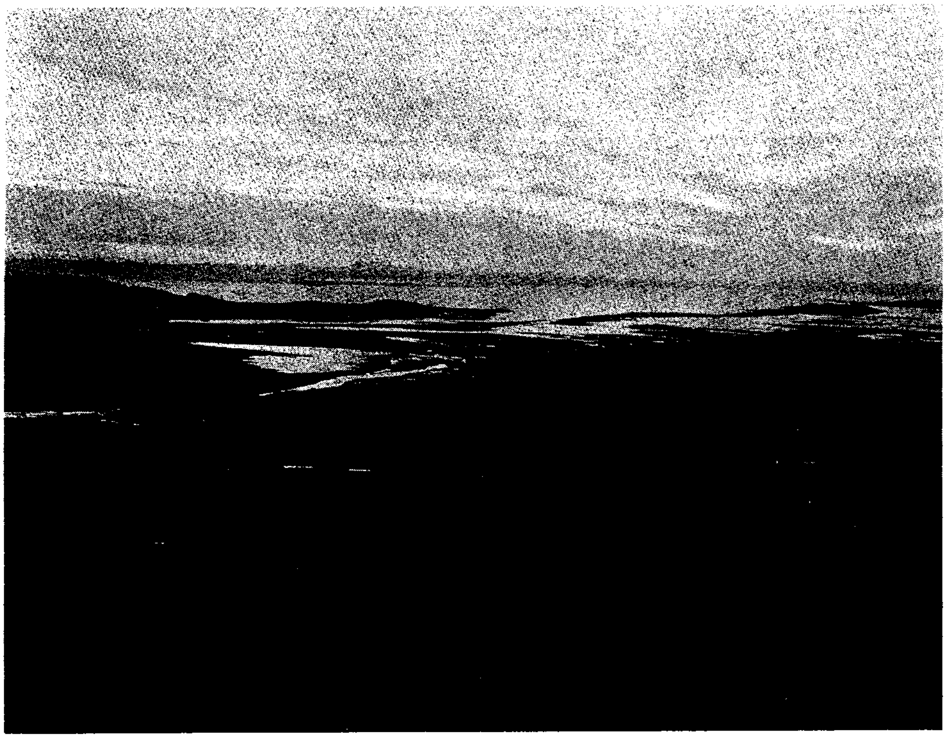
WATER-RESOURCES BULLETIN 3 – PART II

DISSOLVED-MINERAL INFLOW TO GREAT SALT LAKE AND CHEMICAL CHARACTERISTICS OF THE SALT LAKE BRINE

PART II: TECHNICAL REPORT

by D. C. Hahl and R. H. Langford
U.S. Geological Survey



View toward Fremont Island from Francis Peak showing Antelope Island and Promontory Point. (D. C. Hahl, 1963)

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UTAH GEOLOGICAL AND MINERALOGICAL SURVEY

UTAH GEOLOGICAL AND MINERALOGICAL SURVEY

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PART II: TECHNICAL REPORT

by D. C. Hahl and R. H. Langford

U.S. Geological Survey

ABSTRACT

During the 1960 and 1961 water years an annual load of about 2 million tons of dissolved minerals was contributed to the Great Salt Lake area by surficial sources. Almost 60 percent of this load was sodium and chloride. Of the six units contributing to the lake area, three--the Bear River, the Jordan River, and the unit comprising drains and sewage canals--contributed about three-fourths of the runoff and of the load. The water type of these tributaries ranged from bicarbonate in the headwaters to sulfate and chloride near the mouths; the dissolved-solids concentrations were higher in the downstream reaches than in the headwaters.

The Great Salt Lake brine contained from 24 to 28 percent by weight of dissolved solids, and thus, about 4.4 billion tons of dissolved solids during the period of study. The chemical composition of the dissolved solids has remained essentially unchanged during the last century despite an increase in mineralization of the brine from 15 percent in 1869. Sodium and chloride are the major dissolved constituents in the brine, and concentrations of these major constituents as well as of sulfate change seasonally because of dilution by inflow and temperature changes. The observed temperature of the brine ranged from 23° to 89° F.

Because the dissolved-solids concentration of inflow is only about one two-hundredths of that of the brine, surficial inflow acts as a diluent of the brine. In spite of the negligible effect of mineral inflow on the tons of minerals dissolved in the brine, a significant increase in the dissolved-mineral content of the brine occurs with an increase in lake stage. This increase in tons of minerals is largely the result of the solution of minerals precipitated on the lake's bed during a previous period when the lake stage was decreasing.

The dissolved-solids concentration of that part of the lake north of the railroad fill between Promontory Point and Lakeside should remain

reasonably constant and near saturation, whereas the concentration of the main part of the lake, south of the fill, will continue to be governed principally by the precipitation on and runoff from the Uinta Mountains and Wasatch Range.

Studies aimed at determining the evaporation from and precipitation on the lake and its shores, determining the discharge of ground water into the lake, and further refining the estimates of surficial inflow are particularly needed to provide a better basis for evaluating water-management proposals and to develop a fuller understanding of the hydrology of the lake.

