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EFFECTS OF A CAUSEWAY ON THE CHEMISTRY OF THE BRINE IN GREAT SALT LAKE, UTAH

Prepared by
The United States Geological Survey
in cooperation with
The Utah Geological and Mineralogical Survey

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ABSTRACT

During 1957-59, the Southern Pacific Co. constructed a permeable rockfill causeway to carry its railroad track across Great Salt Lake. The causeway divides the lake into two parts and interrupts the formerly free movement of brine about the lake. The causeway has caused significant changes in the chemistry of the lake, including a dilution of the brine in the south part of the lake and a concentration of the brine in the north part.

Prior to construction of the causeway, the dissolved-solids content and the chemical composition of the lake brine were controlled primarily by volume changes resulting from inflow and evaporation. The causeway created two separate but interconnected lakes with different water-surface elevations and densities. As a result, brine flows in both directions through the causeway, with less dense brine from the south part moving northward through the upper part of the causeway and more dense brine from the north part moving southward through the lower part of the causeway. The chemistry of the lake is now controlled by the interchange of dissolved-solids load through the causeway, as well as by changes in the salt crust and by volume changes.

The net movement of dissolved-solids load through the causeway will be dependent upon the relationship between the ratio of water discharges in each direction and the concentration of dissolved solids. Estimates made for the 1969 water year indicated that the ratio of total flow northward to total flow southward was about 11:1 through the culverts and about 3:1 through the causeway fill. Discharge through the culverts accounted for about 45 percent of the total brine moving northward but only about 15 percent of the total brine moving southward. The estimated net movement of dissolved-solids load through the causeway during the 1969 water year was about 210 million tons northward.

The small amount of data available for the period from 1963 to 1969 indicates continued loss in dissolved-solids load from the south part of the lake to the north part. Whether or not this load loss will continue in the future depends on what happens to the ratio of flows through the causeway. Although some limits can be placed on the possible range of these ratios, their interrelationships with other parameters of lake hydrology are extremely complex. More precise definition of the effects of the causeway on future lake hydrology will require the collection of additional field data and the analysis of all available data, preferably with the aid of a model.

INTRODUCTION

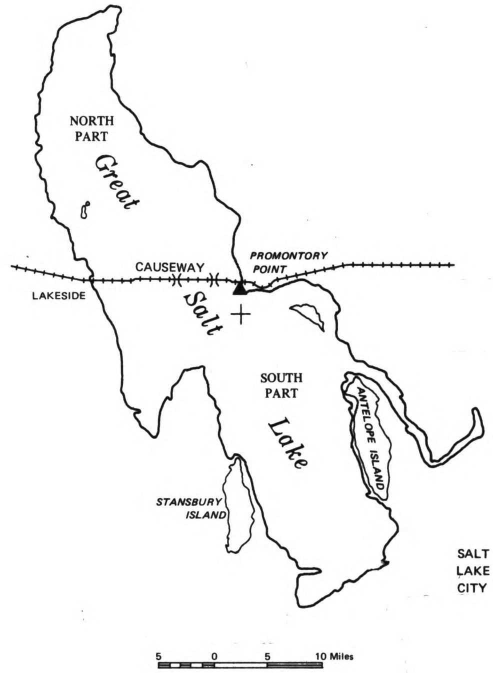
The division of Great Salt Lake, Utah, into two parts by a causeway has caused significant changes in the chemistry of the lake, and it is desirable to know whether these changes will persist or will be modified by time and changing events.

A preliminary study of the chemistry of the lake in the immediate vicinity of the causeway was conducted from 1967 to 1969 by the U. S. Geological Survey as part of a continuing cooperative program with the Utah Geological and Mineralogical Survey. The purpose of the study was to try to define the movement of brine through the causeway and the effects of this movement on the chemistry of the lake. This report will discuss briefly the hydrology of the lake prior to the construction of the causeway, the factors which now control the chemistry, and the possible long-term effects which the causeway may have on the mineral content of the lake.

During 1957-59, the Southern Pacific Co. constructed the causeway for its railroad track across Great Salt Lake. The causeway traverses the lake in an east-west direction from Promontory Point to Lakeside (figure 1), where the lake is about 18 miles wide. Approximately 13 miles of this distance is covered by the causeway fill emplaced in 1957-59; and an older fill, constructed in the early 1900's, abuts each end of the newer fill. The older fill, which has a total length of about 5 miles, formed the approaches to a trestle which crossed the lake before the new fill was emplaced.

The causeway was constructed by dredging a channel 25-40 feet deep and 150-500 feet wide to remove bottom muds. The channel was then backfilled with sand and gravel. The causeway was raised above the lake surface with quarry-run rock and finished with riprap varying in size from 1-ton capstone 15 feet below the surface to 3-ton capstone at the top (Cohenour and others, 1963, p. 16). The causeway is permeable and is also breached by two open culverts, each 15 feet wide,

SOUTHERN PACIFIC CO. CAUSEWAY. SOUTH PART OF LAKE IN FOREGROUND



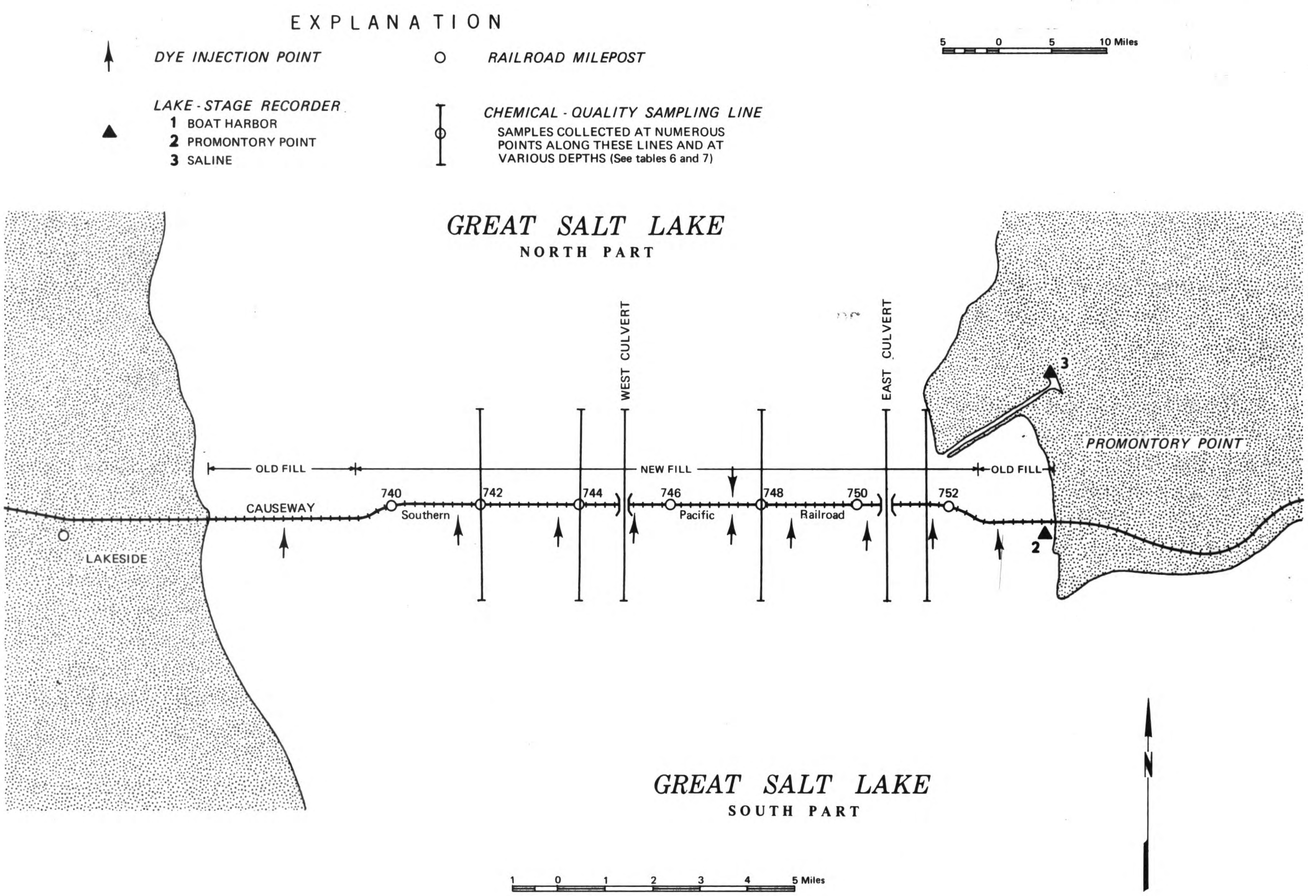


Figure 1. Map of Great Salt Lake showing location of causeway, chemical-quality sampling lines, and dye-injection points.

which allow brine to flow through the causeway (see figure 2). The culverts were placed where the lake is deepest. The bottoms of the culverts are about 10 feet above the lake bottom, but the bottom of the east culvert is about 4 feet lower than that of the west culvert.

Although brine moves through the permeable fill and the culverts, the causeway acts as a partial dike dividing the lake into north and south parts. A little more than one-third of the lake lies north of the causeway. The causeway interrupts the formerly free movement of brine within the lake. This, along with the fact that more than 95 percent of the fresh-water surface inflow enters the lake south of the causeway, has resulted in substantial changes in the hydrology and chemistry of the lake. Hahl and Handy (1969) made a fairly detailed study of the chemistry of the lake and pointed out some of the basic changes that had taken place in the lake–the brine in the south part had become more dilute, the brine in the north part had become more concentrated, and a salt crust of undetermined thickness and extent had been precipitated on the bed of the lake in the north part.

A sampling network was established to define any chemical changes taking place in the immediate vicinity of the causeway (figure 1), and samples for chemical analysis were collected at high and low lake stages and during evaporation and inflow periods. Results of these analyses are given in tables 6 and 7 (appendix C). Measurements of flow in the culverts were made 15 times from October 1968 to September 1969. During late 1969, a dye tracer study was made in an attempt to define brine movement through the permeable fill (appendix A).

The collection of data for the investigation was greatly facilitated by personnel of the Southern Pacific Co., who allowed access to the causeway and provided other assistance on many occasions. Special thanks are due Mr. Lee Schaub of the Ogden Office of the Southern Pacific Co., without whose excellent cooperation the investigation could not have been accomplished.

HYDROLOGY OF THE LAKE PRIOR TO CONSTRUCTION OF THE CAUSEWAY

Prior to 1957, the hydrologic characteristics of Great Salt Lake were typical of a closed lake. The lake stage (altitude of water surface) rose or fell over a period of several years in response to the balance between the amount of water evaporated from the surface and the amount of water contributed to the lake by surface runoff, ground-water inflow, and precipitation on the surface. During periods of falling lake stages, surface area and volume decreased and concentration of dissolved solids increased; conversely, during rising lake stages, surface area and volume increased and concentration decreased.

In addition to long-term changes–because of a series of wet or dry years–the stage, surface area, volume, and concentration were continually changing because the period of maximum inflow differs from the period of maximum evaporation. At lake stages below about 4,195 feet above mean sea level, the concentration of sodium chloride reached saturation and salt was precipitated. When lake stages again rose, the precipitated salt was redissolved.

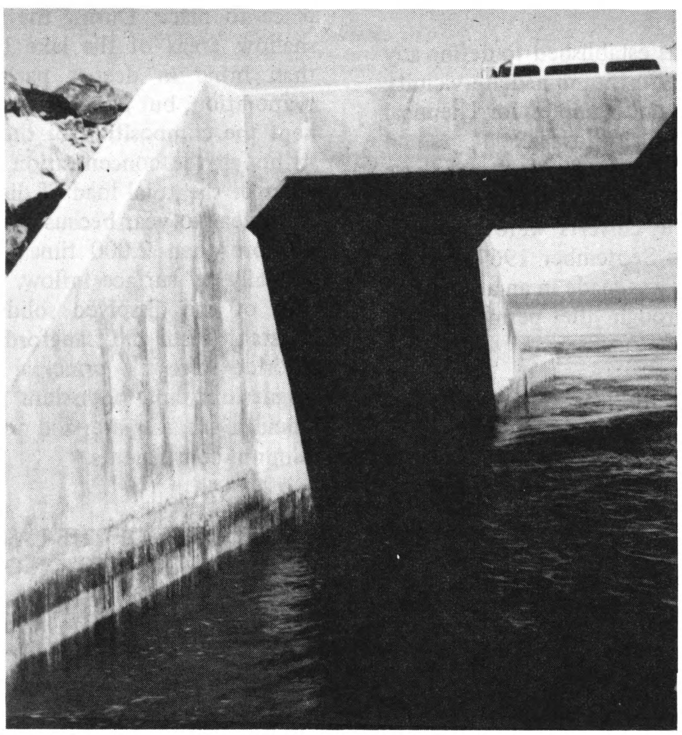
Before the causeway was constructed, the dissolved-solids concentration in all parts of the lake probably was generally similar, although differences in inflow, evaporation, currents, wind, and density have always caused some variation in the concentration from place to place. During the summer, brine in the large shallow areas of the lake became more concentrated than brine in deeper parts of the lake because of evaporation; but periodic mixing during storms probably kept the composition of the lake water fairly uniform. Although the concentration varied with lake stage and volume, the total load of dissolved solids changed little from year to year because the total salt load in the lake is more than 2,000 times the amount of salt added annually by surface inflow. The relative ionic composition of the dissolved solids also remained relatively constant (Hahl and Langford, 1964, p. 25); sodium and chloride were the principal constituents, with sulfate, magnesium, and potassium present in lesser amounts. Calcium, bicarbonate, and other substances were present as minor constituents.

HYDROLOGY OF THE LAKE AFTER CONSTRUCTION OF THE CAUSEWAY

Initial Sequence of Events

During 1959, the average lake stage was about 4,195.5 feet above sea level. At this stage, the original undivided lake would have contained about 350 g/l (grams per liter) of dissolved solids and would have been at or near saturation with respect to sodium chloride. When the causeway was closed, the south part of the lake was diluted because almost all the fresh-water inflow was entering south of the causeway. The north part of the lake remained near saturation because its major inflow was brine flowing through the causeway

A. Overall view of the causeway across Great Salt Lake. Dark line on left side of photograph at the base of the mountains on the western margin of the lake is the trestle of the former railroad crossing. (Photograph by D.C.Hahl, 1964.)



B. View of one of the culverts in the causeway. Depth of water in culvert is about 10 feet. Upper few feet of water is moving northward away from viewer; lower lower few feet is moving southward. (Photograph by D.C.Hahl, 1964.)

Figure 2. Causeway across Great Salt Lake and one of the culverts in the causeway.

