EFFECTS OF BREACHING THE SOUTHERN PACIFIC RAILROAD CAUSEWAY, GREAT SALT LAKE, UTAH—PHYSICAL AND CHEMICAL CHANGES AUGUST 1, 1984—JULY, 1986

By J. Wallace Gwynn, Ph.D. and Paul A. Sturm

UTAH GEOLOGICAL AND MINERAL SURVEY

a division of

UTAH DEPARTMENT OF NATURAL RESOURCES

WATER RESOURCES BULLETIN 25 **1987**

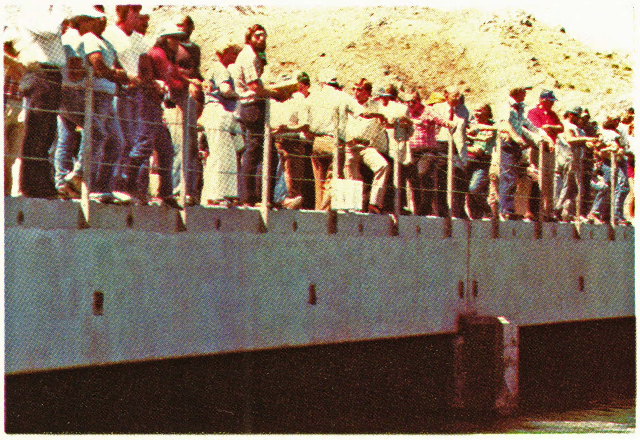
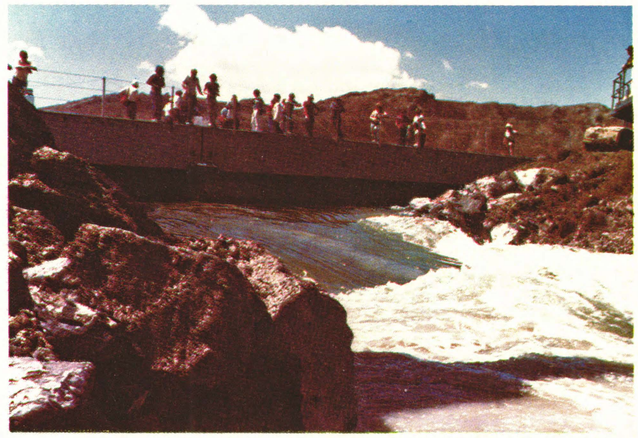


Photo by J.W. Gwynn



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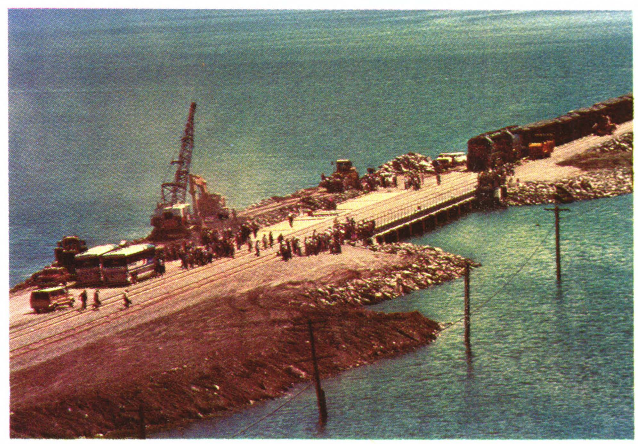

Photo by P.A. Sturm

Upper Left - Closeup view of concrete breach structure.

Lower Left - Plume of muddy water in north arm created from south-to-north rush of water flowing through initial breach opening.

Upper Right - Water flowing from south to north through the initial breach opening.

Lower Right - Completed breach structure near Lakeside, Utah just prior to breaching ceremonies, August 1, 1984.

UTAH GEOLOGICAL AND MINERAL SURVEY

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THE UTAH GEOLOGICAL AND MINERAL SURVEY is one of eight divisions in the Utah Department of Natural Resources. The UGMS inventories the geologic resources of Utah (including metallic, nonmetallic, energy, and ground-water sources); identifies the state's geologic and topographic hazards (including seismic, landslide, mudflow, lake level fluctuations, rockfalls, adverse soil conditions, high ground water); maps geology and studies the rock formations and their structural habitat; and provides information to decisionmakers at local, state, and federal levels.

THE UGMS is organized into five programs. Administration provides support to the programs. The Economic Geology Program undertakes studies to map mining districts, to monitor the brines of the Great Salt Lake, to identify coal, geothermal, uranium, petroleum and industrial minerals resources, and to develop computerized resource data bases. The Applied Geology Program responds to requests from local and state governmental entities for site investigations of critical facilities, documents, responds to and seeks to understand geologic hazards, and compiles geologic hazards information. The Geologic Mapping Program maps the bedrock and surficial geology of the state at a regional scale by county and at a more detailed scale by quadrangle.

THE INFORMATION PROGRAM distributes publications, answers inquiries from the public, and manages the UGMS Library. The UGMS Library is open to the public and contains many reference works on Utah geology and many unpublished documents about Utah geology by UGMS staff and others. The UGMS has begun several computer data bases with information on mineral and energy resources, geologic hazards, and bibliographic references. Most files are not available by direct access but can be obtained through the library.

THE UGMS PUBLISHES the results of its investigations in the form of maps, reports, and compilations of data that are accessible to the public. For future information on UGMS publications, contact the UGMS sales office, 606 Black Hawk Way, Salt Lake City, Utah 84108-1280.

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TABLE OF CONTENTS

ILLUSTRATIONS

EFFECTS OF BREACHING THE SOUTHERN PACIFIC RAILROAD CAUSEWAY, GREAT SALT LAKE, UTAH—PHYSICAL AND CHEMICAL CHANGES AUGUST 1, 1984—JULY, 1986

By J. Wallace Gwynn[1], Ph.D. and Paul A. Sturm[2]

ABSTRACT

The Southern Pacific Railroad causeway was breached on August 1, 1984 as a state-financed lake-level control measure. To determine the effect of the breach on the lake, two monitoring programs were initiated. The U.S. Geological Survey (USGS) monitored the bidirectional flow through the breach opening and the Utah Geological and Mineral Survey (UGMS) monitored the density and brine chemistry of the two arms of the lake. The work done by the USGS was a cooperative effort with the UGMS. This report presents a summary of the pre-and post-breach physical and chemical conditions of the lake based on the data obtained through the two monitoring programs. It also discusses the effects that the breach has had on the lake's mineral-extraction industries and on the railroads. From the data presented within this report, the following conclusions can be reached.

1. Density measurements have shown that the upper north arm (Gunnison Bay) brines have become significantly diluted since the breach, and that the deep south arm (Gilbert Bay) brines have increased in both density and volume. The upper south arm (Gilbert Bay) brine density and that of the deep north arm have remained relatively constant while their volumes have decreased.

2. There is a general linear relationship between the rate of increase in Na, K, Mg, Cl and SO_4 with that of TDS within the lake brines with the exception of the deep, high-density, north arm (Gunnison Bay) brines. In these, the rate of increase of chloride decreases while that of sulfate increases. The same relationships are seen in the dry weight percent data. The increase in sulfate and the corresponding decrease in chloride are related to an enrichment of the deep north arm (Gunnison Bay) brine due to the dissolution of winter-precipitated mirabilite.

3. While the initial changes in lake level brought about by the breach had both positive or negative effects on the extractive industries and on the railroads, the continued rise in the level of the entire lake has, and will continue to have, a severe and costly impact on everyone.

4. The salinity changes within the lake that have been brought about by the breach have not increased the salinity of the feed stock for the south arm (Gilbert Bay) lake extractive industries, and have greatly decreased the salinity of the feed stock of the single north arm (Gunnison Bay) industry. Although there has been a major shift in the dissolved salt load from the north arm to the south arm of the lake, this may not be of value to south arm (Gilbert Bay) industries until after the level of the lake begins to drop. All industries have been severely impacted by the continued dilution associated with the rising lake level.

5. All lake industries could obtain higher salinity brines than they presently access by moving their pump intake lines farther out into deeper areas of the lake although, in the north arm, the quantity of high-salinity brine is limited. This action, however, is very costly. In the south arm of the lake the effect that the fetid, discolored, deep brine would have on salt operations is not known.

INTRODUCTION

The Great Salt Lake, a terminal, complex body of highly saline water, is located in the northwestern quarter of the State of Utah, and within the Basin and Range physiographic province. It is the largest of the modern-day remnants of the fresh-water, Pleistocene Lake Bonneville, which coverd about 54,000 square miles of western Utah to a maximum depth of about 1000 feet, some 10-15 thousand years ago.

Since the settlement of the valley of the Great Salt Lake by the Mormon pioneers in 1847, the lake and its environs have been used for many purposes (see figure 1). Almost from the beginning, the lake has been used as a source of minerals and other saline-related products. Its beaches and waters have been used for recreational purposes. Around its shorelines,

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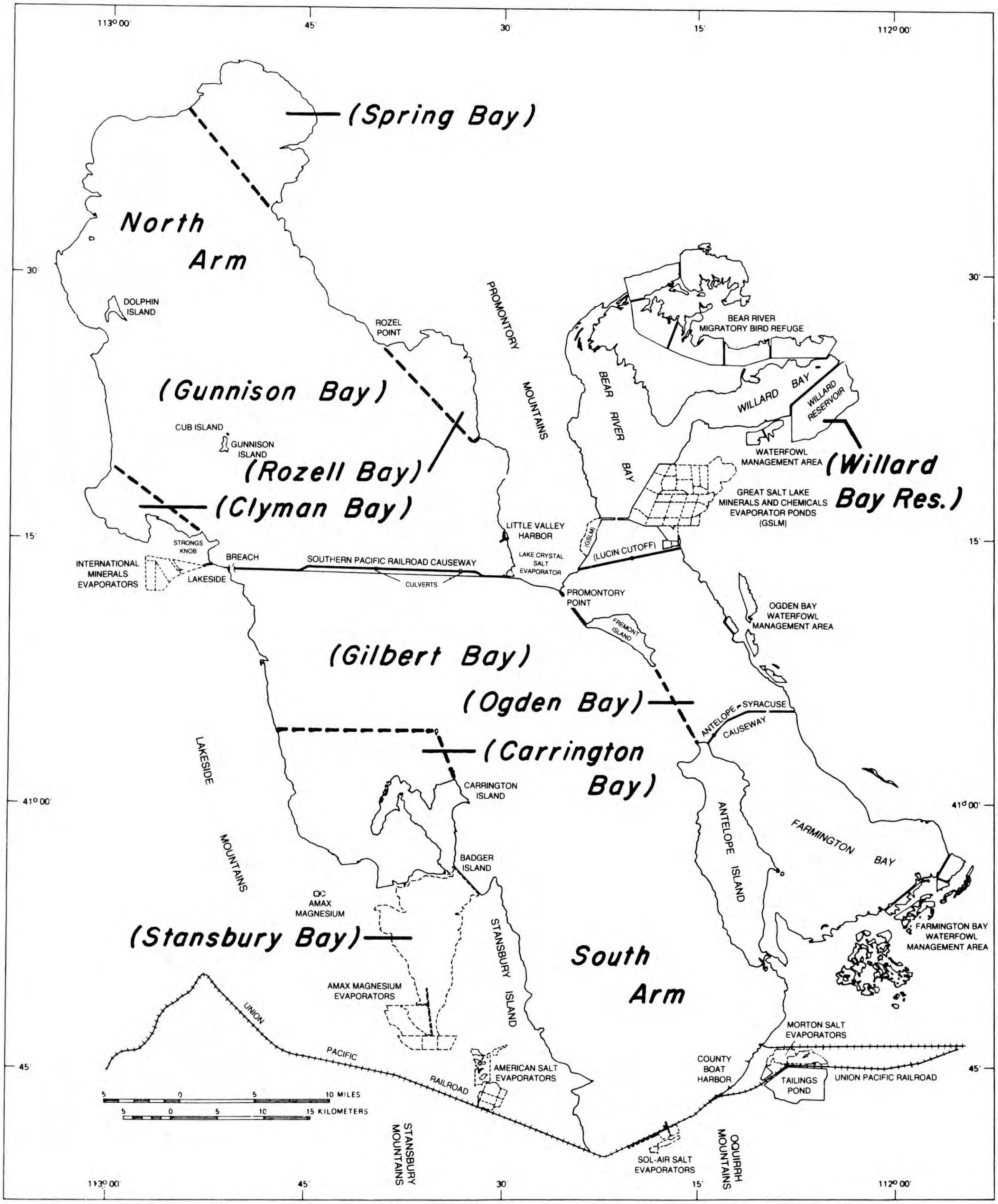

Figure 1. Index map of Great Salt Lake and vicinity using conventional and proposed place names.

waterfowl-management areas have been constructed. Adjacent to the lake, homes, farms, businesses and vital transportation facilities have also been built; the Southern Pacific Railroad was built through the lake.

During these past 140 years, however, man has had to contend with the up and down trends of the surface elevation of the lake. These have fluctuated over a vertical distance of about 20 feet from highs of almost 4212 feet above sea level in 1873 and 1986 to a low of 4191.3 feet in 1963. And with the vertical fluctuations of the lake have come changes in its surface area. Because of the very gradual slope of the lake's shoreline, large areas become covered with water for each foot of rise in its elevation. Because of these continual fluctuations and man's inability to predict them, facilities built during one lake stage were found either high-and-dry or flooded within a few years. In the early 1870s, the pioneer settlers became concerned with the rising waters of the Great Salt Lake as it approached an elevation of 4212 feet, a record which would stand for more than 100 years. From that time the lake began a general downward trend that lasted for 90 years. At that time the lake reached its historic low of 4191.3 feet in 1963.

Not content to stand still, the lake immediately began a steady 13-year rise. In 1976, the Great Salt Lake reached an elevation of 4202.2 feet above sea level, an elevation that had not been seen for nearly 50 years. Concern was expressed by lake industries and other developers around its shores that the 13-year upward lake-level trend would continue, and that extensive damage would result if something were not done. Fears were alleviated the next year, however, as the lake peaked some 1-½ feet lower than the previous year, and continued to drop slowly during the next 2 years. During water years (October of one calendar year through September of the next year) 1980 through 1982, the lake again began to rise, but peaked at less than 4201 feet during 1982.

Water years 1983 and 1984 were a surprise to everyone as the lake rose in response to heavy precipitation an unprecedented 5-plus feet during the first year and nearly that much again during the second year, bringing it to its highest elevation in nearly a hundred years. Between these two years, the annual drop in lake level was the smallest on record for the south arm, and in the north arm the lake level rose continuously throughout the 2-year period without its customary annual drop. During this 2-year period, damages to lake industries, state and federal recreation and waterfowl management areas, and highways and railroads (see figure 1) ran into the hundreds of millions of dollars (Bureau of Economic and Business Research 1983, 1984).

Recognizing the serious flooding that had been caused by the Great Salt Lake, and fearing that it would rise higher the following year, the state reviewed its options for lake-level control, which included upstream development, breaching the causeway, and pumping to the western desert. Upstream development would consist of constructing reservoirs on the tributaries to the lake, principally on the Bear River. Breaching the causeway would consist of constructing a 300-foot opening in the Southern Pacific Railroad causeway which separated the lake, in an east-west direction, into two portions and across which a water-surface elevation difference had developed. This opening would allow the elevation difference to decrease. West Desert pumping would consist of pumping lake water into the desert west of the lake to increase the area available for evaporation and storage and thereby lower the lake level. During the January, 1984 session of the legislature, HB 30 was passed which provided some 3.5 million dollars to breach the Southern Pacific Railroad causeway. The breaching action was expected to lower the water level south of the causeway somewhat less than a foot where the extensive flooding was being felt the most, while raising the level of the lake north of the causeway somewhat more than a foot where the effects of additional flooding would not be as great. It was hoped by some that this action would also increase the density of the upper lake level brines south of the causeway.

Plans for the construction of the breach began immediately, and by the end of July, 1984, the construction of the breach, a 300-foot opening in the railroad causeway, had been completed (see frontispiece). On August 1, at the breach site near Lakeside, the opening ceremony included speeches by Utah's Governor Matheson and railroad officials, the removal of the last few feet of causeway fill, cheers as the south arm (Gilbert Bay) waters flooded into the north arm (Gunnison Bay), and a fine meal for those present which was hosted by the railroad.

This report will address the following: a) a review of the 1984-86 breach-monitoring programs, b) a review of the pre-breach history of the lake, c) a study of the physical and chemical changes that have occurred in the lake since the breach, and d) a brief analysis of the effects of the breach on the lake's mineral-extraction industries and on the railroads.

The breach-monitoring program has been a multi-agency effort. The breach-flow measurements were made by the U.S. Geological Survey through a cooperative agreement with UGMS; brine analyses were made for the UGMS by the AMAX Magnesium Corporation through a Memorandum of Understanding; and boat transportation was provided to UGMS by the Division of Parks and Recreation through a cooperative agreement. UGMS funding was provided partially through a cooperative agreement with the Division of State Lands and Forestry.

New or revised names for various portions of the Great Salt Lake are currently being proposed for adoption by the Utah Committee for Geographic Names. As this report is being published during this transition period, both the long-standing or conventional names and the new or revised names will be used; the new names will frequently follow the conventional names and will be in parenthesis. On figure 1, the new or revised names are placed in parentheses. The name Gunnison Bay refers collectively to all of the areas north of the railroad causeway and west of Promontory Point. The name Gilbert Bay, on the other hand, does not refer to all of the areas south of the causeway. Each of the five areas must be referred to as a separate entity. Within this paper, however, the terms south arm and Gilbert Bay will refer to all five segments collectively unless specifically stated otherwise.

BREACH-MONITORING PROGRAMS

Two programs were established to monitor the effects of breaching the causeway: one by the U.S. Geological Survey and one by the Utah Geological and Mineral Survey (UGMS).

