Hydrologic Characteristics of the Great Salt Lake, Utah: 1847–1986

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By TED ARNOW and DOYLE STEPHENS

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Hydrologic Characteristics of the Great Salt Lake, Utah: 1847–1986

By Ted Arnow *and* Doyle Stephens

Abstract

The Great Salt Lake in Utah is a large body of water bordered on the west by barren desert and on the east by a major metropolitan area. It is the fourth largest terminal lake in the world, covering about 2,300 square miles in 1986. Since its historic low elevation of 4,191.35 feet in 1963, the lake rose to a new historic high elevation of 4,211.85 feet in 1986. Most of this increase (12.2 feet) occurred after 1982. The rise has caused $285 million of damage to lakeside industries, transportation, farming, and wildlife. Accompanying the rapid rise in lake level has been a decrease in salinity—from 28 percent in 1963 to about 6 percent in 1986. This has resulted in changes in the biota of the lake from obligate halophiles to opportunistic forms, such as blue-green algae and, most recently, a brackish-water fish.

INTRODUCTION

Great Salt Lake is unique among lakes of the Western Hemisphere because of its size and salt content. It is a terminal lake, with no outlet to the sea (fig. 1)—the fourth largest such lake in the world (Greer, 1977, p. 23). The size of Great Salt Lake varies considerably, depending on its surface elevation, which can vary dramatically with climatic changes. At the elevation of 4,200 feet above sea level, the approximate average level (fig. 2) about which the lake has fluctuated during historic time (1847–1986), it covers about 1,700 square miles (including evaporation ponds for mineral recovery), with a maximum depth of 34 feet (U.S. Geological Survey, 1974). At the elevation of 4,209.25 feet, as shown on the satellite image (pl. 1), the lake covered about 2,300 square miles. The total area that could drain to the lake is in excess of 35,000 square miles, but this includes nearly 14,000 square miles of arid land west of the Newfoundland Mountains (fig. 7), 25 miles west of the lake, that are virtually noncontributory. The salinity of brine in the lake also has varied considerably, both temporally and areally. The brine has contained as much as 28 percent salt, or about eight times more than that of ocean water, but when the satellite image was taken in 1984, the salinity of the main southern part of the lake was only about 6 percent.

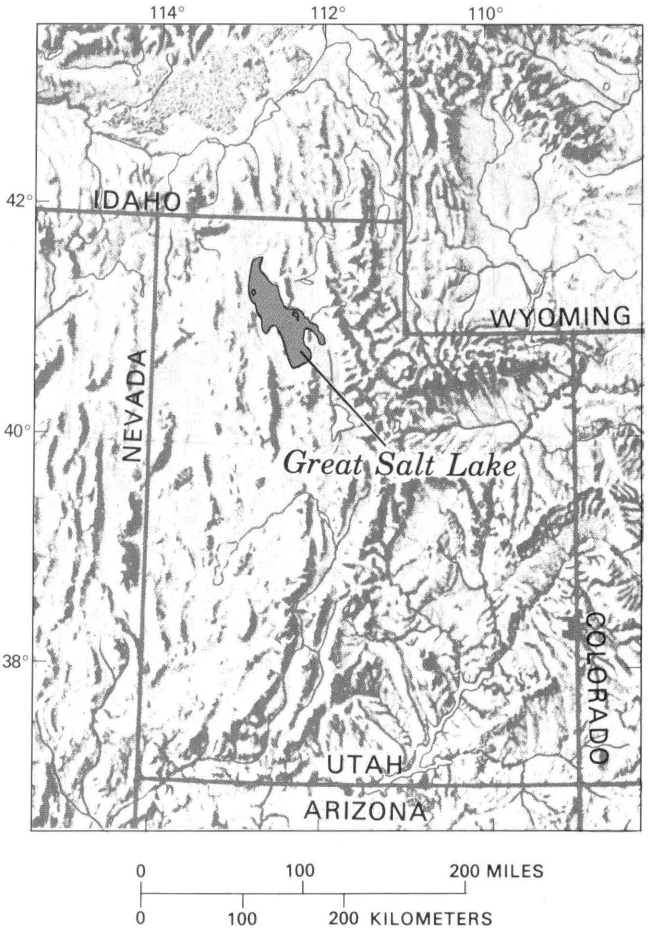

Figure 1. Location of Great Salt Lake. (Adapted from Harrison, 1969.)

Large, rapid changes in the water level of the lake can have a profound effect on roads, railroads, recreational facilities, wildlife-management areas, and industrial installations around the lake. Excessive dilution of the brine also

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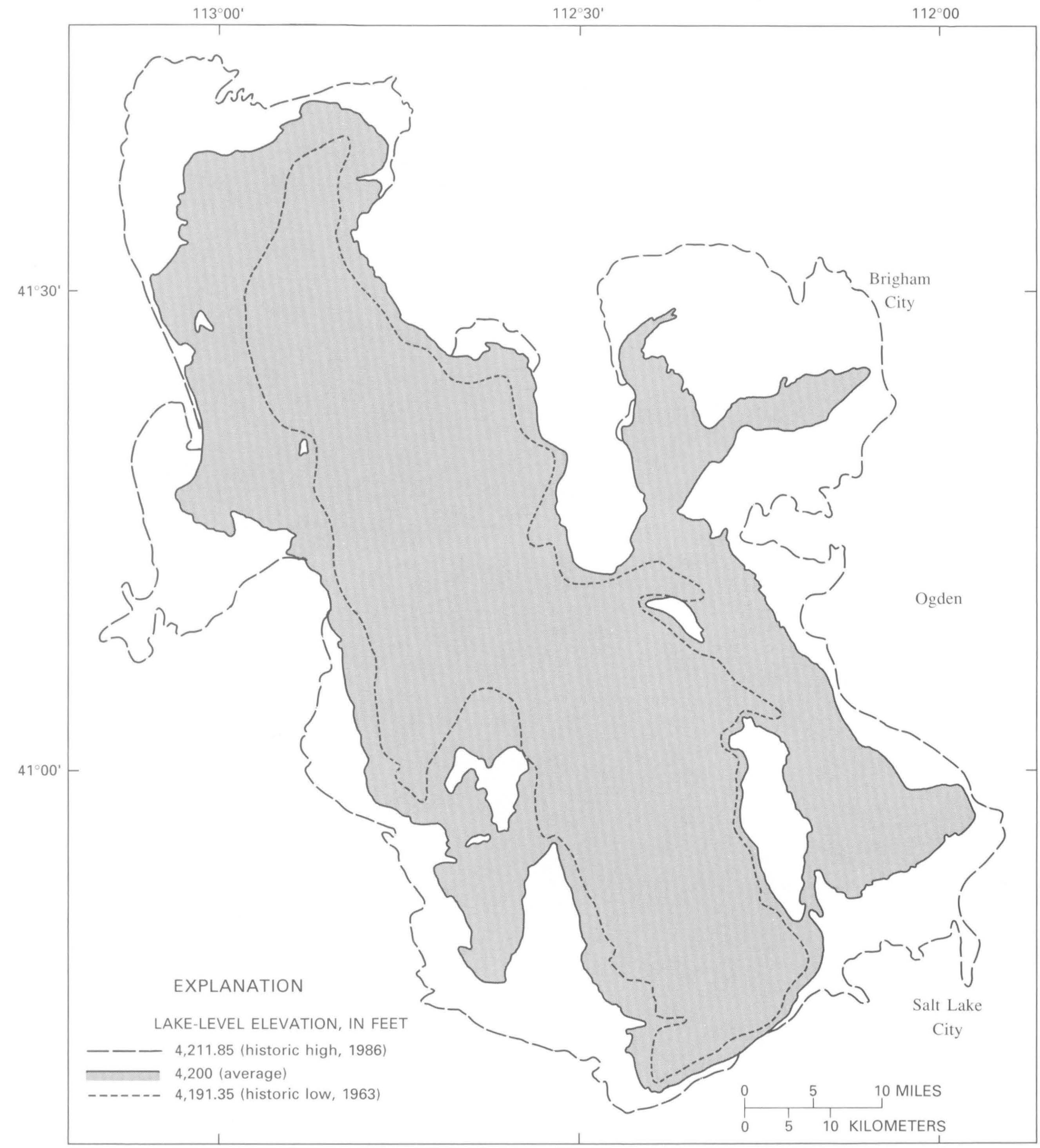


Figure 2. Area covered by Great Salt Lake at approximate historic high, average, and low water levels. (Adapted from Currey, 1980, fig. 2.)

affects recreation and industry on the lake. The record-breaking rise in the southern part of the lake of 12.2 feet between September 18, 1982, and June 3, 1986, coupled with the dilution of the main part of the lake to the lowest known historical salinity, resulted in severe economic impacts on all types of installations and activities in and around the lake.

The purpose of this report is to discuss the changes that led to the condition of Great Salt Lake in 1986. The changes in lake level and the differences in the chemical and biological characteristics of the lake waters are described and explained in the following text and illustrations. Parts of this report were adapted from previous reports by Arnow (1984, 1985) and Stephens (1974). The reader is referred to

Gwynn (1980) for a more complete treatment of other aspects of the lake

The satellite image map of Great Salt Lake (pl 1) shows a huge body of water bordered on the west by barren desert and on the east by a major metropolitan area Contrasting colors on the map also delineate divisions of the lake waters on June 25 and July 2, 1984, and contour lines show the changes in lake outline corresponding to different lake levels in the past

Differences in coloration of the false-color infrared imagery in the satellite image map are due to physical, chemical, and biological factors Terrestrial vegetation appears as bright red throughout the mountains and as well-defined patches in urban areas This coloration represents green vegetation that reflects light in the near-infrared part of the spectrum The white crests on the higher mountain peaks are the remnants of snowpack from the seasonal snowfall

The darker shade of blue in the southern part of Great Salt Lake is due in part to large populations of a blue-green alga (*Nodularia spumigena*), which has become abundant as the salinity of the lake has decreased When the satellite imagery was made during June-July 1984, the southern part of the lake had a salinity of about 6 percent but the northern part had a salinity of about 22 percent A halophilic green alga (*Dunaliella viridis*) with different coloration was common in the southern part prior to 1982, but by 1984 it was more common in the northern part The lighter shades of blue in the northeastern, southwestern, and northern areas of the lake result from greater reflection in the infrared part of the spectrum by shallow water underlain by light-colored sand

The green coloration in the shallow-water areas southwest of Brigham City (pl 1) is due in part to turbidity from blooms of algae in the freshwater that flows into the lake from the Bear River The white-outlined structures at an elevation of 4,205 feet in the same area represent the submerged dikes of the Bear River Migratory Bird Refuge, a large facility flooded by rising lake waters during 1983 The red coloration at the extreme northern end of the lake and at the northern shore of the refuge represents marsh vegetation recently submerged or growing in brackish water By 1984, the rising waters of Great Salt Lake had damaged 75 percent of the marsh acreage available for wildlife habitat (Peter Smith, U S Fish and Wildlife Service, oral commun , 1985)

The deep-purple coloration in diked areas in the southwestern section of the lake is the result of a deep-blue dye added to evaporation ponds used in mineral recovery The dye enhances absorption of solar radiation and solar heating of the water, which increases the rate of evaporation Additional evaporation ponds that do not contain blue dye are visible southeast of the purple ponds and also northwest of Ogden (pl 1)

LAKE LEVELS

The surface level of Great Salt Lake changes continuously, primarily in response to climatic factors Man's activities have had a lesser, but still important, effect on the lake level

The level and volume of the lake reflect a dynamic equilibrium between inflow and evaporation Surface area and brine concentration are the major aspects of the lake that affect the volume of evaporation During dry years, the water level declines, resulting in a decrease in surface area, consequently, the volume of evaporation decreases Moreover, as the water level declines, the brine generally becomes more concentrated, and this also decreases the rate of evaporation During wet years, the water level rises, resulting in an increase in surface area, consequently, the volume of evaporation increases As the lake rises, the brine generally becomes less concentrated, and this also increases the rate of evaporation

The water level of the lake has a yearly cycle (fig 3) It begins to decline in the spring or summer when the weather is hot enough that the quantity of water lost by evaporation from the lake surface is greater than the combined inflow from surface streams, ground water, and precipitation directly on the lake It begins to rise in the autumn when the temperature decreases and the quantity of water lost by evaporation is exceeded by the inflow According to past records, the rise can begin any time between September and December and the decline any time between March and July

Great Salt Lake reaches its annual peak water level between March and July in response to spring runoff, which peaks before warm temperatures result in large water loss by evaporation Comparison of the percentage of years the lake peaked during any one month reveals a changing pattern for 1924–86 compared with 1876–1923 Because the peaks for 1847–1875 and for 9 years between 1877 and 1902 were estimated, they were excluded from the analysis

The lake peaked in July in about 38 percent of the years from 1876 to 1923 Starting in 1924, the peaks occurred earlier in the year, with peaks in July occurring in only about 8 percent of the years (See fig 4) This change may be due partly to a gradual warming of temperatures earlier in the year, which in turn may increase the rate of evaporation from the lake to the point that water loss exceeds water inflow beginning in July A comparison of the average monthly air temperatures for April, May, June, and July recorded near the center of Salt Lake City from 1875 to 1954 and at Salt Lake City International Airport, about 5 miles west of the city, from 1954 to 1985 is shown in figure 5 Statistical testing for trends in temperature by use of Daniel's test (Conover, 1971, p 251) identified a significant upward trend (95-percent confidence level) in the July data Comparison of the 1875–1923 and the