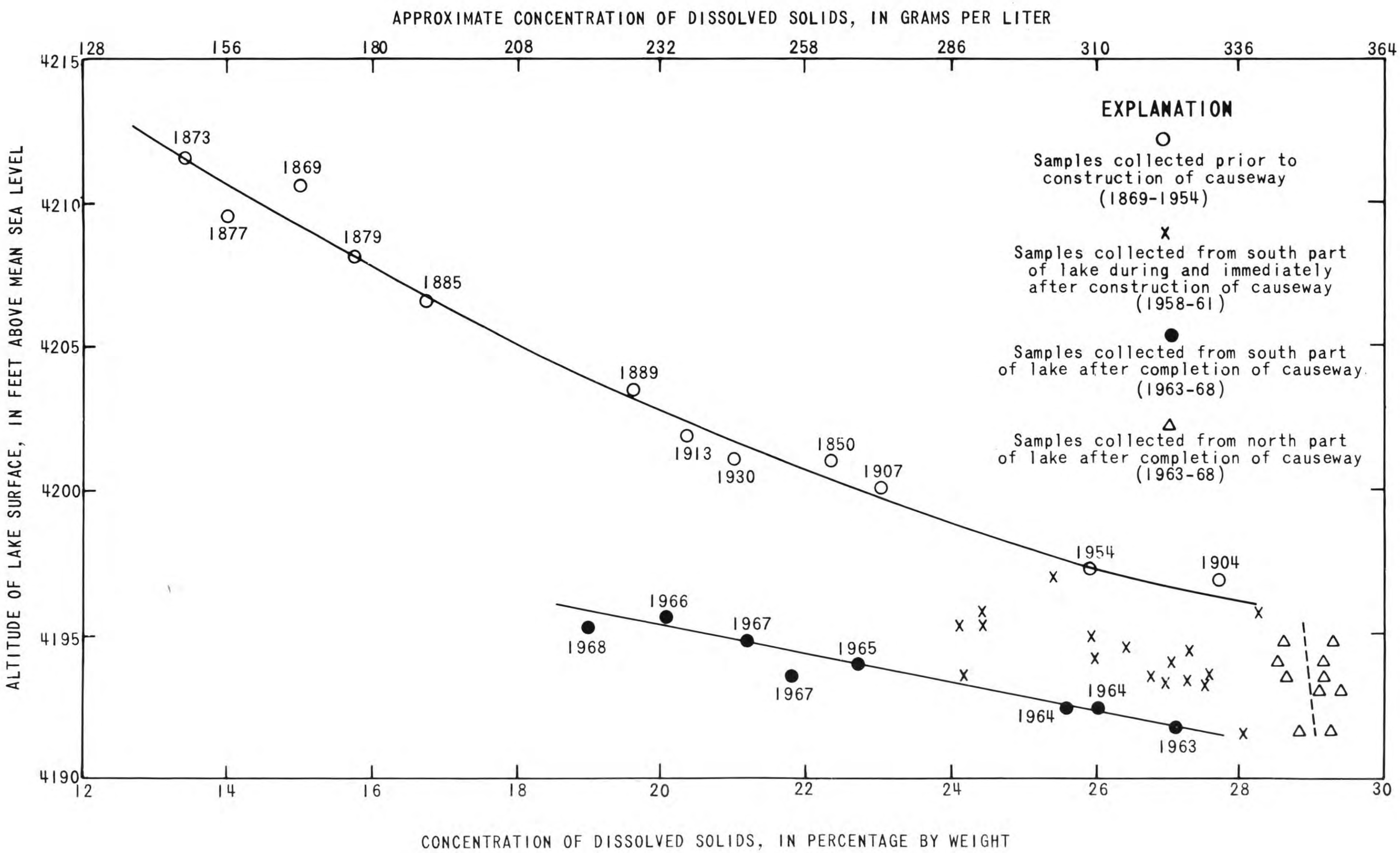


Figure 3. Relationship of dissolved solids concentration to stage of Great Salt Lake.

from the south part, and evaporation during the seasonal lake cycle was sufficient to further concentrate the brine (figure 3).

Because the causeway acts as a partial dike and because most of the inflow is to the south part, a difference in water-surface altitude across the causeway developed, with the south side being higher (figure 4). As a result of this altitude difference, the less concentrated brine in the south part moves northward through the upper part of the culverts and fill. Because this brine is less dense, it spreads out over the surface of the north part in a thin sheet and eventually is mixed by wave action. During certain times of the year, when the lake is calm and temperatures are high, some of this less concentrated brine may evaporate before mixing occurs.

Concurrently, the difference in densities (concentration of dissolved solids) between water in the two parts of the lake causes a density head, and the more dense water in the north part moves southward through the bottom section of the culverts and through the fill. Some mixing probably occurs at the interface as brine moves through the causeway, but most of the southward flow drops to the bottom of the south part of the lake and forms a lower layer of brine that is of greater concentration than the rest of the brine in the south part and slightly less concentrated than the brine in the north part.

At lake stages between 4,194 feet and 4,197 feet, the lower layer of brine in the south part is about 20 feet below the lake surface. Data collected during this study and by Hahl and Handy (1969, figure 1) indicate that the lower layer of brine will be found in all parts of the lake where the lake bottom is below an altitude of about 4,175 feet (figure 5). The volume of the lower layer of brine appears to remain relatively constant. Samples collected from the lake within a day or two after severe storms indicate that this lower layer of brine does not mix rapidly with the less dense upper layer of brine, even with violent wave action. Mixing probably takes place slowly at the interface. The apparent stability of the lower layer of brine is probably due to the fact that a rough equilibrium exists between the amount of brine moving south through the causeway and the amount of mixing taking place at the interface. In the discussions that follow in later sections of this report, it is assumed that this equilibrium exists. Figure 6 shows the three brine zones and the movement of brine as inferred in and near the causeway.

From 1959, when the causeway was completed, until 1963, the lake stage continued a downward trend that had begun in 1952. In 1963, the lake reached an historic low stage of 4,191.35 feet above mean sea level. At this stage the original undivided lake would have reached saturation, and large quantities of sodium chloride probably would have precipitated over the entire lakebed. At some time during the period 1954-63, therefore, a salt crust of undetermined thickness and extent probably formed on the lakebed north and south of the causeway.

The rise in lake stage after 1963 caused a decrease in the concentration of the brine in the south part. If indeed salt had previously been precipitated on the lake bottom, some of the precipitated salt in the south part probably redissolved. However, while the concentration of the brine in the south part was decreasing, the more dense brine in the north part was moving southward through the causeway to form the deeper layer in the south part. Thus some of the precipitated salt may have been trapped under this deeper layer of nearly saturated brine and prevented from redissolving.

The salt crust north of the causeway could not redissolve because it was already covered by nearly saturated brine.

The total amount of salt that has precipitated on the lakebed is not known, but it may be as much as 25 percent of the salt that was in solution prior to the construction of the causeway. Hahl and Langford (1964, p. 25) report that the approximate total load of dissolved salt in both parts of the lake during 1959-61 was 4.4 billion tons. This compares with about 6 billion tons when the lake was at its highest recorded stage in 1873 (Handy and Hahl, 1966, p. 140) and about 5.4 billion tons in 1954. Very rough estimates made in 1969 on the basis of only a few chemical analyses gave a total load of dissolved salt for the entire lake of about 4.2 billion tons.

Apparently not a great deal of additional salt has precipitated since 1961. With the rising lake levels that have occurred since 1963, the south part (exclusive of the lower layer) has remained more dilute than the original undivided lake would have been for the same stage, while the north part has remained at or near saturation (figure 3).

Although there are several mechanisms for the loss of salt from solution in closed lakes (Langbein, 1961, p. 10) and some lost salts are not available for re-solution, probably at least half of the salts lost during the period 1954-63 remains in a salt crust on the lakebed (B. F. Jones, oral commun., 1970).

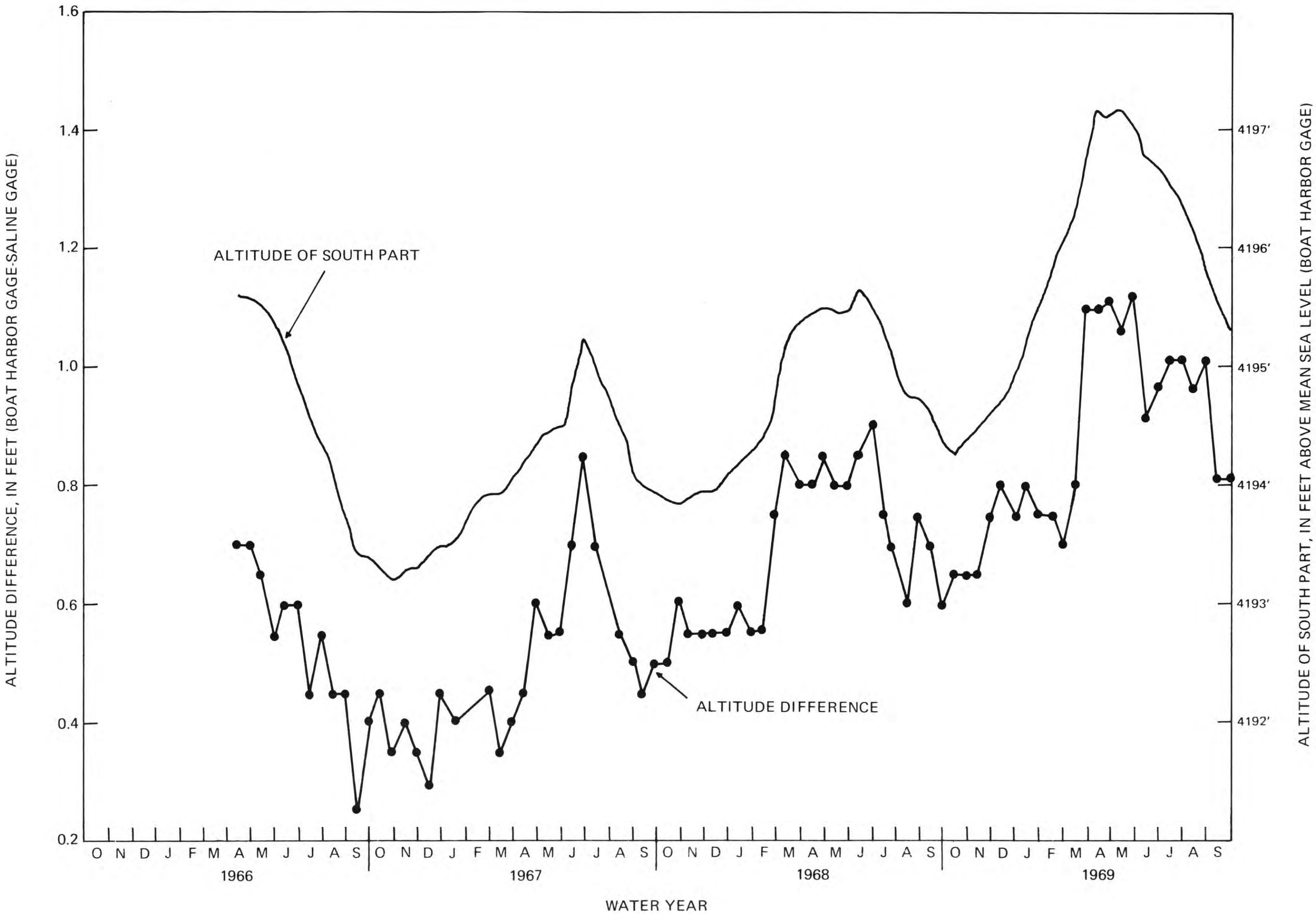


Figure 4. Variation in stage difference between north and south parts of Great Salt Lake.

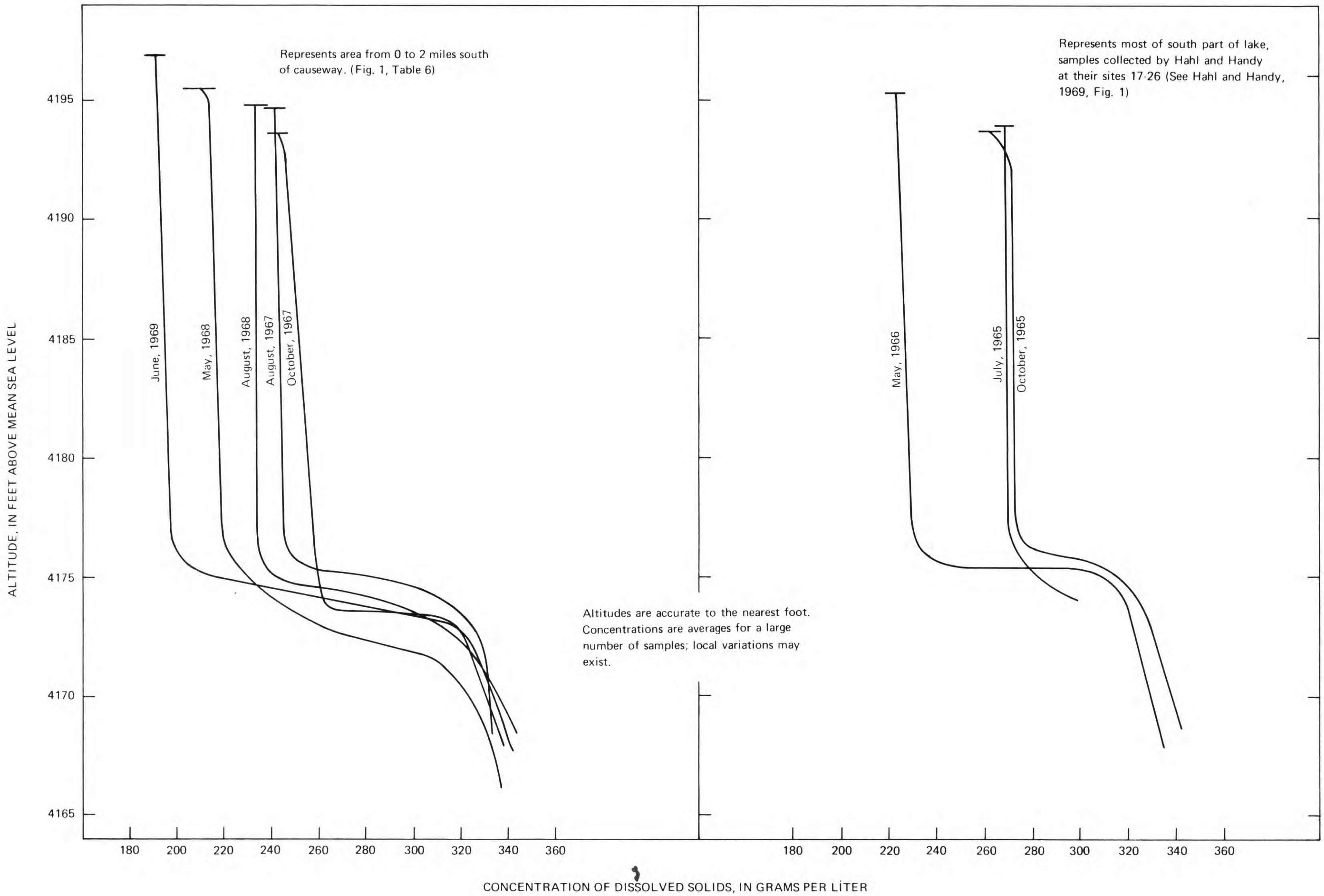


Figure 5. Approximate concentration gradients for south part of Great Salt Lake.

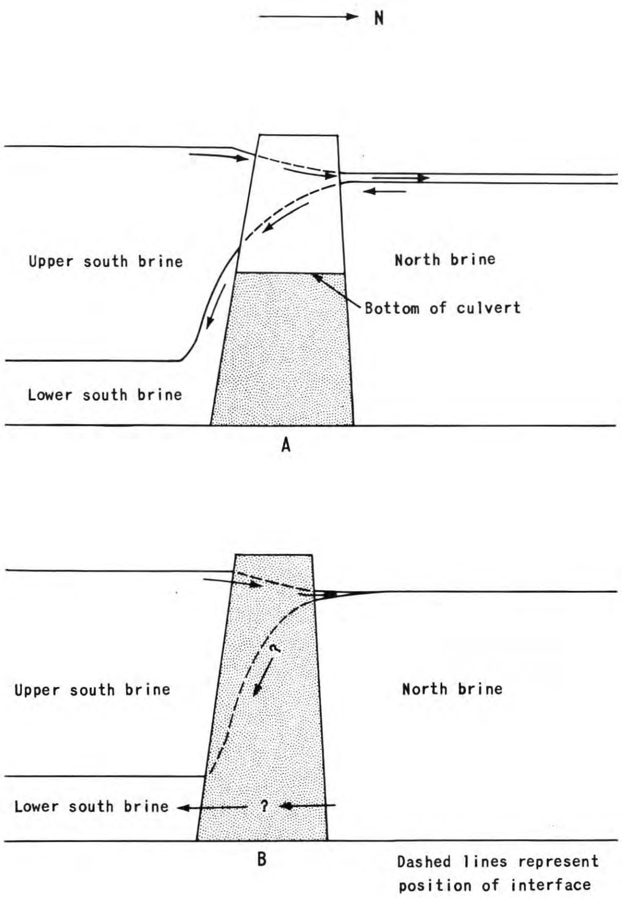


Figure 6. Schematic drawing of Southern Pacific Co. causeway showing (A) direction of flow through the culverts and (B) probable direction of flow through the permeable fill. Figures are not representative of quantities of discharge.

Trends Since 1963

Although the lake is divided into two parts, each with an outlet through the causeway, the lake as a whole is still a closed lake with no outlet. The fresh-water inflow carries a relatively insignificant amount of dissolved salt, thus the total load of salt in the lake does not change significantly over a period of a few years. However, the total dissolved-salt load and the chemical composition of each part may change because of interchange of load through the causeway and because of precipitation or solution of the salt crust.

Dissolved Solids

A change in concentration of dissolved solids in either part of the lake may be considered as the change in dissolved-solids load divided by the change in volume. Volume changes resulting from inflow and evaporation can create seasonal changes in the dissolved-solids concentration in the south part of the lake. Long-term changes in lake stage and volume (related to climatic cycles) will cause corresponding changes in dissolved-solids concentration. Figure 7 shows a comparison between the actual dissolved-solids concentration in the south part for the period 1964-69 and the theoretical dissolved-solids concentration if volume change had been the only factor.