The USGS program was established to monitor the surficial south-to-north and, later when they occurred, the deep north-to-south flows of brine through the newly created breach opening. This flow-measurement work is an extension of another cooperative program between the UGMS and the USGS in which the USGS has been monitoring the bidirectional flow through the two 15-foot-wide culverts on a regular basis since 1968. The UGMS program was established to monitor the density and chemical changes that would occur within the brines of the north and south arms of the lake as a result of the breach. This report is based principally on data derived from these two monitoring programs. The density and chemical data are available for inspection at the UGMS, and the flow data are available through the USGS, Water Resources Division.

PRE-BREACH HISTORY

Knowledge of and involvement with the Great Salt Lake date back many years as the lake has been utilized for 140 years for the purposes of recreation, transportation, and as a source of minerals. The greatest man-made impact on the lake began in about 1900 with the construction of Southern Pacific Railroad's combined solid-fill and trestle-supported railroad. It was built from the east shore westward across Bear River Bay to Promontory Point and from Promontory Point to Lakeside (see figure 1). After 50 years of use, the trestle portion of crossing became in need of substantial maintenance, and rebuilding (Newby, 1980). After reviewing several options, the railroad decided to construct a solid fill causeway 1500 feet north of, and parallel to, the trestle for a distance of some 12 miles. Engineering studies were started in 1955 and the new section of earth/rock-fill causeway was completd in 1959.

With the completion of the solid-fill structure from Promontory Point west to Lakeside, the main body of the lake was now separated into two parts, isolated from each other except for two 15-foot-wide by 20-foot-deep culverts. That portion of the lake north of the Promontory Point-Lakeside section of the causeway is herein referred to as the north arm (Gunnison Bay) and to the south as the south arm (Gilbert Bay). The more dilute Bear River Bay portion of the lake is not considered as part of the north arm although it is located north of the railroad causeway but east of Promontory Point. The causeway has restricted the natural brine circulation patterns within the lake and has become a semi-impervious barrier across which a head differential between the north and south arms has developed. It has been responsible for the development of a substantial salinity difference between the two arms of the lake. It may also have been responsible for the development and/or continued existence of a two-layer or density-stratified brine condition in the south arm. Such a condition has not been found to exist in the north arm from at least 1966 until about 1982. Since 1982, a density-stratified condition has been developing in the north arm, even before the causeway was breached in August of 1984. This has been due to the abnormally high influx of water into the lake and the total dissolution of salt from the floor of the north arm, which was deposited during earlier low-lake level years.

HEAD DIFFERENTIAL

The head differential across the causeway, or the difference in surface elevation between the south and north arms of the lake (Gilbert and Gunnison Bays), began to develop upon the completion of Southern Pacific's earthen/rock-fill structure across the lake in 1959. The development of the differential has occurred in spite of the causeway's seepage and flow through the two 15-foot-wide by approximately 20-foot-deep box culverts within the structure. A study of the movement of water through the causeway was made by Madison (1970). These culverts have estimated invert (bottom of opening) elevations of 4176.5 and 4178 feet for the east and west openings, respectively. These elevations have changed as the culverts have settled since the early 1970s (Waddell, 1986, personal communication).

From figure 2, which shows the Great Salt Lake hydrograph (1966-1987) and the high water (spring) and low water (fall) head differentials between the two arms, it can be seen that the trend of the differentials follows the general trend of lake elevation. The main reason for the increased separation of the high- and low-water head differential lines after 1973 is not known, but may be due in part to a decrease in the causeway's permeability brought about by the continual compaction of the causeway fill and the introduction of fines in the protective and repair materials that were being placed on top of, and down the sides of, the causeway structure. Another reason for the increasing head differential was the increasing difference in density between the two arms of the lake. The sudden drop of the differential lines in 1984 reflects the effect of the August 1, 1984 breaching of the causeway.

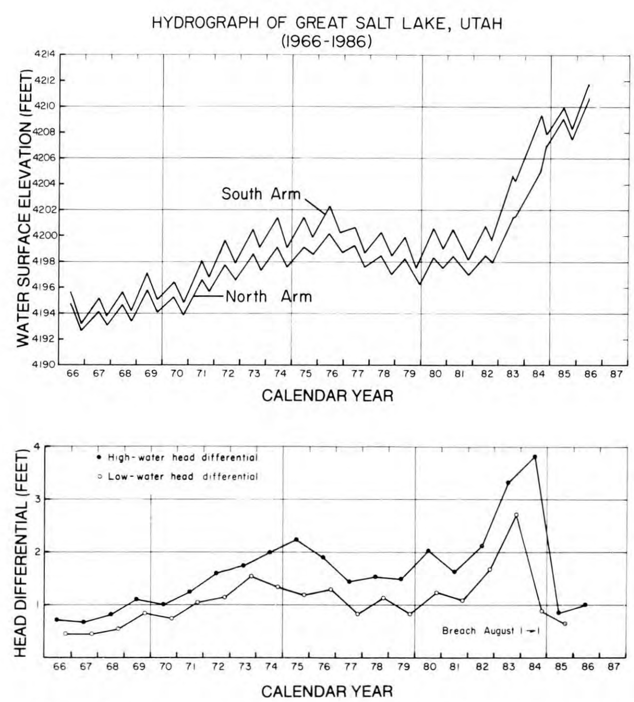

Figure 2. Head differential and lake elevation vs calendar year (1966 - 1986).

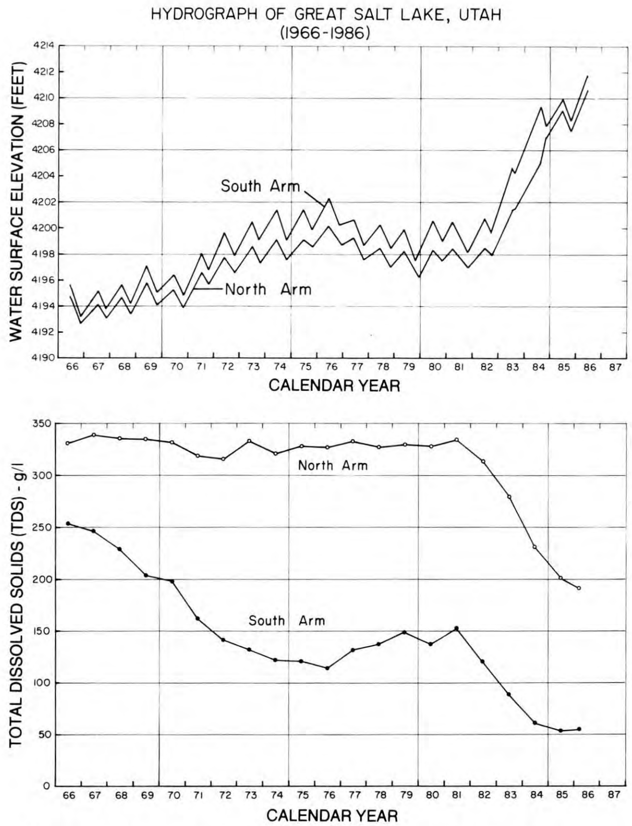

Figure 3. Fluctuation of Total Dissolved Solids (TDS) and lake elevation, 1966 - 1986.

SALINITY DIFFERENCE

Prior to the construction of the earthen/rock-fill causeway, the brine throughout the entire Great Salt Lake was better able to circulate and mix, being driven by the forces of the wind and of tributary inflow waters. Although there were probably local variations in salinity, created in response to differences in depth, restricted circulation, and in precipitation and/or evaporation-rate patterns, the lake is thought to have been relatively homogeneous.

With the construction of the solid-fill portion of the causeway in 1959 conditions changed greatly, and the two arms of the lake became different with respect to salinity. The north arm (Gunnison Bay) (which does not include Bear River Bay) became more saline than the south arm (Gilbert Bay). The principal factor for this change was that nearly all of the fresh-water tributary inflow entered the south arm of the lake and that no major tributaries flowed into the north arm, or north of the Promontory-Lakeside portion of the causeway. The proportion of ground water that enters the two portions of the lake is not known, although the south arm probably receives the greater amount. The major source of inflow to the north arm, on the other hand, was salty water that was transferred northward from the south arm through the causeway fill and the two box culverts. Another factor that contributed to the relative increase in the salinity of the north arm was the distribution of precipitation over the lake; that portion of the lake north of the causeway receiving the least amount of precipitation (Waddell and Fields, 1977).

Both of these influences played a part in making the south arm and north arm (Gilbert and Gunnison Bays) salinities become different. This is shown in figure 3 by the general increasing vertical separation of the two salinity-time profiles. A comparison of the dilution of the south arm with and without the influence of the causeway was computed and is given in figure 2 of Waddell and Bolke (1973). The south arm (Gilbert Bay) salinity/time profile shows that the salinity of that portion of the lake responded inversely, with great sensitivity, to changes in volume or lake elevation. The north arm (Gunnison Bay), on the other hand, shows a much smaller and less predictable response in salinity change for changes in volume. In fact, there is little observable correlation between salinity and north arm (Gunnison Bay) level until about 1982. Several processes acted to stabilize the north arm from 1966 until 1982: 1) A salt crust, which had existed almost continuously on the floor of the north arm since the early 1930s, provided a buffer or reserve of salt which kept the north arm near saturation until about 1983. At that time the reserve was depleted and dilution of the north arm began to take place. 2) A greater amount of dissolved salt was transferred from south to north through the causeway and its culverts than was transferred from north to south through deep return flow. In some cases, especially when the lake level was very low, salt was precipitated on the bottom of the north arm as solid halite. 3) Brine from the south arm fed the north arm whether the lake volume was increasing or decreasing, while fresh water from rivers fed the south arm.

SOUTH ARM (GILBERT BAY) TWO-LAYER SYSTEM

Within the south arm of the lake (Gilbert Bay) there exist two layers of brine which are separated by a narrow transition zone or interface; this condition did not exist within the north arm of the lake, however, prior to about 1983. Since 1966 it has been observed that the upper layer in the south arm consists of a relatively clear and odor-free brine which occupies the upper 70 to 75 percent of the total depth. Below this, the brine within the bottom 25 to 30 percent has been of greater density (though of lower density than the north arm brine), discolored, and laden with noxious hydrogen sulfide gas. The transition zone between the two brine types occurred within a vertical distance of 1 to 3 feet. The density within this zone changes abruptly, increasing rapidly from the upper brines' density downward in elevation to the density of the lower brine. Examples of typical low-water level, 1982 density profiles are shown in figure 4 for both the south and north arms.

There are little data to substantiate whether or not the entire lake was stratified prior to the construction of the earthen/rock-fill causeway which was completed in 1959, but the presence of stratification in the south arm has been known and well documented since 1966. Since that time, the south arm of the lake (Gilbert Bay) has been stratified continuously. The volume and salinity of the deep, dense, south arm (Gilbert Bay) bottom brine are fed and maintained by the north-to-south return flow that moves through the causeway fill and the two box culverts. The density-stratified brines of the Great Salt Lake do not overturn annually as do some thermally-stratified bodies of water.

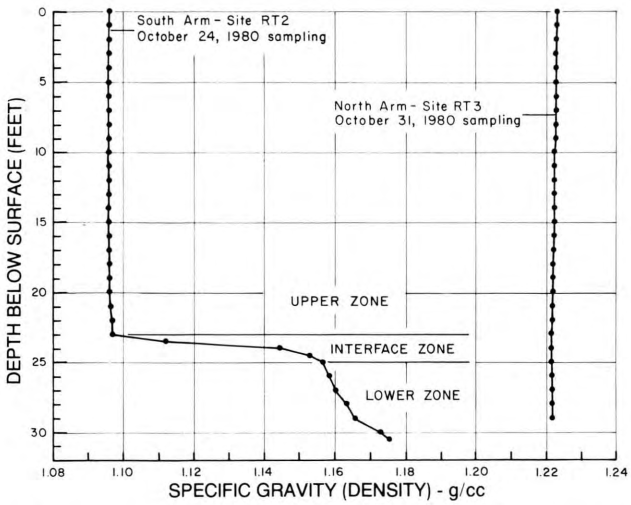

Figure 4. Profiles of specific gravity in the north and south arms, October, 1980.

POST-BREACH PHYSICAL AND CHEMICAL CHANGES

USGS FLOW-MEASUREMENT PROGRAM

The USGS breach-flow measurement program has consisted of: a) installing water-level guages, b) running levels for elevation control, c) conducting flow measurements that include determining the physical bottom profile within the breach opening and the head differential between the two arms, and d) collecting a number of brine samples from within the breach opening for analysis that are representative of the two bidirectional flow brines. Non-standard streamflow measurement techniques have been developed and used and bidirectional flows have been measured when they existed.

FLOW MEASUREMENTS/ HEAD DIFFERENCE

From August 1, 1984 through July 29, 1986, some 29 sets of breach-flow measurements were made by the USGS; 12 in 1984, ten in 1985, and seven (through July) in 1986. For each set of measurements, surficial south-to-north flows and, when they existed, deep north-to-south return flows were determined along with the head differential between the two arms of the lake. A suite of representative brine samples were also taken at a number of points in depth for chemical analysis, representing both components of the bidirectional flow within the breach opening.

The bidirectional flow that occurs through the two culverts, the causeway fill, and the breach opening under the proper conditions is illustrated in figure 5. Bidirectional flow consists of surficial flow from south-to-north while, at the same time, dense north arm brine is flowing in the opposite north-to-south direction. The south-to-north surficial flow is driven by the head differential between the two arms of the lake, the south arm (Gilbert Bay) being at a higher elevation than the north (Gunnison Bay). The north-to-south deep return flow is driven by the differences in density of the two arms of the lake. When the downward hydrostatic pressure of the heavy north arm (Gunnison Bay) brine exceeds that of the greater column of lighter south arm (Gilbert Bay) brine, the north arm brine (Gunnison Bay) flows to the south and into the deep south arm (Gilbert Bay) brine.

While the south-to-north discharge of brine through the breach opening is a function of the head differential, brine densities, brine depth and opening area, there is a direct but non-linear correlation between just the head differential between the two arms of the lake and the discharge rate of the brine as it flows through the breach opening. This relationship for the south-to-north flow can be seen in figure 6. A strong influencing factor on this discharge rate, however, is the wind. Strong, prolonged periods of wind create wind tides, which "pile" the water up on either the north or south shores of the two arms of the lake. South winds which pile the water to the north tend to enhance the head differential between the two

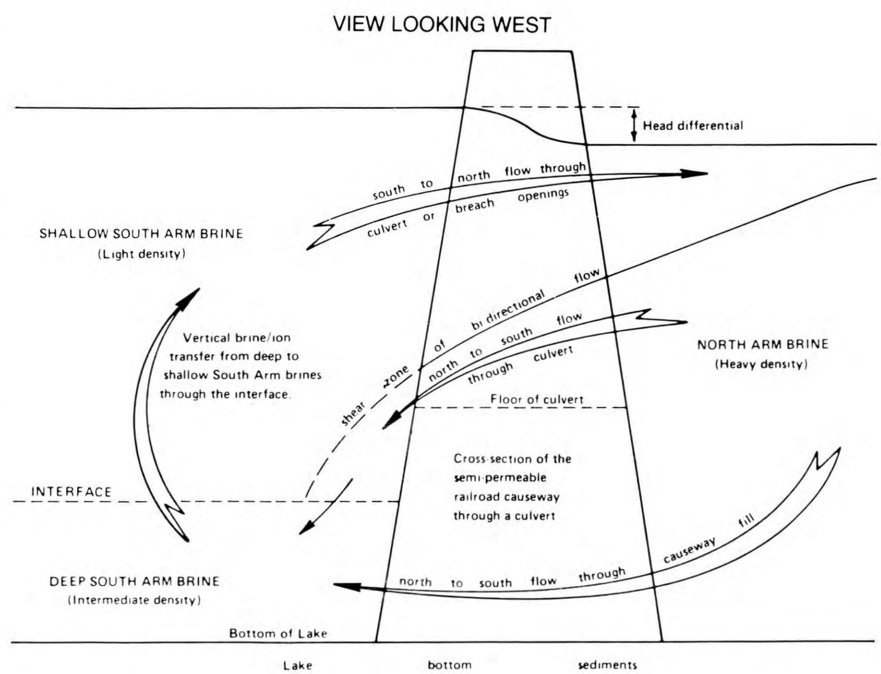

Figure 5. Schematic of bidrectional brine movement through the causeway within the Great Salt Lake, Utah.

arms, which increases the south-to-north discharge rate. North winds "pile" the water to the south and, conversely, tend to diminish the head differential and thus reduce the south-to-north flow rate. A small change in the head differential can result in a significant increase or decrease in the discharge rate. A sufficiently strong north wind can even cause a reversal in the surficial flow direction through the breach opening. (Note: Since the breach site is in a relatively sheltered area of the lake, the winds noted in the USGS field notes do not necessarily represent the conditions over the lake as a whole.) To help in determining the presence of winds and especially of wind tides, the USGS lake-level recorder strip charts from the Boat Harbor station on the south arm and the Saline station on the north arm were also analyzed. From these records, not only can the presence of wind tides be detected, but also their amplitude at a given time and sometimes the direction of the wind.