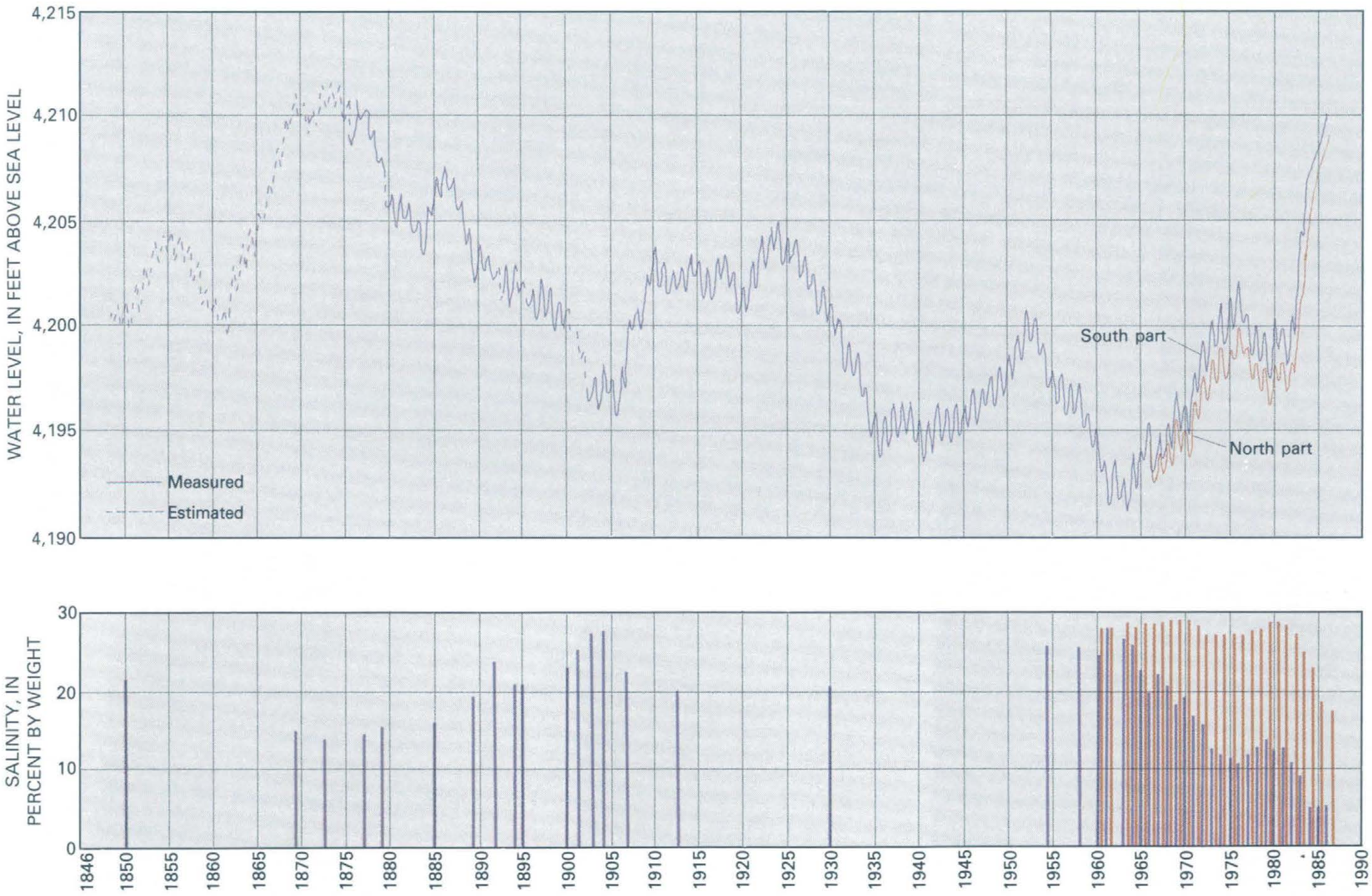


Figure 3. Changes in water level and salinity of Great Salt Lake, 1847–1986. The bars generally represent single measurements of salinity as reported in the literature by various investigators. Bars for 1892, 1900, 1903, 1904, and 1959–86 represent more than one measurement during the year. Since completion of the railroad causeway in 1959, the north and south parts of the lake have differed in water level and mineralization. The bars shown for 1960–86, therefore, represent measurements of salinity in the south (blue) and north (red) parts. Bars for 1977–83 are from data provided by the Utah Geological and Mineral Survey.

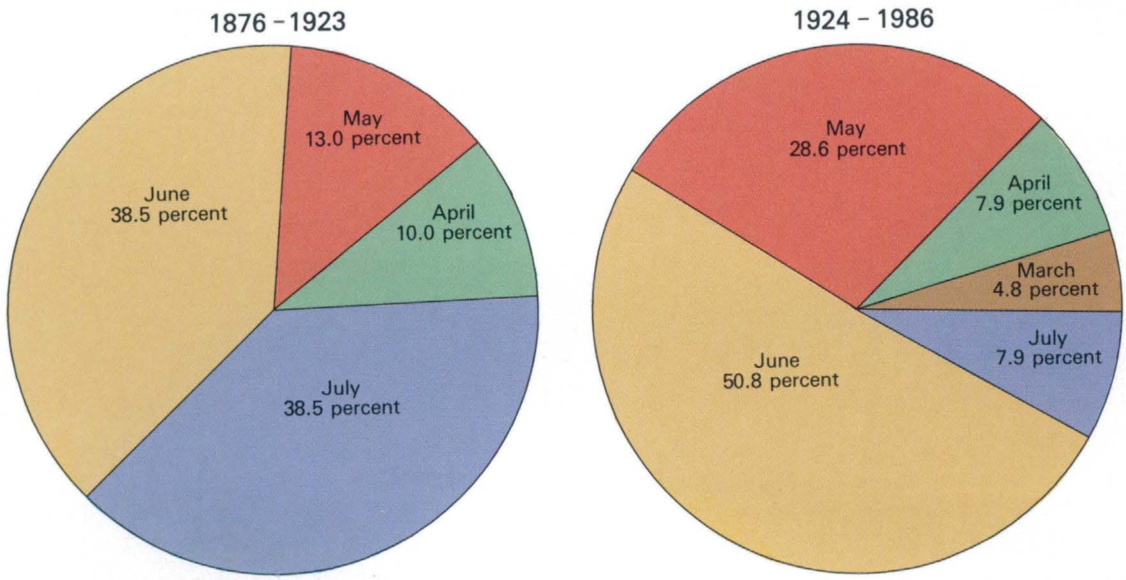


Figure 4. Percentage of years Great Salt Lake peaked during the indicated month for 1876–1923 and 1924–86.

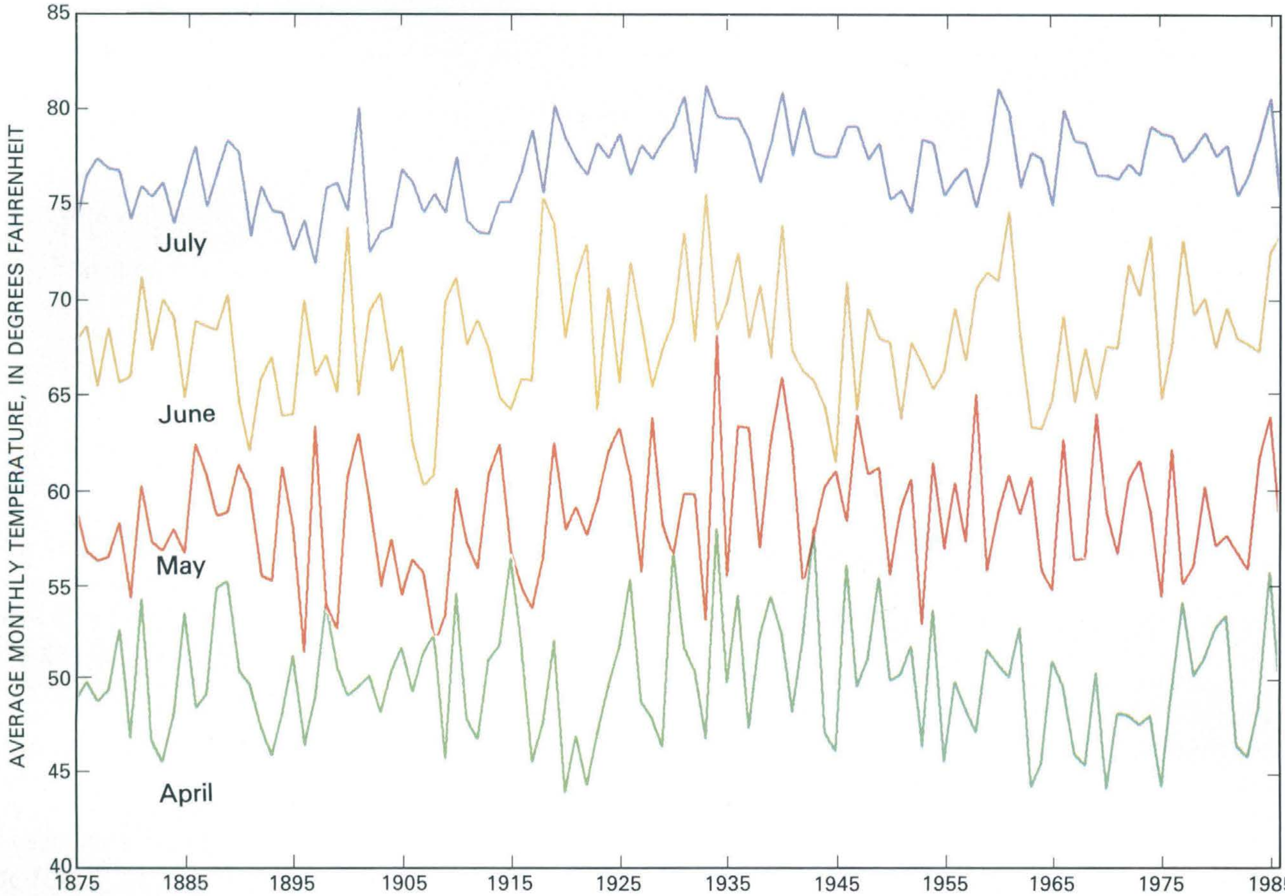


Figure 5. Comparison of average monthly air temperatures for April, May, June, and July at Salt Lake City, 1875–1986.

Figure 6. Cumulative departure of average monthly air temperatures from the 112-year average monthly air temperatures at Salt Lake City, April, May, June, and July, 1875–1986.

1924–86 temperatures for July by use of a t-test on mean temperatures indicated that the mean of 75.8 °F for 1875–1923 was significantly smaller (95-percent confidence level) than the 1924–86 mean of 77.9 °F.

The cumulative departure of the average monthly air temperatures for April, May, June, and July from the corresponding, long-term (112-year) average for each month is shown in figure 6. In general, average monthly temperatures for April through July were less than the long-term average for corresponding months from 1875 to about 1920 but were more from 1920 to 1986. This trend is most apparent for July, a month that typically has less year-to-year fluctuation in temperature than April-June (fig. 5).

In addition to variation in air temperature, many other factors may be responsible for the changing pattern of the time at which the lake peaks. Some of these factors are

1. Changes in diversions from tributary streams.
2. Changes in the management of water levels at Bear Lake (fig. 7).
3. Changes in diversions from Great Salt Lake into evaporation ponds.
4. Effects of the railroad causeway.
5. Deposition or solution of salt in the lake.
6. Water level of the lake in relation to its volume.

Prehistoric

Great Salt Lake is a remnant of a much larger water body—Lake Bonneville—which had a maximum depth of about 1,000 feet and covered about 20,000 square miles in Utah, Nevada, and Idaho (fig. 7) during the latter part of the Pleistocene Epoch. Spencer and others (1984, p. 332) stated that Lake Bonneville began to form about 32,000 years before present (B.P.). It rose in a series of three major steps to reach the freshest water conditions and the highest elevation of approximately 5,200 feet about 17,000 years before present. The lake then overflowed near Red Rock Pass (Malde, 1968, p. 9) into the Snake River drainage system and thence eventually to the Pacific Ocean. The elevations of various stands of Lake Bonneville are vividly marked by benches that were cut into hillsides throughout the lake basin. According to Spencer and others (1984, p. 332), the lake declined to below historic levels from about 14,500 to 12,700 years before present, and "for the past

Figure 7. Extent of Lake Bonneville. (Adapted from Crittenden, 1963, fig. 1.)

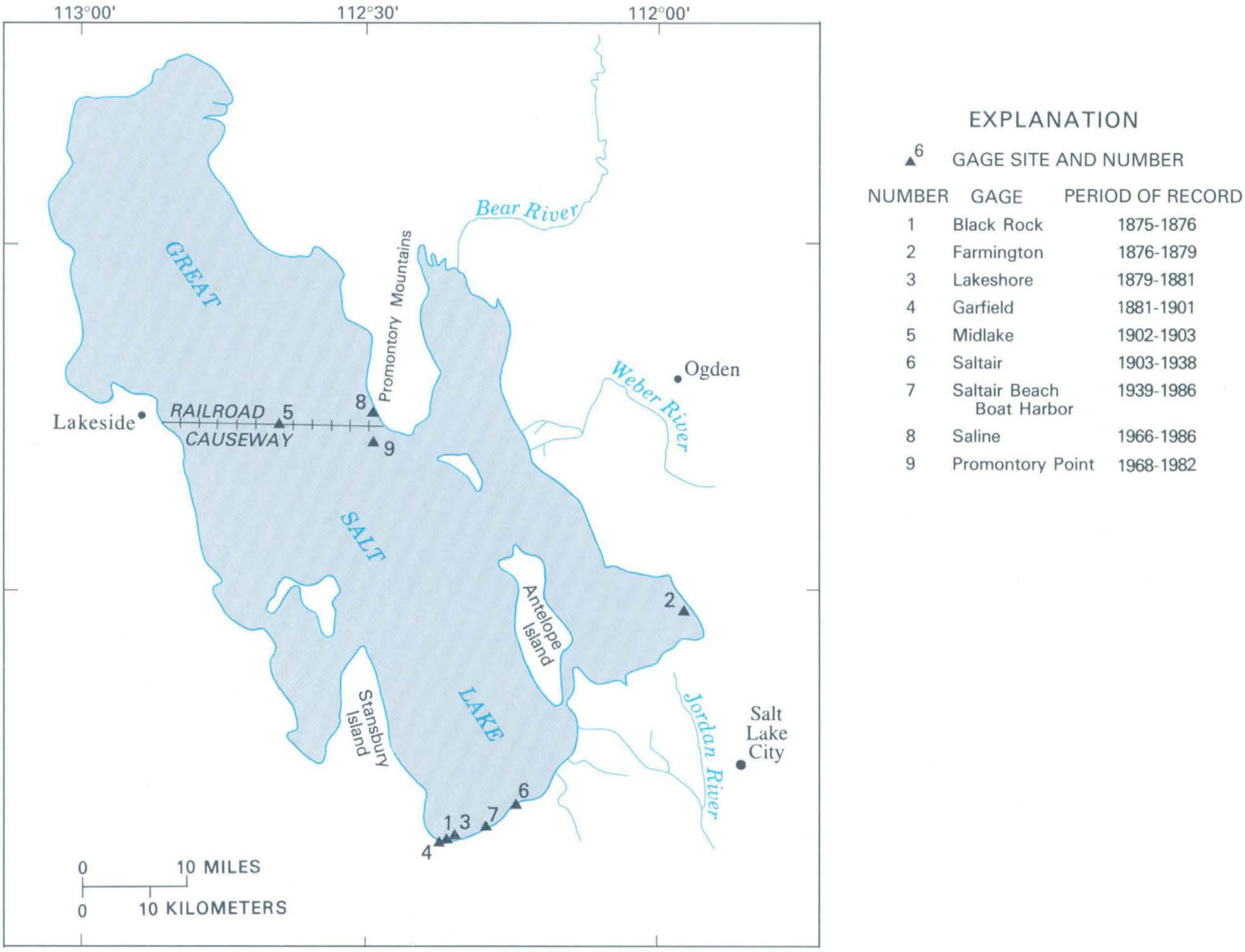


Figure 8. Location of gages used to determine the water level of Great Salt Lake, 1875–1986. (Adapted from Arnow, 1984, fig. 5.)