The concentration in the south part, however, also can increase or decrease over a period of several years, depending on the net exchange of load of dissolved solids through the causeway. The net exchange of load through the causeway is dependent upon the relationship between the ratio of discharge in each direction and the ratio of the concentration of dissolved solids in the water. This relationship may be expressed by the equation:

$$L = V_I C_I - V_O C_O$$

L = Net exchange of dissolved-solids load

V_I = Volume of brine discharging into the north part from the south part through the causeway

C_I = Average concentration of V_I

V_O = Volume of brine discharging out of the north part into the south part through the causeway

C_O = Average concentration of V_O

If, for instance, the ratio of discharge was equal to the inverse of the ratio of concentrations,

$$\left(\frac{V_I}{V_O} = \frac{C_O}{C_I}\right)$$

then net exchange of load (L) would be zero ($V_I C_I - V_O C_O = 0$); and concentration of the south part would be strictly a function of volume change. If V_I/V_O is greater than C_O/C_I, then net load movement will be to the north; and the concentration of the south part for a given lake stage (volume) will decrease with time. If V_I/V_O is less than C_O/C_I, net load exchange will be to the south and the south part will gain concentration for a given lake stage.

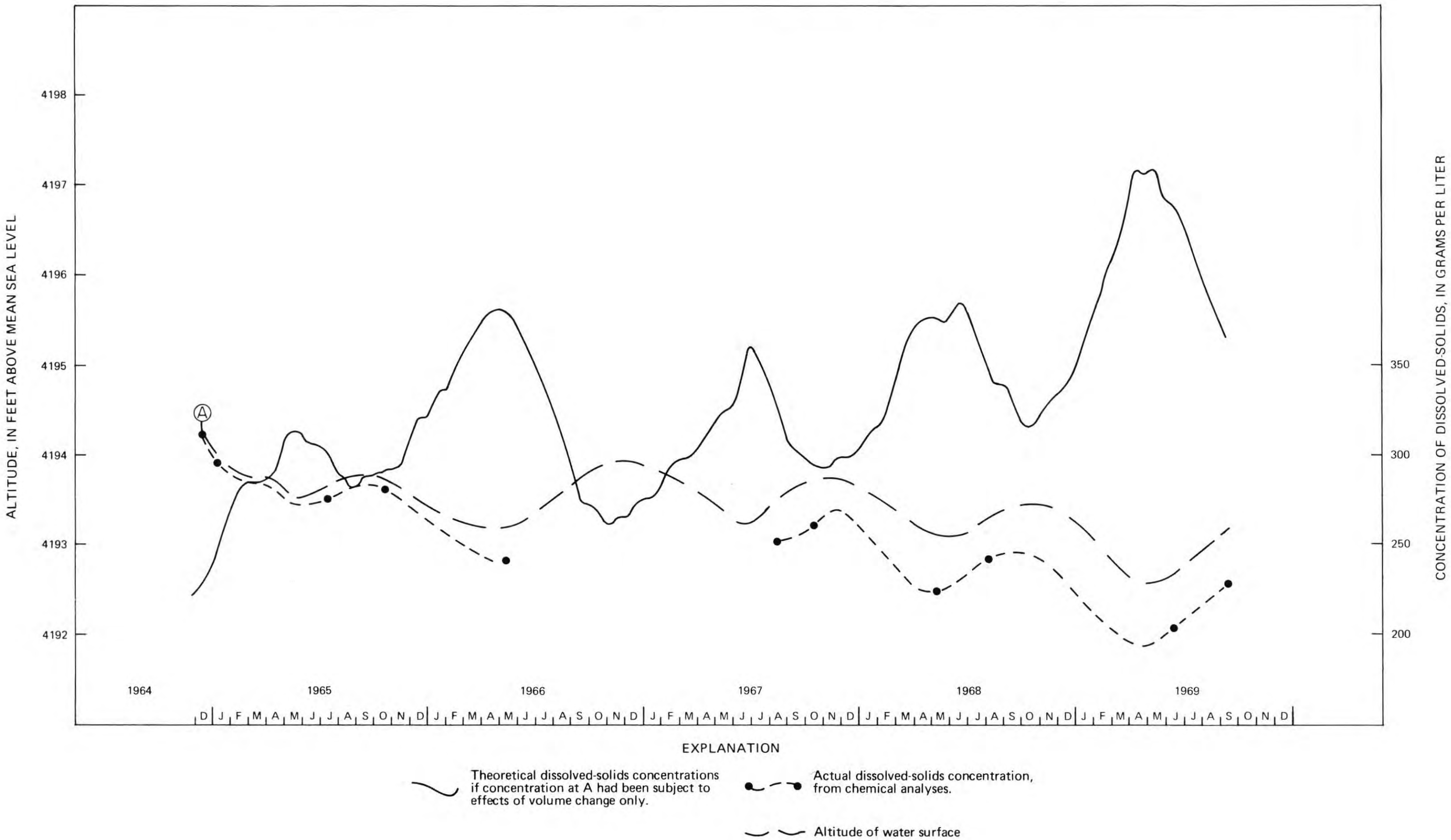


Figure 7. Altitude and actual and theoretical dissolved-solids concentration of water in south part of Great Salt Lake.

In the north part of the lake, the concentration of dissolved solids does not change significantly with season or lake level. The major dissolved ions, sodium and chloride (about 85 percent of the total), apparently are in equilibrium with the salt crust (Hahl and Handy, 1969, p. 15). Assuming that stratification does not occur, the north part will remain at a nearly constant concentration as long as the salt crust is not totally dissolved.

Some of the inflow to the north part may evaporate before it mixes with the more dense brine in the north part. That part of the brine from the south part which does mix, however, temporarily reduces the concentration of the water in the north part below the saturation concentration for sodium chloride. However, the brine then redissolves a small amount of salt crust and again returns to the saturation concentration. During the season of high evaporation, the rate of evaporation exceeds the rate of inflow and salt is precipitated, adding to the salt crust. The net change in the amount of salt crust depends on the amount dissolved during inflow periods compared to the amount precipitated during evaporation periods.

Chemical Composition

The brine of the lake, prior to the construction of the causeway, had a nearly uniform chemical composition. When large amounts of sodium chloride precipitated from solution, however, the ratio of ions in solution changed significantly. Because sodium (Na) and chloride (Cl) were the only ions to precipitate in any quantity, the percentage of the other ions in solution with respect to sodium and chloride increased.

The chemical composition can be affected temporarily due to the precipitation of Glauber's salt ($Na_2SO_4 \cdot 10H_2O$) during the winter months; however, this salt is redissolved each spring as the lake warms, and there is no net change in ratio of ions in solution.

The south part of the lake now receives almost all the fresh-water inflow that previously fed the entire lake. However, the fresh-water inflow still does not significantly affect the ionic ratios in the south part because the total amount of dissolved ions in the fresh-water inflow is still extremely small compared to that in the brine (Madison, 1969, p. 142). The ratio of ions in solution in the south part is now dependent primarily on the interchange of load of dissolved ions through the causeway. For example, the ratio of the concentrations of magnesium (Mg) to chloride (Cl) in the south part at the end of any stipulated period of time will be:

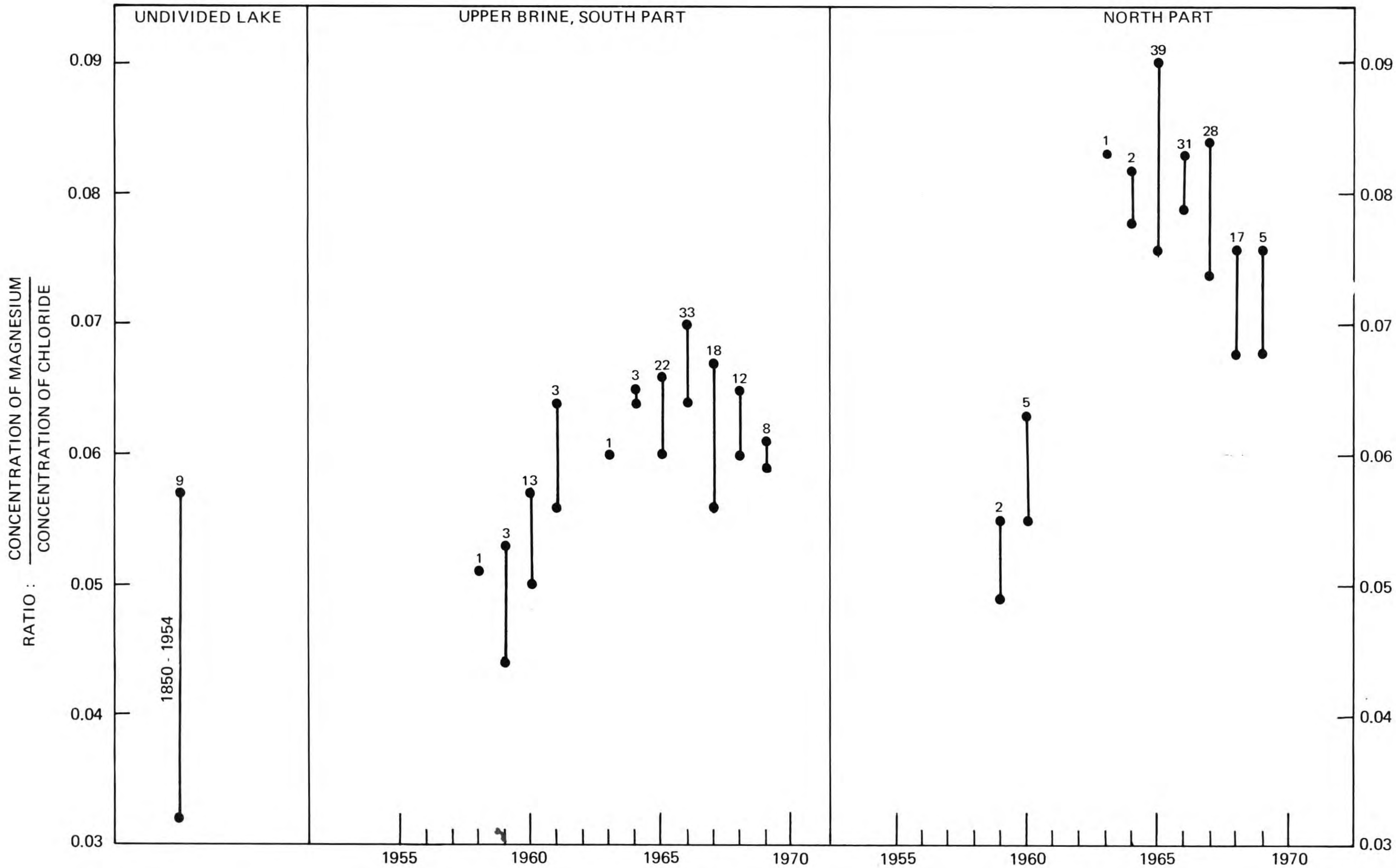
(Initial load Mg + load Mg gained from north part − load Mg lost to north part) ÷ (Initial load Cl + load Cl gained from north part − load Cl lost to north part) *or* (Initial load Mg ± net change in load of Mg) ÷ (Initial load Cl ± net change in load of Cl).

As was the case with dissolved solids, the net movement of individual ions through the causeway is dependent on the ratio of the discharges in each direction and the ratio of concentrations of the ions.

In the north part of the lake, the concentrations of sodium and chloride remain essentially constant regardless of load exchange, because the concentration is kept at or near saturation with respect to these ions as a result of precipitation or solution of the salt crust. Thus, the ratio of any other ion to sodium or chloride (for example, magnesium to chloride) will change primarily in response to changes in concentration of the other ion (magnesium). If the net movement of magnesium load through the causeway is to the north, then for a given lake stage the magnesium-chloride ratio will increase because the magnesium concentration will increase even though the chloride concentration remains constant. The magnesium-chloride ratio in the north part can also change with volume changes even if net movement of magnesium load through the causeway is zero. This can occur because volume change will change the concentration of magnesium but not that of chloride, which remains constant as indicated above.

Figure 8 shows the ratio of magnesium to chloride for samples collected before and after construction of the causeway. The data for 1967-69 are mostly from samples collected within 2 miles of the causeway. However, a comparison of these data with data from a few samples collected simultaneously at other points in the south part of the lake showed no significant areal differences in magnesium-chloride ratios.

The variations in the magnesium-chloride ratios shown in figure 8 are due partly to precipitation of salt and partly to interchange of brine through the causeway. Data are not available at the present time (1969) to define how much of the change in ionic ratios has been the result of salt precipitation and how much the result of interchange through the causeway.



EXPLANATION

Range of mg/cl ratios in all samples collected; number shows total number of samples.

Data prior to 1967 from Hahl and Mitchell (1963) and Hahl and Handy (1969).

Figure 8. Ratio of magnesium to chloride in samples collected from Great Salt Lake before and after construction of the causeway.

Other long-term complex chemical processes, such as interaction of dissolved ions with carbonate and silicate sediments, will affect the ionic ratios. These processes may be negligible over a few years, but they should be considered in long-term projections of changes in brine chemistry.

MEASUREMENT OF DISCHARGE THROUGH CAUSEWAY AND ESTIMATES OF LOAD MOVEMENT DURING 1969 WATER YEAR

In order to evaluate the effects of the causeway on the lake hydrology, it is necessary to know something about the total quantities of water and dissolved solids moving in each direction through the causeway. During the 1969 water year (October 1968-September 1969), measurements were made of discharge through the culverts and estimates were made of discharge through the fill. These data together with the concentration were used to calculate the load movement for the year and to define relationships, if any, between discharge and lake stage and stage difference across the causeway.

Discharge through the Culverts

Discharge in the culverts was measured by standard U. S. Geological Survey stream-gaging techniques. Velocity profiles were measured at four points across the cross section of the culverts (figure 9). From these profiles and the areas of the measuring sections, a total discharge in each direction through the culverts was computed. Because the water moves in both directions in the culverts, turbulence occurs at the interface. The water surface in the culverts is not static and may surge as much as 1 foot during a measurement. For these reasons, the accuracy of the measurements of discharge is considered only fair.

A total of 17 measurements, covering one seasonal range of lake stage was made in the east culvert (figure 1). Fourteen measurements were made in the west culvert, covering about three-fourths of the seasonal lake cycle (table 1). At some time between July 15 and August 7, one or more railroad carloads of fill material were accidently dumped into the west culvert, and flow through that culvert was eventually reduced to seepage through the dumped material.

The water-surface elevation on each side of the causeway at the culverts was measured with a stadia rod and engineer's transit at the time of each discharge measurement. However, because of wave action at the edge of the fill, the elevation measurements were found to give only a general indication of the average elevation difference across the causeway during the discharge measurements. Average elevations obtained from the two lake-level recorders at the east end of the causeway (figure 1 and table 5) were considered to be more representative than the stadia-rod measurements. Density readings were also taken at various depths at the midpoint of the culverts.

The measurements in the culverts showed that the discharge northward was almost always much greater than the discharge southward. With the exception of the measurement of March 4, 1969, the lowest ratio of northward to southward discharges in the east culvert was about 4:1. During the peak of the inflow season in April, there was no southward discharge at all through the culverts. The measurement made on March 4 is not representative of average conditions, but it does show what can occur during storm periods. At the time this measurement was made, the lake was very turbulent from storm activity; and a very strong wind was blowing from the north, giving an added impetus to the southward discharge.

Southward discharge was observed through the west culvert only during storm periods. The bottom of the culvert is approximately 4 feet higher than the bottom of the east culvert, and it is only slightly higher than the point at which the interface usually was found in the east culvert. Unless the interface between northward and southward flow varies by a much greater amount than it did during 1969 (about 2 feet), southward discharge through the west culvert will probably occur only during storm periods.

Discharge through the culverts accounted for about 45 percent of the total brine moving northward through the entire causeway but only for about 15 percent of the total brine moving southward.

An analysis of the data collected during the 1969 water year shows a fair relationship between discharge through the culverts and difference in lake stage across the causeway (figure 10). The discharge northward increased with increasing difference in lake stage, whereas the discharge southward showed very little change with changes in stage difference.

For the one seasonal lake cycle for which data are available, the stage difference across the causeway appears generally to be related to the stage of the south part of the lake (figure 11). The difference in lake stage tends to increase with increasing lake stage. However, the relationship shown in figure 11 is too general to be used to predict the discharge through the causeway on the basis of lake stage.