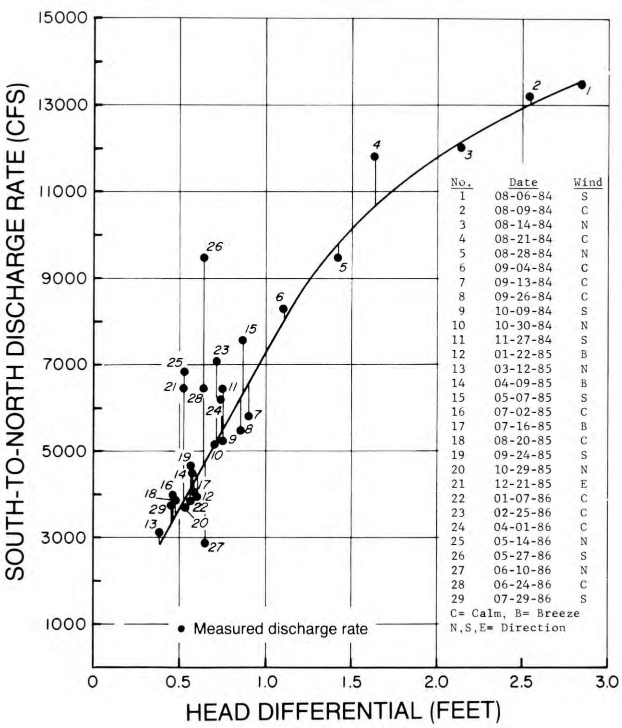

Figure 6. South-to-north discharge rate vs north/south head differential, measured discharge rates.

An attempt was made to produce figure 6 by drawing the head differential/north-to-south discharge rate line through data points derived on calm days only. While this procedure would be more representative of ideal conditons, the results were less definitive than the method used and presented herein.

Data in figure 6 are used in developing figure 7, a plot of discharge rate over time. To minimize the effect of winds, the measured south-to-north discharge rates in figure 6 are adjusted either upwards or downwards to the visually best-fit line. The line-intercept points that were located, for individual sampling dates, are then used to plot the discharge rates over time as seen in figure 7.

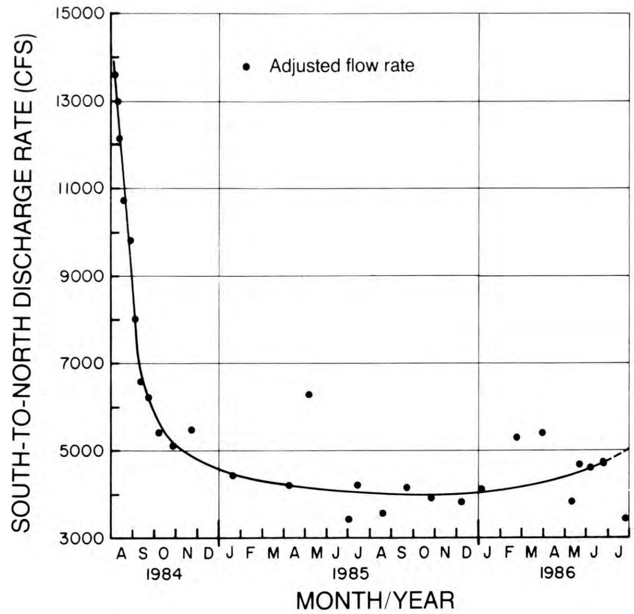

Figure 7. South-to-north discharge rate vs month/year, adjusted flow rates.

Figure 7 shows the enormous south-to-north discharge rates that existed immediately after the breach was opened, and the much subdued rates that existed as the water elevations of the two arms converged and finally reached a new and relatively stable state of head-differential equilibrium. The smaller south-to-north discharge rates seen during 1985 correspond to a more normal rise in lake level and thus lower head differentials that existed during these times, as compared to the increased discharge and lake-level rise rates seen during the first half of 1986 which was a higher inflow year than 1985.

Figure 8 shows a plot of head differential/north-to-south return-flow rate through the breach. These data suggest that north-to-south return flow through the breach is possible at or below a head differential of 0.8 to 1.0 feet, but not above. The wide deviation of the two points above the 1500 cfs line is very likely induced by north-wind tides. Figure 9, a plot of time/north-to-south return flow through the breach, shows that a deep return flow of brine through the breach opening was measured from January 22 onward only, but that dense, north arm (Gunnison Bay) brine was observed in the bottom of the breach as early as September 13, although flow rates were not measured. The abnormally high value recorded during June of 1986 was storm induced.

UGMS BRINE-MONITORING PROGRAM - DENSITY AND CHEMICAL CHANGES

The Utah Geological and Mineral Survey (UGMS) brine-monitoring program has consisted of collecting close, vertically spaced brine samples from fourteen locations; six in the south arm of the lake (Gilbert Bay) and eight in the north arm (Gunnison Bay). UGMS samplings, especially right after the breach was completed, were scheduled to coincide with the USGS flow measurements. Of the nearly 300 brine samples

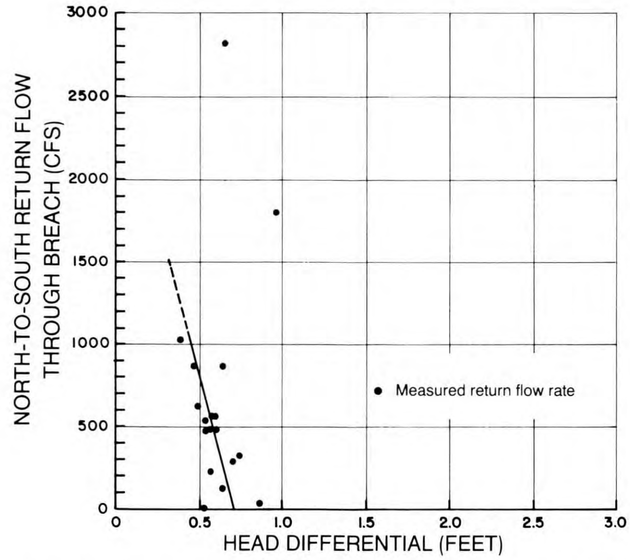

Figure 8. North-to-south return flow vs north/south head differential, measured flow rates.

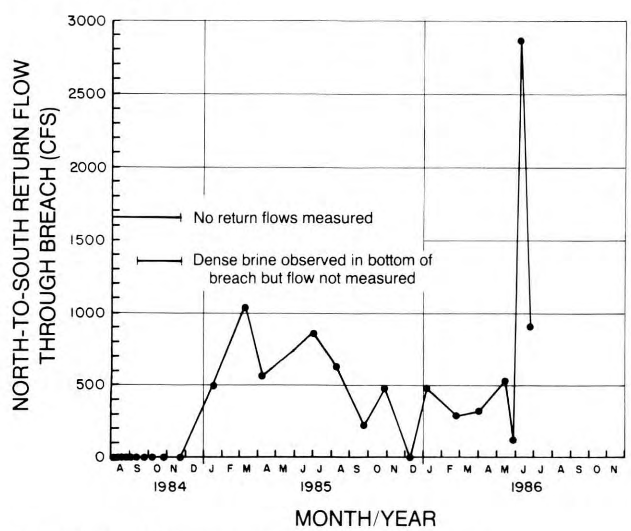

Figure 9. North-to-south return flow vs month/year.

that were collected during each of these sampling trips, all were analyzed for density, and a group representative of major breaks in the density profiles were analyzed chemically for Na, K, Mg, Cl, and SO_4 by the AMAX Magnesium Corporation under a cooperative agreement with the UGMS. Splits of these latter brines were archived should future analyses be required.

As part of the UGMS monitoring program, a 50-foot steel tower, designated as RT4, was constructed and positioned within the West Bay portion of the south arm (Gilbert Bay) and large, orange buoys were set to mark near-breach sites within the two arms. The main purpose of tower RT4 and of two other pre-existing towers, RT2 and RT3, was to provide stable platforms from which to collect accurately positioned, depth-incremental samples. The towers also marked a consistent position from where the samples could be taken. RT2 and RT3 are located in the south and north arms (Gilbert and Gunnison Bay), respectively, and had previously been installed for gathering hydrological and meteorological information in the lake by the AMOCO Corporation as part of its oil-exploration and drilling program. The buoys that were set by the UGMS marked the position of the remaining 11 sampling sites, and also doubled as anchors for the boat while the sampling was being done. The locations of the three towers and 11 buoys are shown on figures 10 and 10a. Unfortunately, during the winter of 83-84, tower RT2 was tipped over by ice. During the winter of 84-85, tower RT4 was tipped over by ice and many of the buoys were torn from their moorings. Additional buoys have also been lost due to the abnormal amount of wear resulting from the often violent nature of the storms on the lake. These losses have had a negative impact on the monitoring program and the data that have been generated.

From July 1984 through July 1986, the UGMS made 30 sampling trips to the 14 breach-monitoring sites which are shown on figures 10 and 10a. The data gathered have been entered into the UGMS computer for storage, for making calculations, and for the production of graphic representations. A number of interim breach-monitoring reports (see listing in references) have been produced and distributed to interested parties. The data contained within these reports are also incorporated within this report.

DENSITY CHANGES

Density data, derived from the analyses of the brines that have been collected at the 14 sampling sites, are plotted against the depth from which they were collected, creating density profiles. Density values were determined at a temperature of

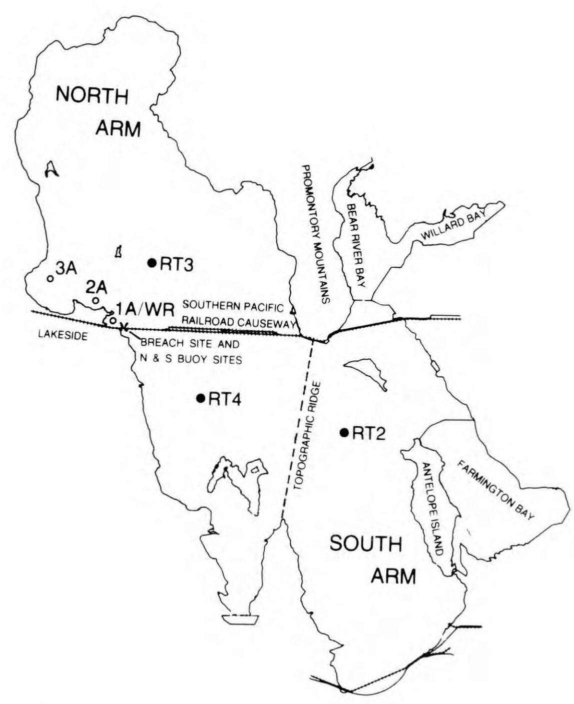

Figure 10. General tower and buoy breach sampling site location map.

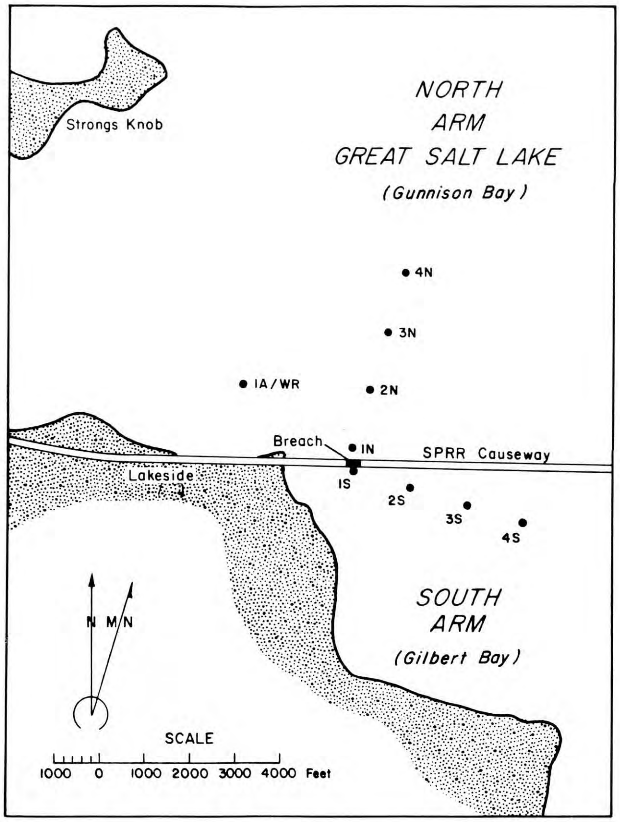

Figure 10a. North and south arm buoy-specific sampling site location map.

about 20 to 22°C and were not corrected to 15°C. If profiles representing consecutive sampling dates are all plotted on the same set of axes, the resulting composite graph can be used to observe net changes in density over time. Such composite graphs have been constructed for the three tower and 11 buoy sites.

South Arm (Gilbert Bay) Tower Sites

The composite density profiles constructed for the two south arm (Gilbert Bay) tower sites are shown as follows: RT2 - figure 11 and RT4 - figure 12.

Although the RT2 and RT4 composite profiles both represent the south arm of the lake (Gilbert Bay), it can be seen that they differ significantly from one another, especially below an elevation of 4174 feet. A note of explanation is in order concerning this difference. The West Bay area in which tower RT4 is located, and the remaining portion of the south arm in which RT2 is located, are separated by a low-lying topographic ridge that runs generally south-southwest between Promontory Point and Bird/Hat Island (see figure 10). Deep, north-to-south return brine flowing from the north arm through the causeway and into the south arm empties first into the West Bay area creating a "pool" of high-density brine. This brine moves over the topographic barrier into the south arm proper and, as it does, it mixes with the less concentrated brine above it and is diluted. Thus, brines of much higher density are found in the West Bay area represented by the RT4 site than in the rest of the south arm represented by RT2. It is estimated from figure 12 and from bathymetric evidence (Katzenberger, 1975) that the effective elevation of the topographic ridge lies at about 4173-4174 feet.

Figure 11 illustrates three basic changes that have occurred within the major portion of the south arm (Gilbert Bay), represented by data collected at RT2, since just before the breaching of the causeway on August 1, 1984 until the present time (July 1986). The inset in figure 11 shows two individual density profiles for July 29, 1984 and September 10, 1986 and illustrates the net changes that have occurred. The first change is the overall dilution of the upper-brine zone (refer to figure 4) due to the inflow of water to the lake and thus an increase in surface elevation and volume. This change is represented by the decrease in brine density from letter A (1.043 g/cc) on 7-29-84 to B (1.034 g/cc) on 7-30-86.

The second change incorporates the loss of the sharp, traditional, well-defined interface depicted in figure 4. This has involved the blending of the interface with the lower zone into a single zone which increases in density with depth. With time, there has been a thickening of this combined zone from letter C (4178 feet) on 7-29-84 up to D (4186 feet) on 7-30-86. The volume of the greater density brine zone in the south arm is estimated from elevation/volume data to have increased by about 260 percent, from 1,355,350 acre feet to 3,566,230 acre feet, during the 22-month period following the breach. The source of this large influx of high-density brine is thought to be the north-to-south return flow from the north arm (Gunnison Bay).

The third change that has taken place is the brief appearance of even higher than normal density brine seen within the bottom foot or so of the main portion of the south arm of the lake (Gilbert Bay) at RT2. This is not illustrated on the figure 11 inset. During the period from September 1985 to February 1986, densities of from 1.14 g/cc to more than 1.16 g/cc were found within this lake-bottom brine where the normal density has ranged from 1.13 g/cc to 1.14 g/cc, as represented by E on figure 11. The appearance of the higher density brine coincides in time with the low, annual lake-level/low-head differential period of the lake. It is during the low lake-level stage that the north-to-south return flow of brine to the deep south arm is the greatest. The presence of the higher density brine did not persist beyond February. This was probably due to the fact that normal mixing and dispersion were sufficient to reduce the density to prior levels during a period when north-to-south return flow was much smaller.

Figure 12 shows that the changes that have occurred at the RT4 site in the West Bay portion of the south arm (Gilbert Bay) are similar to those that have occurred at RT2. These include the dilution of the upper brines from letter A to B and the physical configuration change of the deeper brines from C to D. Figure 12 also shows that the density of the deep brines in the West Bay portion of the south arm increases with depth from an elevation of about 4174 feet down to the bottom of the lake, shown by the letters E and F respectively. This is explained at the first of the "South Arm (Gilbert Bay) Tower Sites" section.

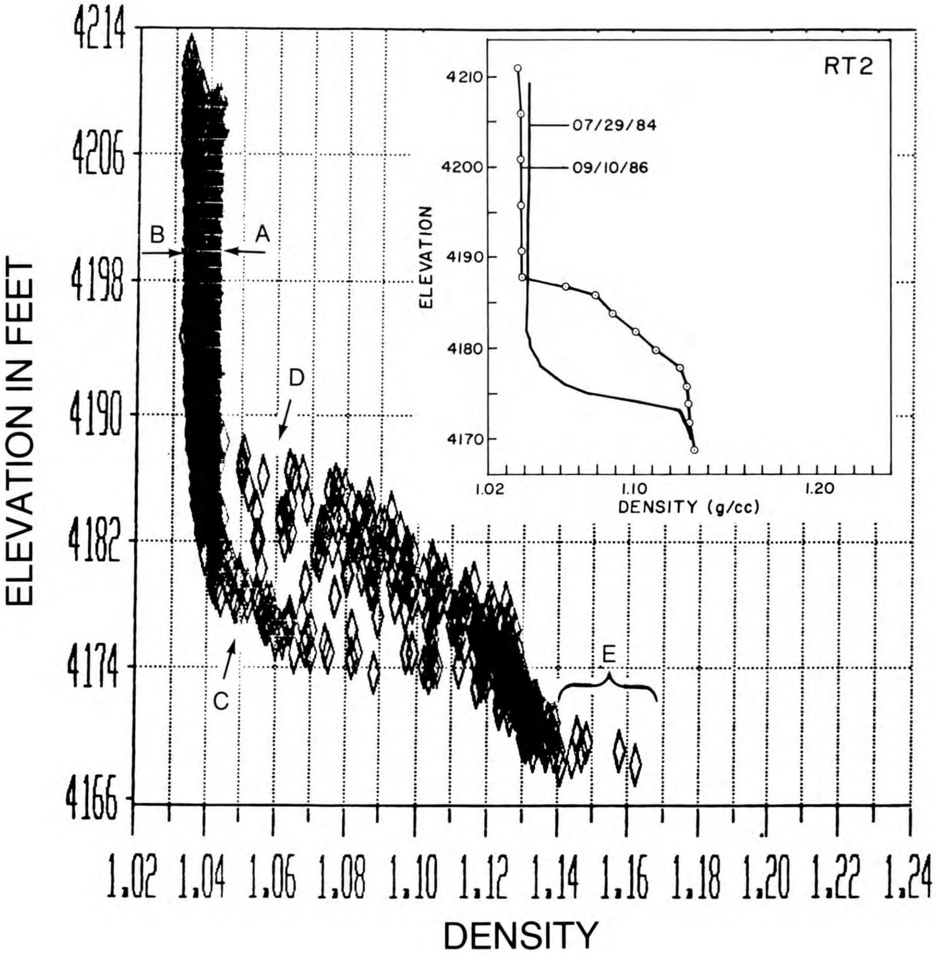

Figure 11. South-arm elevation vs brine density, composite density profile, site RT2, July 1984 - July 1986.

