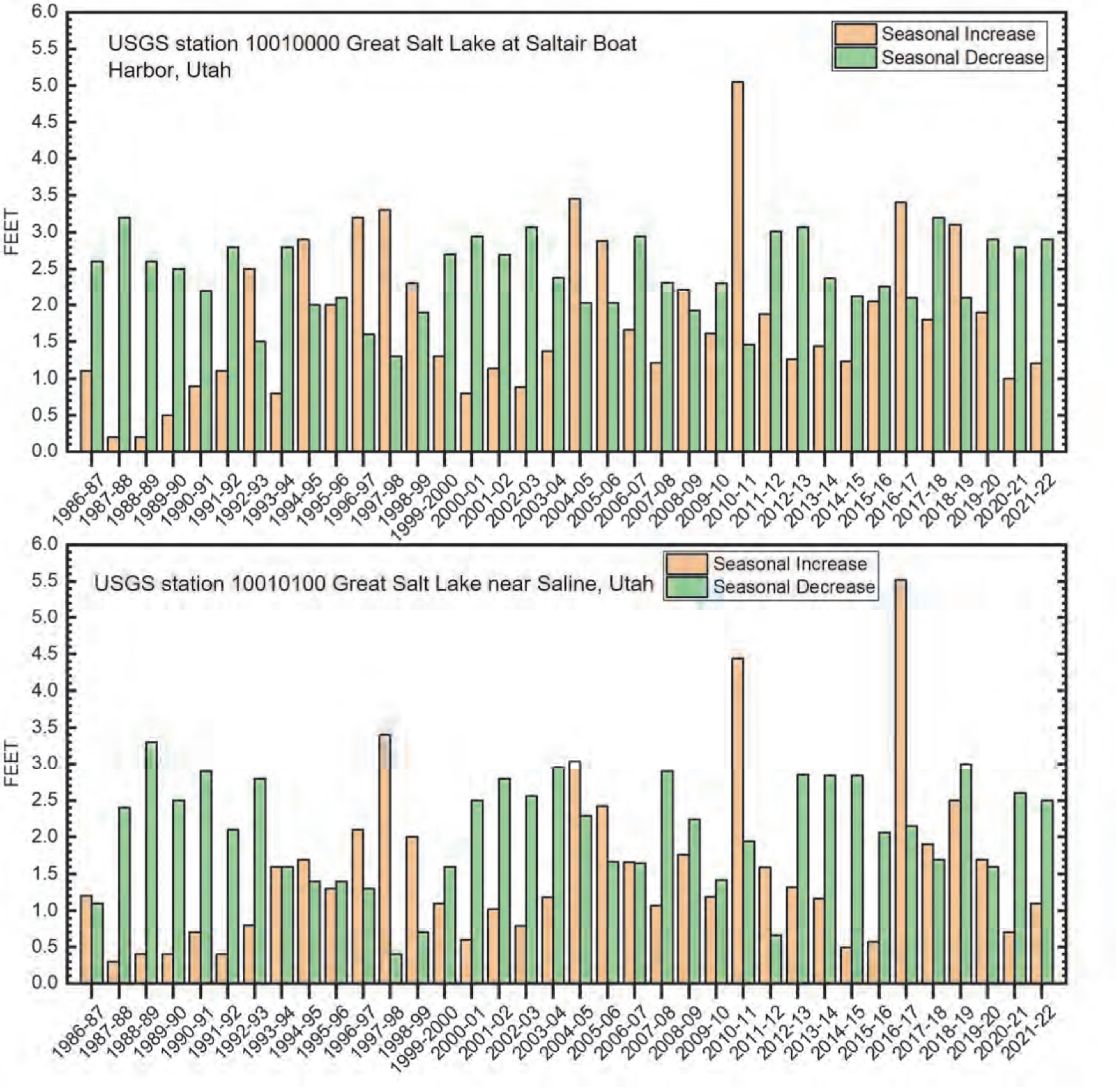

***Figure 5.** Seasonal water-surface elevation increase and decrease at USGS station 10010000 Great Salt Lake at Saltair Boat Harbor, Utah (Saltair gage, top) and USGS station 10010100 Great Salt Lake near Saline, Utah (Saline gage, bottom), 1986 to 2022 (U.S. Geological Survey, 2023). Seasonal increases generally occur from late fall/early winter through the following spring/early summer. Seasonal decreases generally occur from late spring/early summer through mid fall/early winter.*