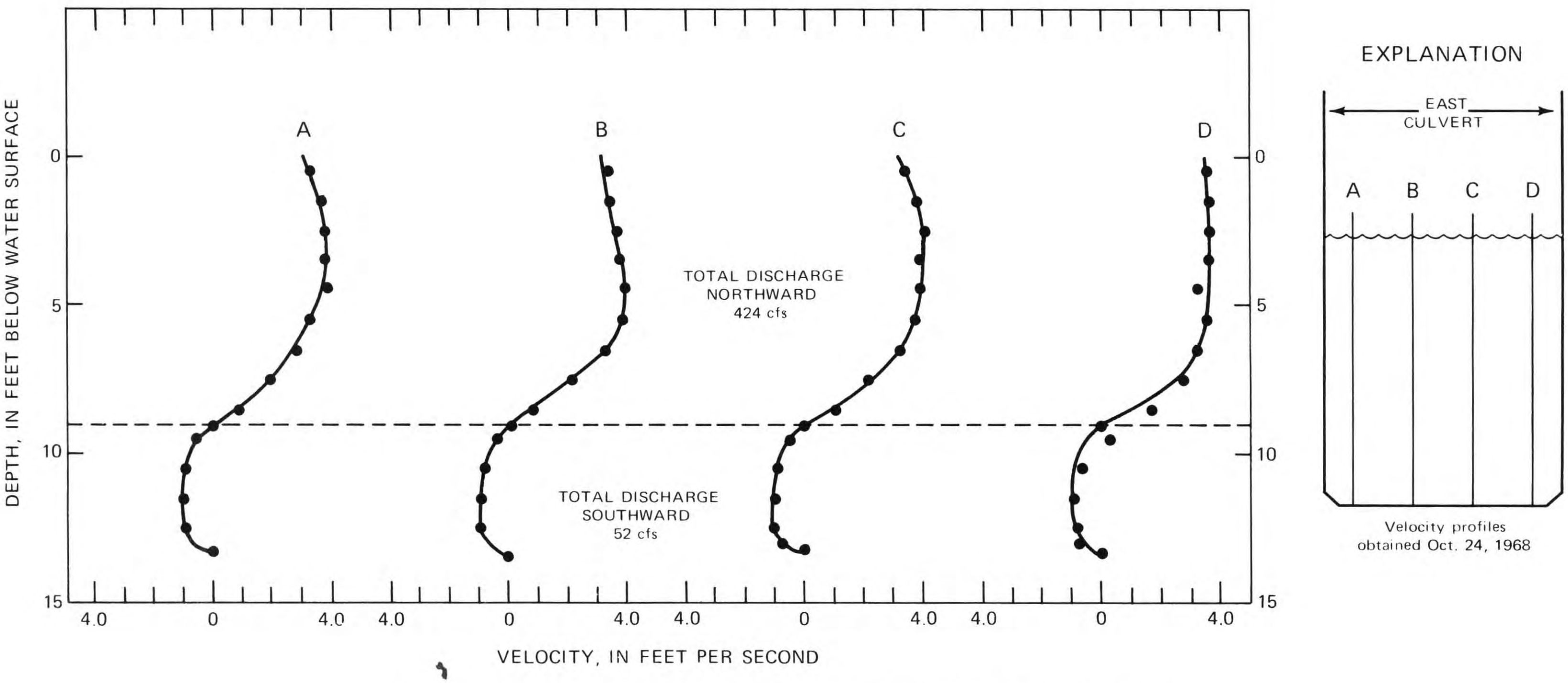


Figure 9. Representative velocity profiles for discharge in the east culvert.

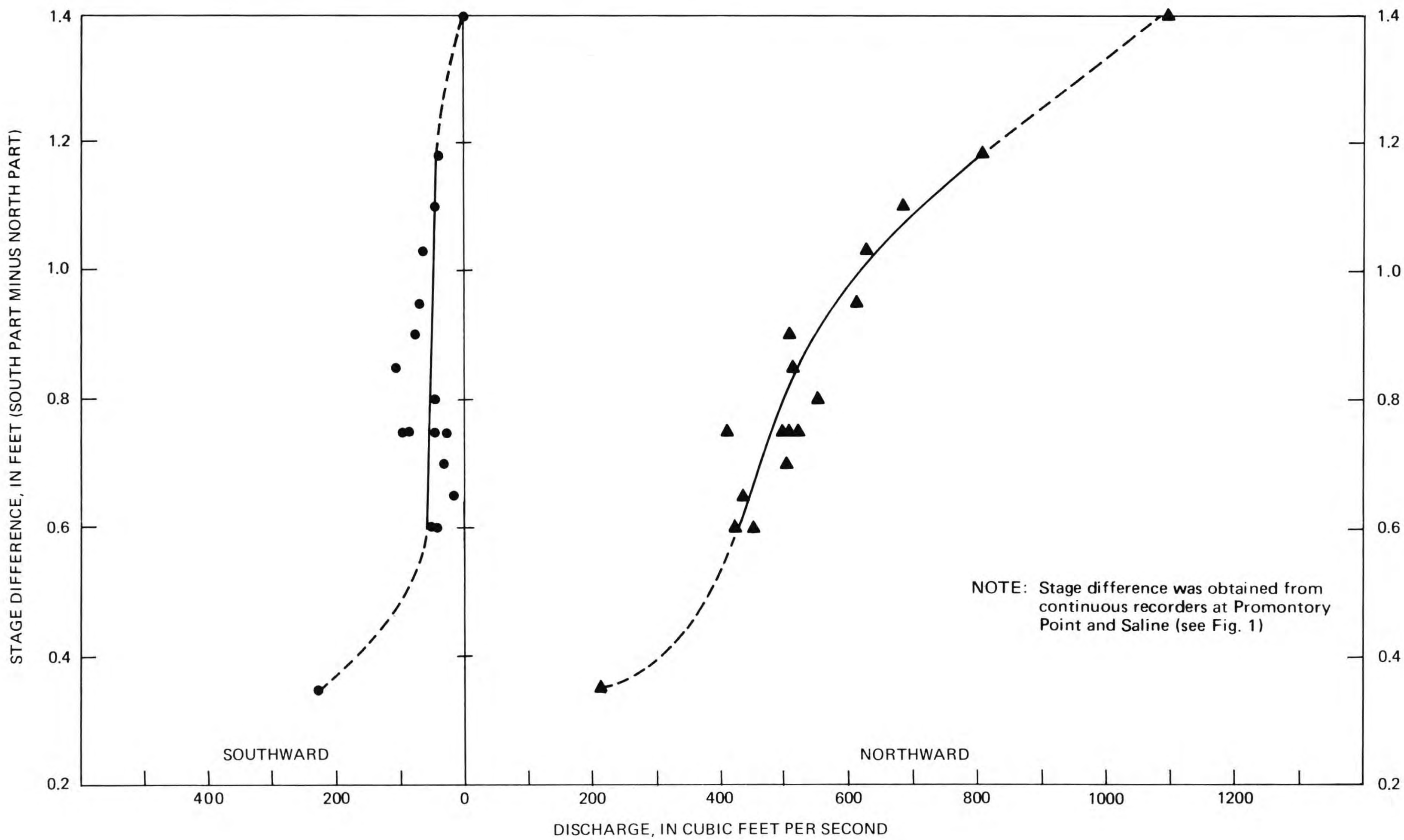


Figure 10. Relationship of discharge in the east culvert to stage difference across the causeway.

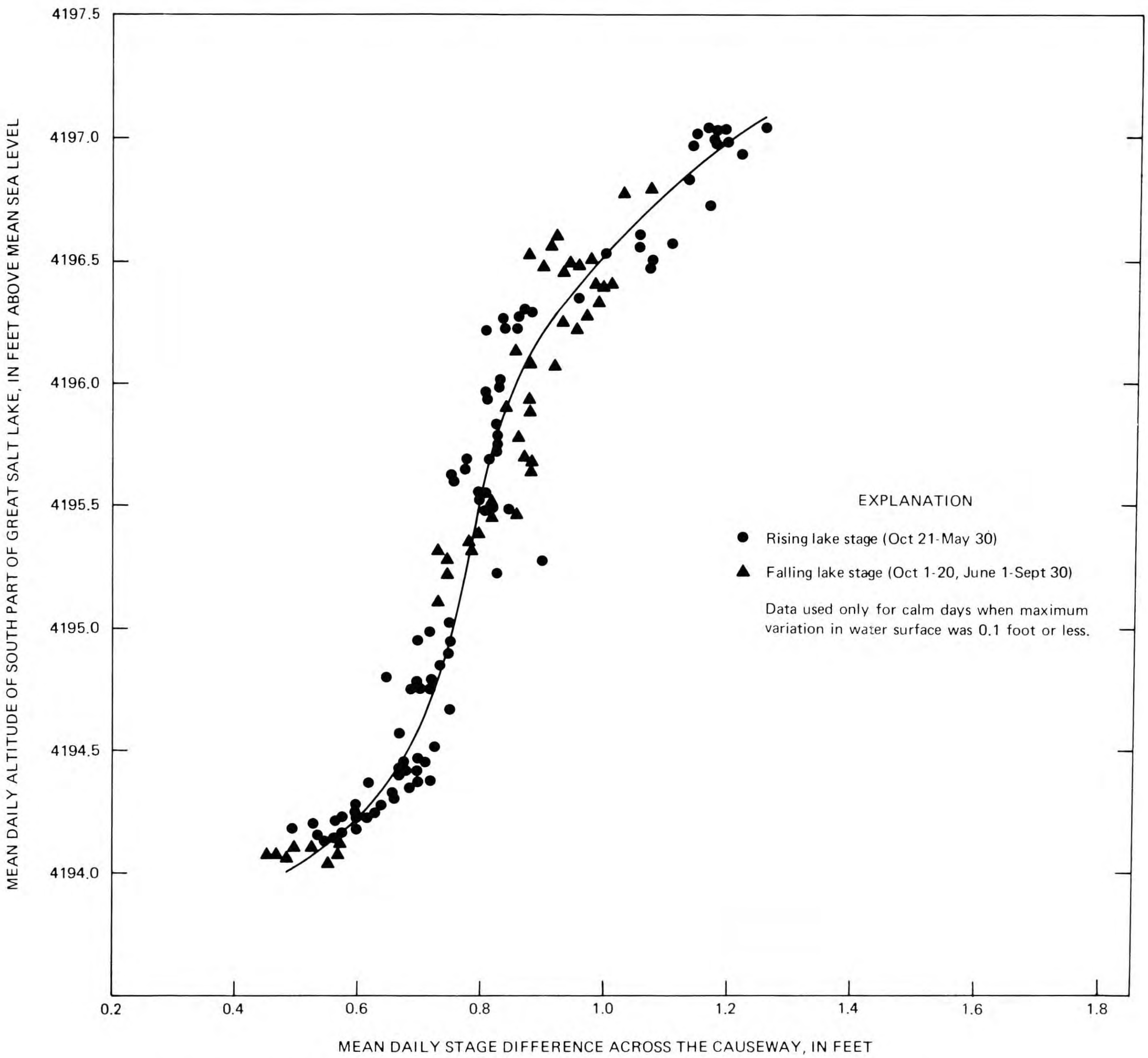


Figure 11. Relation of lake stage difference across the causeway during 1969 water year.

Table 1. Data from discharge measurements made in east and west culverts of Southern Pacific Co. causeway.

Date	East culvert					West culvert				
	Measured stage difference (ft)1/	Depth to interface (ft)2/	Discharge northward (cfs)	Discharge southward (cfs)	Ratio of northward to southward discharge	Measured stage difference (ft)	Depth to interface (ft)	Discharge northward (cfs)	Discharge southward (cfs)	Ratio of northward to southward discharge
10-24-68	0.82	9.0	424	52	8:1	0.70	None	450	0	-
11-15-68	-	9.5	453	41	11:1	-	do	484	0	-
12- 5-68	.82	10.0	503	32	16:1	.98	do	547	0	-
12-17-68	-	-	-	-	-	-	do	378	0	-
1- 7-69	.68	10.5	438	18	24:1	.64	do	386	0	-
1-16-69	.88	10.5	521	28	19:1	.65	do	405	0	-
2- 5-69	.84	10.0	500	43	12:1	.77	do	550	0	-
2-18-69	.77	10.5	556	42	13:1	.89	do	584	0	-
3/3- 4-69	-	7.0	213	226	0.9:1	.28	8.0	238	44	5:1
3-26-69	1.16	11.5	684	43	16:1	1.15	None	706	0	-
4-23-69	1.53	None	1,100	0	-	1.56	do	1,010	0	-
5-13-69	1.17	12.0	810	40	20:1	1.13	do	4/738	0	-
6- 4-69	1.12	10.5	627	62	10:1	1.06	do	4/420	0	-
6-17-69	1.04	9.5	514	104	5:1	-	-	-	-	-
7-15-69	1.03	10.0	614	71	9:1	1.15	None	4/110	0	-
8- 6-69	-	9.5	504	89	6:1	-	-	(5/)	-	-
8-19-69	1.05	9.0	508	79	6:1	-	-	(5/)	-	-
9-15-69	.74	8.5	412	95	4:1	-	-	(5/)	-	-

1/ Represents altitude of south part water surface - altitude of north part water surface.
2/ Depth measurements are accurate to 0.5 foot.
3/ Measured during storm; not representative of average conditions.
4/ West culvert partially filled with gravel.
5/ West culvert completely filled to above water surface with fine gravel.

Discharge through the Fill

The movement of brine from south to north through the approximately 13 miles of newer causeway fill has been visually observed at all times of the year and everywhere along the length of the fill. The less dense water from the south part is readily discernible flowing through the riprap on the north side of the fill and spreading over the surface of the more dense water in the north part. This flow has also been confirmed by density measurements. The actual exit area of the water from the permeable fill material is behind the huge boulders used for riprap, thus the actual thickness of the section through which the water emerges could not be determined. By the time the water has moved out around the riprap into the north part of the lake, it is in a layer that is only an inch to a few inches thick.

Discharge northward is not visually discernible through the older sections of causeway fill, and a density difference could not be detected at the surface near the edge of the older fill. Personnel of the Southern Pacific Co. have stated that the older fill at each end of the causeway was constructed of finer grained materials than that used in the new causeway, and that bottom mud was not dredged before placement of the fill.

Discharge from north to south through the fill could not be visually observed any place along the causeway. Density profiles (figure 1) and chemical analyses of samples collected at various depths (table 6) along the south edge of the causeway showed no evidence of water from the north part entering the south part above the more dense lower layer in the south part.

To determine whether or not the brine was actually moving in both directions through the fill as well as the culverts, and to estimate the time of travel through the fill, tracer studies were made at several points along the fill. (See appendix A for a detailed description of the tracer studies.) The tracer studies, using dye, showed that two-way movement does occur in the fill and that the southward moving water moves out of the fill at or below the level of the deep layer in the south part. The tracer studies also gave a general idea of the travel time of brine through the fill. A most significant finding obtained from the tracer studies, however, is that the patterns of discharge through the fill are extremely complex. Accurate estimates of the discharge in each direction will require a complex analysis that is beyond the scope of the present investigation.

Net Discharge and Load Movement through the Causeway

The discharge through the culverts and fill was estimated for the 1969 water year on the basis of methods described in the previous sections. From the estimated discharge and average concentration of dissolved solids, the movement of load of dissolved solids in each direction was calculated for the 1969 water year. (See appendix B for a detailed description of the computations involved.) The results of these estimates of water and load movement through the causeway are summarized in the following table:

Discharge northward:		Thousands of acre-feet
Culverts		615
Fill		720
Total (V_I)	(approx.)	1,340
Discharge southward:		
Culverts		54
Fill		281
Total (V_O)	(approx.)	340
Load movement northward:		Million tons
Culverts		169
Fill		198
Total ($V_I C_I$)	(approx.)	370
Load movement southward:		
Culverts		25
Fill		132
Total ($V_O C_O$)	(approx.)	160
Net load movement for entire causeway ($V_I C_I - V_O C_O$)		210 northward

Ratio of discharge (V_I/V_O):

Culverts	11:1
Fill	3:1
Average for entire causeway	4:1

These totals give a general idea of the probable amounts of brine and dissolved salts that moved in each direction through the causeway during the 1969 water year. The totals are based on a small amount of data collected during a short period of time. The measurements of discharge in the culverts represent only lake conditions during relatively calm days. During storms or when the lake is rough, the flow in the culverts is much more turbulent than during the calm periods. The relationships used to compute discharges may not be fully applicable under turbulent conditions. Althrough the actual discharge reported may be in considerable error, they are believed to be of the correct order of magnitude. Because of the large volumes of water involved, however, even the relatively small inaccuracies inherent in chemical analysis can have a large effect on estimated loads of dissolved solids.