North Arm (Gunnison Bay) Tower Sites

Figure 13 shows the composite density profile developed from data gathered at tower site RT3, located in the north arm of the lake (Gunnison Bay), as shown in figure 4. The inset in figure 13 shows three lines. The extreme left-hand profile (6-17-86) represents the high and most dilute stage of the lake's annual cycle. The 9-9-86 profile represents conditions as of September 1986. Between these two dates the lake level had dropped, thus concentrating the brines. This was not as pronounced in the south arm (Gilbert Bay). These data show the following: first, by the time the causeway was breached on August 1, 1984, the high inflow to the lake had already begun to cause the north arm to depart from its relatively homogeneous state, as represented in figure 4, and show signs of being stratified as shown by the profile through letters A-C-E-F of figure 13. This profile is similar to that found in the south arm during the same time period. The near-vertical trend from the surface through letter A and down to C comprises the upper-brine zone; the transition zone extends from C down to E; and the deep-brine zone extends from E down to F. Letter F represents the bottom of the lake. Second, from the time of the breach until June, 1986, the upper-brine zone became diluted from a density of 1.164 g/cc (A) to less than 1.12 g/cc (B), representing a decrease of more than .044 g/cc. Third, the elevation of the top of the major density break within the individual density profiles, which separates the upper brine and transition zones, has changed over time. At the time of the breach the elevation of the density break stood nearly 4186 feet as shown in figure 14. From that time until February, 1986, the break elevation generally declined through a vertical distance of 6 feet.

From February through June, 1986, the density break rose about 6 feet, probably in response to the high inflow levels into the lake. It then dropped in July. These fluctuations represent a dilution-related shift in the density-break elevation. The three density profiles, A, B and C on figure 14a, illustrate the shift of the upper density break and correspond to the letters A, B and C on figure 13.

The shrinking of the north arm (Gunnison Bay) transition-zone brine occurs at the greatest rate when the lake and the head differential between the two arms are at their lowest annual levels, or during the fall of the year. The lowest rate of north-to-south exchange occurs during the spring when both the lake level and the head differential are at their highest annual levels. These concepts are illustrated in figure 14. During 1984 and 1986, inflow into the lake was higher than in 1985

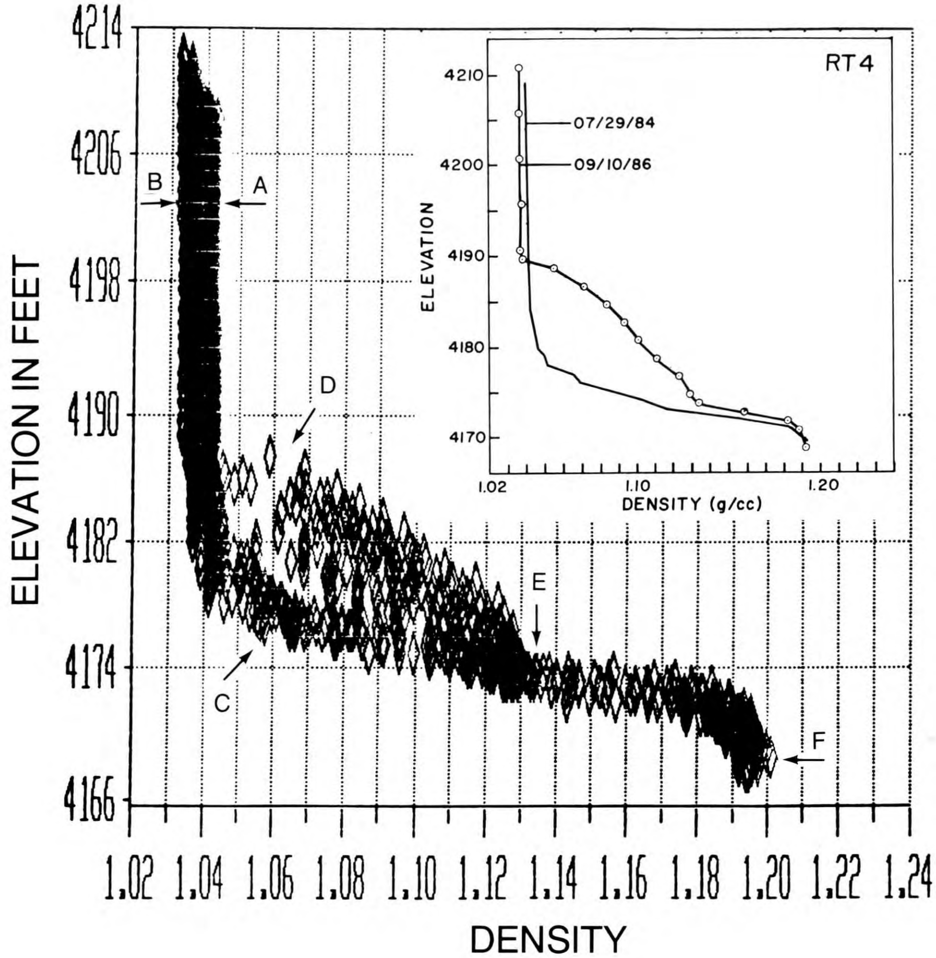

Figure 12. South-arm elevation vs brine density, composite density profile, West Bay area (site RT4), July 1984 - July 1986.

resulting in higher head differentials during those two years. The lower head differentials that existed during 1985 resulted in a higher than normal (1984 and 1986) north-to-south return flow and thus a significant decline in the elevation of the major density break during that time. There was also a decline in the volume of north arm (Gunnison Bay) transition-zone brine.

South Arm (Gilbert Bay) Buoy Sites

There are four buoy sampling sites (1S-4S) which have been established in the West Bay portion of the south arm (Gilbert Bay) adjacent to the breach opening (see figures 10 and 10a). The principal purpose of these sites is to monitor the return flow of north arm (Gunnison Bay) brine into the south arm either through the breach opening or through the causeway fill. Unfortunately, since the time of the breach, some of the large orange buoys have been torn from their moorings and have been lost, resulting in sampling at "approximate" locations.

Figures 15 and 16 show the composite density profiles that have been developed for buoy sites 1S, 2S, 3S, and 4S respectively. In general, all four plots show the following: the density of the upper south arm (Gilbert Bay) brine has decreased from A to B during the 24 months after the breach, and that brines of a greater density are found near the lake's bottom in the range from 4192 to 4195 feet. These brines within the density range indicated by C result from north-to-south return flows which move through the causeway fill or its submerged culverts and along the shallow bottom towards the deeper parts of the lake.

The time period within which the more concentrated brines were found at the 1S-4S sites, and the accompanying brine densities, are shown on figure 17. These data show the following: first, sites 3S and 4S, the farthest from the breach, were the first to receive higher density brines after the breach was opened; these were followed by sites 1S and 2S. The dense brine noted at sites 3 and 4 probably traveled through the causeway as opposed to the breach opening as the head differential decreased and the potential for return flow increased. Second, the further the sampling site is from the breach, the more uniform or consistent are the higher density brines at the near-lake-bottom elevation. Third, anomalous highs (Dec. 1985, Jan. 1986) or lows (Jan. 1985, Feb. 1986) in the Density/-Time profiles are generally seen at all four sites, although their amplitudes diminish with increased distance from the breach. These density highs and lows are probably wind induced.

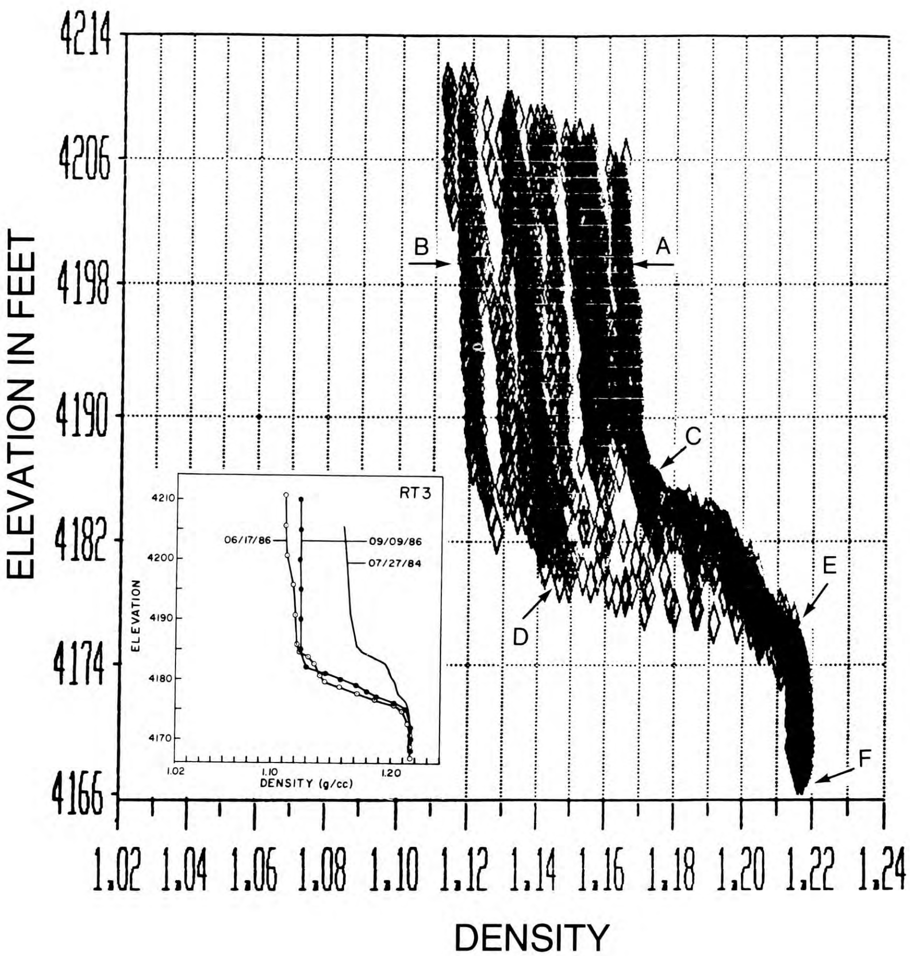

Figure 13. North-arm elevation vs brine density, composite density profile, site RT3, July 1984 - July 1986.

South winds increase the head differential between the two arms and reduce the return flow from the north. This results in a reduction of the lake-bottom brine densities. North winds have the opposite effect. Fourth, in both the 3S and especially the 4S sites, it can be seen that low densities tend to correspond with high seasonal lake-level and high-head differential during June and July 1985, while the opposite is true for the low-lake level periods around October 1985.

The potential for north arm (Gunnison Bay) brine to flow southward through the breach depends upon two main factors: the density of the brines and the head differential between the two arms of the lake. Under the salinity conditions that existed after the causeway was breached, return flow occurred at or below a head differential of about 0.8 to 1.0 feet, but not above. Because the wind could change the head differential over a wide range, the flow rates and sometimes even the flow directions changed. As return flow rates increased so did the brine densities at the 1S-4S sampling sites. The opposite was true for decreased flow rates. These wind-induced influences may be responsible for the erratic nature of the 1S and 2S density/time plots on figure 17. The abrupt increase in density as early as September for the four sites occurred at about the

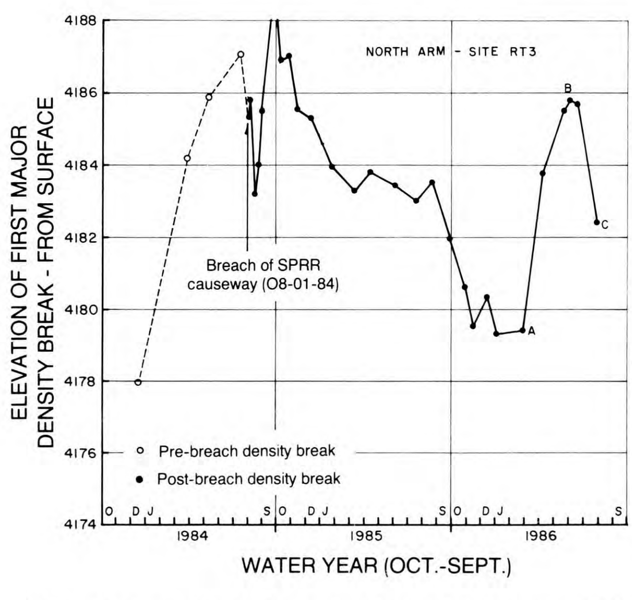

Figure 14. Elevation of first major density break at site RT3, 1984 - 1986 water years.

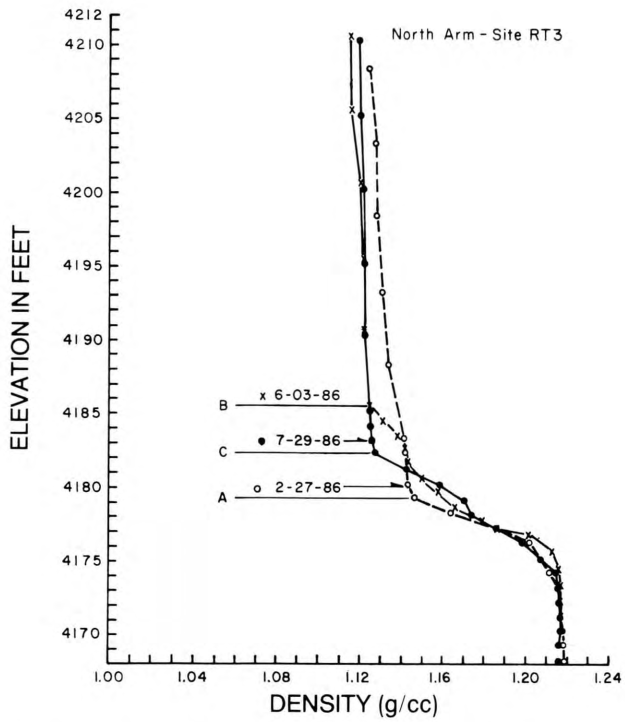

Figure 14a. Elevation vs brine density, north arm, site RT3, composite density profiles.

time the heavy brines and/or return flows were observed within the breach opening. The effect at 3S and 4S may have been moderated by the distance and flow-travel time from the breach to these sites.

North Arm (Gunnison Bay) Buoy Sites

Seven buoy sites were established in the north arm of the lake (Gunnison Bay) adjacent to or north and west (sites 2A, 3A) of the breach. The locations of these sites are shown on figures 10 and 10a. Figures 18 and 19 represent the composite density profiles for sites 1N, 2N, 3N, and 4N respectively and figures 20 and 21 represent sites 1A/WR, 2A, and 3A respectively.

For each of these buoy-site profiles, the following interpretations can be made. First, the density of the upper north arm (Gunnison Bay) brines decreased during the 2-year period following the breaching of the causeway, as indicated between letters A and B on the 1N graph. Second, for nearly all of the sites shown on figures 18 to 21, the surficial dilution effect of the south arm (Gilbert Bay) brine entering and spreading out upon the north arm can be seen as represented by the density range of letter C. An inverse relationship between site distance from the breach and the degree of dilution can also be seen. Site 1N shows a great deal of surface dilution; site 2A has shown some and site 3A shows none at all.

Figure 22 illustrates the degree of surface dilution (less than 5 feet thick) since just before the breach was made to July 1986

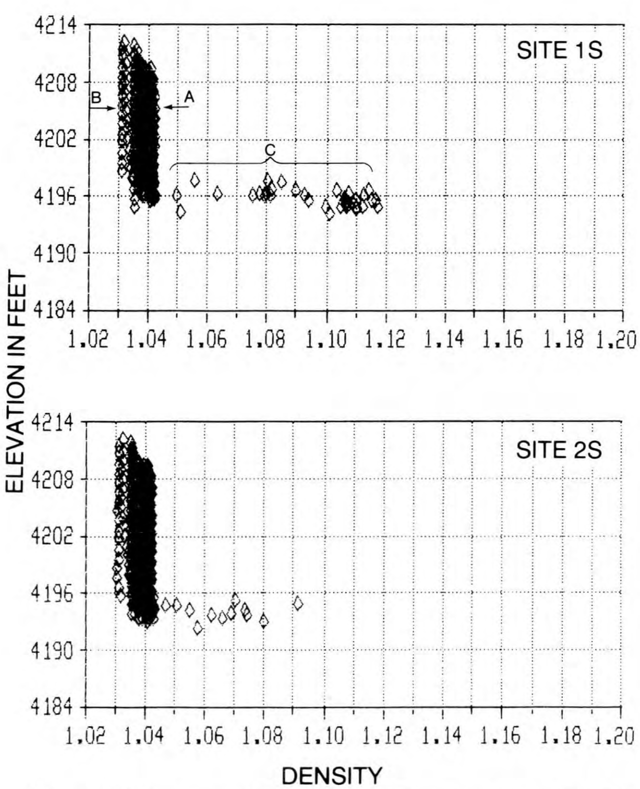

Figure 15. Elevation vs brine density, south arm, composite density profiles, sites 1S and 2S.