low daily mean WSE measured at the Saltair gage on October 16, 1963 (4,191.35 ft NGVD29) was broken on July 21, 2021. The WSE continued to decrease until October 18, 2021, when it reached a short-lived historic low of 4,190.2 ft NGVD29. The seasonal lake level increase from October 18, 2021, to early April 2022, was relatively low at 1.2 ft, and by July 3, 2022, the WSE dropped to 4,190.1 ft NGVD29, breaking the short-lived historic low set less than 9 months prior. By September 28, 2022, continued seasonal decrease resulted in too little water in the harbor at Great Salt Lake State Park for the Saltair gage to operate and it was shutdown. Water-surface elevation data for the south part of the lake continued to be measured at the relatively new (installed August 2020) South Causeway gage, maintaining continuity of the 175-year WSE record that is associated with the south part of GSL. Seasonal decreases continued until November 3, 2022, when the South Causeway gage recorded the new record low daily mean WSE for the south part of the lake of 4,188.5 ft NGVD29. Two days prior, on November 1, 2022, the Saline gage recorded 4,188.5 ft NGVD29, which also is the new historic low daily mean WSE for the north part of the lake (the previous historic low of 4,188.98 ft NGVD29 was measured in September and October 2016 and was related to closure of the two railroad causeway culverts). Net WSE decreases from June 1986 to November 2022 for the south and north parts of the lake were 23.1 ft and 22.7 ft, respectively.

By late November 2022, the south part of the lake began its seasonal increase (figure 4). The Saltair gage was restarted on December 15, 2022, and, as of May 4, 2023, the south part had risen to 4,192.6 ft NGVD29, a 4.1 ft increase. The north part of the lake did not start increasing until late December 2022 and, as of May 4, 2023, it had risen to 4,189.3 ft NGVD29, a 0.8 ft increase. The WSE of the south part of the lake reached 4,192.1 ft NGVD29 on April 17, 2023, exceeding the top of the berm at the new breach allowing for south to north flow (on May 3, 2023, USGS measured south to north discharge of 129 cfs). With a significant snowpack remaining in the Bear, Weber, and Jordan River basins, south to north flows were expected to continue until evaporation exceeds inflows and lake levels begin their seasonal decrease.

Streamflow and Great Salt Lake Water Surface Elevation

Annual discharge for water years 1985 to 2022 for each inflow gage are shown in figure 6. Also included in figure 6 are the median annual discharge values for each inflow gage. The median annual discharge values are based on the period or record associated with each gage (table 2). The Bear River gage has the highest median annual discharge (0.958 maf), followed by the Weber River gage (0.343 maf), Surplus Canal gage (0.170 maf), and Jordan River gage (0.101 maf). Relatively high flow years in the mid-1980s, late 1990s, 2011 and 2017; and relatively low flow years in the late 1980s, early 1990s, mid-2010s, and early 2020s are apparent in the data for the Bear River, Weber River, and Surplus Canal gages (note that a significant amount of flow in the Jordan River is diverted to the Surplus Canal). Of the 36 years of annual discharge record shown for each gage, the Bear River gage had 12 years where annual discharge exceeded its median annual discharge, the Weber River gage had 10 years, the Surplus Canal gage had 21 years, and the Jordan River gage had 12 years.