POSSIBLE FUTURE EFFECTS OF THE CAUSEWAY ON THE CHEMISTRY OF GREAT SALT LAKE

The present investigation has shown that the hydrology of Great Salt Lake is now much more complex than it was prior to construction of the causeway. The movement of brine, and hence the movement of dissolved minerals, in each direction through the causeway is the controlling factor in determining the total mineral content (dissolved load) of each part of the lake. Estimates for the 1969 water year show that the ratio of northward to southward discharge was such that some load loss occurred from the south part during that year. Moreover, the scanty chemical-quality data available from 1963 to 1969 indicate a tendency toward load loss from the south part for the entire period (figure 12).

The effect of this load loss on the concentration of dissolved solids in the south part has been masked somewhat because the lake stage rose continually during the same period. The total change in volume due to rising lake stage over the 7-year period has caused a much larger decrease in concentration of dissolved solids than has the apparent load loss. Figure 13 shows the observed relationship of volume to concentration of dissolved solids in the upper layer of brine in the south part of the lake for the 7-year period. The dotted line in figure 13 indicates the estimated concentration of dissolved solids had there been no load loss through the causeway and had volume change been the only factor. This dilution curve may not exactly represent the true dissolved-solids concentration in the upper layer of brine had there been no load change. The actual concentration for a given volume would probably be a small percentage greater because of salts redissolved from dryland areas as the lake rises.

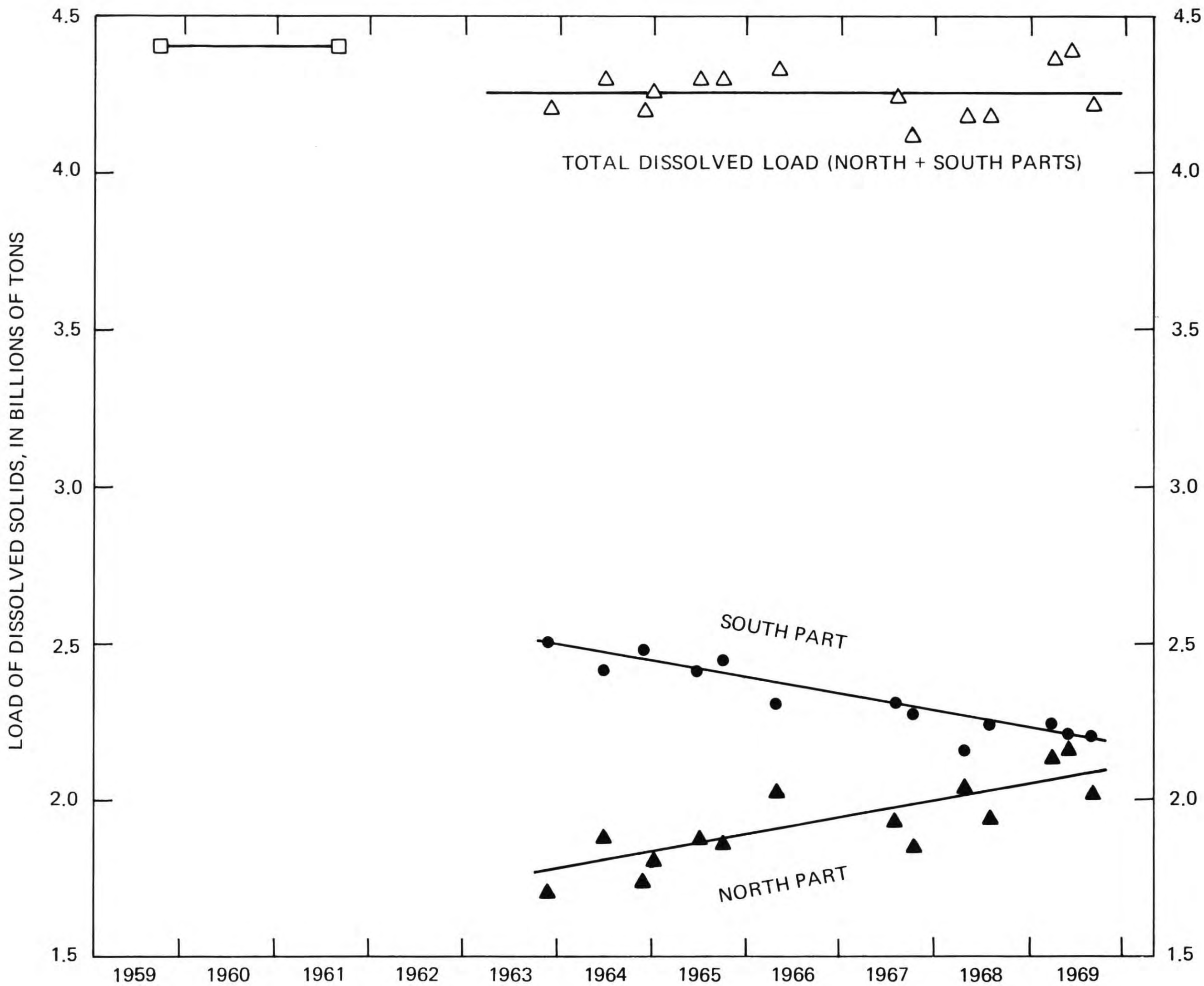
The data in figure 12 for dissolved load in the entire lake do not indicate any upward or downward trend. The small seasonal changes in load appear to indicate that some salt may have been precipitated or dissolved seasonally. There is no indication, however, that large amounts of salt have been precipitated or that large amounts of salt crust have been redissolved during the period 1963-69.

Whether or not the load loss will continue in the south part in the future depends on what happens to the ratio of discharge north and south through the causeway. This ratio will be dependent on the pressure gradient across the causeway, which in turn is a function of stage difference across the causeway, density, and lake stage.

If the average lake stage rises as the result of increased inflow, the difference in stage between the north and south parts should increase (figure 4), thus tending to create a greater pressure gradient to the north and increasing the ratio of flow northward (V_I) to flow southward (V_O). At the same time, however, the increase in lake stage (volume) will result in a decrease in the density of the brine in the south part, thus creating a greater density difference between the north and south parts. This will cause a decrease in the pressure gradient from south to north, and tend to decrease the ratio of V_I to V_O. By contrast, if the average lake stage falls, decreases in the stage difference would tend to decrease the ratio of V_I to V_O, while decreases in the density difference would tend to increase it. The loss or gain of load will also affect the density of the south part, which in turn will affect the ratio of discharge regardless of lake stage.

The lake will be continually rising and falling; therefore, the ratio of discharge and consequently the amount of load movement will be continually changing. The data presently available do not allow an exact definition of the complex interrelationships between water movement and density, stage difference, and lake stage. However, the data allow us to set approximate ranges of values for two of the factors that control the ratio of discharge; thus, we can place some limitations on what may or may not happen in the future.

If the water in the north part of the lake continues to remain at a constant concentration, then we can compute the ratio of flows required for zero net load movement through the causeway for the range of concentrations which may occur in the south part. Also, we can compute, for the expected range of annual inflow to the north part, the approximate quantity of water which must move through the causeway for a given ratio of discharge.



EXPLANATION

Load figures for 1959 - 61 from Hahl and Langford (1964 p. 25)
Load figures for 1963 - 66 estimated from analyses reported by Hahl and Handy (1969, Table 7)
Load figures for 1967 - 69 estimated from data in table 6

Figure 12. Variation of load of dissolved solids in Great Salt Lake, 1959-69.

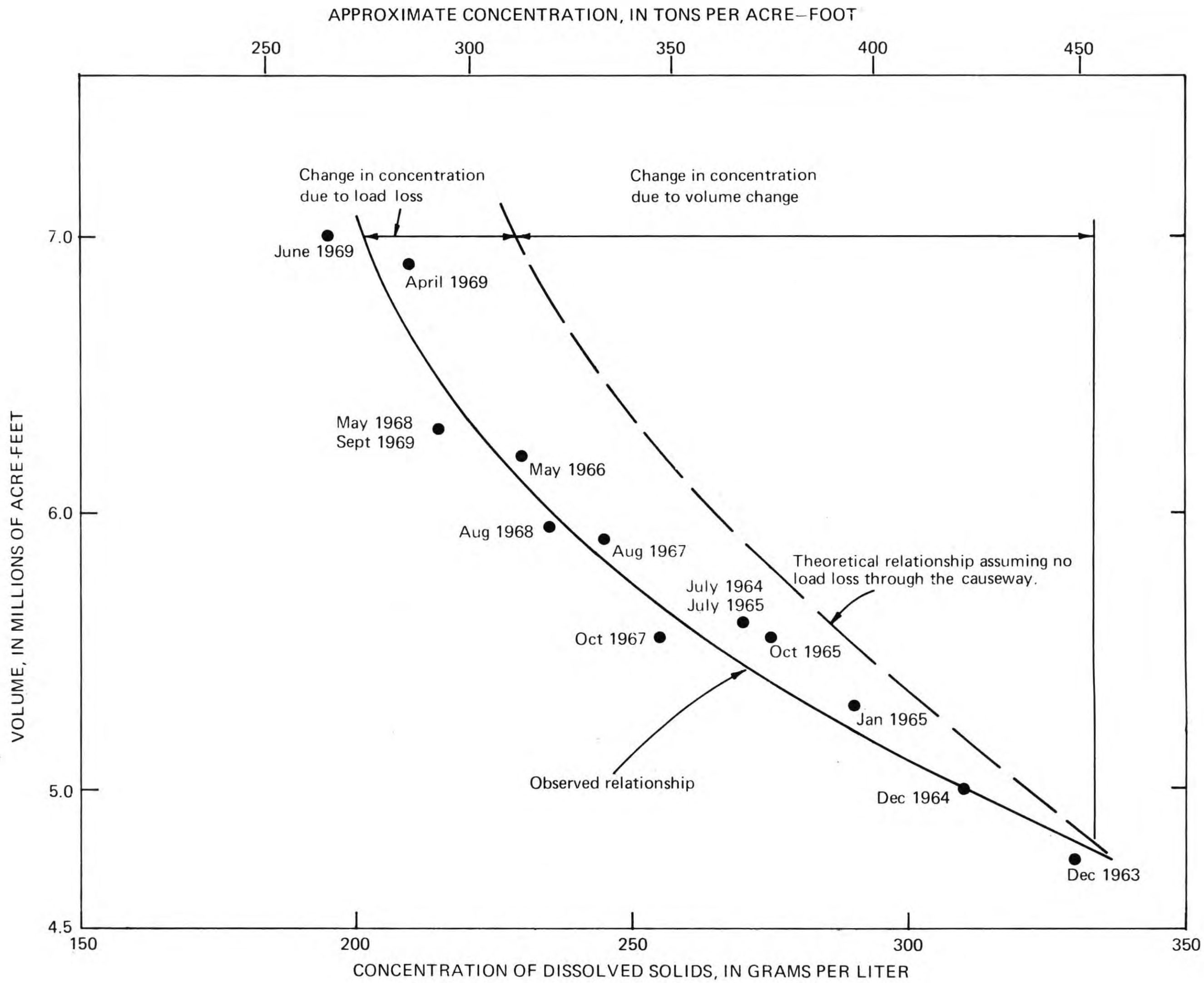


Figure 13. Relationship of volume and concentration of dissolved solids in the upper layer of brine in the south part of Great Salt Lake.

These computations have been made for a range of south part concentrations of from 50 to 450 tons per acre-foot (37-330 g/l) for a range of the net annual inflows to the north part of 400,000 to 2 million acre-feet (table 2). The figure of 400,000 acre-feet represents the approximate quantity of inflow required to maintain the north part at about 4,193 feet above mean sea level under average climatic conditions. The figure of 2 million acre-feet represents the approximate quantity of inflow required to maintain the north part at a stage of about 4,200 feet.

If, for example, the average concentration of dissolved solids in the south part for a given period of time were 200 tons per acre-foot, or about 147 g/l (table 2, column 1), there would be zero net load movement through the causeway when the average ratio of discharge (V_I/V_O) for the same period was 2.4:1 (column 2). For the same concentration, if the average ratio of discharge were greater than 2.4:1, the net load movement would be to the north. If the average ratio of discharge were less than 2.4:1, the net load movement would be to the south. The figures enclosed in parentheses in table 2 are for concentration and discharge that approximate those estimated for the 1969 water year. On the basis of these figures, it would appear that load loss from the south part will continue unless the average ratio of discharge decreases; or, if the ratio of discharge does not change, until the average dissolved-solids concentration in the south part decreases.

The information presented in table 2 indicates that extremely low ratios of discharge northward to discharge southward are probably unlikely because of the exceptionally large quantities of discharge involved.

Although the available data do not permit accurate prediction of the amount of load loss or gain which will occur over a given period of time or for a specific lake stage, the data do make it possible to show the theoretical effect that a given change in load will have on the south part of the lake (See table 3). For example, if 50 million tons of dissolved solids were lost from the south part as a result of interchange through the causeway, the concentration of dissolved solids in the south part would decrease by an amount ranging from 3.8 to 6.5 g/l, depending upon the lake stage. If the interchange of water through the causeway resulted in an increase of 50 million tons in the south part, the concentration would increase by the corresponding amount. By contrast, it should be noted that at the present (1969) average concentration of dissolved solids in the south part (about 220 g/l), the normal seasonal change in lake stage of about 2 feet in itself would result in a concentration change of 20-30 g/l in the south part.

INDUSTRIAL WITHDRAWAL OF BRINE

The withdrawal of brine from the Great Salt Lake for industrial use may become a significant factor affecting the chemistry of the lake. Withdrawals have increased rapidly during the last few years. In 1969 these withdrawals amounted to less than 50,000 acre-feet, a relatively small amount compared to the approximately 7 million acre-feet of brine in the lake. New developments in the mineral-extraction industry, however, could easily double withdrawals in the near future. Withdrawals of this magnitude could be significant in the computation of gains or losses of dissolved minerals from each part of the lake. For example, an annual withdrawal of 100,000 acre-feet of brine from the lake would result in a loss of about 47 million tons of dissolved solids from the north part of the lake or about 28 million tons from the south part at their present concentrations. This compares with a total estimated load loss of 300 million tons from the south part for the 7-year period, 1963-69 (figure 12).

NEEDS FOR ADDITIONAL STUDY

Reliable predictions of future changes in the hydrology of Great Salt Lake cannot be made without the collection of additional data and the analyses of these data. Analysis of presently available data has resulted in a definition of some of the factors that control the hydrology of the lake. Rough estimates have been made of the interchange of brine through the causeway and of the possible effects of this interchange on the chemistry of the lake. If reliable predictions of future changes are required for economic or other considerations, it will be necessary to continue and enlarge the scope of collection of field data and then to analyze all available data.

A program of future data collection should include:

1. Continuous measurement of lake stage north and south of the causeway.

2. Continuous measurement of quantity of discharge, both north and south, through the two existing culverts in the causeway.

3. Measurement of discharge, both north and south, through the causeway fill.

Table 2. Relationship among ranges of possible brine concentrations in the south part, ratios of discharge through the causeway and quantities of water movement through the causeway (assuming constant concentration in the north part).

[Figures in parentheses represent estimates of values for the 1969 water year.]

V_I = Volume of water moving northward through causeway

V_O = Volume of water moving southward through causeway

$V_I - V_O$ = Net volume moving through causeway

1 Average concentration of south part (C_I)		2 Average ratio of discharge (V_I/V_O) for zero net load movement 1/	3 Approximate quantity of water, in millions of acre-feet, which would move through the causeway annually for the indicated ratio of discharge listed in column 2 if the net annual inflow ($V_I - V_O$) to the north part were:								
Tons per acre-foot	Approx. grams per liter		400,000 acre-feet			1,000,000 acre-feet			2,000,000 acre-feet		
			V_I	V_O	$V_I + V_O$	V_I	V_O	$V_I + V_O$	V_I	V_O	$V_I + V_O$
50	37	9.4:1	0.45	0.05	0.50	1.12	0.12	1.24	2.24	0.24	2.48
100	74	4.7:1	.51	.11	.62	1.27	.27	1.54	2.54	.54	3.08
125	92	(3.8:1)	.54	.14	.68	(1.36)	(.36)	(1.72)	2.72	.72	3.44
150	110	3.1:1	.59	.19	.78	1.48	.48	1.96	2.95	.95	3.90
200	147	2.4:1	.69	.29	.98	1.71	.71	2.42	3.43	1.43	4.86
250	184	1.9:1	.84	.44	1.28	2.11	1.11	3.22	4.22	2.22	6.44
(275)	202	1.7:1	.97	.57	1.54	2.43	1.43	3.86	4.86	2.86	7.72
300	220	1.6:1	1.07	.67	1.74	2.67	1.67	4.34	5.33	3.33	8.66
350	257	1.3:1	1.73	1.33	3.06	4.33	3.33	7.66	8.67	6.67	15.34
400	294	1.2:1	2.40	2.00	4.40	6.00	5.00	11.00	12.00	10.00	22.00
450	331	1.04:1	10.40	10.00	20.40	26.00	25.00	51.00	52.00	50.00	102.00

1/ For the indicated concentration a higher ratio would result in net load movement to the north, a lower ratio would result in net load movement to the south.