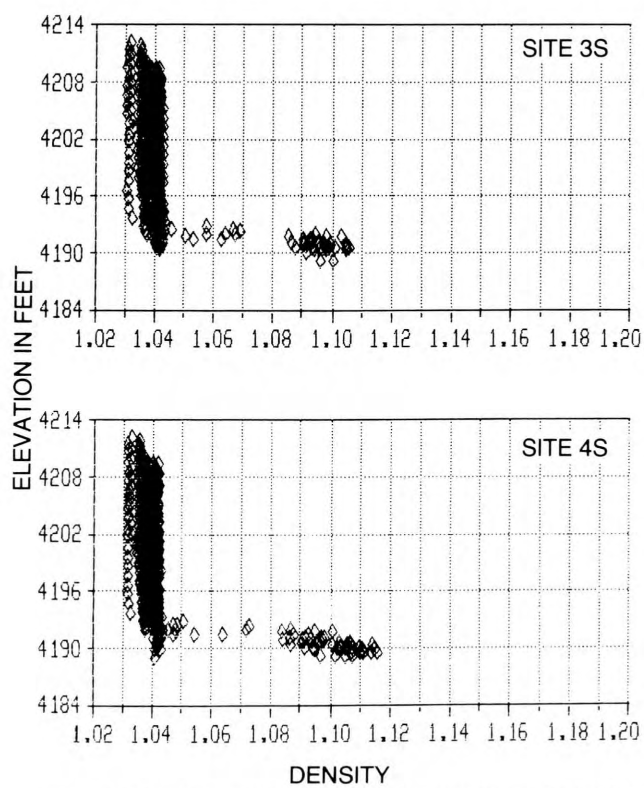

Figure 16. Elevation vs brine density, south arm, composite density profiles, sites 3S and 4S.

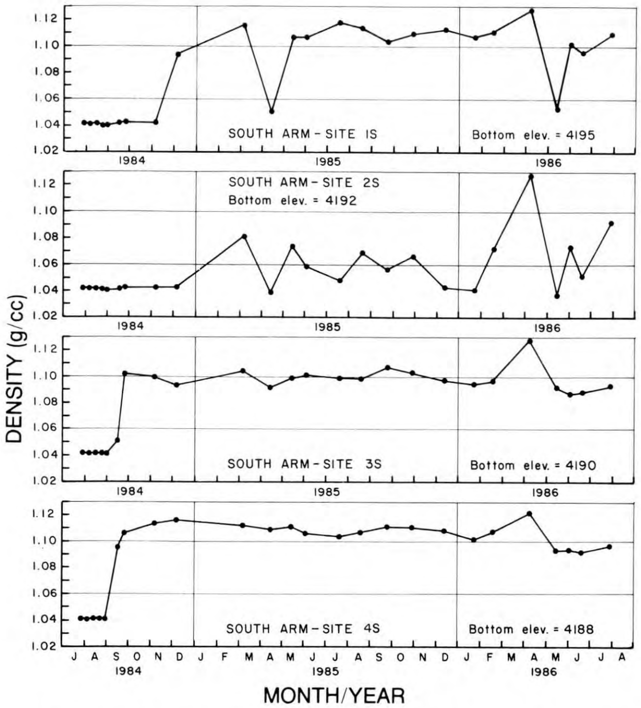

Figure 17. Brine density vs month/year, south arm, lake bottom samples, sites 1S - 4S.

for sites 1N to 4N. The 5-foot depth at site 1N is also plotted over time to show the comparison between the surface dilution and the general density trend of the upper north arm (Gunnison Bay) brines. At site 1N, the extreme surficial dilution caused by the south-to-north breach flow is not seen at the 5-foot depth.

Data from figure 22 suggest several things concerning sites 1N to 4N. First, the degree of dilution of the surface brines decreases as the distance outward from the breach increases. This is due mainly to the spreading, thinning, and mixing of the south arm (Gilbert Bay) brines after they emerge from the breach opening. Second, over the 24-month period since the breach, the general decline-in-density rate of all the upper north arm (Gunnison Bay) brines (top 25 feet), represented by the 5-foot interval at site 1N, shows a greater decline rate than that of the surface (top 0 to 5 feet) brines at any of the N-site locations. This difference in long-term dilution rates is due to the stabilizing influence of south arm (Gilbert Bay) brines (because of their relatively consistent density) on the surface-brine (top 0-532 feet) mixture. Third, the increasingly radical fluctuation of the density/time plots from sites 2N towards 4N is caused by winds which mix the surface waters. The further from the breach, the thinner the surface layer becomes and the faster and more thorough this layer can be mixed with the underlying brine.

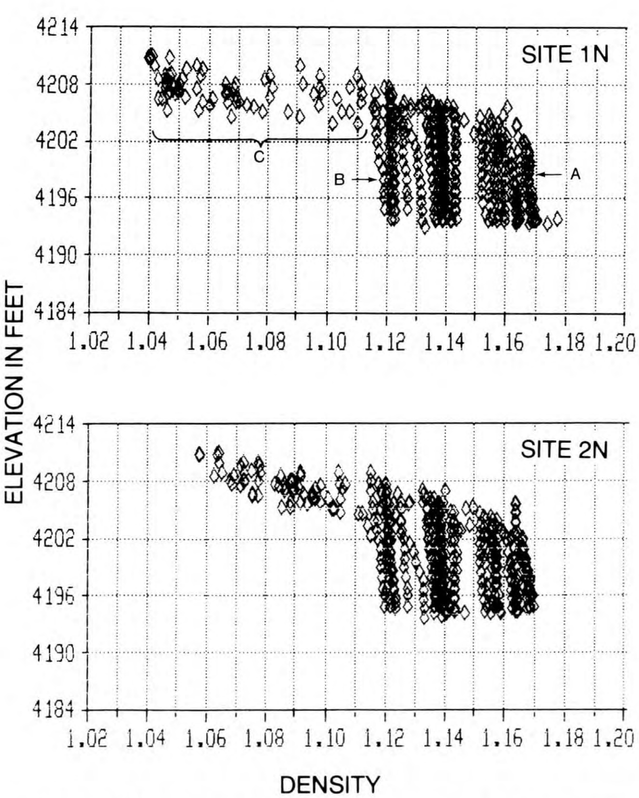

Figure 18. Elevation vs brine density, north arm, composite density profiles, sites 1N and 2N.

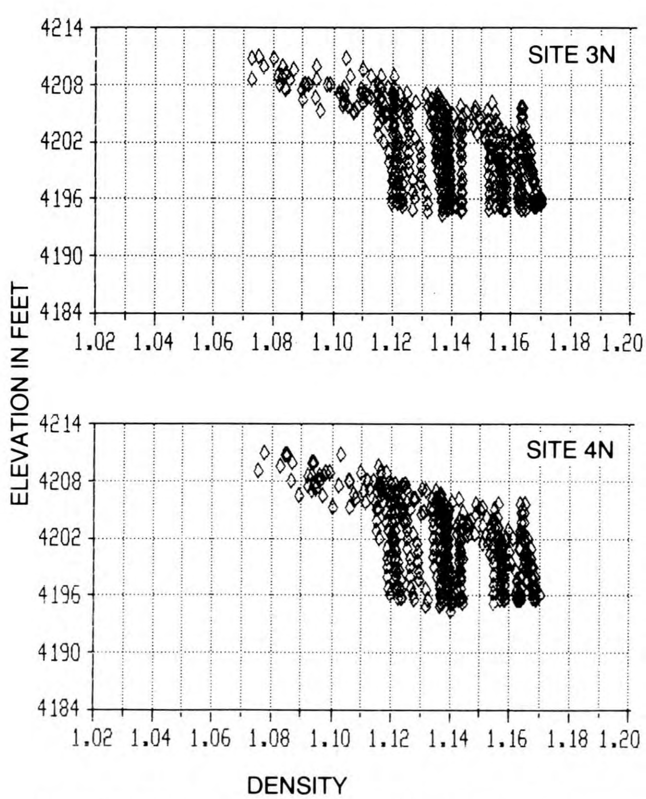

Figure 19. Elevation vs brine density, north arm, composite density profiles, sites 3N and 4N.

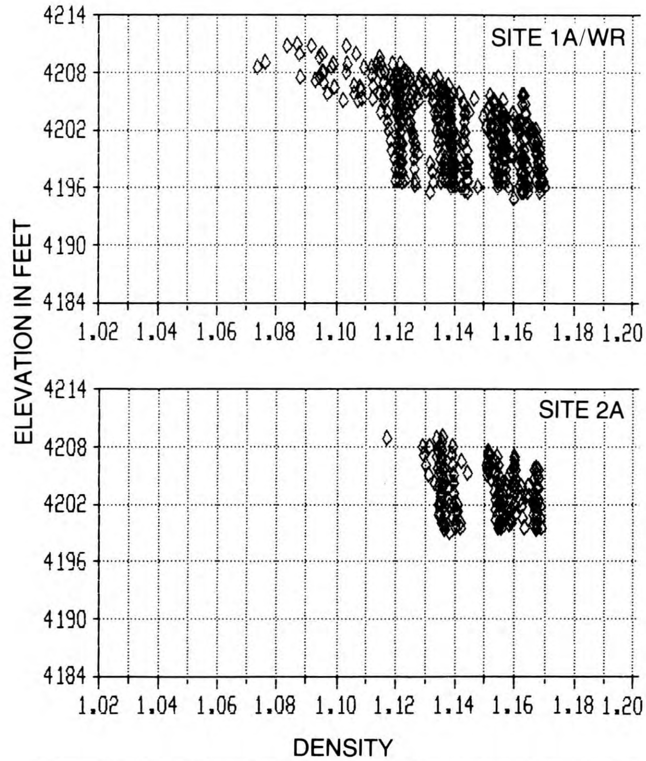

Figure 20. Elevation vs brine density, north arm, composite density profiles, sites 1A/WR and 2A.

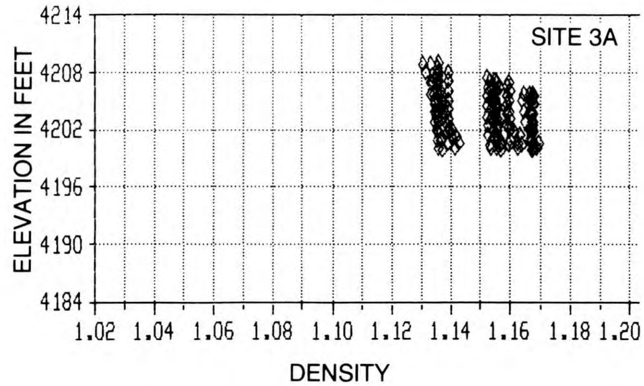

Figure 21. Elevation vs brine density, north arm, composite density profile, site 3A.

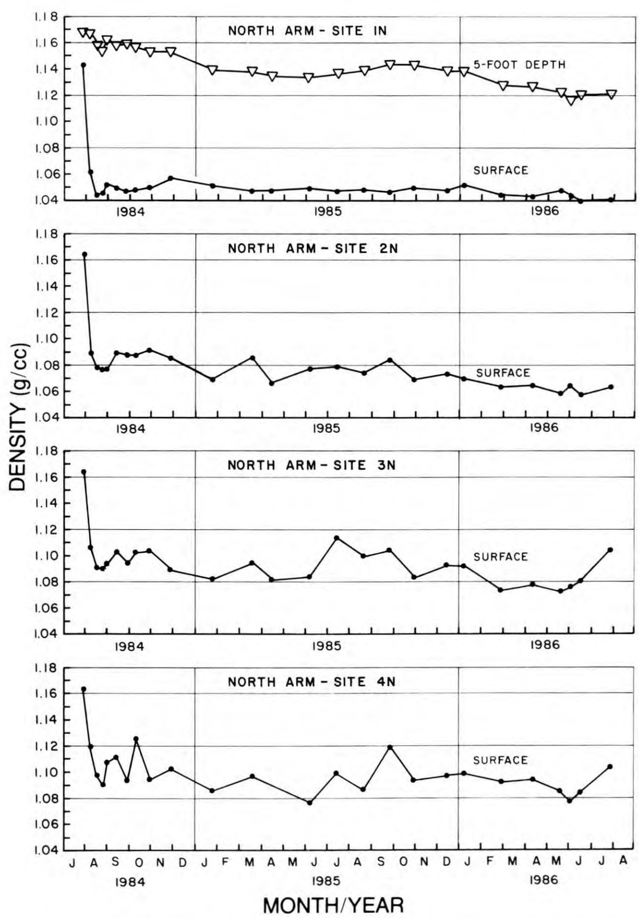

Figure 22. Brine density vs month/year, north arm, lake surface and site 1N (5-foot reference) samples, sites 1N - 4N.

GREAT SALT LAKE CHEMISTRY

The lake's inorganic chemistry, represented by data collected since the breaching of the causeway, is characterized as follows within this report: a) data and interpreted line plots for weight percent ion concentration vs total dissolved solids (TDS) concentration; b) data and interpreted line plots for dry weight percent ion concentration vs TDS concentration; and c) monthly averaged dry weight percent ion concentration vs time. Data and interpreted line plots are also presented for TDS vs density, grams per liter (GPL) vs density, and GPL vs TDS.

Weight Percent vs TDS Concentration

Weight percent ion concentrations/TDS concentration plots developed for Na, K, Mg, Cl, and SO_4, for both the north and south arms of the lake (Gunnison and Gilbert Bays), are shown on figures 23 and 24 respectively. Figures 23a and 24a are interpreted line plots of the same data sets.

Sodium: The plot of Wt. % Na vs TDS shows that there is a linear relationship between the increase in sodium concentration and that of TDS from about 4 through 29 percent. This relationship holds true for both the north and south arms of the lake.

Potassium: The plots of Wt. % K vs TDS contain a considerable amount of scatter in the data points as a result of the low values being analyzed. There is a general linear relationship between the increase in potassium concentration and that of TDS for both the north and south arms of the lake.

Magnesium: The plots of Wt. % Mg vs TDS also contain a considerable amount of scatter in the data points. There is a general linear trend between the increase in the amount of magnesium and that of TDS below about 20 percent TDS, although at the higher concentration ranges the rate-of-increase of magnesium decreases somewhat.

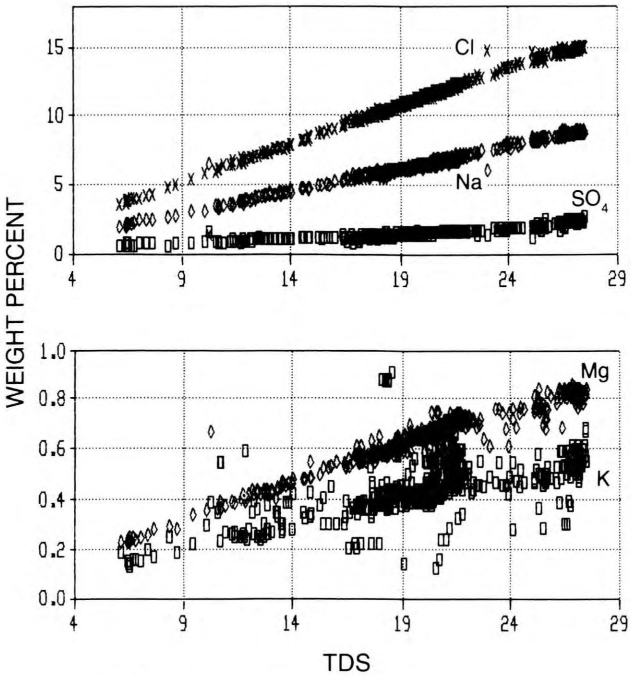

Figure 23. Weight percent Na, SO_4, Cl and Mg, K vs Total Dissolved Solids (TDS), north arm.

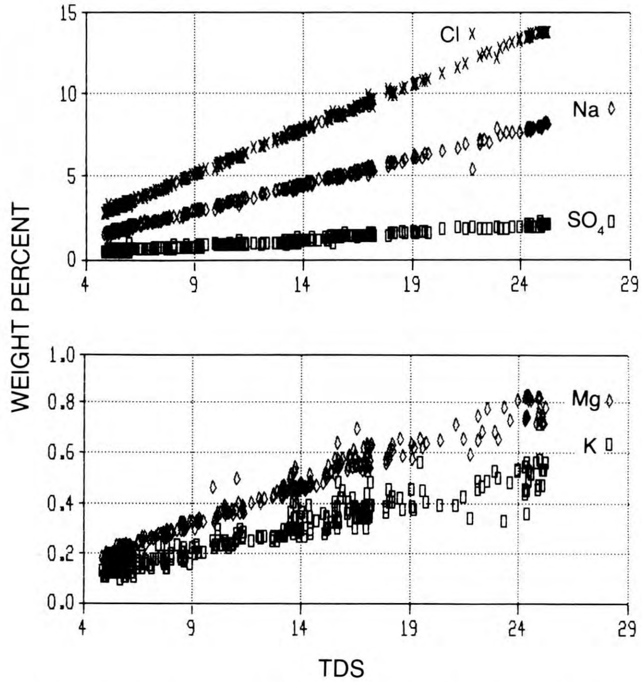

Figure 24. Weight percent Na, SO_4, Cl and Mg, K vs Total Dissolved Solids (TDS), south arm.