8,000 years, with the exception of two stands between 1,290 and 1,295 m [4,230 and 4,250 feet] around 2,300 and 3,500 yr B.P., the lake has fluctuated near its present elevation of 1,280 m [4,200 feet]."

Historic

The earliest known measurement of the surface level of Great Salt Lake was made by John C. Fremont during 1843 (Miller, 1980, p. 3). Fremont reported that the lake was "4,200 feet above the sea"; based on the assumption that he took careful readings with several barometers, his determination could be accurate to within 1 foot.

No measurements are available for 1844–74, but Gilbert (1890, p. 240–241) estimated lake levels for 1847–74 on the basis of reported observations of the depth of water over the sandbars between the mainland and Antelope and Stansbury Islands (fig. 8). That information was obtained by Gilbert around 1877 from stockmen who had ridden horses across the bars to reach the islands. Gilbert related their oral reports to later measurements by determining the elevations of the Antelope and Stansbury Island bars, making soundings on the Antelope Island bar, and relating the water levels there to gage readings near Black Rock and Farmington (fig. 8). Considering the reliance on memory of long-past events, the lake water levels for 1847–74, which are shown by a dashed line in figure 3, probably should be considered accurate only to within 1 foot.

From 1875 to 1938, the lake level was measured periodically at staff gages at six different sites by many different individuals and organizations (fig. 8). The measurement interval was variable, ranging from weekly to monthly. As a result, there are major gaps in the record (shown as dashed lines in figure 3). The lake level has been measured continuously by an automatic recorder operated by the U.S. Geological Survey, in cooperation with the Utah Division of Water Rights, at the Saltair Beach Boat Harbor since 1939 and at Saline since 1966.

The following discussion of lake-level changes is divided into two time periods The first is from 1847 to 1982, when annual lake fluctuations averaged only about 1 5 feet over a range of 20 feet The second is from 1982 to 1986, when the lake rose an unprecedented 9 6 feet in the first 2 years and rose a total of 12 2 feet in 4 years

1847–1982

During 1847, when the Mormon pioneers arrived in Utah, the surface of Great Salt Lake was at about 4,200 feet (fig 3) The lake had risen about 4 feet by 1855 but then declined again to 4,200 feet by 1860 From 1862 to 1873 the lake rose about 12 feet, reaching a historic high of about 4,211 5 feet At this level, the lake covered about 2,300 square miles (See figure 2 and the 4,212-foot contour on the satellite image map (pl 1))

The rapid rise of the lake during 1862–73, as well as the continued high levels of the lake for several years after 1873, was of considerable concern to the settlers in Salt Lake City They feared that the city and adjacent farmlands might be flooded if the lake continued to rise In the hope of avoiding such a calamity, on September 8, 1876, "a party of gentlemen, accompanied by a surveyor, left for the north-west shore of the Salt Lake, with a view to determining the feasibility of cutting an outlet for the waters in that direction, and thereby greatly reducing the body of waters of the Lake" (*Latter-Day Saints' Millenial Star*, October 9, 1876) "They coasted the west shore to the extreme north-west, a distance of forty miles, finding no point where an outlet was possible, there being an average incline of the desert, from the present water line, of four to six inches to the mile" (*Latter-Day Saints' Millenial Star*, October 16, 1876) The decline of the lake during the following years ended the concern at that time

During the 31 years after the historic high level of 1873, the lake declined almost 16 feet, and in November 1905 it was at a then-historic low level of 4,195 8 feet The decline from 1873 to 1905 was at a fairly uniform rate, except for 1884–1886, when the lake level rose 4 2 feet (fig 3)

From 1906 to 1910, the lake level rose almost 7 feet—the steepest rise during a 5-year period since the beginning of record keeping During the next 14 years, the lake rose an additional foot to peak at 4,205 1 feet in May 1924 The lake level gradually declined to a low of 4,193 7 feet in November 1940 and then rose again to a peak of 4,200 95 feet in June 1952 This was followed by another lengthy period of decline, and by October 1963 the lake had reached an all-time historic low level of 4,191 35 feet (fig 3) At that level, the lake covered only about 950 square miles (See fig 2)

The overall trend from about 1873 to 1963 had been declining lake levels, and many people thought the lake would become dry As a result, railroads, interstate highways and other roads, wildfowl-management areas, recreational facilities, and industrial installations for the processing of lake brine were established on the exposed lakebed In 1964, however, the lake began to rise again, and by June 1976 it had risen about 11 feet, to 4,202 25 feet Again, concern arose about potential flooding of facilities and installations around the lake, and studies were made of the feasibility of pumping water out of the lake to the west into the desert During 1977, however, the lake began to decline because of unusually small snowfall during the preceding winter, ending the concern at the time

On September 18, 1982, the lake surface was at 4,199 65 feet, approximately the same level it had been 135 years earlier when the pioneers arrived Thus, the lake had fluctuated between 4,191 35 and about 4,211 5 feet but had shown no apparent net water-level change The major fluctuations of the lake surface generally reflected fluctuations of precipitation as represented by the record for Salt Lake City, which began in 1874 (see fig 9)

It is interesting to note that many of the periods of marked rise of lake level began after a major volcanic eruption The rise of 1884–86 followed the eruption of Krakatau, Indonesia, during August 1883 That was one of the largest known explosive eruptions in historic time, with a Volcanic Explosivity Index of 6 (Tilling, 1984, p 30) Eruptions that are designated by a Volcanic Explosivity Index of 5 or greater are considered "very large" eruptions, and they occur worldwide on the average of about once every 20 years The eruption of Krakatau resulted in ejection into the atmosphere of about 4 4 cubic miles of ash (Tilling, 1984, p 29) The large volume of Krakataun aerosol ash in the atmosphere may have resulted in a decrease in solar radiation, which could have caused a decrease in evaporation or an increase in precipitation This in turn would have resulted in a rise in lake level The steep rise of 1907–10 followed the eruption of Ksudach, Kamchatka, during March 1907 That eruption had a Volcanic Explosivity Index of 5 (Newhall and Self, 1982, p 1237) The rise of 1964–76 followed the eruption of Gunung Agung, Bali, during March 1963 Although that eruption had a Volcanic Explosivity Index of only 4, it emplaced a long-lasting aerosol cloud composed mainly of droplets of sulfuric acid in the stratosphere It was considered to be "among the most important volcanic events of the twentieth century, primarily because of its possible effects on global climate" (Rampino and Self, 1984b, p 677)

These three volcanic eruptions may have had a worldwide influence on climate, considering also their effect on the water level of another terminal lake, the Dead Sea in Israel-Jordan The Dead Sea rose markedly in 1884, 1907, and 1964 (Sauer, 1978, p 17) It should be emphasized, however, that other rises of the level of Great Salt Lake cannot be correlated with known major eruptions

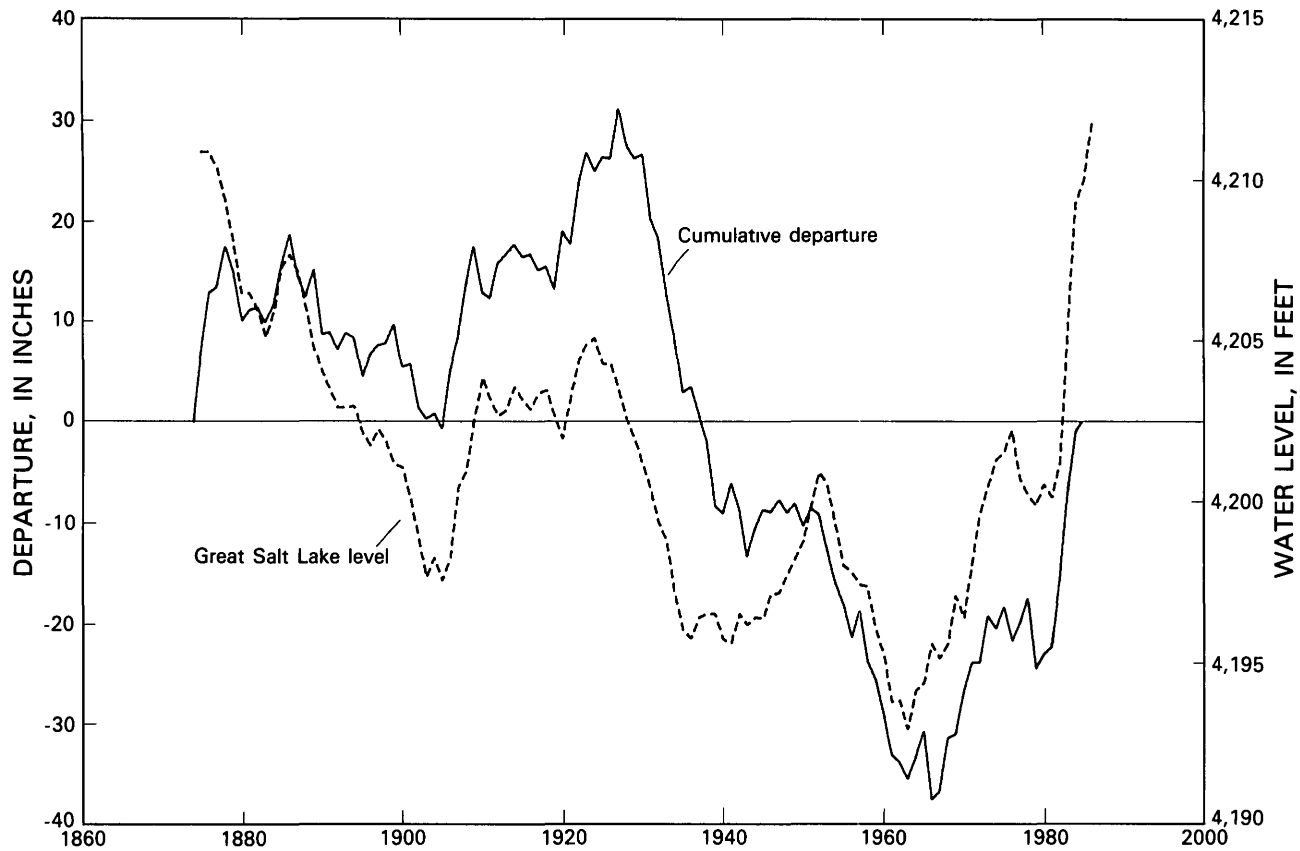


Figure 9. Cumulative departure from average annual precipitation of 15 79 inches at Salt Lake City recording sites (downtown and airport), 1875–1986, compared with annual peak water levels of Great Salt Lake

1982–1986

The lake began to rise on September 18, 1982, in response to a series of storms earlier in the month On September 26, during a record-breaking storm, 2 27 inches of rain was recorded at Salt Lake City International Airport, the maximum precipitation ever measured for 1 day during the 108 years for which records have been kept for the city Precipitation of 7 04 inches for the month made it the wettest September on record for the city Total precipitation at Salt Lake City during 1982 was 22 86 inches, compared with an average annual of 15 75 inches

The unusually intense rainfall resulted in unseasonably large inflow to Great Salt Lake, from precipitation directly on the lake and from tributary surface streams (fig 10) The peak flow in the Jordan River on September 27, 1982, was 2,795 cubic feet per second, or about 20,900 gallons per second, the maximum during 40 years of record keeping The large flows in the Jordan River, resulting from greater than average precipitation and from continuous overflow from Utah Lake (fig 7), continued for the remainder of the year The flow in the Jordan River from October to December was 3 8 times greater than average During the same period, the flows in the Bear and Weber Rivers were 2 0 and 2 7 times greater than average Great Salt Lake continued to rise rapidly throughout autumn in response to the large surface inflow and the concurrent relatively cool weather and extensive cloud cover, which decreased evaporative loss of water from the lake

The snowfall in the drainage basin of Great Salt Lake from autumn of 1982 through the following spring was much greater than average, providing the potential for enormous quantities of water to enter the lake The maximum reported snowfall was 845 inches at Alta, about 20 miles southeast of Salt Lake City (*Salt Lake Tribune*, July 7, 1983) The snow cover on June 1, 1983, ranged from about 2 4 to 3 4 times greater than average in the Bear River basin, from about 4 2 to 5 2 times greater than average in the Weber River basin, and from about 3 7 to 5 2 times greater than average in the Jordan-Provo River basin (Whaley, 1983, p 7–11)

The lake continued to rise throughout the winter of 1982–83—a normal annual occurrence The weather remained unseasonably cool throughout most of the spring of 1983, however, so the lake lost relatively little water by evaporation and continued its steady rise

Snowmelt during 1983 began about a month later than usual, and the water content of the snow increased until mid-May Soil moisture in the drainage basin was consid-