Table 3. Effect of load loss or gain on the concentration of dissolved solids in the south part of Great Salt Lake

Lake stage (feet)	Approximate change in average concentration of dissolved solids, in grams per liter, for the indicated load loss or gain in the south part			
	Load loss or gain, in millions of tons			
	10	50	100	200
4,192	±1.3	±6.5	±13	±26
4,194	1.1	5.7	11	23
4,196	1.0	5.0	10	20
4,198	.9	4.4	8.8	18
4,200	.8	3.8	7.7	15

4. Continuous or closely spaced periodic measurement of quality of discharge, both north and south, through the culverts.

5. Measurement of quality of flow, both north and south, through the causeway fill.

6. Determination of the areal extent and volume of salt crust on the lakebed north and south of the causeway.

7. Measurement of changes in thickness of the salt crust.

8. Periodic measurement of chemical quality of the brine at representative points in both parts of the lake.

9. Determination of quantity of brine withdrawn for industrial use.

The analysis of the data will be extremely complex because it will involve the manipulation of many interdependent variables. Meaningful predictions will best be obtained by the construction of a model which incorporates all available data. After the model is verified, it can then be used to predict changes in the chemistry of the lake under stipulated future conditions.

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APPENDIX A

RESULTS OF TRACER STUDIES

Tracer studies using Rhodamine WT dye were conducted during August and September 1969 in an attempt to trace movement of brine through the causeway fill. In the first phase of the study, Rhodamine WT fluorescent dye, adjusted to the density of the south part brine, was injected at the surface on the south side of the fill. Injections were made at nine sites along the causeway. Two sites were along the old fill, constructed in the early 1900's; and the other seven sites were along the new fill (figure 1). One liter of dye was injected at each site, at a rate which resulted in a total injection time of approximately one-half hour. Samples for fluorescence analysis using a Turner Model 111 fluorometer were collected on the north side of the fill directly across from the injection points. Sampling began with injection of the dye and continued until a peak fluorescence occurred or until the dye was visually observed on the north side. The following information was gained from these tests:

1. The travel time of water (at the surface) through the new section of the causeway ranged from less than 19 minutes to 1 hour (table 4). At milepost 745.2, however, the travel time through the fill was 3 hours. This travel time is representative of only about a half mile stretch of causeway where a berm exists on the north side. The water stage inside this berm is approximately 0.9 foot higher than the stage in the north part of the lake.

2. Water appears to "pipe" through the fill. In a given section of the fill, water moves very rapidly through a "pipe" at one point and much more slowly where no "pipe" exists only a few feet away. These initial observations would seem to indicate that the fill in the causeway is not at all homogeneous. At certain places along the causeway, the material is fairly compact with relatively small, poorly connected pore spaces. At other places, connected openings between larger rocks appear to exist all the way through the causeway. For these reasons, calculating an average travel time for movement through the entire causeway or assigning an average permeability to the entire causeway may give extremely misleading results.

3. Dispersion of the dye at both the injection sites and the measuring points was one of the biggest problems encountered in the first phase of the tests. The dye was injected as far back into the large boulders of the riprap (figure 1) as possible, but wave action and diffusion of the dye itself still caused considerable dispersion. In addition, the prevailing lake current is from east to west, parallel to the causeway. As a result, dye clouds as much as 300 feet long formed along the causeway at the injection sites. Because of this dispersion, the distance traveled and the travel times through the fill can only be approximated. In some cases, the actual travel time of the water from the point of injection to the measuring point directly across from it may have been considerably longer than the shortest observed travel time of the dye. This would be true where the dye dispersed up or down the length of the causeway on the south side until it hit a "pipe" with much higher permeability than the material at the injection site. The only points where dispersion was not a problem were where the observed travel times were less than about one-half hour. At these points, almost all the injected dye entered the fill at the injection site.

4. Travel time through the older fill at either end of the causeway was much longer than travel time through the new fill. The longer travel times are probably due to the methods used to construct the older fill (see p. 1) and possibly to compaction of the materials with time.

The second phase of the tracer study was made in order to trace movement from below the water surface on the south side of the causeway to the north side. The purpose of these tests was to try to locate the interface between northward and southward moving water and to find the deepest point at which water was moving northward. The site chosen for the test was at railroad milepost 747.2, where the observed travel time at the surface had been the shortest. This site was chosen with the hope of avoiding the dispersion problems that had been encountered previously.

A sample was obtained on the south side of the causeway, 10.5 feet below the surface. The density of the sample was determined, and the dye was then concentrated to this same density by adding the proper amount of water from the north part. One liter of the dye was injected into the rocks where the edge of the causeway was 10.5 feet below the water surface. The dye immediately began dispersing from the injection point to the west and upward. Downward dispersion may also have taken place; but if so, it would not have been visible. Within 5-7 minutes the dye cloud was touching the causeway at the water surface along a 50-75 foot

Table 4. Results of tracer studies at Southern Pacific Co. causeway during August - September 1969.

Dye injection point (see fig. 1) (railroad milepost)	Distance from injection point1/ to measuring point 2/ (feet)	Time from beginning of injection to first appearance of dye	Measured stage difference across causeway (feet)
737.6	89	>7 hours	0.83
741.5	75	45 minutes	.89
743.6	78	<33 minutes	.93
745.2	74	3 hours	3/.03
747.2	78	<19 minutes	.97
748.5	72	1 hour	1.02
750.0	75	45 minutes	.99
751.5	80	1 hour	1.24
752.8	149	>8 hours	1.07

1/ Water surface on south side.

2/ Water surface on north side.

3/ Measuring point was inside of berm on north side of causeway. Stage inside berm was approximately 0.9 foot higher than stage in north part of lake.

length that was about 60-80 feet west of the injection point. The dye appeared visually on the north side of the causeway about 60-80 feet west of the injection point, 41 minutes after injection was started. Because of the dispersion, however, it was impossible to know whether dye entered the causeway at depth and moved through the causeway in 41 minutes or whether it dispersed upward and entered a "pipe" at some other depth, moving through in less than 41 minutes.

Dye was also injected 18 feet below the water surface. This dye had been concentrated to approximately 0.01 density units greater than the water in situ at a depth of 18 feet in order to avoid the dispersion problem that had occurred at 10.5 feet. Dispersion occurred again, however, and within 7-10 minutes the dye cloud had reached the surface.

Because of the masking effects caused by dispersion, the information obtained for travel time of water from south to north through the lower sections of the fill is not considered reliable.

The third phase of the tracer study was an attempt to trace movement from north to south through the fill. The site chosen for the injection was again at railroad milepost 747.2. This site was chosen because it was hoped that the travel time there would be less than 8 hours–the maximum uninterrupted time available for measuring. The following information was gained from two injections which were made a week apart:

1. A "piping" effect occurs with the north to south flow. Both dye injections were at the same injection point and at the same depth–5.5 feet below the water surface on the north side. After the first injection, dye appeared in 3.5 hours on the south side of the causeway directly across from the injection point, which was about 30 feet east of the point on the surface where the travel time south to north was less than 19 minutes. The dye entered the south side at a point below the top of the deep layer of brine. The exact point of entry could not be determined because the dye dispersed through the entire depth of the deep layer of brine. After the second injection, dye appeared south of the causeway in 1 hour, directly across from the point of injection.

2. The actual point on the north side where the dye entered the causeway cannot be determined because of dispersion at the injection point.

3. Sampling on the south side gave no indication of movement from north to south above the deep layer of brine. If there is any such movement, the flow is small enough so that the southward-moving brine trickles down through the rocks on the south side and is undetectable before it enters the deeper layer of brine.

GENERAL CONCLUSIONS FROM THE TRACER STUDY

1. A large amount of water moves through the fill from south to north near the lake surface. The approximate average velocity of movement through the new fill ranges from about 1 to 5 feet per minute. If any water moves through the old sections of the fill, the quantity is insignificant compared to that which moves through the new section.

2. Visual observations indicate that the rate of water movement is not uniform through the fill, but it may vary from very slow to very fast over a span of a few feet.

3. The thickness of the layer discharging from the north side of the causeway cannot be measured accurately, but it is estimated to be from 2 to 6 inches at the edge of the fill.

4. Water moves from north to south through the fill, and it probably discharges at or below the level of the deeper, more dense layer of brine south of the causeway. The maximum velocity observed was about 1 foot per minute. Because the depth of discharge makes visual observation impossible, however, the first observed dye may not represent the first dye actually through the causeway. Thus the

actual rate of movement from north to south may be greater than that observed.

5. The results of the tracer study do not permit determination of the absolute ratio of northward to southward discharge. The fill is not homogeneous, and the position or shape of the interface between the northward and southward flowing water could not be determined. Although an average rate of movement could be estimated, the actual discharge areas on either side could not be determined; thus a calculation could not be made of actual quantities of discharge. The tracer study, however, did yield enough information to allow an estimate of the probable range of permeability of the fill. This information will be of value if an analysis is made of a model of the causeway.

6. Additional, more reliable, information could be obtained from subsequent tracer studies if injections of dye could be made directly into the fill through wells.

APPENDIX B

COMPUTATIONS OF DISCHARGE AND MOVEMENT OF DISSOLVED SALTS THROUGH THE CAUSEWAY, 1969 WATER YEAR

In order to compute the dissolved-solids load moving through the causeway during the 1969 water year, the volume of water moving in each direction was estimated. Then, using the small amount of chemical-quality data available, an average concentration of dissolved solids for that flow was calculated. Finally, from the volume and concentration, the load of dissolved solids was calculated. All the figures used in the following computations are averages or estimates. The results of the computations should be considered as only a general indication of the probable discharge and load movement for the one seasonal lake cycle that was considered.

1. The discharge through the culverts was estimated as follows: the difference in stage across the causeway, as determined from the records of the lake-stage recorders on either side of the causeway, averaged 0.8 feet for the entire year (table 5). Using this stage difference and the relationship between discharge in the east culvert and the stage difference (figure 10), the discharge through the east culvert was calculated. A corresponding relationship based on measurements at the west culvert could not be made, because that culvert was plugged with fill during part of the year. Discharge through the west culvert was estimated on the basis of measurements made in the west culvert prior to the time of plugging and comparison of these measurements with measurements of discharge made at the same time in the east culvert. The following figures resulted from these estimates:

	Cubic feet per second	Acre-feet per year
Average discharge northward		
East culvert	500	362,000
West culvert	350	253,000
Total		615,000
Average discharge southward		
East culvert	75	54,000
West culvert	0	0
Total		54,000
Net discharge northward (Rounded)		560,000

2. The discharge through the fill could not be estimated from direct measurements; therefore, it was estimated indirectly. The net inflow to the north part of the lake was estimated by using the following formulas:

> Total inflow to north part = evaporation ± change in volume - precipitation - ground-water inflow

and, because an estimated 15 percent of the inflow to the north part came from other surface inflow (streams and springs), 85 percent came through the fill. Thus,

> net inflow to north part through causeway = 85 percent of total inflow.

The variables in the formulas were assigned a range of values which represents the possible maximum and minimum values that might have occurred during the 1969 water year.

The range in evaporation was estimated to be from 780,000 to 1,560,000 acre-feet, from the following considerations: Peck (1954, p. 8) estimated the total average-annual depth of evaporation to be 3.14-3.80 feet, depending upon salt content of the lake. Dickson and McCullom (1965, p. 24) estimated evaporation during the summer of 1963 (July-September) to be about 4.2 feet. Evaporation for the whole year was probably in excess of 5 feet. The actual evaporation during the 1969 water year is assumed to be somewhere between 3 and 6 feet, and the average area of the water surface of the north part was about 260,000 acres. The range in possible evaporation, therefore, was from 3 x 260,000 to 6 x 260,000 or from 780,000 to 1,560,000 acre-feet.

The change in volume during the 1969 water year was obtained by using the beginning and ending stages from the lake-stage recorders and the stage-volume relationships. The volume change in the north part was an increase of 150,000 acre-feet, based on the assumption that the north part contained about 40 percent of the total lake volume at the average lake stage during the year.

The average annual precipitation for the north part of the lake is about 8 inches. A possible range of precipitation of 6-10 inches (0.50-0.83 foot) was assumed for the 1969 water year. The average water-surface area during the year was about 260,000 acres; hence, the estimated range of precipitation was 130,000-216,000 acre-feet.

The north part receives only a small percentage of the total ground-water inflow to the lake. The

Table 5. Mean daily difference of stage, in feet, across Southern Pacific Co. causeway, 1969 water year.

[Figures represent difference between continuous recorders at Promontory Point and Saline (see fig. 1)]

Day	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
1	-	0.60	0.62	0.69	0.75*	0.77*	1.05*	1.05*	1.03	0.96	0.88	0.82
2	0.49	.62	.61*	.69	.79*	.79	1.21*	.89*	1.08	.98	1.01*	.86
3	.49	.62*	.70	.70	.85	.79*	.96*	1.17*	1.06	.90	1.00*	.85*
4	.57	.52*	.68	.72	.81	.54*	1.17	1.09*	1.03	.93	.93*	.77*
5	.53	.58	.67	.70	.82	.85*	1.23	1.04*	1.03*	.95	.73*	.80
6	.48	.53	.67	.67	.82*	.75*	1.22*	1.17*	1.01*	.83*	.81*	.79
7	.36*	.60	.71	.57*	.79*	.69*	.83*	1.15*	1.05*	.98*	.88	.78
8	.38*	.60*	.68	.46*	.80	.86	1.12	1.16*	1.09*	.95*	.84	.79*
9	.55	.27*	.70	.67	.81	.89*	1.14	1.19	1.04*	.99*	.88	.78
10	.57	.57*	.76*	.65	.80	.91*	1.07*	1.18	.80*	.99	.91*	.73*
11	.69*	.63	.51*	.66	.79	.84	1.01*	1.15	.92	1.01	.86*	.74*
12	.75*	.53*	.61	.65	.81*	.86	1.14	1.17	.96*	1.00	.80*	.73
13	.60*	.50	.73	.74	.69*	.81	1.03*	1.07*	.86*	1.05*	.83	.75
14	.53*	.57	.69*	.75	.76	.84	.97*	1.02*	.86*	1.05*	.86	.65*
15	.37*	.60*	.75*	.75	.76	.86	.61*	1.06*	.85*	.97*	.93*	.70*
16	.25*	.50*	.68*	.70	.78	.88	1.13*	1.19	.98*	.98*	.97*	.78*
17	.47	.60	.60*	.72	.82	.87	1.22	1.26	.92	.98*	.86*	.74
18	.45*	.64	.87*	.77	.83	.58*	1.03*	1.19*	.91*	.99	.88*	.84*
19	.46	.60	.88*	1.18*	.83	.87*	1.22*	1.06*	.90*	.98	.93*	.77*
20	.42*	.66	.53	1.14*	.78	.96	1.18*	.99*	.81*	.98*	.93*	.63*
21	.45*	.66	.57	1.31*	.83	.96	1.18	1.10*	.89*	.98*	.87	.66*
22	.54	.70	.75	.88*	.83	1.00*	1.20*	1.14	.81*	.97	.91*	.71*
23	.53	.69	.70*	.78*	1.05*	.47*	1.37*	1.20*	.88	.93	.88	.76*
24	.55	.54*	.70*	.90	1.21*	.79*	.73*	1.20	.53*	.95	.88	.70*
25	.57	.55*	.70*	.83	.94*	1.08	.98*	1.20	.82*	.92*	.83*	.73*
26	.54	.61	.67*	.98*	.81	1.08	.86*	1.19*	.78*	.86	.84*	.73*
27	.58	.69	.69	.88*	.83	1.10*	1.15*	.92*	.83*	.90*	.78*	.73
28	.60	.66	.82*	.91*	.83	1.00	1.18	.93*	.82*	.87*	.97*	.73*
29	.59	.72	.57	.57*	-	1.06	.97*	1.09*	.87*	.98*	.67*	.71*
30	.48*	.70*	.72	.84*	-	1.11	1.18*	.95*	.89	.92	.79*	.65*
31	.58	-	.72	.78*	-	1.06	-	.81*	-	.92	.82	.75
Mean	.51	.60	.69	.78	.83	.87	1.08	1.10	.91	.96	.87	.75

* Storm day, maximum variation in stage more than 0.1 foot.

possible range in ground-water inflow to the north part is estimated to be from 10,000 to 40,000 acre-feet.