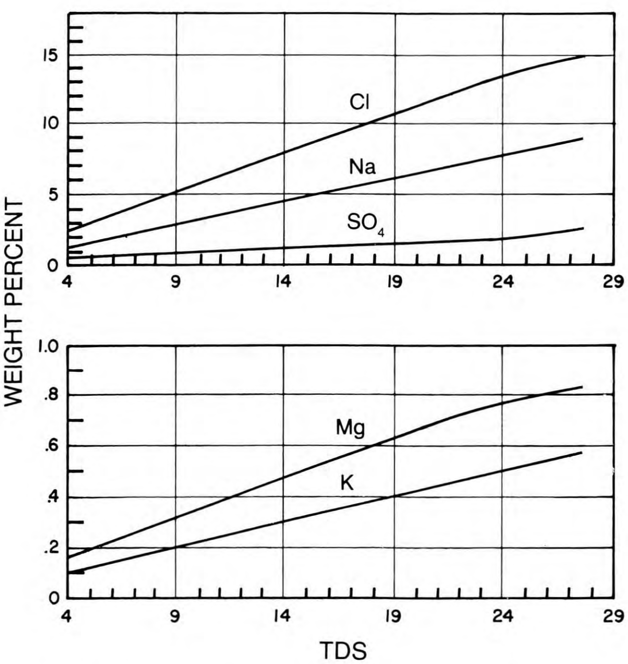

Figure 23a. Interpreted line plot of weight percent Na, SO_4, Cl and Mg, K vs Total Dissolved Solids (TDS), north arm.

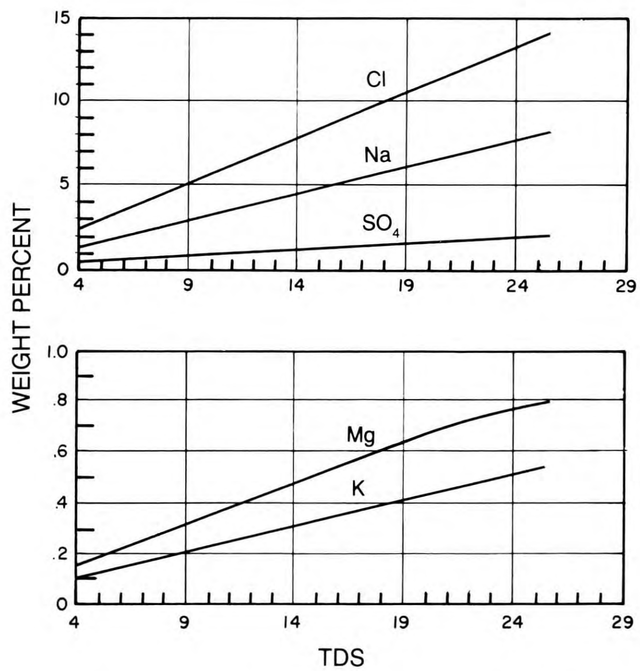

Figure 24a. Interpreted line plot of weight percent Na, SO_4, Cl and Mg, K vs Total Dissolved Solids (TDS), south arm.

Chloride: The plot of Wt. % Cl vs TDS for the south arm shows that there is a linear relationship between the concentration of chloride and that of TDS. For the north arm there is a decrease in the rate of chloride increase in the otherwise linear relationship starting at about 23 percent TDS. These higher densities represent the deep north arm (Gunnison Bay) brines which have become enriched with sulfate due to mirabilite dissolution and thus a depletion in chloride.

Sulfate: The plot of Wt. % SO_4 vs TDS for the south arm shows a general linear relationship between the increase in concentration of sulfate and that of TDS, although it shows a few irregularities. For the north arm the same general linear relationship holds true up to about 18 percent TDS. From there, the concentration increases at a higher rate than does the TDS. This upward swing is the result of sulfate enrichment due to the dissolution of mirabilite. Mirabilite ($Na_2SO_4.10H_2O$) is precipitated from winter-cooled brine and is deposited on the floor of the north arm. Here it dissolves as the brines warm during the spring and summer, thus enriching the deep brines with sulfate and sodium. Because brines in the south arm are presently quite dilute, the precipitation of mirabilite does not take place.

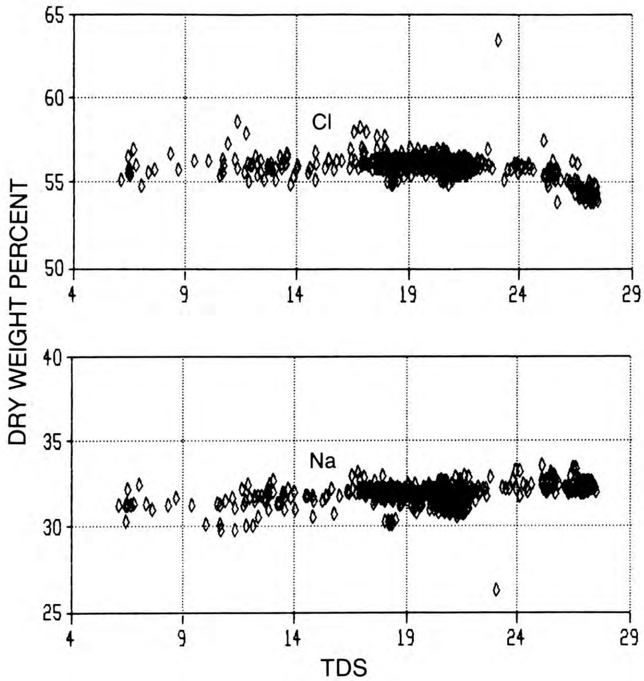

Figure 25. Dry weight percent Cl and Na vs Total Dissolved Solids (TDS), north arm.

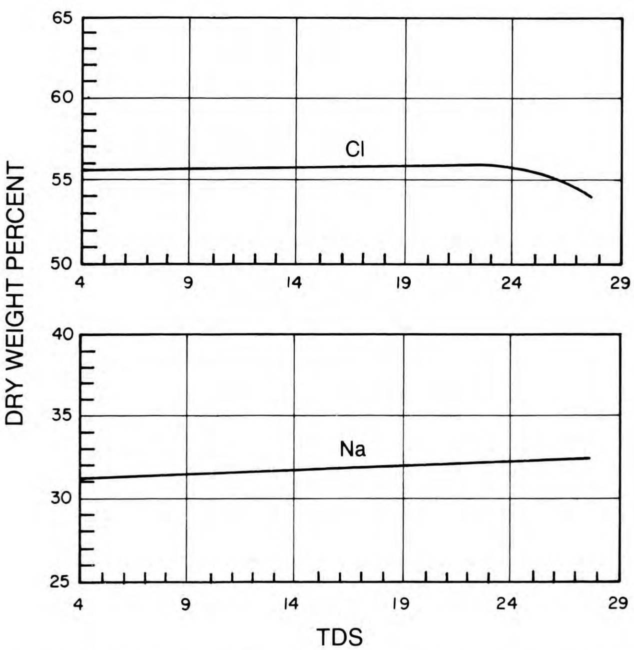

Figure 25a. Interpreted line plot of dry weight percent Cl and Na vs Total Dissolved Solids (TDS), north arm.

Dry Weight Percent vs TDS Concentration

Dry weight percent ion concentration vs TDS plots developed for Na, K, Mg, Cl, and SO_4 for both the north and south arms (Gunnison and Gilbert Bays) are shown in figures 25, 26, 27, and 28. These plots show the quantity of each ion as a percentage of the total amount of dissolved salts where the previous Weight Percent vs TDS plots reflect the concentration of the ions in the brine. Figures 25a, 26a, 27a and 28a are interpreted line plots of the same data.

Chloride: The plot of Dry Wt. % Cl vs TDS for the north arm (see figure 25) shows a very slight increase in the percentage of chloride as TDS increases up to about 23 percent. Beyond that point, the dry weight percent of chloride decreases with continued increase in TDS. This downward trend reflects the lower chloride/higher sulfate environment of the deep north arm (Gunnison Bay) brine, discussed previously within the Wt. % vs TDS discussion. In the south arm

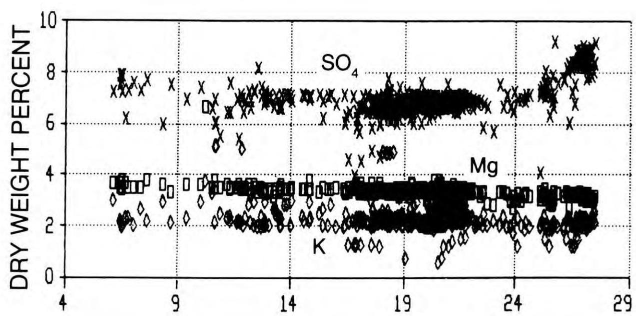

Figure 26. Dry weight percent K, Mg, SO_4 vs Total Dissolved Solids (TDS), north arm.

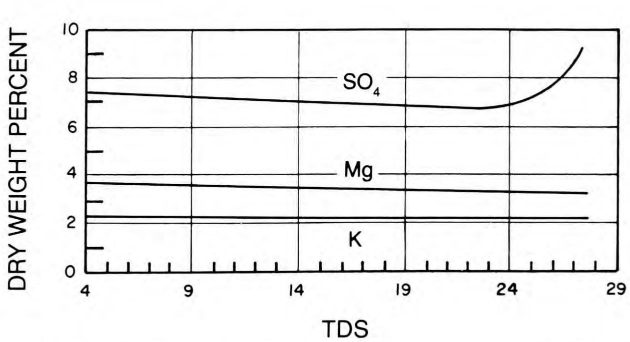

Figure 26a. Interpreted line plot of dry weight percent K, Mg, SO_4 vs Total Dissolved Solids (TDS), north arm.

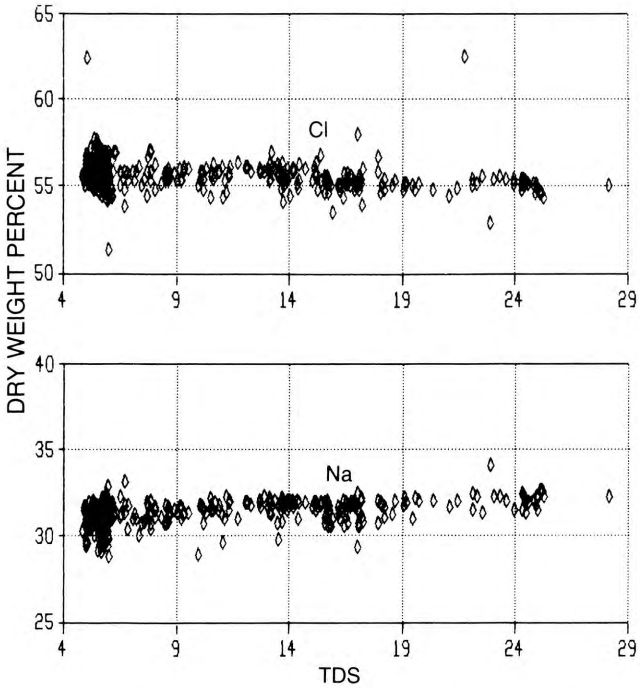

Figure 27. Dry weight percent Cl and Na vs Total Dissolved Solids (TDS), south arm.

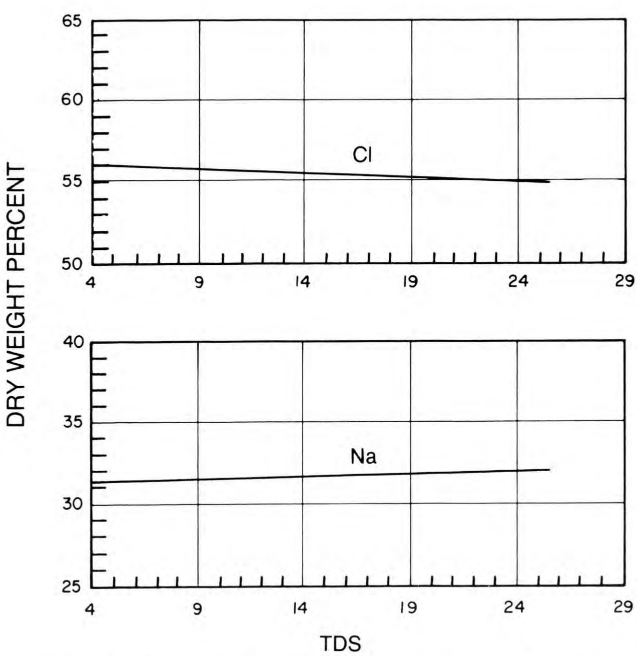

Figure 27a. Interpreted line plot of dry weight percent Cl and Na vs Total Dissolved Solids (TDS), south arm.

(see figure 27) the Dry Wt. % of chloride decreases slowly with increased TDS concentration. This relationship is nearly linear although the data points contain minor fluctuations. The main portion of the south arm's decreasing chloride trend line (figure 27) from about 6 to 29 percent is representative of deep brines. This decreasing trend may be attributed to the probable source of these brines, that is, the deep north arm (Gunnison Bay) brines, which are low in chloride.

Sodium: The plot of Dry Wt. % Na vs TDS for the north arm (see figure 25) shows an increase in the percentage of sodium with increasing TDS. This relationship appears to be linear throughout the entire TDS interval from about 4 to 29 percent. The south arm (Gilbert Bay) plot (see figure 27) shows a similar relationship. The possible source of sodium that supplies both the denser south arm and north arm brines is the sodium chloride that was deposited on the bottom of the lake during the early to mid-1960s and again in the late 70s and early 80s. Although this salt was completely dissolved prior to the time of the breach, the deep brines which had become anomalously high in sodium are slowly and continuously diffused or mixed upward into the upper north arm (Gunnison Bay) brines and then distributed throughout the lake.

Sulfate: The plot of Dry Wt. % SO_4 vs TDS for the north arm (see figure 26) shows a non-linear relationship, with sulfate decreasing as the TDS increases up to about 23 percent. At that point, the sulfate increases rapidly from about 7 to 9 percent. The abrupt increase in sulfate is found only within the deep brines. The reason for its presence was discussed in the Wt. % vs TDS section. In the south arm (see figure 28) the plot shows sulfate to be increasing slightly with increasing TDS. The plot shows a linear increase in sulfate even though it is irregular. There is a considerable amount of scatter in both the north arm and south arm data.

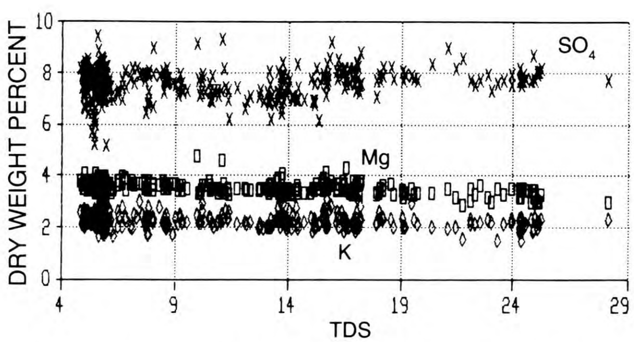

Figure 28. Dry weight percent K, Mg, SO_4 vs Total Dissolved Solids (TDS), south arm.

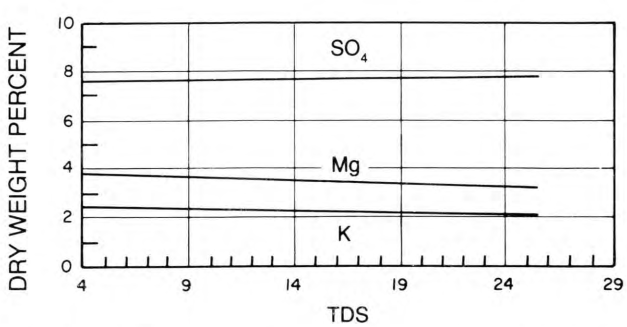

Figure 28a. Interpreted line plot of dry weight percent K, Mg, SO_4 vs Total Dissolved Solids (TDS), south arm.

Magnesium: The plots of Dry Wt. % Mg vs TDS for both the north and south arms, as shown in figures 26 and 28 respectively, show the percentage of magnesium to decrease with increasing TDS. In both plots, the relationships are relatively linear with some scatter in the data points. The decrease in magnesium is in response to the increase in sodium.

Potassium: The plots of Dry Wt. % K vs TDS for both the north and south arms, as shown in figures 26 and 28 respectively, show relationships very similar to those of magnesium except that potassium is in lower concentrations.

Monthly Averaged Dry Wt. % Ion Concentration vs Time

The purpose of these plots is to show the variation in the various ion concentrations, on a dry weight basis, with the passage of time since the causeway was breached.

Chloride: The plots of Monthly Averaged Dry Wt. % Cl vs Time for both the north and south arms of the lake are shown on figures 29 and 31 respectively. These data show that the percentage of chloride has remained relatively stable since the time of the breach.

Sodium: The plots of Monthly Averaged Dry Wt. % Na vs Time for the north and south arms of the lake are shown on figures 29 and 31 respectively. These data show that there is a very slight gain in the percentage of sodium over time. This suggests that the probable movement of sodium from the deep north arm (Gunnison Bay) brine is still proceeding slowly.

Sulfate: The plots of Monthly Averaged Dry Wt. % SO_4 vs Time for the north and south arms of the lake are shown on figures 30 and 32 respectively. In both plots, the data points are very erratic, possibly due to analytical or other unknown problems. It appears that the sulfate in the south arm tends to

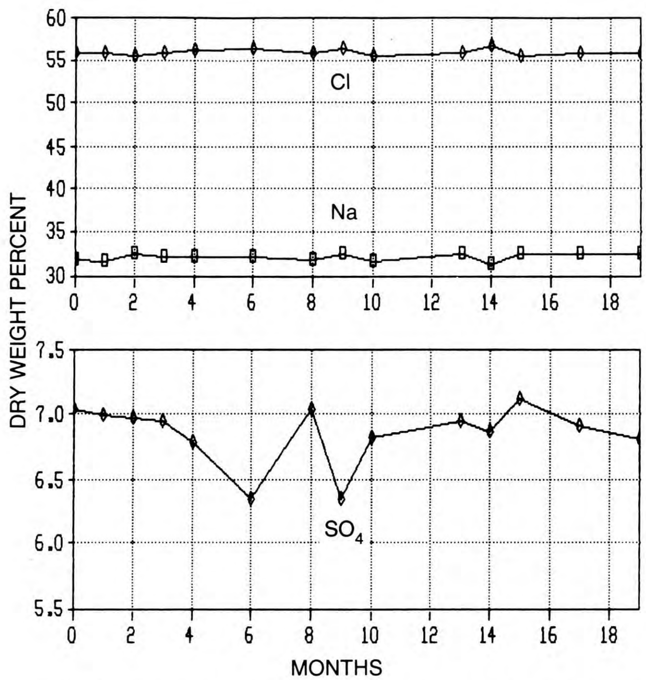

Figure 29. Monthly averaged dry weight percent Cl, Na and SO_4 vs months, north arm.