Annual discharge measured at the inflow gages and annual mean WSE measured at the Saltair gage for water years 1985 to 2022 are shown in figure 7. Annual mean WSE is related to annual discharge as consecutive years of relatively high flows from 1985-1987, 1995-1999, 2005–2006, and 2011–2012 contributed to annual mean WSE increases. Consecutive years of relatively low flows from 1988–1994, 2001–2004, 2013–2016, and 2021–2022 contributed to annual mean WSE decreases. During water years 2021 and 2022, when new record low WSEs were measured at GSL, combined annual discharge values were 0.704 and 0.743 maf, which are less than half of the median combined annual discharge of 1.57 maf (indicated by the horizontal dashed line in figure 7).

To put the WSE and discharge records into context with broader climatological conditions, monthly Palmer Drought Severity Index (PDSI) values for Utah (National Oceanic and Atmospheric Administration, 2023b), monthly mean WSE at Saltair, and combined monthly mean discharge for inflow gages, in cfs, are plotted in figure 8. The PDSI uses precipitation and temperature data to evaluate moisture supply and demand using a simple water balance model. A PDSI value of greater than 4 represents very wet conditions, while a PDSI less than -4 represents an extreme drought. Extended periods of negative PDSI values from November 1988 to November 1992, October 1999 to August 2004, November 2006 to November 2009, November 2011 to August 2016, and August 2019 to October 2022 correspond to net WSE declines and lower monthly mean discharge. These periods of extended negative PDSI are offset by relatively few periods of extended positive PDSI values and increased monthly mean WSE and higher combined monthly mean discharge.