Substituting the above ranges of values in the formulas results in an estimated range of possible net inflow to the north part during the 1969 water year of 670,000 to 1,240,000 acre-feet. Using the average of these two figures gives an estimated net inflow through the causeway to the north part of about 1 million acre-feet.

As a check, the net inflow through the causeway to the north part was also estimated from data collected during the first 7 months of the water year (October-April), when evaporation is minimal. From October 1968 through April 1969, the volume of the north part of the lake increased by about 700,000 acre-feet. During the same period, the discharge through the culverts (and presumably through the fill as well) was about one-half the total discharge for the year. Thus the net inflow to the north part for the year was about twice the October-April inflow, or about 1,400,000 acre-feet. It is assumed that about 80 percent of the net inflow to the north part comes from discharge through the causeway, and the remaining 20 percent from surface runoff, ground-water inflow, and precipitation. Hence, the net inflow through the causeway for the water year is 80 percent of 1,400,000, or about 1,120,000 acre-feet.

From the net inflow through the causeway to the north part during the year and the net northward discharge through the culverts, we can obtain the net northward discharge through the fill by difference:

	Acre-feet
Net discharge through the causeway	1,000,000
Net discharge through culverts	560,000
Net discharge through fill	440,000

3. The total change in load in the south part of the lake for the 1969 water year was assumed to be entirely due to northward movement through the causeway. It was estimated from chemical analyses and volumes, thus:

change in load = (initial concentration x initial volume) – (final concentration x final volume) = (355 tons/ac-ft x 5,770,000 ac-ft) – (295 tons/ac-ft x 6,220,000 ac-ft) change in load = 210 million tons loss.

4. The load movement in each direction is calculated from the relationship:

$$V_I C_I - V_O C_O = L \qquad (A)$$

where V_I = average discharge northward,
V_O = average discharge southward,
C_I = average concentration of water in the south part,
C_O = average concentration of water in the north part, and
L = net load movement

Now, C_I = 275 tons per acre-foot, C_O = 470 tons per acre-foot, and, for the culverts, V_I = 615,000 acre-feet, V_O = 54,000 acre-feet.

hence: $V_I C_I$ = 615,000 x 275 = 169 million tons (load moving northward)

and: $V_O C_O$ = 54,000 x 470 = 25 million tons (load moving southward)

so: L (culverts) = 144 million tons northward

But the total net load movement was 210 million tons northward,

so: L (total) = 210 million tons

and: L (culverts = 144 million tons

hence: L (fill) = 66 million tons northward

Now, for the fill, the values of C_I and C_O are unchanged; and, for the fill, L = 66 million tons,

$V_I - V_O$ = 440,000 acre-feet;

so $V_O = V_I - 440{,}000$

hence, using relationship (A) again, (V_I x 275)-(V_I - 440,000) x 470 = 66,000,000

and: V_I = 720,000 acre-feet

but: $V_O = V_I - 440{,}000$

so: V_O = 280,000 acre-feet

and: V_I/V_O = 2.6/1

so, for the fill;

hence: $V_I C_I$ = 720,000 x 275 = 198 million tons (load moving northward)

$V_O C_O$ = 280,000 x 470 = 132 million tons (load moving southward)

APPENDIX C

Table 6. Chemical analyses of water from Great Salt Lake.

Depth from surface: The approximate altitudes, in feet, above mean sea level of the water surface of the north and south parts of the lake during the time of sample collection were as follows:

Date	North part (Saline gage)	South part (Boat Harbor gage)
August 1-3, 1967	4,194.0 (estimated; recorder not functioning)	4,194.7
October 10-13, 1967	4,193.4	4,193.9
April 4, 1968	4,194.5	4,195.4
April 29–May 1, 1968	4,194.6	4,195.5
August 27-29, 1968	4,194.1	4,194.8
June 5, 1969	4,195.7	4,196.9

Table 6 continued.

Location and distance from causeway (see fig. 1)	Date	Depth below surface (ft)	Temper-ature (°C)	Grams per liter							Density (gms/ml at 20°C)
				Magne-sium (Mg)	Sodium (Na)	Potas-sium (K)	Lithium (Li)	Sul-fate (SO_4)	Chlo-ride (Cl)	Dissolved solids (Residue at 180°C)	
Milepost 744											
0.8 mile north	8- 2-67	0	30	11.5	91.4	6.75	.050	24.7	160	307	1.193
0.8 mile north	8- 2-67	2	29	12.7	101	7.62	.059	28.7	180	350	1.218
0.4 mile north	8- 2-67	0	30	12.4	96.3	7.15	.054	26.6	168	327	1.204
0.4 mile north	8- 2-67	2	29	13.7	102	7.71	.059	29.0	180	348	1.216
30 yards north	8- 2-67	0	28	13.2	99.5	7.64	.058	28.2	176	343	1.214
30 yards north	8- 2-67	2	28	13.6	101	7.84	.060	29.2	180	349	1.219
At north edge of causeway	8- 2-67	0	28	8.97	76.5	4.98	.037	19.4	131	251	1.158
15 yards south	8- 3-67	6	28	7.69	71.8	4.51	.034	18.2	122	242	1.151
0.2 mile south	8- 3-67	18	28	7.25	71.2	4.50	.035	18.1	122	243	1.151
0.2 mile south	8- 3-67	26	18	12.8	97.2	7.26	.056	30.4	172	336	1.208
0.8 mile south	8- 3-67	18	27	8.48	75.0	4.77	.036	19.3	126	248	1.156
0.8 mile south	8- 3-67	25	18	12.6	97.7	7.18	.056	29.0	170	332	1.209
West Culvert											
1.0 mile north	8- 2-67	0	30	12.6	96.7	7.32	.056	25.9	166	327	1.204
1.0 mile north	8- 2-67	2	28	13.7	101	7.85	.062	28.7	175	348	1.217
1.0 mile north	8- 2-67	26	15	14.0	102	7.92	.062	33.7	175	354	1.224
0.6 mile north	8- 2-67	0	28	12.0	101	7.19	.057	27.3	172	337	1.208
0.6 mile north	8- 2-67	2	28	13.4	102	7.44	.062	28.8	184	351	1.216
0.6 mile north	8- 2-67	25	17	13.7	104	7.62	.063	33.0	175	356	1.221
40 yards north	8- 2-67	0	28	10.7	90.9	6.21	.049	24.0	155	307	1.188
40 yards north	8- 2-67	2	27	12.4	101	7.09	.058	27.8	172	325	1.210
40 yards north	8- 2-67	14	27	13.0	104	7.45	.062	28.6	181	356	1.219
Between south wingwalls	8- 3-67	0	27	7.66	73.5	4.72	.035	18.5	122	239	1.151
Between south wingwalls	8- 3-67	14	-	11.1	97.8	7.25	.057	27.0	166	326	1.206
25 yards south	8- 3-67	2	27	7.22	76.8	4.62	.036	18.3	122	239	1.150
0.2 mile south	8- 3-67	0	27	7.36	75.4	4.64	.036	18.1	122	239	1.151
0.2 mile south	8- 3-67	18	27	7.03	76.6	4.60	.036	17.8	122	241	1.153
0.2 mile south	8- 3-67	26	18	12.0	102	7.32	.058	29.4	168	336	1.209

Location and distance from causeway (see fig. 1)	Date	Depth below surface (ft)	Temperature (°C)	Grams per liter								Density (gms/ml at 20°C)
				Magnesium (Mg)	Sodium (Na)	Potassium (K)	Lithium (Li)	Sulfate (SO_4)	Chloride (Cl)	Dissolved solids (Residue at 180°C)		
West culvert												
0.8 mile south	8- 3-67	0	28	6.98	76.2	4.56	.036	18.3	124	239		1.150
0.8 mile south	8- 3-67	18	27	6.81	76.6	4.53	.036	18.4	122	241		1.151
0.8 mile south	8- 3-67	26	17	10.9	102	7.20	.057	29.1	172	337		1.210
Milepost 748												
0.8 mile north	8- 2-67	0	28	12.9	102	7.06	.056	27.6	174	337		1.209
0.8 mile north	8- 1-67	2	29	14.0	104	7.60	.060	29.1	178	350		1.219
0.6 mile north	8- 2-67	0	26	12.5	98.8	7.15	.055	26.8	169	328		1.205
0.6 mile north	8- 2-67	2	29	14.8	102	7.83	.059	28.7	177	350		1.219
30 yards north	8- 2-67	0	28	12.7	104	7.58	.060	28.7	181	352		1.218
30 yards north	8- 2-67	2	28	12.9	105	7.91	.059	28.8	180	351		1.218
20 yards south	8- 3-67	18	28	8.06	73.0	4.54	.035	18.5	128	241		1.152
20 yards south	8- 3-67	20	26	10.4	89.8	6.13	.047	24.7	154	298		1.188
0.2 mile south	8- 3-67	18	28	7.87	72.6	4.56	.035	18.2	125	239		1.152
0.2 mile south	8- 3-67	23	25	12.5	101	7.43	.057	28.4	172	335		1.211
0.8 mile south	8- 3-67	18	28	7.51	72.8	4.56	.035	18.1	125	240		1.153
0.8 mile south	8- 3-67	23	20	11.9	99.5	7.01	.056	28.4	170	334		1.208
East culvert												
0.8 mile north	8- 1-67	0	28	12.8	101	7.25	.059	28.0	181	341		1.213
0.8 mile north	8- 1-67	22	16	13.4	103	7.54	.059	32.0	179	352		1.221
0.4 mile north	8- 2-67	0	28	12.7	100	7.12	.057	27.3	172	336		1.210
0.4 mile north	8- 2-67	2	28	13.4	104	7.41	.061	28.7	182	349		1.218
0.2 mile north	8- 2-67	0	28	13.2	101	7.32	.059	28.1	177	346		1.213
30 yards north	8- 2-67	0	27	10.3	90.6	6.16	.048	23.5	148	295		1.188
30 yards north	8- 2-67	2	28	13.5	106	7.41	.059	28.2	176	347		1.218
30 yards north	8- 1-67	18	25	14.0	103	7.51	.060	31.4	182	352		1.219
10 yards south	8- 3-67	0	28	7.77	74.8	5.02	.035	18.2	126	239		1.152
10 yards south	8- 3-67	18	27	8.37	76.7	4.69	.037	19.3	132	250		1.159
10 yards south	8- 3-67	27	27	11.3	89.1	6.06	.049	25.2	158	309		1.192

Table 6 continued.

Location and distance from causeway (see fig. 1)	Date	Depth below surface (ft)	Temperature (°C)	Grams per liter								Density (gms/ml at 20°C)
				Magnesium (Mg)	Sodium (Na)	Potassium (K)	Lithium (Li)	Sulfate (SO_4)	Chloride (Cl)	Dissolved solids (Residue at 180°C)		
East culvert												
0.2 mile south	8- 3-67	18	28	7.97	77.4	5.26	.036	19.1	130	253		1.158
0.2 mile south	8- 3-67	22	26	12.2	97.8	6.75	.055	27.2	169	331		1.205
0.8 mile south	8- 3-67	0	29	7.83	75.3	5.22	.035	18.3	125	243		1.151
0.8 mile south	8- 3-67	18	28	7.96	75.5	5.13	.037	18.5	128	243		1.150
0.8 mile south	8- 3-67	22	24	11.7	98.1	6.52	.053	27.0	159	322		1.201
Milepost 751.5												
0.6 mile north	8- 1-67	0	30	11.1	96.5	6.67	.051	25.3	159	312		1.198
0.6 mile north	8- 1-67	2	30	13.1	101	7.50	.059	28.1	170	344		1.217
0.6 mile north	8- 1-67	17	17	13.4	107	7.78	.061	28.8	179	352		1.221
0.2 mile north	8- 1-67	0	30	13.2	103	7.49	.058	28.2	175	340		1.217
0.2 mile north	8- 1-67	21	18	13.9	104	7.92	.061	31.5	173	350		1.221
20 yards north	8- 1-67	0	29	12.3	104	7.15	.055	26.6	166	329		1.206
20 yards north	8- 1-67	2	31	13.2	103	7.66	.059	28.4	175	341		1.216
20 yards north	8- 1-67	17	25	14.0	105	7.93	.060	29.4	175	350		1.221
North at causway	8- 1-67	0	29	11.3	92.9	6.87	.050	24.4	155	308		1.192
10 yards south	8- 3-67	11	28	8.19	76.7	4.40	.035	18.4	124	239		1.152
0.2 mile south	8- 3-67	2	28	7.98	73.9	4.17	.034	18.3	120	242		1.151
0.2 mile south	8- 3-67	19	28	9.20	84.5	5.15	.039	21.3	139	270		1.171
0.8 mile south	8- 3-67	18	27	8.23	77.8	5.12	.035	18.8	125	246		1.154
0.8 mile south	8- 3-67	21	27	11.1	93.6	6.68	.049	25.3	158	308		1.193

Table 6 continued.

Location and distance from causeway (see fig. 1)	Date	Depth below surface (ft)	Temperature (°C)	Grams per liter							Density (gms/ml at 20°C)
				Magnesium (Mg)	Sodium (Na)	Potassium (K)	Lithium (Li)	Sulfate (SO_4)	Chloride (Cl)	Dissolved solids (Residue at 180°C)	
Milepost 742											
2 miles north	10-11-67	0	19	13.7	100	8.78	.060	30.4	181	352	1.220
2 miles north	10-11-67	2	19	13.8	99.1	8.43	.060	30.0	178	353	1.220
1.0 mile north	10-11-67	0	19	14.4	102	8.39	.062	33.1	179	353	1.222
1.0 mile north	10-11-67	2	19	14.1	102	8.58	.061	31.0	178	352	1.221
25 yards north	10-11-67	0	19	13.8	101	8.66	.060	31.5	175	346	1.217
25 yards north	10-11-67	2	19	14.1	101	8.40	.062	34.7	175	356	1.222
25 yards north	10-11-67	8	18	14.2	103	8.70	.063	34.7	178	353	1.221
25 yards south	10-11-67	0	18	7.68	74.1	5.19	.033	18.5	125	240	1.152
25 yards south	10-11-67	5	19	7.91	75.5	5.11	.034	19.0	126	245	1.154
0.5 mile south	10-13-67	21	20	9.33	82.2	5.53	.038	21.1	139	268	1.171
1.0 mile south	10-13-67	20	19	8.60	81.4	5.36	.036	20.1	135	261	1.164
Milepost 742.5											
0.5 mile south	10-13-67	22	21	12.0	97.8	7.25	.050	26.4	169	327	1.204
West culvert											
2 miles north	10-11-67	0	20	13.9	100	8.81	.065	31.0	179	348	1.219
2 miles north	10-11-67	2	20	13.9	98.0	8.82	.065	30.3	177	349	1.218
2 miles north	10-11-67	25	18	14.6	97.0	9.18	.068	32.3	178	352	1.221
1.0 mile north	10-11-67	0	20	13.9	98.2	8.77	.065	31.3	176	348	1.218
1.0 mile north	10-11-67	2	20	14.0	99.5	8.93	.066	31.4	178	351	1.219
200 yards north	10-11-67	2	19	14.2	100	9.12	.067	31.7	181	353	1.221
25 yards north	10-11-67	0	19	10.9	86.7	6.99	.051	25.7	155	303	1.190
25 yards north	10-11-67	2	18	13.3	95.2	8.07	.062	29.8	169	335	1.212
Between south wingwalls	10-11-67	10	18	14.0	98.9	8.86	.066	31.1	178	347	1.217
35 yards south	10-11-67	0	19	7.85	71.7	5.16	.033	18.4	122	237	1.150
35 yards south	10-11-67	14	19	8.60	79.7	5.35	.036	20.2	132	260	1.163
0.5 mile south	10-13-67	20	17	8.31	79.1	5.35	.036	19.6	125	258	1.160
0.5 mile south	10-13-67	26	20	12.2	101	7.50	.054	29.1	178	337	1.212
1.0 mile south	10-13-67	20	18	8.36	79.3	5.29	.036	19.9	130	259	1.163
1.0 mile south	10-13-67	25	20	12.0	101	7.48	.053	30.8	172	334	1.211

Table 6 continued.