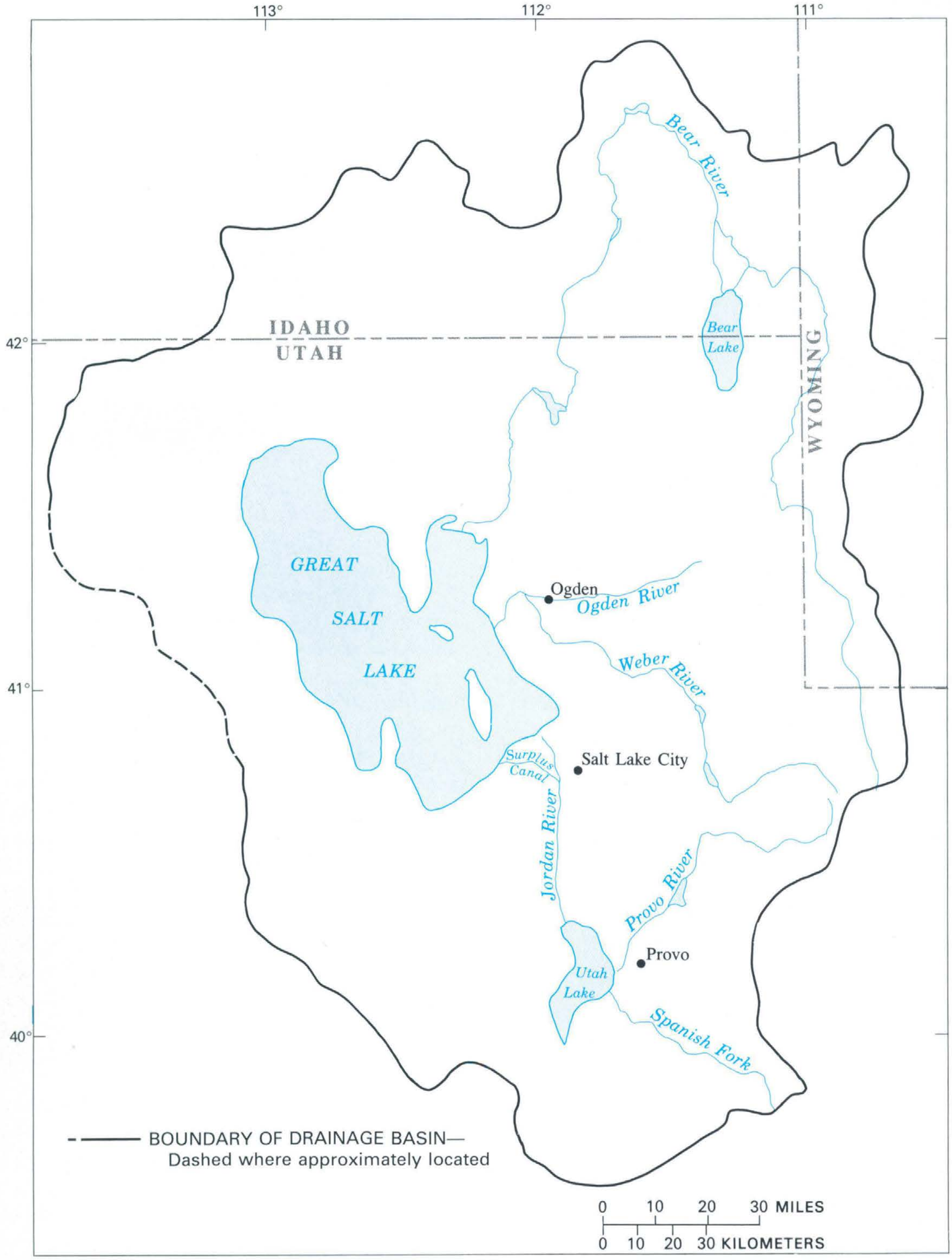


Figure 10. Drainage basin of Great Salt Lake. (Adapted from Hahl and Langford, 1964, fig. 2.)

erably greater than average, thus diminishing the potential for water to infiltrate the ground. The major snowmelt began at the end of May, during a heat wave on Memorial Day weekend, and record-breaking quantities of water flowed into the lake from many tributary streams. The discharge of the Bear River peaked at 9,770 cubic feet per second on June 4, 1983, considerably greater than its previously recorded peak of 7,880 cubic feet per second during 1980. The Jordan River peaked at 3,350 cubic feet per second on June 12, 1983, which was greater than the recent record flow of the previous September The Weber River peaked at 7,250 cubic feet per second on June 2, 1983, the third greatest flow in 78 years of record keeping From January to May 1983, the flows in the Bear, Jordan, and Weber Rivers were about 1 7, 3 6, and 1 6 times, respectively, greater than average Inflow to Great Salt Lake from the three rivers during October 1982 through May 1983 is compared with average inflow in figure 11

In addition to the inflow from the tributary streams, Great Salt Lake received substantial inflow from the normally dry desert area to the west Larry Sower (Great Salt Lake Minerals and Chemicals Corp , written commun , 1984) estimated that inflow from the desert area was 300,000 acre-feet during 1982–83

The large streamflows continued for many weeks, and the lake level continued to rise until June 30, 1983, when losses by evaporation finally exceeded inflow and the lake level peaked at 4,204 75 feet The rise from September 18, 1982, until June 30, 1983, was 5 1 feet, which is the greatest seasonal rise ever recorded This represents a net increase in the volume of the lake of about 6 million acre-feet That quantity of water is equivalent to what might be used by about 36 million people (with an average daily per capita consumption of 150 gallons) in 1 year, or by 1 5 million people (the entire population of Utah) in 24 years The previous largest seasonal rise known was 3 4 feet during 1906–07

During the summer of 1983, precipitation was greater than average and evaporation was relatively small because of greater than usual cloud cover These conditions resulted in an unusually small decline in lake level during the summer By September 25, 1983, when the seasonal rise began, the level of the southern part of the lake had declined only 0 5 foot The excessive precipitation continued throughout fall and culminated in the wettest December ever recorded at Salt Lake City By New Year's Day, Salt Lake City had received 24 26 inches of precipitation during calendar year 1983, about 1 5 times the average

The cumulative precipitation from January to June 1984 also was greater than average Much of the precipitation fell in the form of snow on the mountains in the drainage basin The snowmelt began soon after May 1, at which time the water content of the snow cover ranged from about 1 2 to 1 5 times greater than the average for May 1 in the Bear River basin, was about 1 5 times the average in the Weber River basin, and ranged from about 1 3 to 1 8 times the average in the Jordan-Provo River basin (Whaley, 1984, p 9–13)

The lake rose steadily from October 1983 through June 1984, primarily in response to the surface inflow that resulted from the excessive precipitation Precipitation at Salt Lake City International Airport was about 1 4 times the average for the 9-month period, and the resultant inflow from the three major surface tributaries to the lake during that period greatly exceeded their average flows for this 9-month period the Bear River flow was 2 7 times greater (3 12 million acre-feet), the Weber River flow was 2 1 times greater (923,000 acre-feet), and the Jordan River flow was 5 2 times greater (1 23 million acre-feet) The flow in the Bear River during water year 1984 was the greatest measured during 95 years of record, and the flow during water year 1983 was the second greatest on record Similar record-breaking flows, based on the past 35 years of records, were measured for the Weber and Jordan Rivers during water years 1983 and 1984

When the lake level peaked on July 1, 1984, it was at an elevation of 4,209 25 feet and the lake covered an area of about 2,300 square miles, including evaporation ponds for mineral recovery (pl 1) Because of the shape of the lakebed, more water is needed to raise the level of the lake each additional foot as the water level rises Thus, the 5 0-foot rise from September 25, 1983, to July 1, 1984, involved about 15 percent more water than did the 5 1-foot rise from September 18, 1982, to June 30, 1983 When the lake peaked on July 1, 1984, the net increase in volume represented by the 9 6-foot rise since September 18, 1982, was about 12 million acre-feet (an increase of about 80 percent), and the increase in area was about 600 square miles (an increase of about 35 percent) The previous recorded maximum net rise during a 2-year period was 4 75 feet from 1970 to 1972

The Utah legislature had passed a law in 1979 making the Utah Department of Natural Resources responsible for managing the lake so as to maintain the water level below the elevation of 4,202 feet The excessive precipitation during 1982–83 prevented achievement of that goal, but during 1983, the Utah Division of Water Resources (1984) began studies to consider various methods of controlling the level of the lake The three methods that seemed to have the most merit were (1) pumping water out of the lake into the desert to the west, (2) impounding water in Bear River for diversions that would decrease inflow to the lake, and (3) breaching the railroad causeway (fig 8), thereby causing a decrease of water level in the southern part of the lake, where most of the damage was occurring

The first two methods would involve extensive construction and considerable delay before effects on the water level of the lake would be achieved The third method promised relatively quick relief, and it was approved by the Utah legislature during 1984 A 300-foot-wide opening at the western end of the causeway was completed on August 3, 1984, at a total cost to the State of $3 million (fig 12) The effect of the breach on the lake level is discussed in the section "Railroad Causeway "

The lake started to decline on July 1, 1984, and it reached a seasonal low of 4,207 85 feet on October 1, 1984 It then rose to 4,209 95 on May 21, 1985, the highest level since 1877 (fig 3) Precipitation at Salt Lake City International Airport during 1984 was 21 55 inches, the third successive year in which the precipitation exceeded

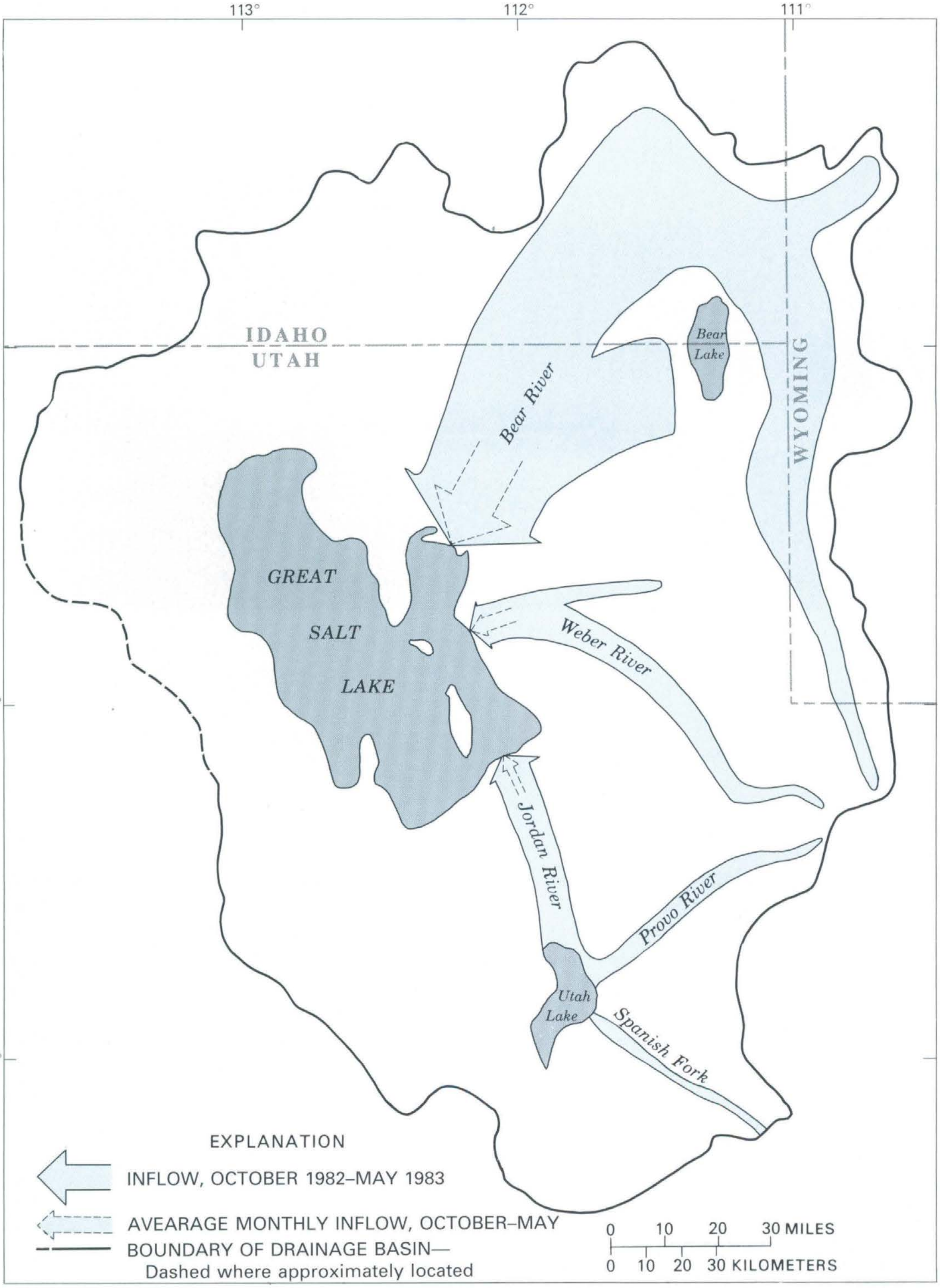


Figure 11. Relative magnitude of streamflow into Great Salt Lake from major rivers during October 1982 through May 1983 compared with average monthly streamflow during October through May. (From Arnow, 1984, p. 10.)

Figure 12. A 300-foot breach in the Southern Pacific Transportation Company causeway which was constructed to reduce the level of the southern part of Great Salt Lake. View to the northwest on June 19, 1986.

the average by more than 35 percent. The overall rise of the lake of 0.7 foot from July 1, 1984, to May 21, 1985, corresponded to greater than average precipitation of more than 22 percent during the same period.

Between May 21 and November 1, 1985, the lake declined 1.6 feet, primarily because of evaporation during a warm, dry summer. June 1985 was the fifth warmest June on record, July 1985 was the second warmest July on record, and August 1985 was the second driest August on record. The lake then began to rise during the wettest and snowiest November on record, when more than 27 inches of snow fell at Salt Lake City International Airport. January through March 1986 was characterized by unusually warm temperatures and less than average precipitation. On February 19, the lake rose an unprecedented 1.5–2 inches in response to a week of storms in northern Utah. A 1.5-inch rise represents a 1-day inflow of about 38 billion gallons, or about 7.5 gallons for every person on Earth. By April 1, 1986, the lake level was 4,210.50 feet, a rise of more than 2 feet during the winter. April precipitation exceeded 150 percent of normal over most of northern Utah, and both April and May were the third wettest on record at Salt Lake City International Airport. On May 12, 1986, the lake reached 4,211.65 feet, which surpassed the recognized historical peak of about 4,211.5 feet during 1873. By the end of May, the water content of the snowpack in the major drainage basins of Great Salt Lake ranged from 144 to 264 percent of normal.

The lake continued to rise during the first week of June 1986 in response to record inflows of water from the Bear, Weber, and Jordan Rivers. Inflow to the lake from October through May 1986 was 4 million acre-feet, nearly equaling the 1983–84 record of 4.5 million acre-feet during the equivalent time period. On June 3, 1986, the lake peaked at 4,211.85 feet. The net increase since the 1985 peak was greater than 2.6 million acre-feet. The 30 million acre-feet of water in the lake on June 6 was about equal to the combined usable storage of Lake Powell and Flaming Gorge and Strawberry Reservoirs in southern and central Utah, and if spread evenly over the State would cover it to a depth of 6.5 inches.

The 1986 peak elevation was short lived, however, as winds developed 5-foot waves on the lake on June 7, causing a breach in the outer dike of the AMAX Magnesium Corporation facility at the southwestern end of the lake (the light-blue area on pl. 1). By June 10, the water level in the southern part of the lake had declined 5 inches. This represents an estimated volume of 370,000 acre-feet of water that flowed from the lake into the previously isolated brine ponds.

The increase in the lake's surface area from 1982 to 1986 resulted in extensive damage to roads, railroads, wildfowl-management areas, recreational facilities, and industrial installations that had been established on the exposed lakebed (figs. 13–17). The capital damage at these facilities as the lake rose more than 12 feet was approximately $285 million (L. Douglas James, Utah Water Research Lab, Logan, oral commun., 1986). This economic loss prompted the Utah legislature to appropriate $71.7 million on May 14, 1986, for dikes and pumps designed to contain the lake and decrease its volume. Water would be pumped from near the western end of the Southern Pacific Transportation Company causeway over a land ridge and then allowed to flow into the western desert, thus creating a new lake of about 500 square miles with an average depth of 2.5 feet. Evaporation would decrease the water volume, and the concentrated brine would then be recycled back into Great Salt Lake.