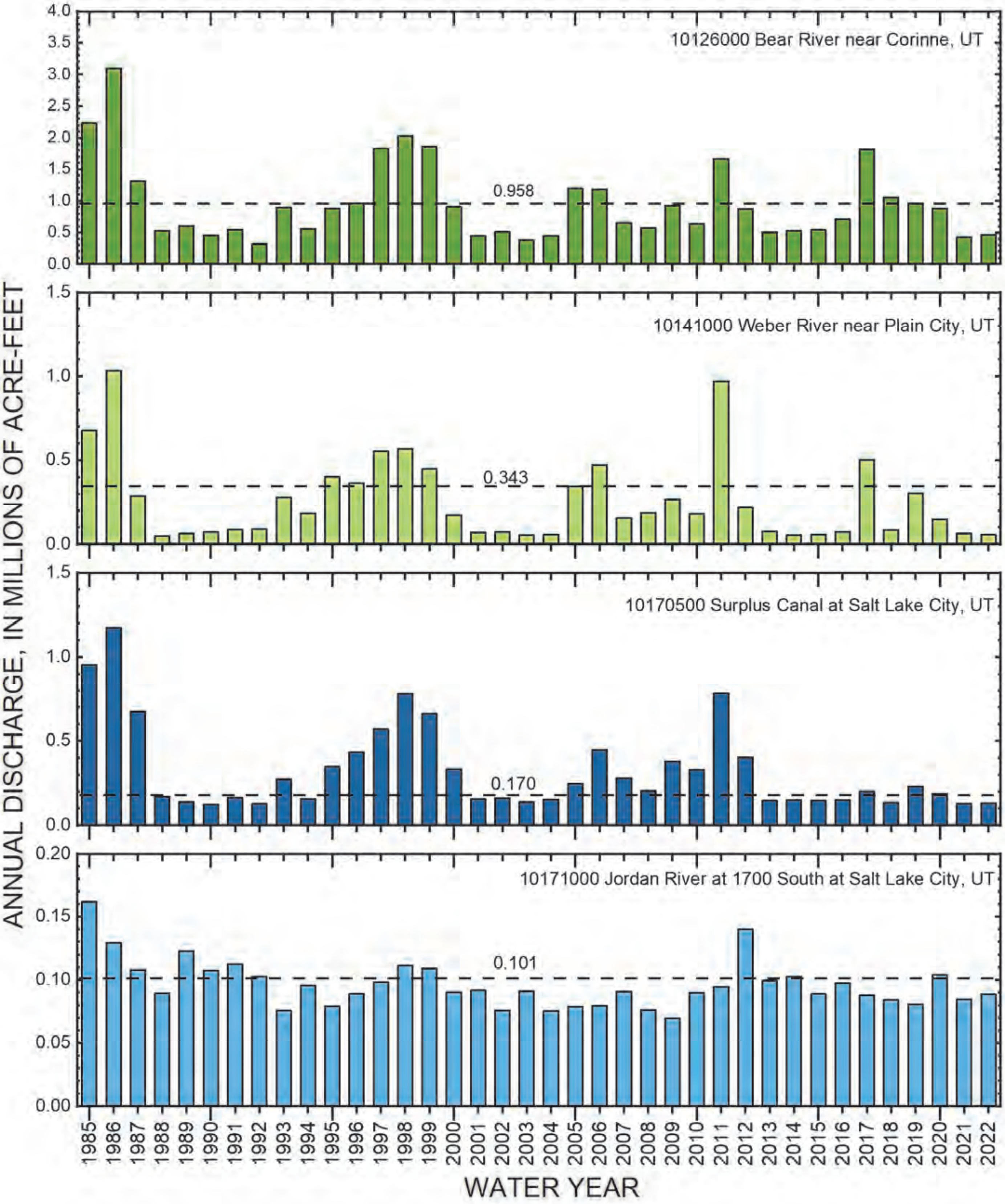

Figure 6. *Annual discharge measured at USGS inflow gages, water years 1985-2022 (U.S. Geological Survey, 2023). The median annual discharge for the period of record associated with each gage is indicated with a dashed line. The y-axis scale, discharge in millions of acre-feet, is customized for each gage.*