INTRODUCTION

This report summarizes a recent study of the magnitude and chemical composition of the dissolved mineral load contributed by surficial sources to Great Salt Lake, Utah. The study was conducted by the U.S. Geological Survey in cooperation with the University of Utah from July 1959 through June 1962, and is part of an overall investigation of the Great Salt Lake basin by the University. Financial support for the study was provided by the U.S. Geological Survey and by the University of Utah Research Fund and Uniform School Fund. Some of the data used in the study were obtained as part of cooperative programs between the U.S. Geological Survey and other agencies.

The major objective of the study was to determine the source and magnitude of the dissolved-mineral inflow to the lake and the chemical composition of that inflow. Corollary objectives included definition of the chemical composition of the lake brine, of differences in composition of the brine from place to place in the lake, and of changes in composition of the brine with time and with fluctuations in lake stage.

To determine the salt load being delivered to the lake brine at any particular lake stage would be difficult due to the continually changing stage. At times of low stage some inflow crosses as much as 15 miles of marshes and salt beds before reaching the lake body. For this study, therefore, the term "lake area" is defined as that area occupied by the lake body and its surrounding shores, the outer perimeter of which is marked generally by the closest sampling points to the lake on the lake's tributaries (Fig. 1).

Comprehensive investigations of the chemical characteristics of the water in the major tributaries to the lake area and of the lake brine were made during 1959-61, and less comprehensive investigations were made of the water in the springs and drains bordering the lake. The basic data collected and the locations of sampling sites are given in Part I of this report by Hahl and Mitchell (1963). In all, data for the chemical characteristics of tributaries to the lake area were obtained at 121 sites, and for the lake brine at 11 sites. Comprehensive data were collected in Utah at the following sites:

Bear River at Bear River Bay Bird Refuge, near
Brigham City
Weber River near Oakley
Weber River near Coalville
Chalk Creek at Coalville
Weber River near Echo
Weber River at Gateway