The net rise of the lake from September 18, 1982, to June 3, 1986, was 12.2 feet. By comparison, the previously recorded maximum net rise during a 4-year period was 6.8 feet during 1906-10. Again, it is interesting to note that the record rise of 1982–86 was preceded in March and April 1982 by a major volcanic eruption, at El Chichón in Mexico. That eruption had a Volcanic Explosivity Index of only 4, but it emplaced a long-lasting aerosol cloud of about 2×10^{13} grams of sulfuric acid (Rampino and Self, 1984b, p. 678) in the stratosphere. It "was the densest cloud seen in the Northern Hemisphere since the eruption of Krakatau in Indonesia in 1883," and the "sulfuric acid droplets will take several years to settle out completely" (Rampino and Self, 1984a, p. 48). The eruption-induced decrease in solar radiation could have resulted in a decrease of evaporation or in an increase of precipitation, or both, which in turn would have contributed to a rise of lake level. In fact,

Figure 13. Entrance to Antelope Island causeway, looking west, with the lake water level at 4,209.15 feet on June 16, 1984. Note center line of the causeway showing through the water. The causeway was completed in 1968 when the lake water level was at 4,195 feet.

Figure 14. Bear River Migratory Bird Refuge first flooded in 1983 and still under water on June 19, 1986.

Figure 15. New Saltair, a large dance and recreation pavilion, August 2, 1983, shortly after completion. The water level of Great Salt Lake was 4,204.45 feet. The pond in the foreground is for children's paddle boats. (Photograph by Paul A. Sturm, Utah Geological and Mineral Survey.)

Figure 16. New Saltair on June 19, 1986, as the water level of Great Salt Lake reached 4,211.55 feet.

Figure 17. The Davis County North wastewater treatment plant, which required extensive diking to prevent inundation by rising lake waters. Photographed on June 19, 1986, when the lake level was 4,211.55 feet. (Photograph by Conrad Keyes, Jr., Rio Grande Compact Commission.)

pan-evaporation data for the Saltair Salt Plant, 7 miles northeast of the Saltair Beach Boat Harbor (fig. 8), indicate that the 1982–85 evaporation was only 72–84 percent of the long-term (1931–70) average for June-September. Also, the average annual precipitation during 1982–85 was 21.41 inches, or 39 percent greater than during 1875–1981.

Effects of Man's Activities

Consumptive Use

Diversion of water for irrigation, public supply, and other uses and impoundment of water in large, open reservoirs have led to a steady increase of consumptive use in the drainage basin of Great Salt Lake since 1847. Whitaker (1971) described the effect of consumptive use on the level of the lake, as shown in figure 18. The difference between the measured level and the level adjusted for consumptive use reached a maximum of about 5 feet around 1925 and remained relatively constant until 1965. No major water projects have been constructed in the basin since 1965, and the difference is assumed to have been about the same from 1965 to 1982. Thus, the lake surface is assumed to have been about 5 feet lower in 1982 than it would have been had man not increased the evapotranspiration of water by impounding it in reservoirs and marshes upstream from the lake and diverting it for irrigation and other uses.

The actual difference between the measured water level and the level adjusted for consumptive use in 1986 would have been less than 5 feet because of the relation between the level and volume of the lake (fig. 19). The volume of the lake at 4,212 feet is about twice as great as it

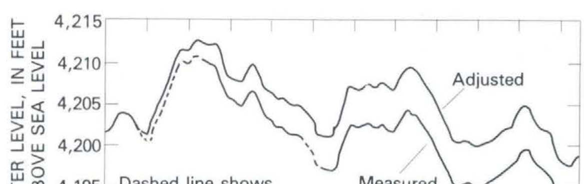


Figure 18. Effects of consumptive use of water resulting from man's activities on measured water levels of Great Salt Lake, 1850–1965. "Adjusted" line shows where lake level would have been had man not diverted and impounded water in the drainage basin. (Adapted from Whitaker, 1971, fig. 3.)

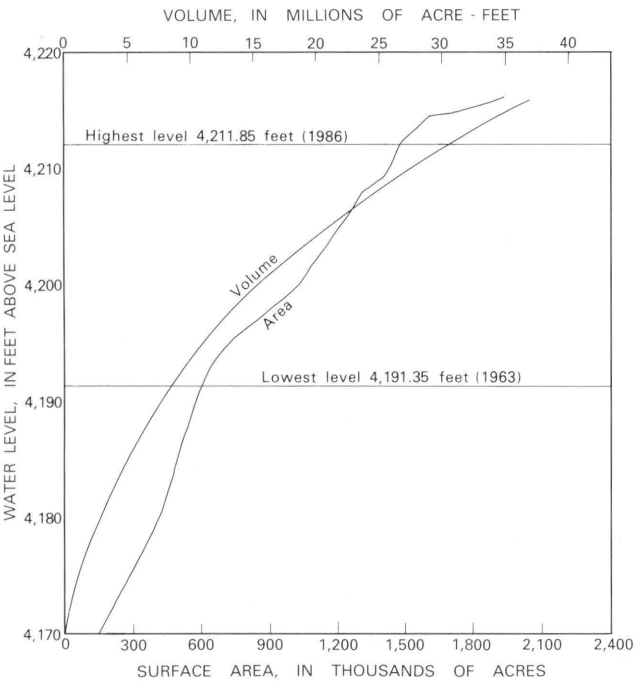


Figure 19. Relations among the water level, surface area, and volume of Great Salt Lake, excluding evaporation ponds for mineral recovery.

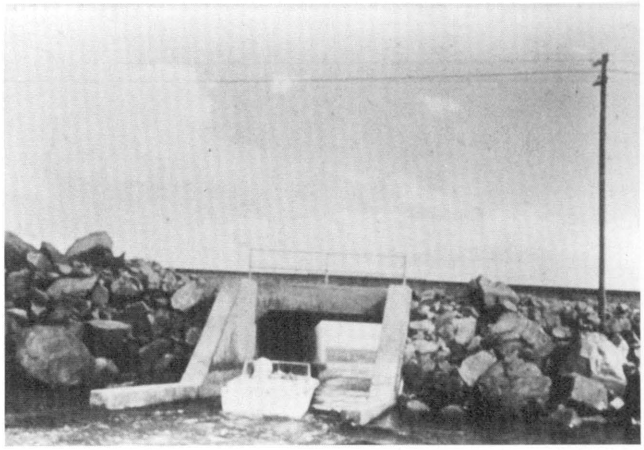
is at 4,200 feet; therefore, excluding increased evaporative losses due to the increased surface area, the difference in lake level in 1986 due to consumptive use probably was about 2.5 feet.

Railroad Causeway

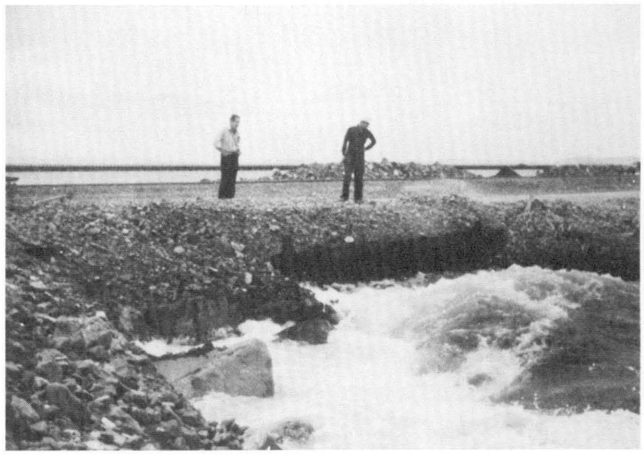
The Southern Pacific Transportation Company during 1902–03 constructed 20 miles of railroad track across the lake from the south end of the Promontory Mountains to Lakeside (fig. 8). At each end of the stretch, the track was laid on solid-fill causeway, but a central 12-mile section was supported by an open wooden trestle, which allowed free movement of the brine. During 1957–59, the open trestle was bypassed by a solid-fill section which was constructed mostly of gravel and sand capped with boulder-sized riprap. It is breached by two box culverts, each 15 feet wide (fig. 20). The causeway separates the lake into two parts: about two-thirds of the lake is south of the causeway, and about one-third is north of the causeway. Although the causeway is permeable, it restricts the movement of brine.

The southern part of the lake receives most of the freshwater inflow, whereas the northern part receives most of its water in the form of brine that moves through the culverts and causeway from the southern part of the lake. These factors, in conjunction with restriction of flow by the causeway, have caused differences in salinity and in water levels between the two parts of the lake. The differences increased steadily throughout the 1960's. Since 1966, when measurements of the water level were begun in the northern part of the lake, the water level in the southern part has been consistently higher, reaching a maximum difference of 3.7 feet on July 1, 1984 (fig. 3). The difference in water levels also varies seasonally, with the minimum generally occurring during fall and the maximum generally occurring during late spring.

The causeway was breached with a 300-foot-wide opening on August 3, 1984, to provide flood relief to areas along the shore of the southern part of the lake. Within 2 months, the difference in water levels across the causeway had decreased to 0.75 foot, and within 1 year it had



A



B

Figure 20. Flow through the culverts in the railroad causeway at different lake water levels. *A*, Boat entering culvert; view to north. (Photograph from files of Utah Geological and Mineral Survey dated "1962–63"; thus, elevation of the southern part of the lake was between 4,191.35 and 4,193.85 feet.) *B*, Submerged culvert on June 15, 1983, when elevation of southern part of the lake was 4,204.75 feet; view to south. (Photograph by Elmer Gerhart, U.S. Geological Survey (deceased).)

Figure 21. Railroad cars used as a breakwater to protect the Southern Pacific Transportation Company causeway across Great Salt Lake; view to east on September 16, 1983. (Photograph by Elmer Gerhart, U.S. Geological Survey (deceased).)

decreased to 0.5 foot. The difference is not expected to decrease further unless the breach is widened. According to Waddell and Bolke (1973, p. 10), complete equalization would require an opening greater than 750 feet.

Since 1982, when the lake began its monumental rise, the Southern Pacific Transportation Company has continually raised its railroad roadbed to prevent its destruction. Scrap railway cars have been filled with rock quarried nearby and transported to the causeway, where they are used as riprap (fig. 21). Despite these efforts, however, storm-tossed waves occasionally force closure of the tracks, as on June 8, 1986, shown in figure 22.

WATER BUDGET

The level of Great Salt Lake indicates an equilibrium between inflow to the lake from surface streams, ground water, and direct precipitation and outflow by evaporation. During dry years, the water level declines, causing a decrease in surface area; consequently, the volume of evaporation decreases. As the lake declines, the brine generally becomes more concentrated, also decreasing the rate of evaporation. During wet years, the water level rises, causing an increase in surface area; consequently, the volume of evaporation increases. As the lake rises, the brine generally becomes less concentrated, also increasing the rate of evaporation.

Less inflow is required to raise the lake level when the lake level is low than when it is high. For example, at the 1963 historic low level of 4,191.35 feet, a net increase in inflow of about 600,000 acre-feet was necessary to raise the lake level 1 foot. At the 1986 historic high level of 4,211.85 feet, however, a net increase in inflow of about 1.5 million acre-feet would have been necessary to raise the lake level 1 foot. (See fig. 19.)

The relation of inflow, outflow, and change of water level can be shown in a water budget for the lake. For any given time, the water budget can be written as

$$\text{Inflow} = \text{Outflow} \pm \text{Storage change}$$

The inflow comes from surface water that flows into the lake, from ground water that moves upward through the bottom of the lake, and from precipitation that falls on the lake surface. The outflow is entirely by evaporation. The storage change is the difference in the volume of the lake during the selected time period. Values for the elements of the water budget for 1931–76 are discussed in the following pages. Most of the discussion is based on the results of computer-model studies by Waddell and Fields (1977) and Waddell and Barton (1980).

Inflow

Streams contribute about 66 percent of the average annual inflow to Great Salt Lake, precipitation about 31 percent, and ground water about 3 percent (fig. 23). Total

Figure 22. A section of the Southern Pacific Transportation Company causeway near Lakeside which was damaged and partly submerged during a storm on June 8, 1986; view to northeast on June 19, 1986.

annual inflow during 1931–76 ranged from about 1.3 (1961) to 5.0 (1971) million acre-feet and averaged about 2.9 million acre-feet. The annual distribution of inflow from all sources for 1931–76 is shown in figure 24.

Streams

Approximately 92 percent of the average annual surface-water inflow to Great Salt Lake is from three drainage systems: the Bear (59 percent), Weber (20 percent), and Jordan (13 percent) Rivers. The U.S. Geological Survey has operated gaging stations on the main stems of these streams upstream from the lake for many years. During 1971–76, records were obtained at numerous gaging stations near the lakeshore in the three drainage basins. Streamflow to the lake during 1931–76 was estimated by correlation of the short-term records obtained near the lakeshore with the long-term records obtained farther upstream. The location of each gaging station is shown in figure 25, and the period of record at each station is shown in table 1.

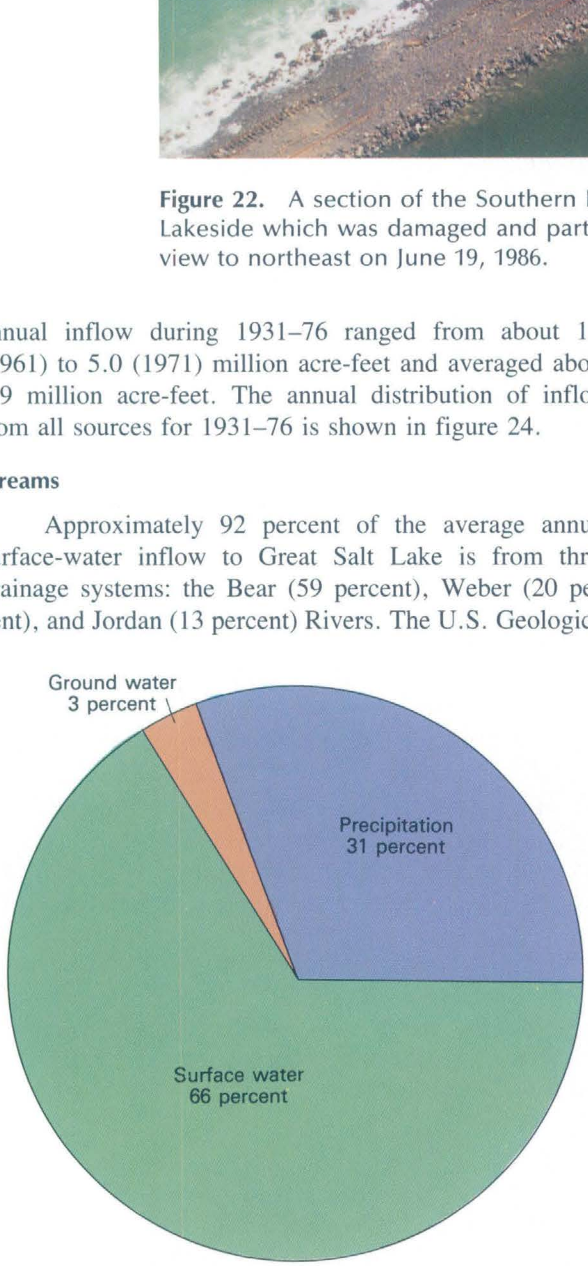


Figure 23. Sources of inflow to Great Salt Lake.