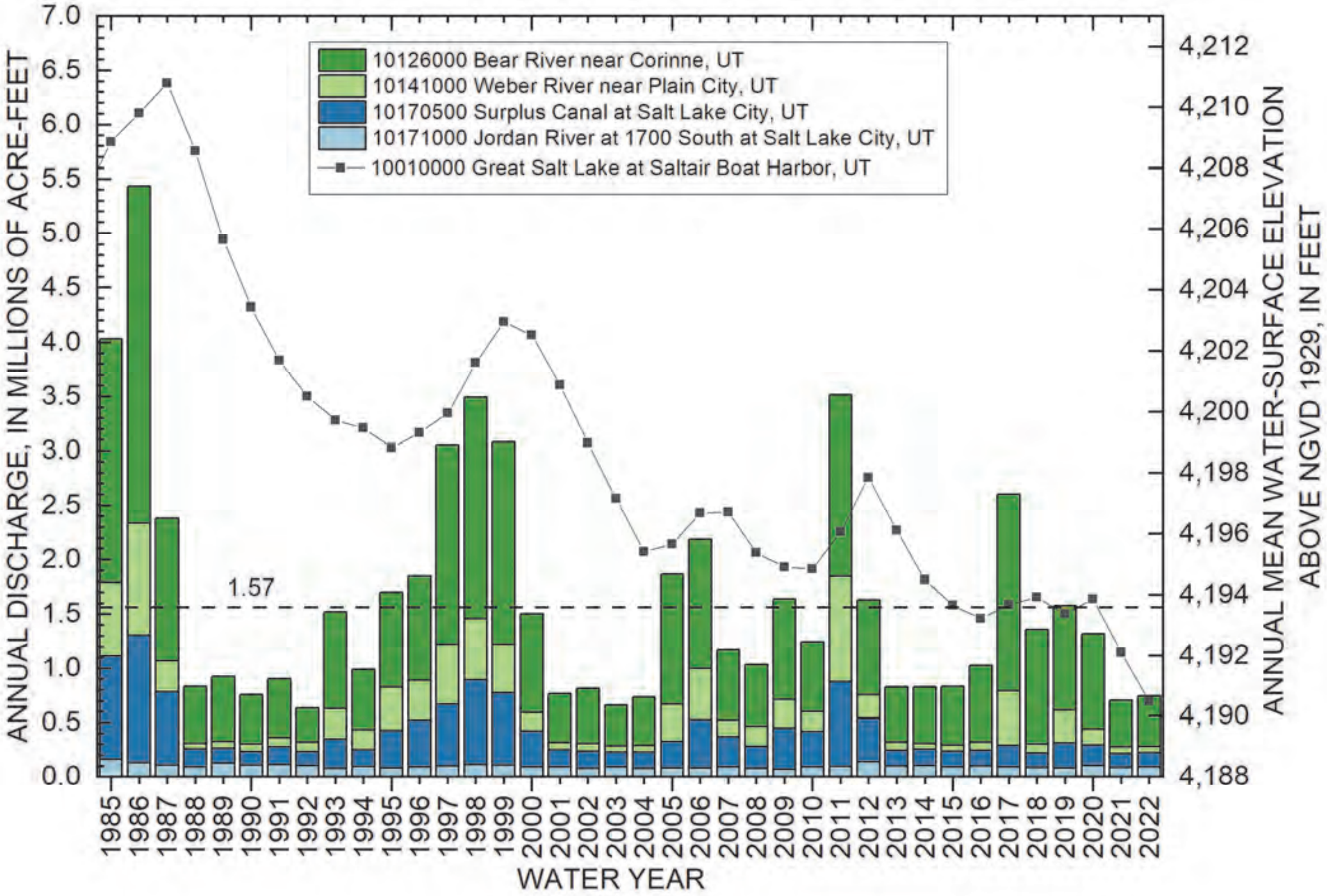

Figure 7. *Annual discharge for USGS inflow gages and annual mean water surface elevation at USGS station 10010000 Great Salt Lake at Saltair Boat Harbor, Utah (Saltair gage), water years 1985-2022 (U.S. Geological Survey, 2023). The combined median annual discharge for all four gages, based on the period of record for each gage, is indicated by the horizontal dashed line.*

CONCLUSIONS

A new historic low daily mean WSE of 4,188.5 ft NGVD29 was measured during November 2022 at gages north and south of the GSL causeway. From September 28 to December 15, 2022, there was too little water in the harbor at Great Salt Lake State Park for the Saltair gage to operate and the new historic low daily mean WSE for the south part of the lake was measured at a relatively new gage located just south of the causeway (South Causeway gage). Data collected at the South Causeway gage were used to estimate the daily mean WSE record for the Saltair gage for the period it was shut down, preserving the continuity of the 175-year WSE record that is associated with this gage.

Many factors, including direct precipitation, groundwater inflow, West Desert Pumping Project withdrawals (1987–1989), evaporation, and surface-water inflow contribute to the water balance and thus WSE of GSL. In this document, data were presented only for a portion of the surface-water inflow budget as measured by four long-term streamgages. For water years 1985 to 2022, trends in Saltair gage WSEs correspond to trends in combined annual discharge measured at the four streamgages, and both WSE and combined monthly mean discharge correspond to trends in PDSI values for Utah. This basic observation is true when the data records are examined back to 1950 when concurrent monitoring began at all sites (Cordova and Angeroth, 2012). For detailed analyses of GSL WSE variation and climate, see Wang and others (2010) and Mann and others (1995). The impact of upstream diversions from surface water inflow sources to GSL is beyond the scope of this document; however, Wurtsbaugh and others (2017) estimated that 11 ft of GSL WSE decrease from 1847 to 2016 can be attributed to consumptive use and related changes to evaporation. Detailed monitoring of GSL's water budget may support quantification of the complex interplay between drought cycles, consumptive use, and WSEs.