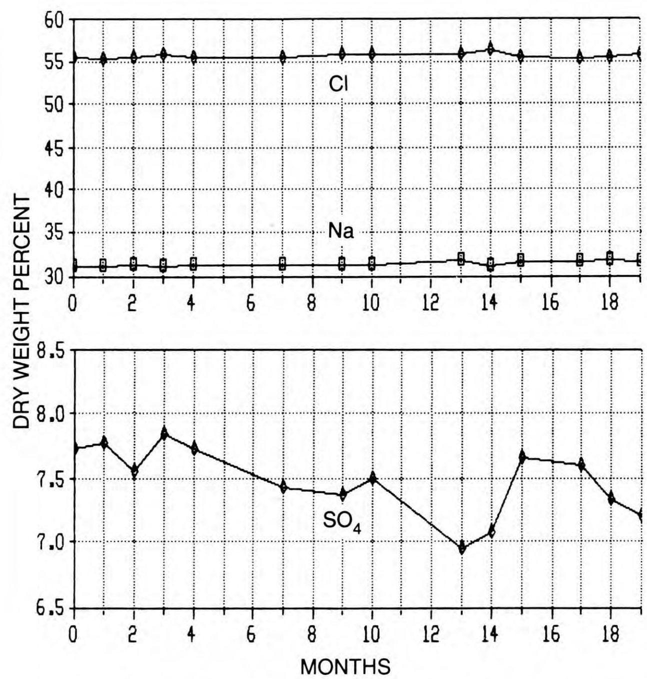

Figure 31. Monthly averaged dry weight percent Cl, Na and SO_4 vs months, south arm.

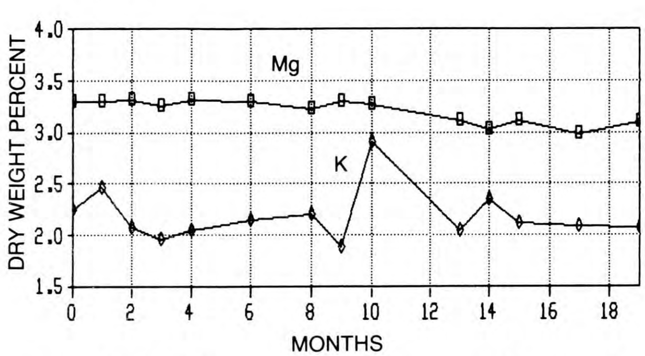

Figure 30. Monthly averaged dry weight percent K, Mg vs months, north arm.

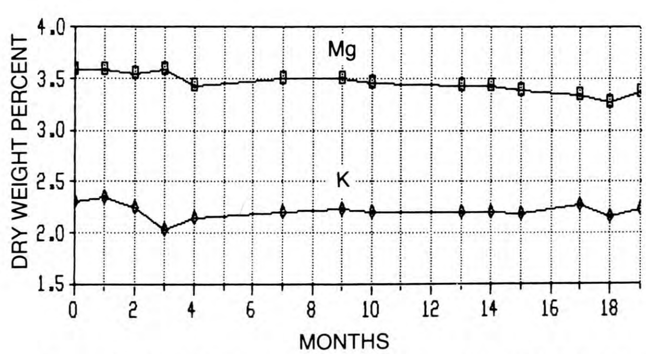

Figure 32. Monthly averaged dry weight percent K, Mg vs months, south arm.

decrease over time while remaining overall about the same in the north arm.

Magnesium: The plots of Monthly Averaged Dry Wt. % Mg vs Time for the north and south arms of the lake are shown in figures 30 and 32 respectively. These data suggest that the relative magnesium content is decreasing over time in both arms. This decrease is likely in response to an increase in the amount of sodium.

Potassium: The plots of Monthly Averaged Dry Wt. % K vs Time are shown in figures 30 and 32 for the north and south arms of the lake respectively. Data points on the north arm (Gunnison Bay) plot are somewhat erratic, but the general trend of both the north and south arm plots suggests that the potassium content has remained about the same since the time of the breach. It is not known why the potassium content appears to remain about constant while the magnesium content decreases.

Miscellaneous Plots

TDS vs Density: Plots of weight percent TDS vs Density for the north and south arms of the lake are given in figures 33 and 34 respectively. These data suggest that a slightly non-linear relationship exists between TDS and density, in which the increase in density occurs at a slightly higher rate than that of TDS. This non-linear relationship is slightly more pronounced in the north arm (Gunnison Bay) brines than in the south arm (Gilbert Bay) brines.

Grams/Liter vs Density: Plots of Grams/Liter vs Density for the north and south arms of the lake are shown on figures 35 and 36 respectively. These data suggest that a slightly non-linear relationship exists between grams/liter and density, where density increases at a slightly slower rate than grams/liter.

Grams/Liter vs TDS: Plots of Grams/Liter vs TDS for the north and south arms of the lake are shown on figures 37 and 38 respectively. These data suggest that the relationship between GPL and TDS is also slightly non-linear, in which TDS increases at a greater rate than does grams per liter.

Interpreted line plots of each of the six miscellaneous data plots are shown as figures 33a through 39a.

EFFECTS OF BREACH ON LAKE INDUSTRIES

The breaching of the Southern Pacific Railroad causeway brought about both lake-level and salinity changes within the Great Salt Lake. These changes have had and will yet have varying impacts on the lake's mineral extraction and transportation industries.

LAKE-LEVEL CHANGES

Just prior to the breaching of the causeway on August 1, 1984, the lake had reached its annual high-water peak of 4209.25 feet and was beginning to drop, as shown on figure 39. At the time of the breach, the south arm (Gilbert Bay) stood at an elevation of 4209.05 feet and the north arm (Gunnison Bay) at 4205.60 feet. The differential between the two arms of the lake was 3.45 feet. By the end of September, 1984, two months after the breach was opened, the lake (as recorded on the south arm) had reached its annual low level. The south arm had dropped to 4207.85 feet, a distance of 1.2 feet; the north arm

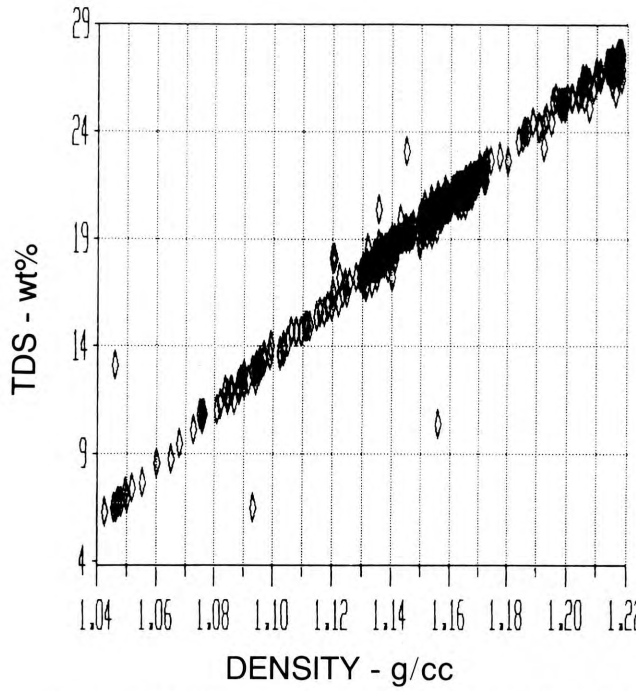

Figure 33. Total Dissolved Solids (TDS) vs brine density, north arm.

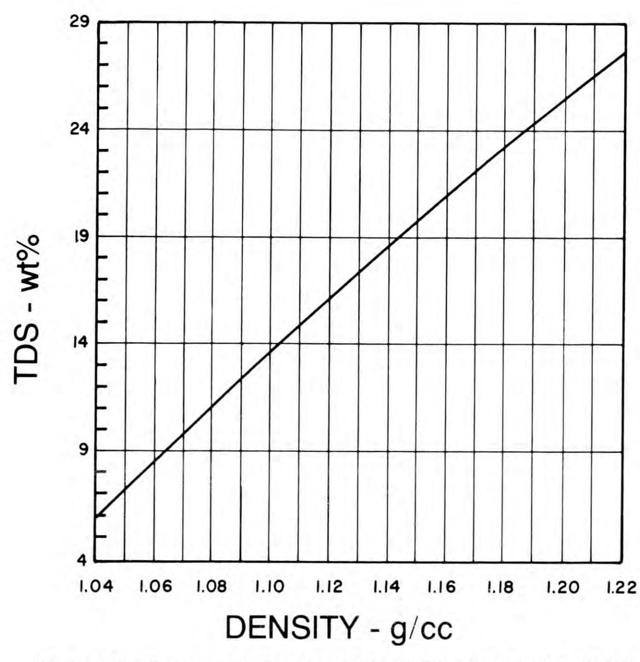

Figure 33a. Interpreted line plot of Total Dissolved Solids (TDS) vs brine density, north arm.

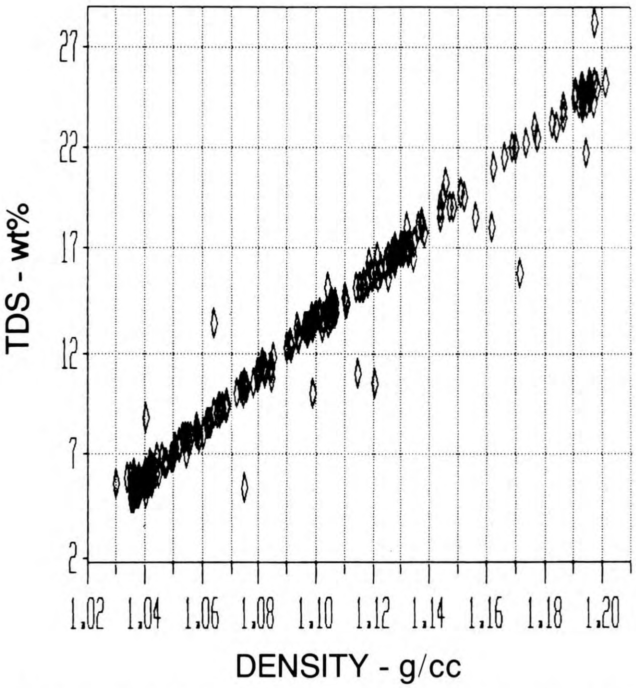

Figure 34. Total Dissolved Solids (TDS) vs brine density, south arm.

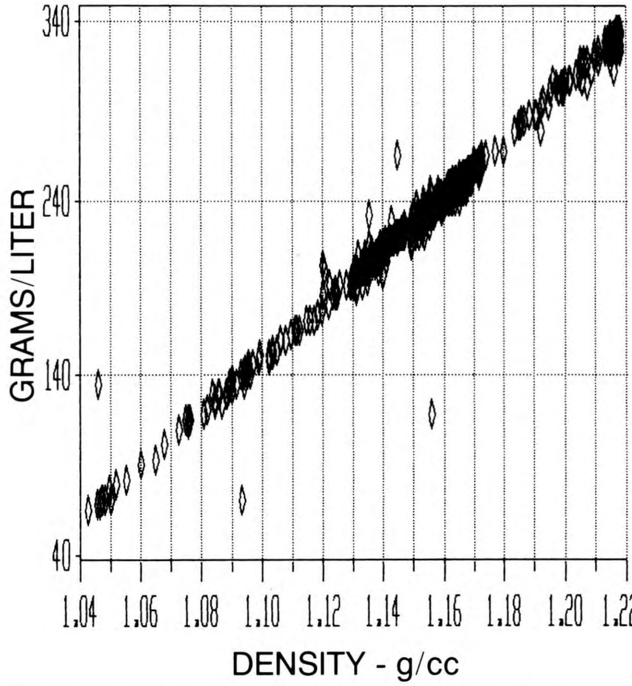

Figure 35. Grams per liter (GPL) vs brine density, north arm.

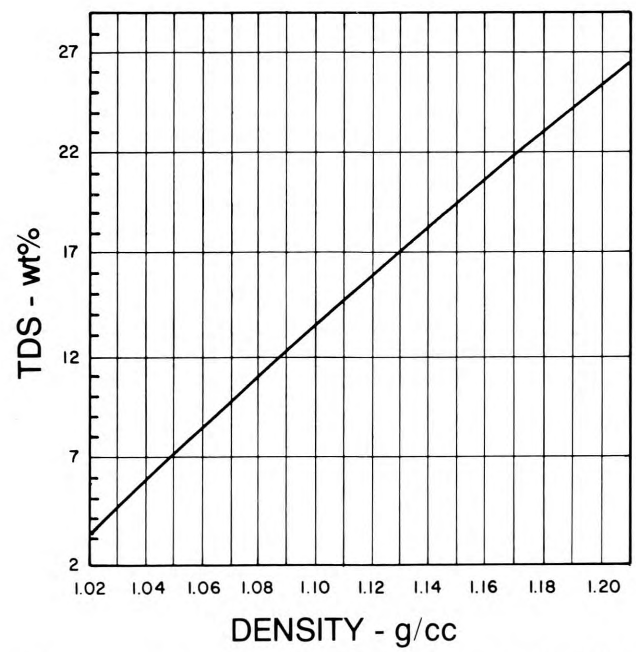

Figure 34a. Interpreted line plot of Total Dissolved Solids (TDS) vs brine density, south arm.

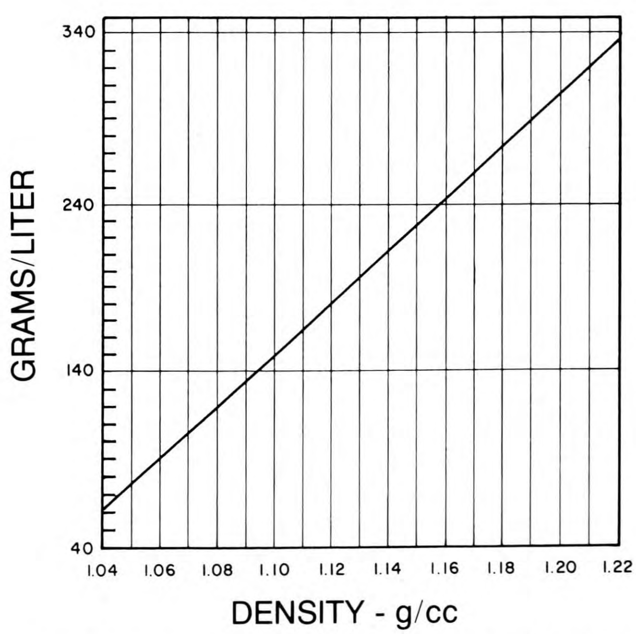

Figure 35a. Interpreted line plot of grams per liter (GPL) vs brine density, north arm.

had raised to 4206.9 feet, a gain of 1.3 feet. The head differential stood at 0.95 feet, a decrease of 2.5 feet. This is the difference between the Boat Harbor (Saltair Beach) and the Saline (Little Valley Harbor) gauging station readings. It cannot be determined accurately what percentage of these level changes was due to the breach and what was due to normal surface evaporation. It is estimated that the breach caused the south arm (Gilbert Bay) level to lower 0.8 feet.

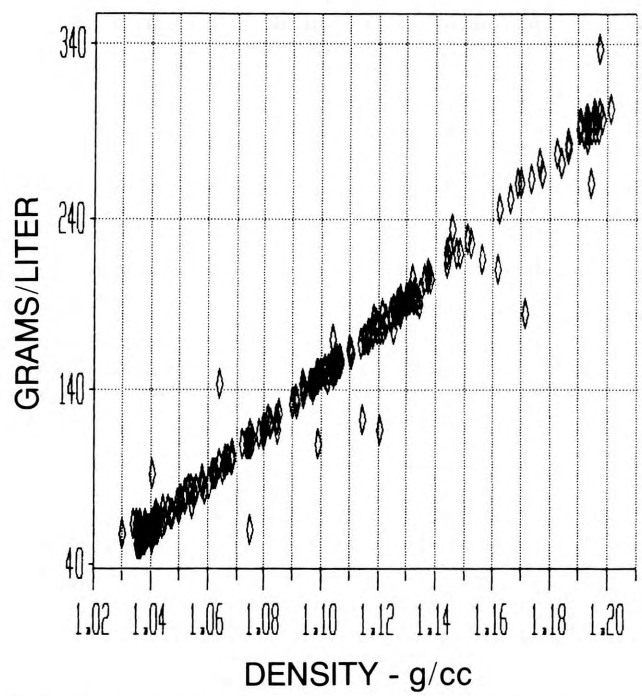

Figure 36. Grams per liter (GPL) vs brine density, south arm.