An additional 5 percent of the surface-water inflow to the lake is from 10 tributaries on the east and south shores. Measurements at stations on these tributaries for varying periods during 1950–76 were used as a basis for estimating inflow during 1931–76. These stations also are shown in figure 25 and are listed in table 1. Surface-water inflow from the remainder of the lakeshore is negligible.

Approximately 3 percent of the surface-water inflow to Great Salt Lake is from sewage-treatment plants. These discharge their effluent directly into Farmington Bay, east of Antelope Island.

Total annual surface-water inflow from all sources during 1931–76 ranged from about 700,000 (1934) to 3.8 million (1971) acre-feet and averaged about 1.9 million acre-feet.

Precipitation

Inflow to Great Salt Lake from precipitation directly on the lake surface was calculated by using average annual precipitation during 1931–76 at each of 68 sites in a large area surrounding the lake. A multiple-regression equation

Table 1 Period of gaging-station records, 1931–76

[See fig 25 for location of stations]

Station number	Station name
10118000	Bear River near Collinston
10126000	Bear River near Corinne
10127110	Bear River basin outflow across State Highway 83 near Corinne
10141000	Weber River near Plain City
10141050	South Fork Weber Canal near Hooper
10141100	South Fork Weber River near Hooper
10141150	Middle Fork Weber River near Hooper
10141200	North Fork Weber River near Hooper
10141400	Howard Slough at Hooper
10141500	Holmes Creek near Kaysville
10142000	Farmington Creek above diversions, near Farmington
10142500	Ricks Creek above diversions, near Centerville
10143000	Parish Creek above diversions, near Centerville
10143500	Centerville Creek above diversions, near Centerville
10144000	Stone Creek above diversions, near Bountiful
10145000	Mill Creek at Mueller Park, near Bountiful
10167000	Jordan River at narrows, near Lehi
10167500	Little Cottonwood Creek near Salt Lake City
10168500	Big Cottonwood Creek near Salt Lake City
10170000	Mill Creek near Salt Lake City
10170500	Surplus Canal at Salt Lake City
10170700	North Point Consolidated Canal below Goss Flume, at Salt Lake City
10170750	Surplus Canal at North Temple Street, near Salt Lake City
10170800	Surplus Canal at Cohen Flume, near Salt Lake City
10171000	Jordan River at Salt Lake City
10171600	Parleys Creek at Suicide Rock, near Salt Lake City
10172500	City Creek near Salt Lake City
10172600	Jordan River below Cudahy Lane, near Salt Lake City
10172630	Goggin Drain near Magna
10172640	Lee Creek near Magna
10172650	Kennecott Drain near Magna
	Salt Lake City sewage canal

Period of record

Records available but not used

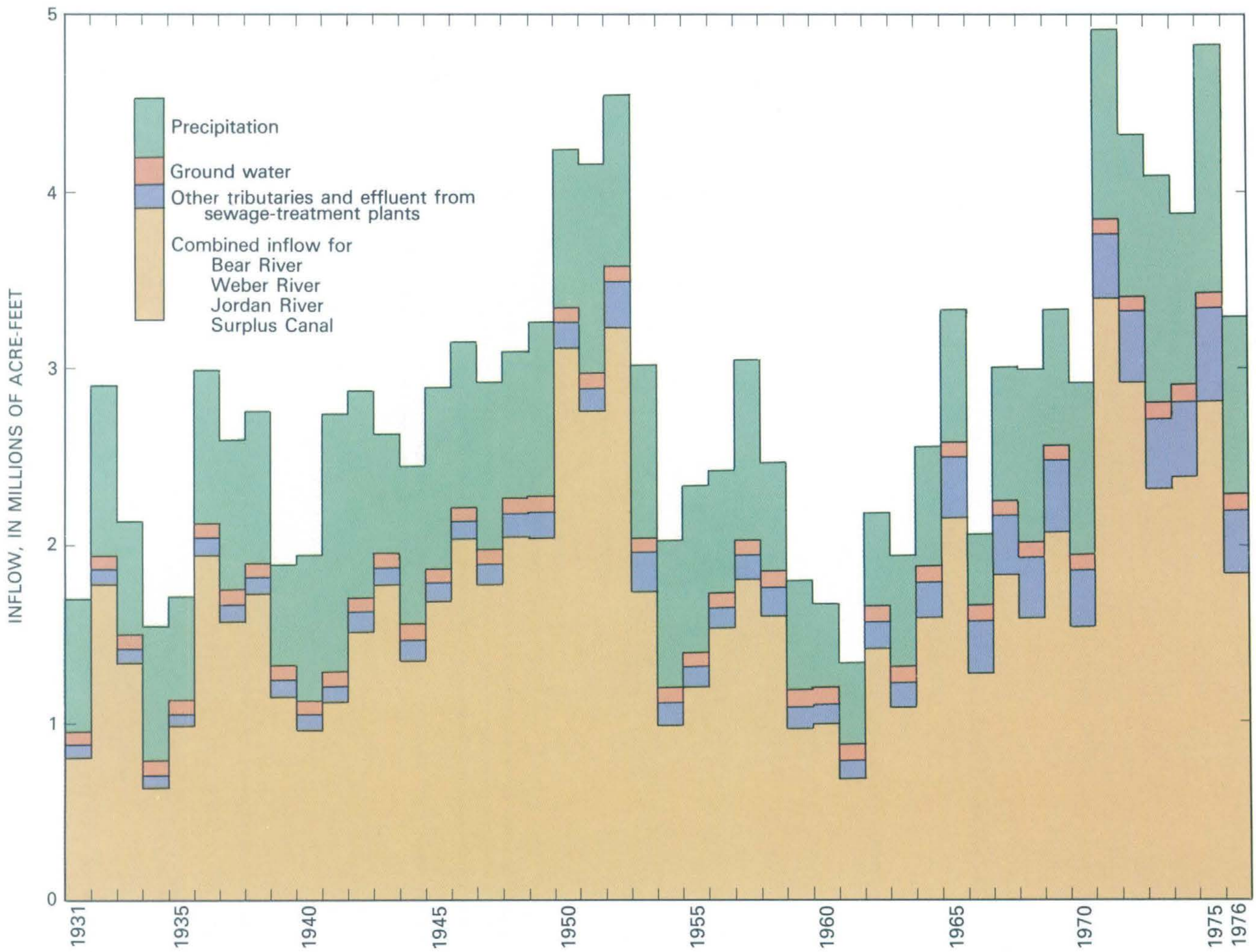


Figure 24. Annual inflow to Great Salt Lake from all sources, 1931–76. (Adapted from Waddell and Barton, 1980, fig. 7.) Inflow calibration from the original model not included. (Height of bar is summation of all inflow sources. Each individual source is shown only by the size of the colored section.)

was derived to describe average annual precipitation as a function of elevation, latitude, and longitude. Precipitation values estimated by the equation were used to construct lines of equal average annual precipitation for the lake area. Then annual precipitation directly on the lake was computed for 1931–76 on the basis of monthly lake-surface areas during that period. The estimated annual precipitation on the lake during 1931–76 ranged from about 500,000 (1966) to 1.5 million (1941) acre-feet and averaged about 900,000 acre-feet.

Precipitation that falls on the lakeshore runs into the lake and must be considered part of the inflow. The quantity is relatively small, however, and was included as a residual term, "inflow calibration," by Waddell and Barton (1980, p. 20) to balance their water budget for the lake.

Ground Water

Ground-water inflow to Great Salt Lake was estimated by adding inflow values determined in previous investigations for 12 segments of the lakeshore (Arnow and Stephens, 1975). The values, in acre-feet per year, were 0 for Curlew, Sink, and Skull Valleys, the lower Bear River basin, and the northern Great Salt Lake Desert (west of Great Salt Lake; see fig. 7), 1,000 for Hansel Valley, 3,000 for Antelope Island and Park Valley, 4,000 for Salt Lake County, 7,000 for Tooele Valley, 9,000 for the Promontory Mountains, and 48,000 for the area east of Great Salt Lake.

Total ground-water inflow to the lake was estimated to be about 75,000 acre-feet per year. This was assumed to be an average annual inflow value for 1931–76.

Outflow

Outflow from Great Salt Lake by evaporation from the lake surface was calculated primarily on the basis of pan-evaporation data from 49 sites in Utah and bordering States. Short-term records were extended to the full period 1931–76 by correlation with a site near Lehi (about 30 miles southeast of Great Salt Lake), and seasonal records were

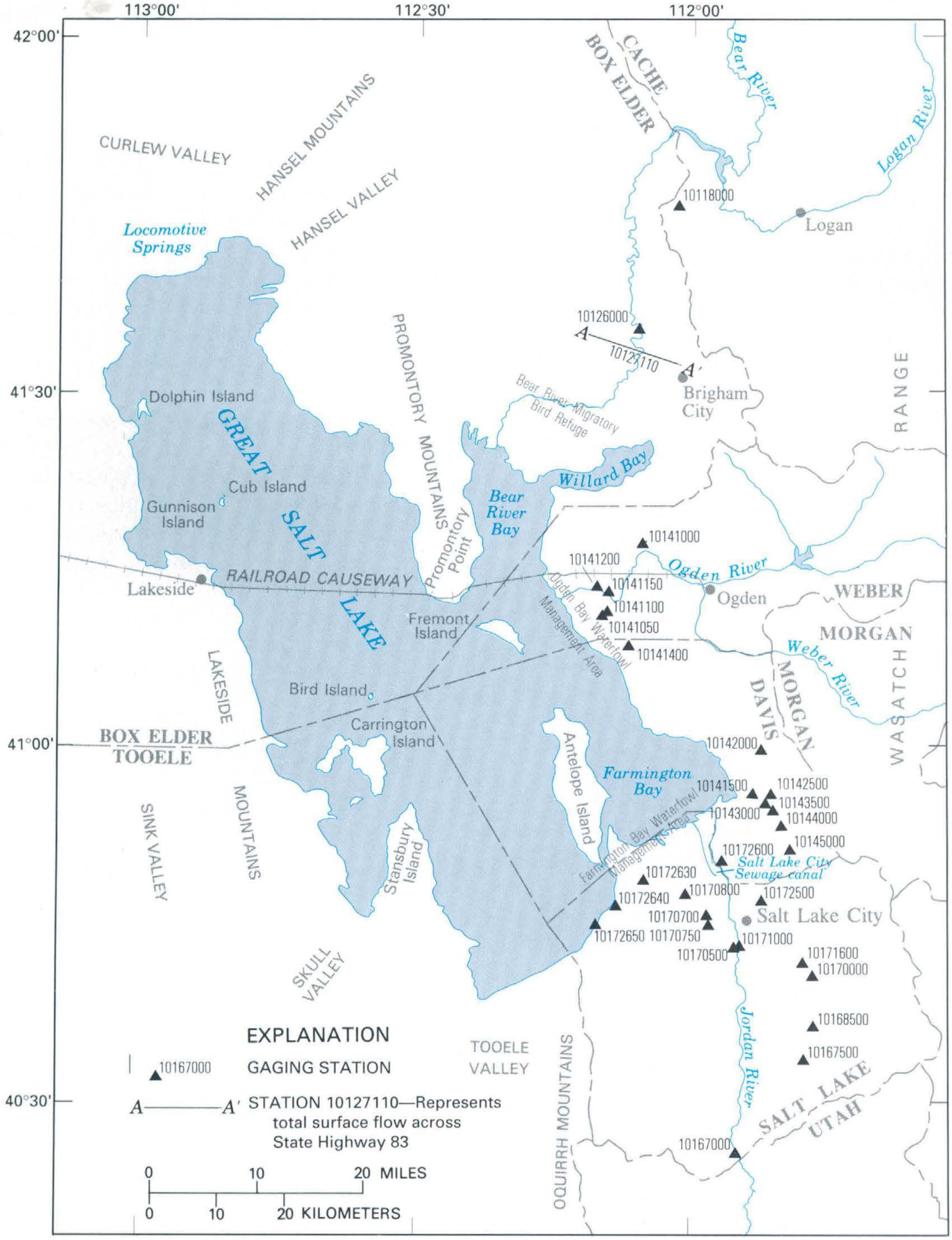


Figure 25. Location of railroad causeway and gaging stations used for estimating surface-water inflow to Great Salt Lake. (Adapted from Waddell and Barton, 1980, fig. 3.)

extended to the entire year by use of ratios developed for a few sites where complete annual records were available. Pan coefficients were applied, and a multiple-regression equation based on elevation, latitude, and longitude was used to draw lines of annual freshwater evaporation for the lake. The volume of freshwater evaporation then was corrected for the effect of salinity by applying appropriate factors for each part of the lake.

Estimated annual evaporation from the lake for 1931–76 ranged from about 2.1 million to 3.9 million acre-feet and averaged 2.9 million acre-feet. The latter is equivalent to about 45 inches per year for the average lake water level of 4,196 feet during 1931–76.

A small volume of water was withdrawn from Great Salt Lake during 1931–67 and evaporated for common salt production, but since 1967 the volume withdrawn has increased because of withdrawals for production of additional minerals. Total withdrawal for mineral production during 1976 was about 71,000 acre-feet.

Storage Change

The final element in the water budget—storage change—is the change in the volume of the lake. Changes in volume are computed on the basis of changes in the water level of the lake; figure 19 illustrates the relation between volume and water level. The lake at the end of 1976 was at the same level as at the beginning of 1931. Thus, there was no net change in storage during the period.

THE BRINE

Chemical Characteristics

Great Salt Lake is one of the saltiest large permanent bodies of water in the world. It is not as salty as the Dead Sea, but it is considerably saltier than the oceans. The lake has a dissolved-mineral content of almost 5 billion tons (Sturm, 1980, p. 155). More than 2 million tons have been added to the lake annually in recent years (Arnow and Mundorff, 1972, table 3), primarily by inflowing streams. More than half of this is calcium carbonate, which precipitates to form oolitic sand and other sediments. It was the density resulting from these dissolved minerals that gave the lake brine its buoyancy and permitted swimmers to float on the lake without effort.