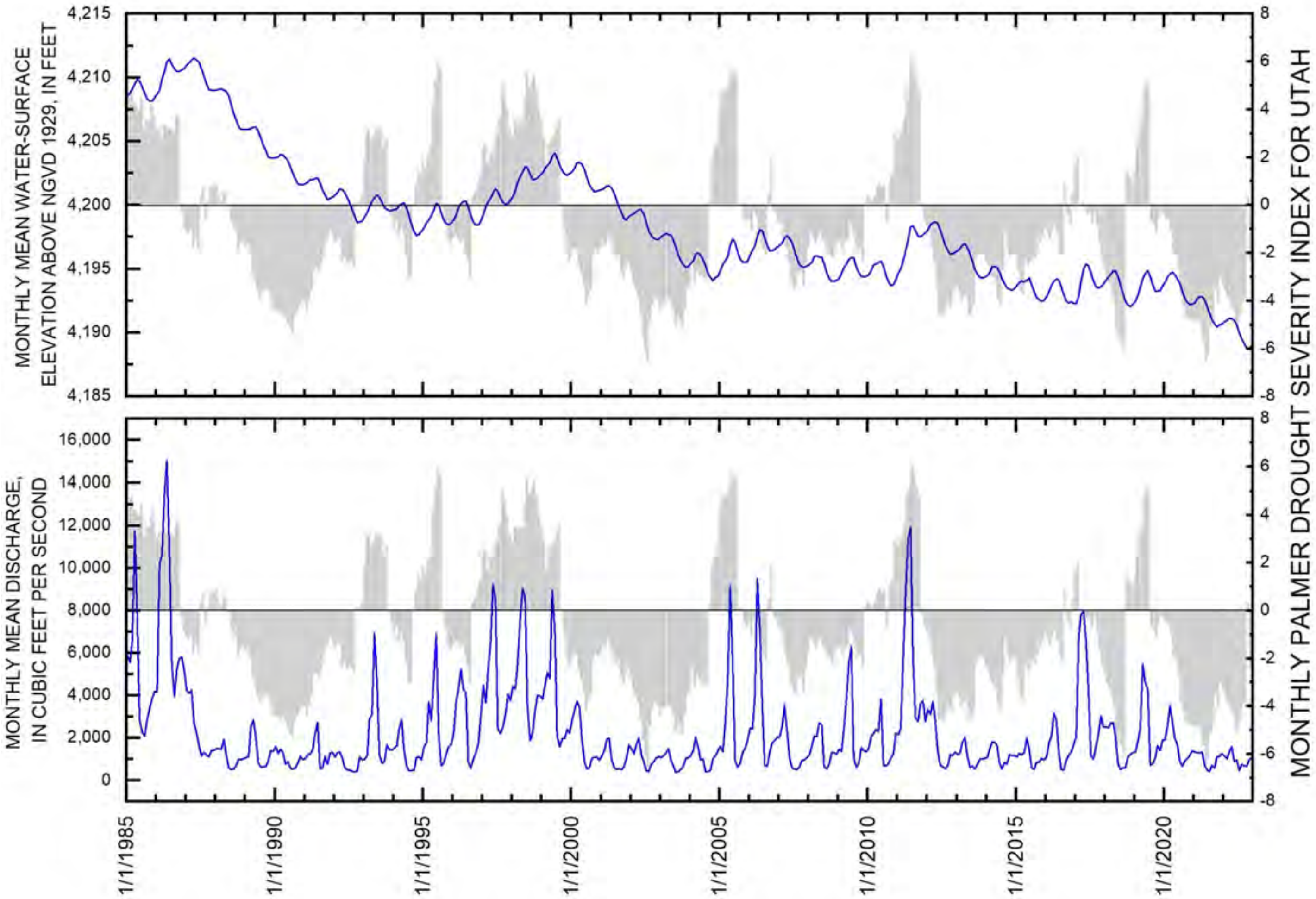

Figure 8. *Monthly mean water-surface elevation at USGS station 10010000 Great Salt Lake at Saltair Boat Harbor, Utah (Saltair gage, top), and combined monthly mean discharge for USGS inflow gages (bottom) (U.S. Geological Survey, 2023), compared to the monthly Palmer Drought Severity Index for Utah (indicated by light gray bars), January 1985 to December 2022 (National Oceanic and Atmospheric Administration, 2023b).*

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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