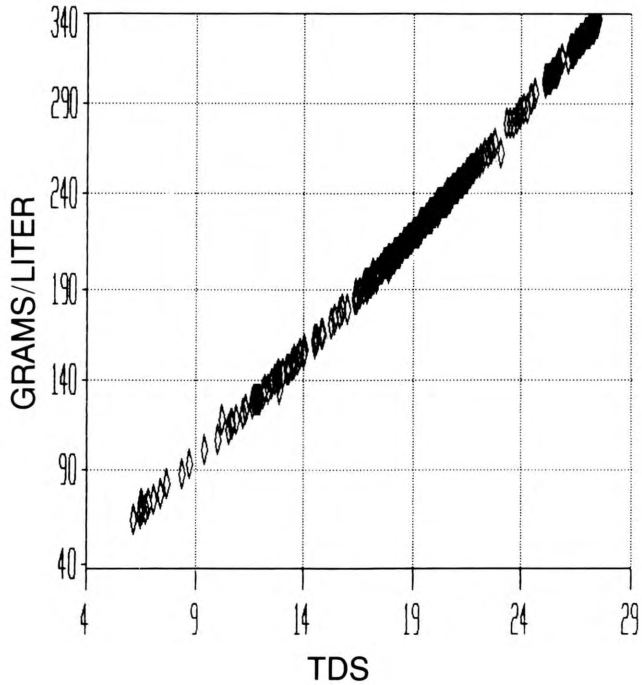

Figure 37. Grams per liter (GPL) vs Total Dissolved Solids (TDS), north arm.

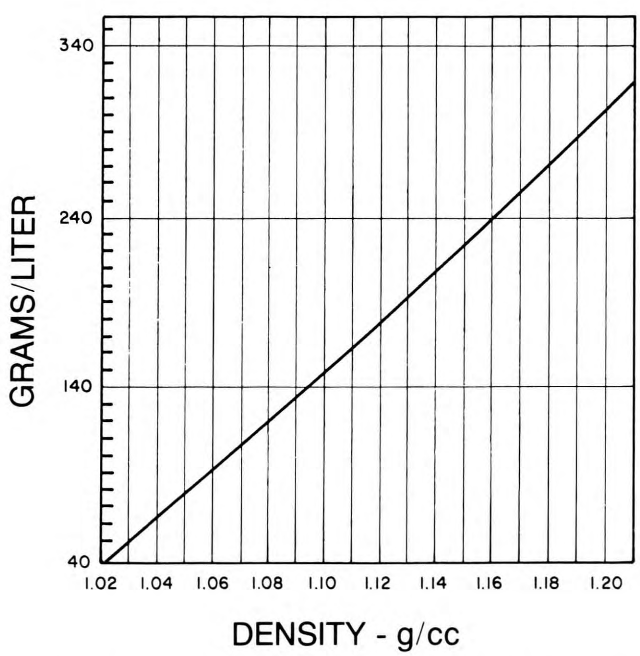

Figure 36a. Interpreted line plot of grams per liter (GPL) vs brine density, south arm.

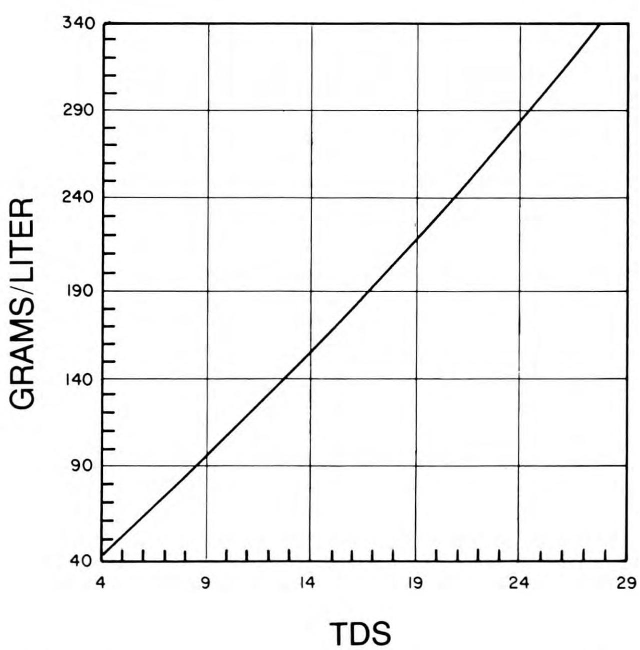

Figure 37a. Interpreted line plot of grams per liter (GPL) vs Total Dissolved Solids (TDS), north arm.

For the lake industries located on the south arm (Gilbert Bay) (and on Bear River Bay), which include all of the currently existing companies, the accelerated drop of 1.2 feet was welcomed. Although, with the lake level still at almost 4208 feet, the beneficial effect was minimal. With the exception of Great Salt Lake Minerals and Chemicals Corporation's primary pumping facilities located near the south end of Promontory Point but on the north arm of the lake (Gunnison Bay),

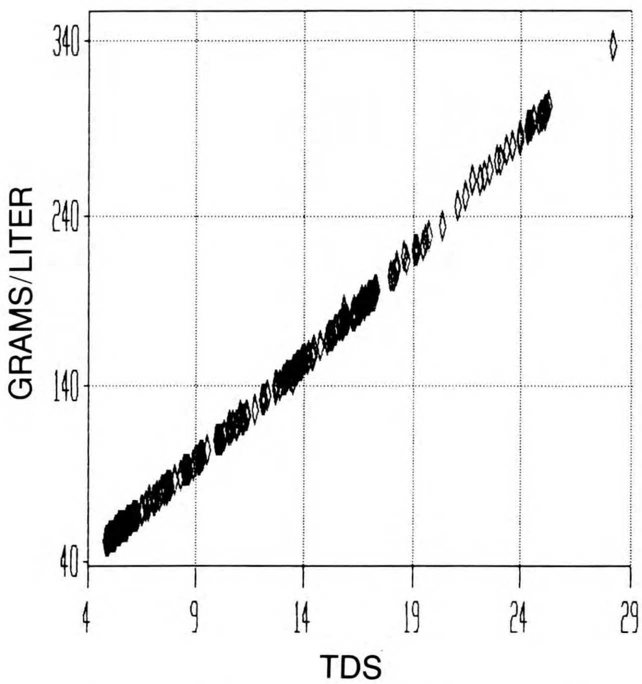

Figure 38. Grams per liter (GPL) vs Total Dissolved Solids (TDS), south arm.

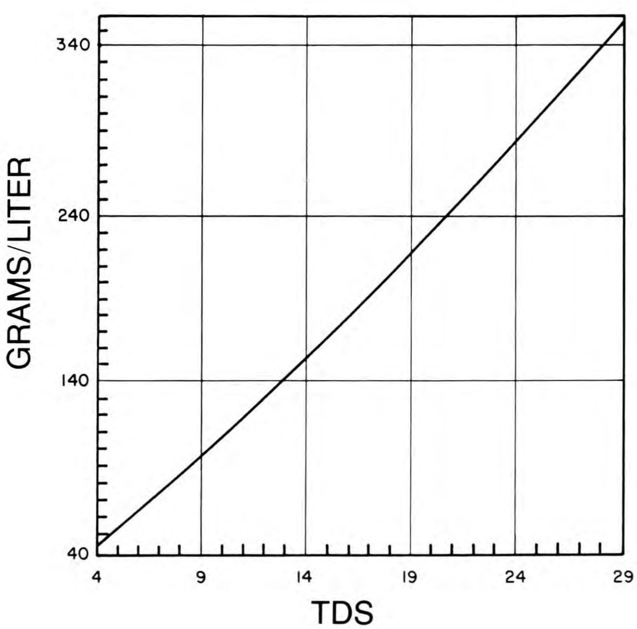

Figure 38a. Interpreted line plot of grams per liter (GPL) vs Total Dissolved Solids (TDS), south arm.

there were no significant, active industrial facilities affected by the 1.3-foot rise in the level of the north arm.

By March of 1985 the south arm (Gilbert Bay) level had reached the 1984 peak elevation of 4209.25 and by May it had reached 4209.95 feet, a gain of 2 feet since the 1985 low level. The north arm (Gunnison Bay) continued to rise and reached a peak elevation in May of 4209.00 feet, a distance of 2.10 feet. Had the causeway not been breached it is possible that the south arm (Gilbert Bay) elevation would have reached an elevation of 4211 feet or more in 1985 and nearly 4213 feet in 1986. The lake industries would have had an additional foot or more of lake level to deal with in raising and protecting dikes during 1985 and 1986.

Although the two railroads running south of or through the center of the lake are not extractive industries, the breach affected these entities as well. The Union Pacific Railroad on the south end of the lake, like the extractive industries, was relieved of the effect of 0.8 feet of lake level against its rail base. The Southern Pacific Railroad running through the center of the lake, on the other hand, while being relieved of 0.8 feet of water elevation of the south side of its causeway, was subjected to an additional 1.3 feet of lake level on the north side. This additional elevation on the north side of the causeway during hard north-wind-driven storms has had an increasingly adverse affect on the causeway since strong and frequent storms come from the north and heavy north arm (Gunnison Bay) brine causes more damage than the lighter south arm (Gilbert Bay) brine.

Irrespective of the positive and negative effects of the breach, these are minor when compared to the continued rise of the level of the Great Salt Lake which has had profoundly adverse effects on the lake industries. Many millions of dollars have been spent to raise dikes in order to protect critical solar evaporation ponds. In the case of one south arm (Gilbert Bay) industry, because of increased diking costs the lake has reluctantly been allowed to rise above protective dikes and inundate solar ponding facilities. Those industries that have been able to raise their protective dikes have unfortunately also suffered major, unpreventable dike failures which have caused extensive flooding of solar ponds. On June 7, 1986, one of the AMAX Magnesium Corporation's northern perimeter dikes failed during a north-wind-driven storm and their entire solar-

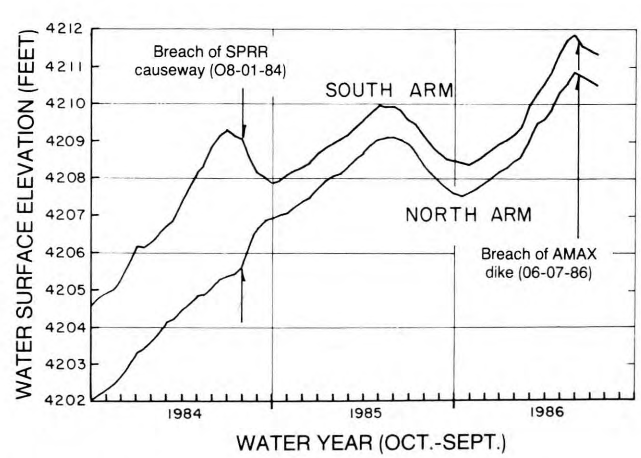

Figure 39. Lake surface elevation vs water year (1984-1986).

ponding system was flooded. The elevation of the south arm of the lake (Gilbert Bay) at that time was 4211.85 feet, which was increased by up to a foot because of wind-tide conditions. During the same storm, the Southern Pacific Railroad had several miles of track destroyed, which closed the causeway to rail traffic for more than a month while the damage was repaired. The lake's north arm (Gunnison Bay) elevation at that time was at a high of 4210.7 feet. Even before the breaching of the causeway, both the AMAX Magnesium Corporation and Great Salt Lake Minerals and Chemicals sustained high-water-related dike failures on May 8, 1983 and on May 5, 1984, respectively. These major industries have or will suffer great losses in the production of salt, concentrated brine, and/or other products for years to come.

SALINITY CHANGES

The major changes in salinity that have occurred within the Great Salt Lake as a result of the breach are: a) a significant density/concentration decrease in the upper north arm (Gunnison Bay) brines due to the large and rapid influx of more dilute south arm (Gilbert Bay) brine, and b) an increase in the density/concentration and volume of the deep south arm (Gilbert Bay) brine (see preceding section on Density Changes).

It was hoped by many that the breach would cause an increase of the salinity of the upper south arm (Gilbert Bay) brine. To date, however, there has not been a significant increase but only a combining and thickening of the deep and transition-zone brines. Because the extractive industries all pull their feed-stock brine from above an elevation of 4186 feet, they still do not have the availability of the deeper brines of greater density. These deep brines would be available if pump intakes and additional intake structures were placed well below the 4186-foot level, although this would be very costly and involve extending intakes out into the lake for a number of miles. It is not known what effect the deep, discolored, hydrogen sulfide-laden brines would have on the quality of salts and brines that would be produced from this deep south arm (Gilbert Bay) brine.

Since the breach, the upper north arm (Gunnison Bay) brine has been diluted from more than 21 percent to about 16 percent. Within the north arm, however, deep, dense brine, exceeding 26 percent TDS, is available at or below an approximate elevation of 4176 feet. If north arm (Gunnison Bay) industries wished to obtain these brines of greater salinity they could, like the south arm (Gilbert Bay) industries, extend their intakes out farther and deeper into the lake.

The concern of the lake's extractive industries over the salinity of the brines involves not only the quantity of salt in a given volume of brine, but also the amount of time that is required to evaporate that brine to the point at which the desired salt(s) will precipitate or brine densities will be achieved. If the salt content of the lake water is reduced by half, then at least twice the volume of brine must be pumped and evaporated to yield the same quantity of salt. This requires more than twice the amount of solar ponding surface area, which is not normally available, or available only at a premium price.

The amount of time required to evaporate the brines down to the point of sodium-chloride saturation (27 percent TDS), or beyond, is also effected by the initial concentration of the brine. As a hypothetical example, if it takes two months to evaporate 10 percent brine up to 27 percent, the point of sodium-chloride saturation, then it may take four months or more to concentrate 5 percent brine to the same concentration. As can be seen, there comes a point at which there is not enough time during the evaporative season, which usually lasts from about May through September, to produce the desired amount (if any) of salt(s) and/or concentrated brines. In the production of high magnesium and potassium brines and salts, which takes a minimum of two years to complete the ponding circuit, another factor plays an adverse time-dependent role, that of pond leakage. If the evaporation of a diluted brine takes too long, the more concentrated brine that is finally produced may simply leak out of the ponding system and back into the lake before it can precipitate the desired salts or be harvested and utilized, thus making the operation futile.

SUMMARY AND CONCLUSIONS

1. The U.S. Geological Survey breach-monitoring program consists of measuring the bidirectional flow of brine through the breach opening while that of the Utah Geological and Mineral Survey consists of measuring changes in the density and chemistry of the lake.

2. Density measurements have shown that the upper north arm (Gunnison Bay) brines have become significantly diluted since the breach, and that the deep south arm (Gilbert Bay) brines have increased in both density and volume. The upper south arm (Gilbert Bay) brine density and that of the deep north arm have remained relatively constant while their volumes have decreased.

3. There is a general linear relationship between the rate of increase in Na, K, Mg, Cl and SO_4 with that of TDS within the lake brines with the exception of the deep, high-density, north arm (Gunnison Bay) brines. In these, the rate of increase of chloride decreases while that of sulfate increases. The same relationships are seen in the dry weight percent data. The increase in sulfate and the corresponding decrease in chloride are related to an enrichment of the deep north arm (Gunnison Bay) brine due to the dissolution of winter-precipitated mirabilite.

4. While the initial changes in lake level brought about by the breach had both positive or negative effects on the extractive industries and on the railroads, the continued rise in the level of the entire lake has, and will continue to have, a severe and costly impact on everyone.

5. The salinity changes within the lake that have been brought about by the breach have not increased the salinity of the feed stock for the south arm (Gilbert Bay) lake extractive industries, and have greatly decreased the salinity of the feed stock of the single north arm (Gunnison Bay) industry.

Although there has been a major shift in the dissolved salt load from the north arm to the south arm of the lake, this may not be of value to south arm (Gilbert Bay) industries until after the level of the lake begins to drop. All industries have been severely impacted by the continued dilution associated with the rising lake level.

6. All lake industries could obtain higher salinity brines than they presently access by moving their pump intake lines farther out into deeper areas of the lake although in the north arm (Gunnison Bay) the quantity of high-salinity brine is limited. This action, however, is very costly. In the south arm of the lake (Gilbert Bay) the effect that the fetid, discolored, deep brine would have on salt operations is not known.

REFERENCES

Bureau of Economic and Business Research, 1983, Actual and potential damages incurred by industries, governments, and other lake users due to the rising level of the Great Salt Lake: Bureau of Economic and Business Research, University of Utah.

Bureau of Economic and Business Research, 1984, Flooding and landslides in Utah: an economic impact analysis: Bureau of Economic and Business Research, University of Utah.

Gwynn, J.W., 1984, Monthly breach monitoring report (July-August, 1984): Utah Geological and Mineral Survey, unpublished interim report.

Gwynn, J.W., 1984, Continuing breach monitoring report (II) (July-October, 1984): Utah Geological and Mineral Survey, unpublished interim report.

Gwynn, J.W., 1985, Continuing breach monitoring report (III) (July-December, 1984: Utah Geological and Mineral Survey.

Katzenberger, W.M., 1975, Navigational chart of the Great Salt Lake, south arm: Utah Geological and Mineral Survey Map 38.

Madison, R.J., 1970, Effects of a causeway on the chemistry of the brine in Great Salt Lake, Utah: Utah Geological and Mineralogical Survey Water-Resources Bulletin 14, 52 pages.

Newby, J.E., 1980, Great Salt Lake railroad crossing *in* Gwynn, J. Wallace, ed., Great Salt Lake, a Scientific, Historical and Economic Overview: Utah Geological and Mineral Survey Bulletin No. 116, p. 393-400.

Sturm, P.A., 1985, Continuing breach monitoring report (IV) (December 1984-July 1985): Utah Geological and Mineral Survey, unpublished interim report.

Sturm, P.A., 1985, Continuing breach monitoring report (V) (August-December, 1985): Utah Geological and Mineral Survey, unpublished interim report.

Sturm, P.A., 1986, Continuing breach monitoring report (VI) (January-April, 1986): Utah Geological and Mineral Survey, unpublished interim report.

Waddell, K.M., and Fields, F.K., 1977, Model for evaluating the effects of dikes on the water and salt balance of Great Salt Lake, Utah: Utah Geological and Mineral Survey Water-Resources Bulletin 21, 54 p.

Waddell, K.M., and Bolke, E.L., 1973, The effects of restricted circulation on the salt balance of Great Salt Lake, Utah: Utah Geological and Mineral Survey Water-Resources Bulletin 18, 54 p.