The major dissolved ions in the brine are chloride, sodium, sulfate, magnesium, and potassium. Chloride and sodium account for about 90 percent (by weight) of the dissolved ions. That percentage decreases somewhat when halite (rock salt) is precipitated at low lake levels (Hahl and Handy, 1969, p. 14). The brine contains small quantities of dissolved calcium, bicarbonate, lithium, boron, fluoride, silica, bromium, and other trace elements. The composition of the brine has remained fairly constant throughout the recorded history of sampling on the lake. Some variations occurred, however, when the lake was divided by the railroad causeway, particularly during 1966–70, when halite was precipitated. (See table 2.)

Variations in Salinity

The salinity of the brine in Great Salt Lake always has varied somewhat with depth and from place to place. These variations were caused by differences in distance to sources of freshwater inflow and differences resulting from greater rates of evaporation in shallow parts of the lake compared with deep parts.

Prior to completion of the railroad causeway, mineral concentrations throughout the lake probably were fairly uniform because of mixing of the brine by wind and currents. During years of high lake levels (resulting from large quantitites of freshwater inflow), the salinity of the brine was less than during years of low lake levels (when the concentration of the brine increased because evaporation exceeded inflow). This is illustrated in figure 3 and table 2, which show that prior to 1959 the salinity of the brine varied inversely with lake level. In 1869, for example, when the lake was within a few feet of its historic high level, salinity was 15 percent of brine weight. In 1930, however, when the lake level was about 10 feet lower, the salinity was 21 percent.

Completion of the railroad causeway in 1959 divided the lake into two parts and restricted movement of the brine. The southern part of the lake receives more than 90 percent of the freshwater inflow, but that inflow contributes directly to only an upper layer of brine in the southern part. A lower, denser layer, occupying only the deepest areas of the southern part, is derived from dense brine in the northern part that is driven by a density gradient to flow southward through the lower parts of the culverts and causeway. (See fig. 26.) The northern part of the lake has been cut off from

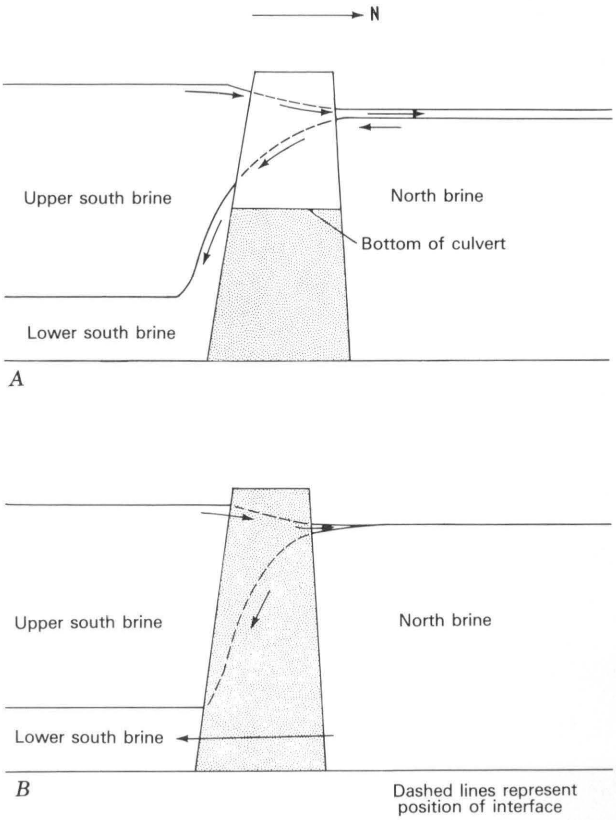


Figure 26. Schematic drawing of railroad causeway showing direction of flow (*A*) through a culvert and (*B*) through the permeable fill. (Adapted from Madison, 1970, fig. 6.)

Table 2. Composition of Great Salt Lake brine, in percentage by weight, 1850–1986

[Percentages are the ratio of the concentration of the indicated constituent to the sum of the concentrations for all constituents determined Data prior to 1976 from Hahl and Handy (1969, p 14), data for 1976 adapted from Sturm (1980, p 155), data for 1986 from Utah Geological and Mineral Survey, unpublished]

Date	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Lithium (Li)	Bicarbonate (as CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Boron (B)	Bromium (Br)	Total percentage	Dissolved solids
							Precauseway							
1850	—	—	0 27	38 29	—	—	—	5 57	55 87	—	—	—	100 0	22 3
1869	—	0 17	2 52	33 15	1 60	—	—	6 57	55 99	—	—	—	100 0	15 0
August 1892	—	1 05	1 23	33 22	1 71	—	—	6 57	56 22	—	—	—	100 0	23 8
October 1913	—	16	2 76	33 17	1 66	—	0 09	6 68	55 48	—	—	—	100 0	20 3
March 1930	—	17	2 75	32 90	1 61	—	05	5 47	57 05	—	—	—	100 0	21 0
							South of causeway							
April 1960	0 002	12	2 91	32 71	1 71	—	06	6 60	55 88	—	0 01	—	100 0	24 7
December 1963	001	09	3 29	31 02	1 86	—	07	9 02	54 64	—	01	—	100 0	27 3
May 1966	003	09	3 80	30 56	2 22	0 02	10	7 99	55 21	0 003	01	—	100 0	18 9
June 1976	—	17	3 47	31 29	2 66	02	—	7 22	55 11	—	01	0 04	100 0	9 9
June 1986	—	24	3 66	31 14	2 41	—	—	6 99	55 56	—	—	—	100 0	4 7
							North of causeway							
December 1963	001	09	4 66	29 08	2 75	—	09	7 28	56 04	—	01	—	100 0	27 5
May 1966	—	05	4 38	29 67	2 61	02	09	8 58	54 59	002	01	—	100 0	26 9
June 1976	—	13	3 17	32 04	2 58	02	—	6 62	55 39	—	01	04	100 0	24 7
June 1986	—	16	3 17	32 17	1 82	—	—	6 81	55 87	—	—	—	100 0	15 2

most of the direct freshwater inflow, and almost all its inflow consists of brine that moves through the culverts and causeway from the south, where the water level is higher The changes brought about by the causeway have had a profound effect on the relation of lake level to salinity (fig 3)

The brine north of the causeway remained relatively constant at or close to saturation, with the salinity near 28 percent from at least 1959 to 1982, regardless of changes in lake levels The salinity decreased, however, during the large lake-level rises of 1983 and 1984, and a steady decrease continued after the breach of the causeway and as the lake continued to rise in 1985 By June 1986, the salinity north of the causeway had decreased to about 18 percent

In 1963, at the historic low level of the lake, the brine south of the causeway was saturated and the salinity was about 28 percent As the lake rose, however, the salinity of the brine south of the causeway continued to change inversely with the lake level, although the salinity was less than it would have been prior to construction of the causeway (fig 3) In 1977, for example, at a lake level of about 4,200 feet, the salinity south of the causeway was-approximately 12 percent, whereas prior to 1957 it would have been more than 20 percent at that level In June 1986, the salinity south of the causeway decreased to about 5 6 percent At this salinity, which is 1 6 times that of seawater, the famed buoyancy of Great Salt Lake was considerably diminished

Biological Characteristics

Hypersaline water is not a suitable environment for most living organisms because the brines "dry out" living tissue by removing water The few types of organisms able to tolerate this environment (table 3) thrive in brine because of their ability to adapt and the lack of competition from other organisms for inorganic nutrients and food As salinity decreases, more organisms are capable of existing in the water These organisms compete with the more salt tolerant forms and generally are more successful, resulting in a gradual change toward communities of fresher water organisms (fig 27) Changes in the biology of the lake were first evident after 1959 following completion of the Southern Pacific Transportation Company causeway, which separated the lake into two parts, with progressive freshening of the southern part The large quantity of inflow to the lake since 1982 has further accentuated the changes in the lake's ecosystem

Prior to 1960

At the time of the first permanent settlement in the Salt Lake Valley, during 1847, little was known about aquatic life in the lake Exploration parties dispatched by Captain B L E Bonneville (Relyea, 1937, p 612) noted that small animals were found in the water during his 1831–33 survey, but as late as 1861 it was common to find written statements such as, "No living thing of any kind

Table 3. Principal organisms found in Great Salt Lake, in general decreasing order of their tolerance to salinity

Common name	Scientific name	Principal habitat (dates of occurrence)
Red bacteria	*Halobacterium* sp *Halococcus* sp	Water and sediment of the northern part (1960–83)
Red brine algae	*Dunaliella salina*	Water of the northern part (1960–83)
Biostrome blue-green algae	*Coccochloris elebens*	Biostromes of the southern part (unknown–1983)
Green brine algae	*Dunaliella viridis*	Water of the southern part (unknown–1983) Water of the northern part (1983–86)
Brine fly (two species)	*Ephydra cinerea* *Ephydra hians*	Sediment and biostromes of the southern part (unknown–1986)
Brine shrimp	*Artemia salina*	Water of the southern part (unknown–1986) Water of the northern part (unknown–1986)
Blue-green algae (several species)	*Nodularia spumigena*	Water of the southern part (1983–86)
Diatoms (four species)	*Amphora coffeiformis*	Do
	Navicula graciloides	Do
	Navicula tripunctata	Do
	Rhopalodia musculus	Do
Water boatman	*Trichocorixa verticalis*	Shallow surface water of the southern part (1973–86)

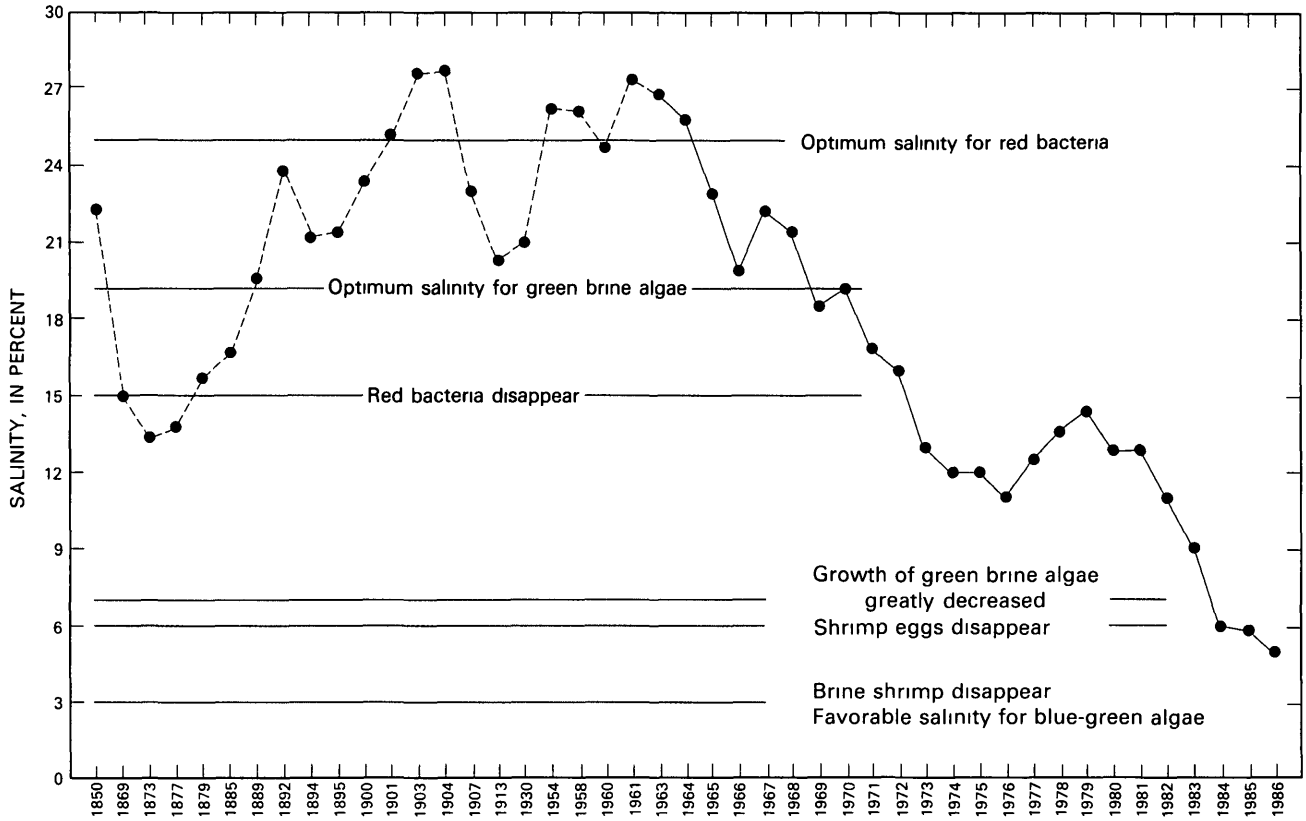


Figure 27 Change in salinity of the southern part of Great Salt Lake and its effect on the biota, 1850–1986 Dashed curve indicates measurements made in nonconsecutive years

exists in the lake" (Anonymous, 1861) During the late 1800's, salinity ranged from about 13 to 23 percent, which is four to seven times more saline than ocean water It was during this period that brine shrimp (table 3) and brine flies were reported inhabiting the lake (Verrill, 1869, Packard, 1871), although the local Indians had been dining on the shrimp eggs and larval flies for many years Five different types of green and blue-green algae, which likely served as food for the shrimp and flies, also were described from the lake by Tilden during 1898 (Kirkpatrick, 1934, p 2)

The fact that Great Salt Lake was salty like the ocean and supported plant and animal life sparked the attention of the settlers, who investigated whether marine animals could be introduced and "farmed" in its waters According to newspaper reports in 1882, seedling oysters were planted at the mouths of the Bear and Weber Rivers, but the excessive salinity and deposition of mud in the oyster beds prevented their establishment (*Deseret Evening News*, August 12 and 14, 1882) The U S Commission of Fish and Fisheries issued a formal report in 1900 stating that the lake was not suitable for marine organisms because the salinity, even at the mouths of rivers, was too great and deposition of sediment was unfavorable to shellfish (Moore, 1900, p 249, 250)

The period from the turn of the century to the early 1960's was characterized by considerable interest in the biology of the lake and by further descriptions of the diversity of organisms in the lake Extensive deposits of carbonate minerals in ridges and mounds called biostromes were described by Eardley (1938) and Carozzi (1962) These deposits are produced by a blue-green alga, which lives on the bottom muds where the water is less than 15 feet deep and secretes the carbonate as a byproduct Nearly 100 square miles of these deposits have been formed, primarily along the west shore of the lake and near islands These algae, in turn, serve as a principal source of food for larvae of brine flies, which have been estimated to number 370 million per mile of beach (Garvanian and Havertz, 1973) The role of lake organisms in the production of sediments was further identified when Eardley (1938, p 1401–1408) wrote that brine shrimp remove suspended sediment from the water and deposit it as fecal pellets By 1938 these pellets constituted one-third of the lake sediments Between 1930 and 1959, the discovery of additional organisms was limited to the identification by Evans (1960) of about 15 species of bacteria and 8 species of protozoa