Location and distance from causeway (see fig. 1)	Date	Depth below surface (ft)	Temperature (°C)	Grams per liter: Magnesium (Mg)	Sodium (Na)	Potassium (K)	Lithium (Li)	Sulfate (SO_4)	Chloride (Cl)	Dissolved solids (Residue at 180°C)	Density (gms/ml at 20°C)
Milepost 748											
2 miles north	10-11-67	0	19	14.4	104	8.42	.063	30.6	180	353	1.218
2 miles north	10-11-67	2	19	14.6	103	8.52	.063	30.7	174	352	1.219
1.0 mile north	10-11-67	0	19	14.4	103	8.40	.064	30.7	180	351	1.219
1.0 mile north	10-11-67	2	19	14.4	104	8.46	.063	30.8	178	351	1.220
25 yards north	10-11-67	0	19	13.6	99.1	8.03	.057	29.7	172	338	1.211
25 yards north	10-11-67	2	19	14.8	102	8.52	.060	32.6	181	350	1.219
25 yards north	10-13-67	16	18	15.3	103	8.69	.066	34.4	181	353	1.221
25 yards south	10-11-67	0	19	7.68	71.7	4.72	.034	17.7	118	227	1.144
25 yards south	10-11-67	18	19	8.46	80.5	5.38	.037	19.6	130	253	1.160
25 yards south	10-11-67	22	19	13.5	96.5	7.70	.059	28.7	169	330	1.206
0.5 mile south	10-13-67	20	18	8.76	81.7	5.57	.038	20.1	135	259	1.162
0.5 mile south	10-13-67	24	20	12.8	98.1	7.99	.055	28.2	170	329	1.206
1.0 mile south	10-13-67	20	18	8.97	80.8	5.80	.037	19.8	135	255	1.162
1.0 mile south	10-13-67	23	21	12.9	101	8.39	.055	28.0	169	334	1.208
East culvert											
2 miles north	10-10-67	0	21	12.6	93.0	7.98	.059	28.2	169	328	1.204
2 miles north	10-10-67	2	20	13.6	101	8.54	.065	30.6	181	353	1.220
2 miles north	10-10-67	20	18	14.0	101	8.80	.068	31.7	180	352	1.221
1.0 mile north	10-10-67	0	19	13.2	96.6	8.15	.061	28.9	169	336	1.209
1.0 mile north	10-10-67	2	21	13.8	102	8.64	.065	30.6	178	353	1.219
25 yards north	10-10-67	0	18	10.5	86.6	5.90	.046	23.1	146	288	1.182
25 yards north	10-10-67	2	19	12.2	90.0	7.18	.054	26.1	158	311	1.197
25 yards north	10-10-67	20	19	14.9	105	8.60	.066	30.8	181	351	1.221
5 yards south	10-13-67	0	15	7.43	70.9	4.89	.035	17.8	121	233	1.147
5 yards south	10-13-67	20	17	10.7	87.5	6.76	.051	25.0	152	300	1.189
5 yards south	10-13-67	29	18	12.8	98.7	9.13	.061	29.4	170	333	1.210
0.5 mile south	10-13-67	0	16	7.78	76.0	4.74	.036	18.0	125	241	1.153
0.5 mile south	10-13-67	18	17	8.33	79.9	5.05	.039	19.3	134	257	1.164
0.5 mile south	10-13-67	21	19	12.0	95.9	6.90	.054	26.7	164	317	1.200

Table 6 continued.

Location and distance from causeway (see fig. 1)	Date	Depth below surface (ft)	Temper-a-ture (°C)	Grams per liter							Density (gms/ml at 20°C)
				Magnesium (Mg)	Sodium (Na)	Potassium (K)	Lithium (Li)	Sulfate (SO_4)	Chloride (Cl)	Dissolved solids (Residue at 180°C)	
East culvert											
1.0 mile south	10-13-67	18	18	8.53	77.8	5.46	.038	19.6	134	255	1.160
1.0 mile south	10-13-67	22	20	11.8	92.5	7.32	.054	27.0	166	318	1.202
Milepost 751.5											
2 miles north	10-10-67	0	21	13.8	101	8.11	.059	28.6	169	334	1.209
2 miles north	10-10-67	23	18	15.1	103	9.06	.066	31.0	181	356	1.223
1.0 mile north	10-10-67	0	21	13.7	98.7	7.95	.058	32.1	168	333	1.209
1.0 mile north	10-10-67	2	21	15.0	104	8.75	.062	30.6	181	352	1.219
25 yards north	10-10-67	0	21	14.4	102	8.94	.061	29.3	178	343	1.214
25 yards north	10-10-67	2	21	14.5	103	8.27	.063	31.0	181	354	1.219
25 yards north	10-10-67	18	19	14.8	103	8.69	.064	31.0	179	354	1.221
25 yards south	10-13-67	0	15	7.64	74.3	4.83	.034	17.7	124	234	1.148
25 yards south	10-13-67	16.5	16	8.90	82.5	5.44	.037	19.5	134	254	1.161
0.5 mile south	10-13-67	19	18	9.00	82.0	5.58	.038	20.0	136	262	1.164
0.5 mile south	10-13-67	21	20	12.0	97.1	6.74	.050	26.5	161	319	1.199
1.0 mile south	10-13-67	18	18	8.85	81.9	5.28	.037	19.6	135	261	1.162
1.0 mile south	10-13-67	22	20	11.9	98.1	7.17	.050	25.9	166	319	1.200

Table 6 continued.

Location and distance from causeway (see fig. 1)	Date	Depth below surface (ft)	Temper-ature (°C)	Grams per liter							Density (gms/ml at 20°C)
				Magnesium (Mg)	Sodium (Na)	Potassium (K)	Lithium (Li)	Sulfate (SO_4)	Chloride (Cl)	Dissolved solids (Residue at 180°C)	
Milepost 742											
1.0 mile north	4-30-68	0	15	12.3	96.0	7.99	.057	25.9	172	336	1.211
1.0 mile north	4-30-68	2	14	12.5	96.0	8.21	.057	26.5	173	338	1.211
0.5 mile north	4-30-68	24	12	13.2	98.6	8.35	.051	31.2	179	348	1.218
30 feet north	4-30-68	0	15	11.2	87.2	6.54	.047	23.3	161	305	1.191
30 feet north	4-30-68	2	15	12.3	97.2	7.60	.057	25.8	178	342	1.213
Milepost 743.5											
25 yards south	5- 1-68	0	16	7.18	65.8	4.47	.031	16.0	112	217	1.137
100 yards south	5- 1-68	18	13	7.16	66.0	4.49	.031	16.2	110	217	1.138
100 yards south	5- 1-68	20	13	7.94	71.8	4.90	.034	18.7	121	237	1.150
100 yards south	5- 1-68	25.5	13	11.0	90.0	7.11	.042	27.2	160	313	1.196
0.2 mile south	5- 1-68	20	13	7.39	69.2	4.62	.027	18.1	116	230	1.146
0.2 mile south	5- 1-68	26.5	11	11.0	93.8	7.15	.043	31.2	161	324	1.203
West culvert											
2.0 miles north	4-30-68	0	14	11.9	88.8	7.09	.052	23.9	161	319	1.197
2.0 miles north	4-30-68	2	15	12.3	96.4	7.96	.058	25.8	172	341	1.210
2.0 miles north	4-30-68	26.5	10	12.4	99.4	8.01	.058	34.7	175	352	1.219
1.0 mile north	4-30-68	0	14	11.8	94.0	7.56	.055	24.7	167	323	1.203
1.0 mile north	4-30-68	2	13	12.3	96.1	8.03	.058	26.3	177	340	1.212
100 yards north	4-30-68	0	12	10.1	85.0	6.65	.048	22.6	152	297	1.186
100 yards north	4-30-68	2	12	11.6	92.3	7.36	.054	24.2	166	319	1.200
100 yards south	5- 1-68	15.5	13	7.00	65.8	4.32	.031	16.2	112	218	1.138
0.2 mile south	5- 1-68	24	12	10.9	87.5	6.85	.048	24.8	156	308	1.194
0.2 mile south	5- 1-68	26.5	11	11.4	97.6	7.14	.050	33.3	169	335	1.212
Milepost 748											
1.0 mile north	4-30-68	0	12	12.3	95.7	8.25	.054	26.1	175	340	1.212
1.0 mile north	4-30-68	2	13	12.2	94.9	8.16	.049	26.5	176	341	1.212
25 yards north	4-30-68	0	12	9.81	81.1	6.40	.040	21.6	145	286	1.178
25 yards north	4-30-68	2	12	12.4	96.6	8.14	.049	26.4	175	341	1.211

Table 6 continued.

Location and distance from causeway (see fig. 1)	Date	Depth below surface (ft)	Temperature (°C)	Grams per liter: Magnesium (Mg)	Sodium (Na)	Potassium (K)	Lithium (Li)	Sulfate (SO_4)	Chloride (Cl)	Dissolved solids (Residue at 180°C)	Density (gms/ml at 20°C)
East culvert											
2.0 miles north	4-29-68	0	12	11.7	91.7	7.41	.052	24.1	166	318	1.200
2.0 miles north	4-29-68	2	14	12.4	97.6	8.05	.058	26.2	178	345	1.215
2.0 miles north	4-29-68	18	11	12.5	98.2	8.08	.057	26.5	176	347	1.214
2.0 miles north	4-29-68	22	10	12.6	101	7.99	.058	35.8	176	353	1.222
1.0 mile north	4-29-68	0	15	11.8	92.9	7.53	.053	24.1	169	321	1.201
1.0 mile north	4-29-68	2	13	12.7	97.6	8.13	.058	26.3	176	342	1.214
1.0 mile north	4-29-68	22	10	12.4	101	8.10	.058	35.5	171	353	1.222
25 yards south	5- 1-68	0	20	6.59	61.8	3.80	.027	15.4	109	206	1.131
25 yards south	5- 1-68	20	12	8.46	75.6	5.23	.037	19.9	133	255	1.162
25 yards south	5- 1-68	32	13	12.4	98.3	7.60	.054	31.9	174	343	1.216
0.2 mile south	5- 1-68	18	13	7.10	66.1	4.25	.032	16.6	116	220	1.138
0.2 mile south	5- 1-68	22.5	12	8.28	76.9	5.00	.036	21.7	133	256	1.163
Milepost 751.5											
1.0 mile north	4-29-68	0	15	12.1	94.0	8.05	.050	25.7	178	340	1.210
1.0 mile north	4-29-68	2	13	12.3	94.9	8.22	.049	26.3	175	345	1.213
1.0 mile north	4-29-68	17.5	12	12.2	96.0	8.30	.057	26.5	178	346	1.213
25 yards north	4-29-68	0	13	9.96	82.0	6.69	.045	22.0	155	293	1.184
25 yards north	4-29-68	2	12	12.4	96.4	8.16	.058	25.8	175	342	1.212
25 yards south	5- 1-68	10	15	6.95	64.0	4.43	.028	15.8	114	217	1.137
0.1 mile south	5- 1-68	19.5	13	7.26	65.8	4.50	.029	16.6	120	222	1.142
0.2 mile south	5- 1-68	20.5	13	7.32	66.8	4.52	.028	17.5	118	227	1.145
0.5 mile south	5- 1-68	22.5	12	8.12	72.7	5.05	.032	20.2	125	248	1.158

Table 6 continued.

Location and distance from causeway (see fig. 1)	Date	Depth below surface (ft)	Temperature (°C)	Grams per liter							Density (gms/ml at 20°C)
				Magnesium (Mg)	Sodium (Na)	Potassium (K)	Lithium (Li)	Sulfate (SO_4)	Chloride (Cl)	Dissolved solids (Residue at 180°C)	
Milepost 744											
10 yards north	8-27-68	0	22	9.7	77.2	6.29	0.040	22.3	144	279	1.177
		1	23	13.5	94.8	8.93	.053	29.3	178	351	1.219
West culvert											
1.0 mile north	8-28-68	14	22	12.3	101	8.42	.062	29.8	180	352	1.217
100 yards north		0	22	11.9	86.6	7.59	.054	24.9	158	304	1.191
		2	23	13.7	95.3	8.63	.066	29.4	178	348	1.218
		14	22	13.8	96.1	8.74	.050	29.6	178	350	1.217
Between south wing-walls	8-29-68	0	22	7.61	72.1	4.65	.034	18.1	122	236	1.148
		14	22	10.9	85.9	7.34	-	25.4	158	307	1.192
0.2 mile south	8-29-68	22	23	11.8	85.9	7.49	.056	26.0	160	313	1.197
		26	20	11.7	101	7.50	.057	32.8	170	342	1.214
East culvert											
1.0 mile north	8-28-68	11	22	12.2	103	8.14	.061	29.8	180	351	1.218
60 yards north	8-28-68	0	22	11.5	83.8	7.09	.055	24.8	160	303	1.190
		2	22	13.1	97.8	8.68	.062	28.8	181	347	1.214
		18	21	14.2	97.0	8.71	.051	29.8	175	353	1.219
Between south wing-walls	8-29-68	0	21	7.75	73.5	4.65	.036	17.8	125	235	1.147
		7	22	10.6	85.9	7.02	.044	24.5	155	300	1.187
		12	22	13.9	97.0	8.94	.053	32.3	181	350	1.217
0.2 mile south	8-29-68	21	24	9.64	85.6	6.36	.049	24.1	150	291	1.182
Milepost 751											
10 yards north	8-27-68	0	23	12.1	89.2	7.78	.049	27.6	169	325	1.203
		1	23	13.1	97.8	8.76	.052	30.0	181	348	1.216
Milepost 750											
10 yards north	8-27-68	0	22	9.74	79.7	6.09	.039	21.8	145	274	1.171

Table 6 continued.

Location and distance from causeway (see fig. 1)	Date	Depth below surface (ft)	Temperature (°C)	Grams per liter							Density (gms/ml at 20°C)
				Magnesium (Mg)	Sodium (Na)	Potassium (K)	Lithium (Li)	Sulfate (SO_4)	Chloride (Cl)	Dissolved solids (Residue at 180°C)	
East culvert											
0.2 mile north	6- 5-69	2	22	12.2	99.2	7.96	0.057	29.4	178	345	1.217
		21.5	19	12.4	101	8.19	.058	30.9	178	354	1.220
0.2 mile south	6- 5-69	2	24	5.78	56.1	3.74	.029	14.5	98	192	1.118
		20	23	5.92	57.4	3.81	.030	14.7	100	196	1.122
		22	21	7.35	69.0	4.77	.037	18.2	120	235	1.146
		24	22	11.5	90.6	7.02	.051	24.7	162	320	1.197
West culvert											
0.2 mile south	6- 5-69	2	24	5.94	55.7	3.74	.029	14.6	98.5	191	1.119
		20	22	5.94	57.0	3.79	.030	15.0	99.0	194	1.119
		28	14	12.0	96.1	7.64	.054	27.1	172	338	1.210

Table 7. Chemical analyses of water collected from culverts in Southern Pacific Co. Causeway.

Location and distance from causeway (see fig. 1)	Date	Depth below surface (ft)	Temperature (°C)	Grams per liter							Density (gms/ml at 20°C)
				Magnesium (Mg)	Sodium (Na)	Potassium (K)	Lithium (Li)	Sulfate (SO_4)	Chloride (Cl)	Dissolved solids (Residue at 180°C)	
East culvert 0.0 mile	6-20-68	0.5	22	7.25	64.2	4.52	0.030	16.6	120	218	1.138
		7	22	9.23	75.5	5.96	.038	20.4	138	263	1.164
		11	23	13.0	96.6	7.95	.049	26.8	162	335	1.208
		14	23	13.7	96.1	8.03	.049	27.2	175	343	1.212
	10-24-68	1	--	6.17	56.0	4.40	.025	14.7	101	193	1.123
		13	--	13.6	95.3	8.83	.067	30.6	179	350	1.219
	2-18-68	5	3	6.14	56.0	4.19	.026	14.5	101	194	1.125
		14	3	13.4	94.6	8.33	.062	27.3	175	332	1.207
	4-23-69	8	16	5.33	52.3	3.46	.026	13.0	90.6	172	1.108
West culvert 0.0 mile	2-18-69	5	4	6.17	56.7	4.47	.025	15.0	103	199	1.126
	4-23-69	6.5	17	5.83	55.1	3.70	.028	13.8	96.9	186	1.114

UTAH GEOLOGICAL AND MINERALOGICAL SURVEY

103 Utah Geological Survey Building
University of Utah
Salt Lake City, Utah 84112

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