1960–1982

Completion of the railroad causeway between Promontory Point and Lakeside in 1959 resulted in creation of two ecologically distinct lakes because of differences in salinity In addition to osmotic stress on the organism, the large concentrations of dissolved salts in the northern part greatly decreased the ability of the water to absorb oxygen The organisms most capable of living in brines that contain small dissolved-oxygen concentrations are bacteria, specifically two types that have a purple pigment called bacteriorhodopsin This pigment is closely related to a pigment that aids human eyesight In these bacteria, this pigment allows the organisms to use light as an alternative energy source to respiration in environments where the dissolved oxygen needed for respiration is limited It is this purple pigment that imparted a distinct red color to the northern part of the lake which was visible until about 1982, when salinity in the northern part began to decrease

The northern part also contains a species of algae that has a red pigment and is closely related to the green brine algae of the southern part of the lake The dominance of the red bacteria in the biology of the northern part, however, is evident in biomass calculations from data in Post (1980, p 314) The total bacterial population of the northern part exceeded 2 million metric tons, with the weight of the red algae at 8 percent and the brine shrimp at less than 0 05 percent of the bacteria The bacteria are so well adapted to the concentrated brines that they will not grow if salinity is less than 15 percent

During the early 1960's, the southern part of the lake reached a salinity of 28 percent At this salinity, competition from organisms that are not tolerant of concentrated brines is eliminated and populations of halophilic organisms greatly increase From 1960 to 1982, salinity in the northern part remained near 28 percent while salinity in the southern part gradually declined It was at this time that commercial harvesting of brine shrimp and shrimp eggs essentially stopped in the northern part and increased in the southern part as shrimp populations in the south were increasing

During the early 1970's, small aquatic insects were collected from the water surface at the southern end of the lake (Rawley and others, 1974, p 25, 26) These were corixids, or "water boatmen," which are predatory on brine shrimp and brine flies They typically reproduce in less saline waters nearby and feed in the lake The species identified was *Trichocorixa verticalis*, which also has been found in brine ponds near San Francisco, Calif

By 1979, salinity of the southern part had decreased to near 14 percent, and the 29 species of algae present included 17 species of diatoms (Felix and Rushforth, 1980, p 306) This is in marked contrast to earlier, more saline, periods, when only two diatoms likely were residents of the lake (Rushforth and Felix, 1982, p 158) The most common algae in the southern part were the green brine alga *Dunaliella viridis* and the diatoms *Amphora coffeiformis*, *Navicula graciloides*, *Navicula tripunctata*, and *Rhopalodia musculus* The biostrome-forming blue-green alga *Coccochloris elebans* was quite rare, as it prefers salinities near 25 percent (Felix and Rushforth, 1980, p 306)

Subsequent to 1982

Unusually large quantities of precipitation falling within the watershed of Great Salt Lake during 1982–85 resulted in average annual surface-water inflows to the lake of about 4 6 million acre-feet, compared with the average of about 1 9 million acre-feet for 1931–76 (Arnow, 1984, p 15) As a result of these inflows, salinity in the southern part decreased from about 13 percent in 1981 to about 5 percent in 1986 This dramatic decrease in salinity has greatly affected the composition of the algal and shrimp communities A filamentous blue-green alga, *Nodularia spumigena*, which was common in Farmington Bay but which appeared infrequently in the southern part during the early 1980's, was quite common throughout the southern part by mid-1984

Harvest of brine-shrimp eggs, which during 1960–82 had been economically feasible only in the southern part, decreased steadily from 85 tons in 1965 to less than 9 tons in 1981 (fig 28) The demise of the brine shrimp in the southern part has been a result of decreasing salinity As salinity reaches 6 percent, the hard winter eggs produced by the shrimp sink to the bottom of the lake, where they cannot hatch in response to inflow of freshwater in the spring At salinities near 3 percent, adult shrimp fail to reproduce (fig 27) The large inflows of freshwater, which began in 1982, also resulted in decreases in salinity in the northern part, by 1986, salinity there had decreased to about 17 percent, down from about 28 percent in 1982 Commercial harvest of brine-shrimp eggs has been limited to the northern part since 1982, and harvests have greatly increased (fig 28) The breach of the Southern Pacific Transportation Company causeway in 1984 resulted in an increase in the volume of dilute brine from the southern part that mixes with the more concentrated brine in the northern part, and this gradually decreases the salinity of the northern part

Brine flies, the other major animal group in the lake, are tolerant of waters that are moderately saline and warm and have small concentrations of dissolved oxygen Some brine flies in other areas even live in pools of crude petroleum Another species closely related to the brine flies in Great Salt Lake was found to be tolerant of salinities ranging from 1 to 8 percent, with optimum growth at 4 or 5 percent, although it would not live in freshwater or more dilute brine (Simpson, 1976, p 490) Of the two species of brine flies living in the Great Salt Lake, the smaller *Ephydra cinerea* is more tolerant of salinity and in the past has been 100 times more abundant than *Ephydra hians* (Rushforth and Felix, 1982, p 158) With the decreasing salinity of the southern part, *Ephydra hians* is now becoming more dominant (Betinna Rosay, Salt Lake City Mosquito Abatement District, oral commun , 1986)

The decreased salinity of the southern part allowed a breeding population of rainwater killifish (*Lucania parva*) to enter the lake near Stansbury Island during 1986 The

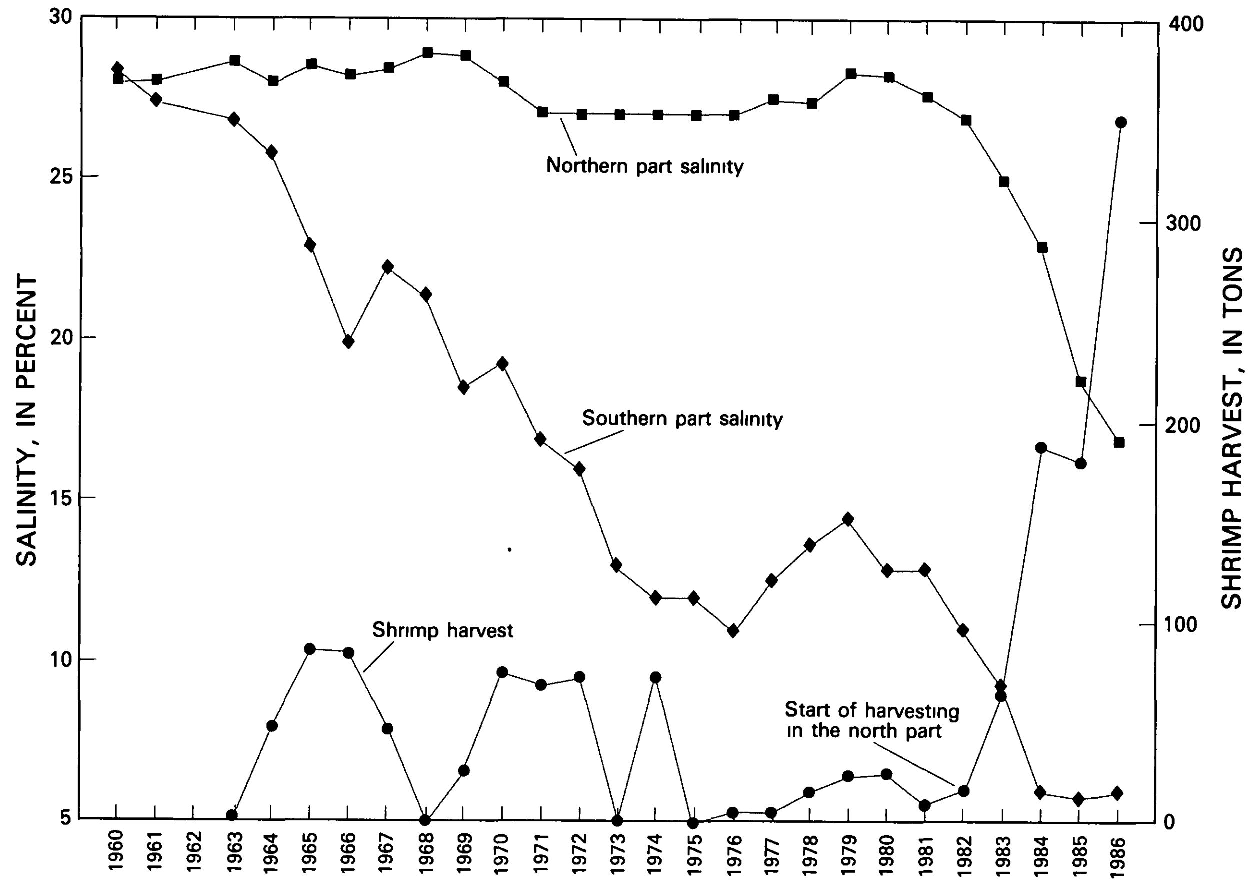


Figure 28. Change in salinity of Great Salt Lake since completion of the Southern Pacific Transportation Company causeway in 1959 and its effect on the commercial harvest of brine shrimp and eggs

1 5-inch fish are members of the minnow family and commonly are found in brackish and saline waters The fish likely entered the lake from warm spring water discharging in the area (*Salt Lake Tribune*, August 8, 1986) Their continued existence and increase within the lake will be contingent largely upon continued small salt concentrations and their ability to withstand subfreezing temperatures of −1 to −3 °C that commonly occur every winter

SUMMARY

The Great Salt Lake is a remnant of Lake Bonneville, which had a maximum depth of about 1,000 feet and covered about 20,000 square miles in Utah, Nevada, and Idaho during the latter part of the Pleistocene Epoch Lake Bonneville began to form about 32,000 years before present and rose in three major steps to reach the freshest water conditions and the highest altitude about 17,000 years before present The lake then overflowed near Red Rock Pass into the Snake River drainage system and thence eventually to the Pacific Ocean

The size of Great Salt Lake varies considerably, depending on its surface elevation, which can vary dramatically with climatic changes At an elevation of 4,200 feet above sea level, the approximate average water level about which the lake has fluctuated during historic time (1847–1986), it covers about 1,700 square miles, with a maximum depth of 34 feet However, the record inflows during 1982–86 have raised the lake about 12 feet and increased the surface area of the lake to about 2,300 square miles

In 1847, when Utah was settled by Mormon pioneers, the water level of Great Salt Lake was about 4,200 feet From 1862 to 1873 the lake rose approximately 12 feet, to cover an area of about 2,300 square miles at a historic high of about 4,211 5 feet During the next 90 years, the lake level severely declined, and in October 1963 it reached an all-time historic low level of 4,191 35 feet At that level, the lake covered only about 950 square miles

The consensus of local people was that the lake would never rise again As a result, railroads, interstate highways and other roads, wildfowl-management areas, recreational facilities, and industrial installations were established on the exposed lakebed But in 1964, the lake began to rise again, and by 1986 it had risen approximately 20 feet, about 12 feet between 1982 and 1986

The rise from 1982 to 1986 resulted in capital damage of about $285 million to roads, railroads, wildfowl-management areas, recreational facilities, and industrial installations that had been established on the exposed lakebed This loss prompted the Utah legislature to appropriate $71 7 million for dikes and pumps designed to contain the lake and to reduce its volume Water would be pumped from near the western end of the Southern Pacific Transportation Company causeway over a land ridge and then allowed to flow into the western desert, creating a new lake of about 500 square miles with an average depth of 2 5 feet Evaporation would reduce the water volume, and the concentrated brine would then be recycled back into Great Salt Lake

Many periods of marked lake level rise followed major volcanic eruptions The rise of 1884–86 occurred after the eruption of Krakatau, Indonesia, during August 1883 The steep rise of 1907–10 followed the eruption of Ksudach, Kamchatka, during March 1907 The rise of 1964–76 followed the eruption of Gunung Agung, Bali, during March 1963, and the record rise of 1982–86 was preceded in March and April 1982 by a major volcanic eruption at El Chichón in Mexico The decrease in solar radiation caused by volcanic eruptions could have resulted in decreased evaporation or increased precipitation, or both, which in turn would have contributed to a rise of lake level These hypotheses are corroborated by pan-evaporation data for the Saltair Salt Plant, which indicates that evaporation during 1982–85 was only 72 to 84 percent of the long-term (1931–70) average for June-September Also, the mean annual precipitation for 1982–85 was 21 41 inches, or 39 percent greater than for 1875–1981 Other rises of the level of Great Salt Lake cannot be correlated with known major volcanic eruptions

Total inflow to the lake during 1931–76 consisted of streamflow (66 percent), precipitation (31 percent), and ground water (3 percent) Average annual inflow was about 2 9 million acre-feet About 92 percent of the total surface inflow to the lake was from the Bear, Weber, and Jordan Rivers The only outflow from the lake is through evaporation, which averaged 2 9 million acre-feet annually

The completion of a solid-fill railroad causeway in 1959 separated the lake into two parts Although the causeway is permeable, it restricts the movement of brine such that the northern part of the lake has become quite saline The lake brine is primarily sodium chloride but also contains small quantities of trace elements The salinity of the brine varies inversely with lake level and has ranged from about 6 percent in the southern end of the lake in 1986 to 28 percent in the northern end in 1963

Changes in the salinity of the lake have resulted in many changes in the biota of the lake When the salinity of the lake is about 15 to 25 percent, halophilic green brine-algae, brine shrimp, and brine flies are the principal inhabitants in the lake As the salinity of the lake decreases to about 6 percent, more opportunistic forms, such as blue-green algae and diatoms, begin to appear and the population of brine shrimp decreases In 1979, when the salinity of the southern part of the lake was about 14 percent, 29 species of algae were present During earlier times, when the lake was more saline, the algal community consisted of about three species The great reduction in salinity from 1982 to 1986 resulted in the appearance of a population of rainwater killifish near Stansbury Island

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METRIC CONVERSION FACTORS

For readers who wish to convert measurements from the inch-pound system of units to the metric system of units, conversion factors are listed below

Multiply inch-pound units	By	To obtain metric units
acre	4,047	square meter
acre-foot	1,233	cubic meter
cubic foot per second	0 02832	cubic meter per second
cubic mile	4 1655	cubic kilometer
foot	0 3048	meter
gallon per second	3 785	liter per second
inch	25 40	millimeter
mile	1 609	kilometer
square mile	2 590	square kilometer
ton	0 9078	metric ton

ALTITUDE DATUM

Sea level In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929