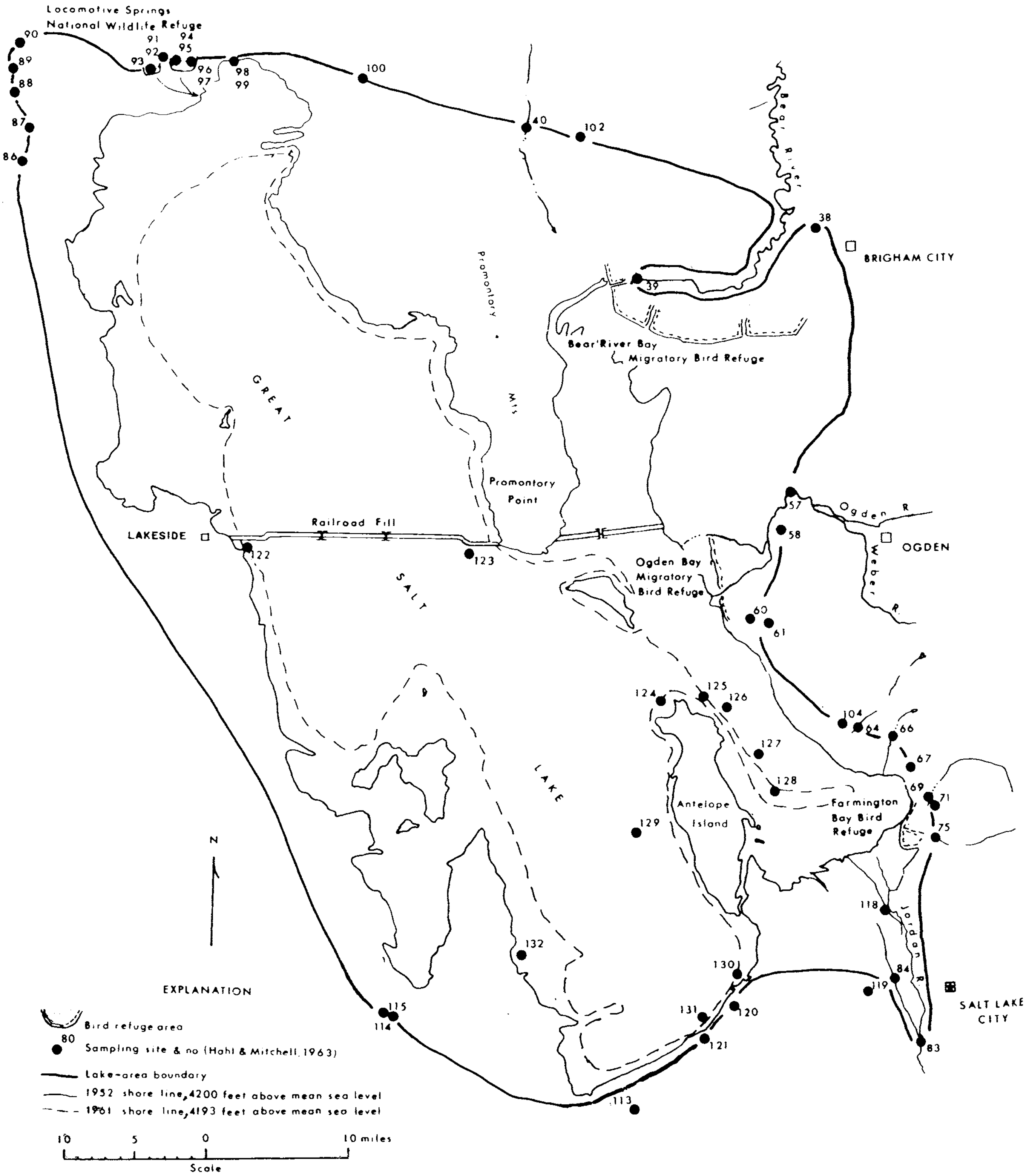

Figure 1. — Sketch of Great Salt Lake showing sampling sites and boundary of the "lake area," 1959-61.

Weber River near Plain City
Jordan River at Salt Lake City
Jordan River at mouth, at Woods Cross
Great Salt Lake at Salt Lake Co. boat harbor, outside breakwater

The data collected on the tributaries are considered to be representative of the chemical quality of inflow to the approximately 3,000 square mile catchment basin referred to as the lake area. Because of the amount and diversity of the available basic data, summary tables were compiled for this report to present the estimates of inflow loads. The summary data will be useful in aiding potential industrial development, in planning recreational facilities, and as a guide to the efficient use of tributary waters of Great Salt Lake.

The study was under the immediate supervision of J. G. Connor (to July 1961) and R. H. Langford (from August 1961), district chemists in charge of water-quality investigations in Utah by the U.S. Geological Survey. A. M. Diaz conducted the early phases of the investigation and reported the significant findings resulting from analysis of the first-year's data (Diaz, 1963). He was succeeded by D. C. Hahl in October 1961. A. J. Eardley, Dean, College of Mines and Mineral Industries, University of Utah, represented the University in the cooperative study and provided valuable assistance in the planning of the study and in the review of the findings. Personnel of other Geological Survey offices in Salt Lake City and Logan, Utah, aided in the collection of samples and provided water discharge data. The sampling program in the lower Bear River was carried out by personnel of the Bureau of Sport Fisheries and Wildlife, U. S. Department of of Interior. Local observers sampled the lower Jordan River and the Weber River at Gateway.

DISSOLVED MINERALS CONTRIBUTED TO THE LAKE AREA

Most of the water in streams draining into the Great Salt Lake is derived from snow or rainfall on the Uinta Mountains and the Wasatch Range. The three major drainage systems (Bear, Weber, and Jordan Rivers) head in the western Uinta Mountains which are mantled mainly by quartzite of Precambrian age, carbonate rocks of Paleozoic age, and glacial deposits of Quaternary age. Runoff from these highlands is of the bicarbonate type and generally of excellent chemical quality. The Paleozoic rocks are undoubtedly responsible for major bicarbonate contributions.

The chemical character of water in the Bear River changes from a bicarbonate type in the highland areas to a chloride bicarbonate type in the lower reaches of the river. Similarly, water in streams draining into Utah Lake is of the bicarbonate type. Analyses of water from Utah Lake (Connor, Mitchell, and others, 1958) indicate that concentrations of chloride and sulfate are about equal to that of bicarbonate. It would be inviting to attribute such changes in chemical character solely to the influence of Bonneville sediments; however, other factors such as discharge of industrial wastes, return flow from irrigated lands, and disposal of human wastes are equally important in determining water types. Water in the Weber River is also bicarbonate in type before leaving the mountains. Almost all of the Weber and Ogden River water entering the valley is diverted for irrigation and for use in communities between Brigham City and Farmington. After use, some of this water returns to the lake area through drainage systems other than the Weber River. Thus, the absence of large amounts of return flow in the lower reach of the Weber River could be one reason why the water remains bicarbonate in type until it enters the lake area.

Figure 2 illustrates the downstream changes in chemical characteristics for the major tributaries and was adapted from the illustration in Diaz (1963); it includes additional data from the companion report by Hahl and Mitchell (1963) and from the report by Connor, Mitchell, and others (1958).

Dissolved-Solids Load

The various types and sources of surficial inflow to the lake area were grouped into units for this study. Most units include the inflow near a major tributary with the inflow of that tributary; some units group inflows of a particular type, such as from springs or from industries and municipalities. Estimates of the dissolved-solids load contributed by tributaries to the lake area are summarized in Table 1. These estimates are based on chemical-quality data, streamflow records, climatological data, and water use and storage records.

The average annual load of 1.9 million tons of minerals delivered by surficial sources to the lake area does not include the mineral load contributed by subsurface sources. However, based on rough estimates of subsurface inflow and concentration, the load contributed by surficial sources is believed to be about 80 percent of the total load of dissolved minerals contributed to the lake area.

The method described by Langbein (1961) for computing the water budget for a lake can be used to compute ground-water inflow by algebraically

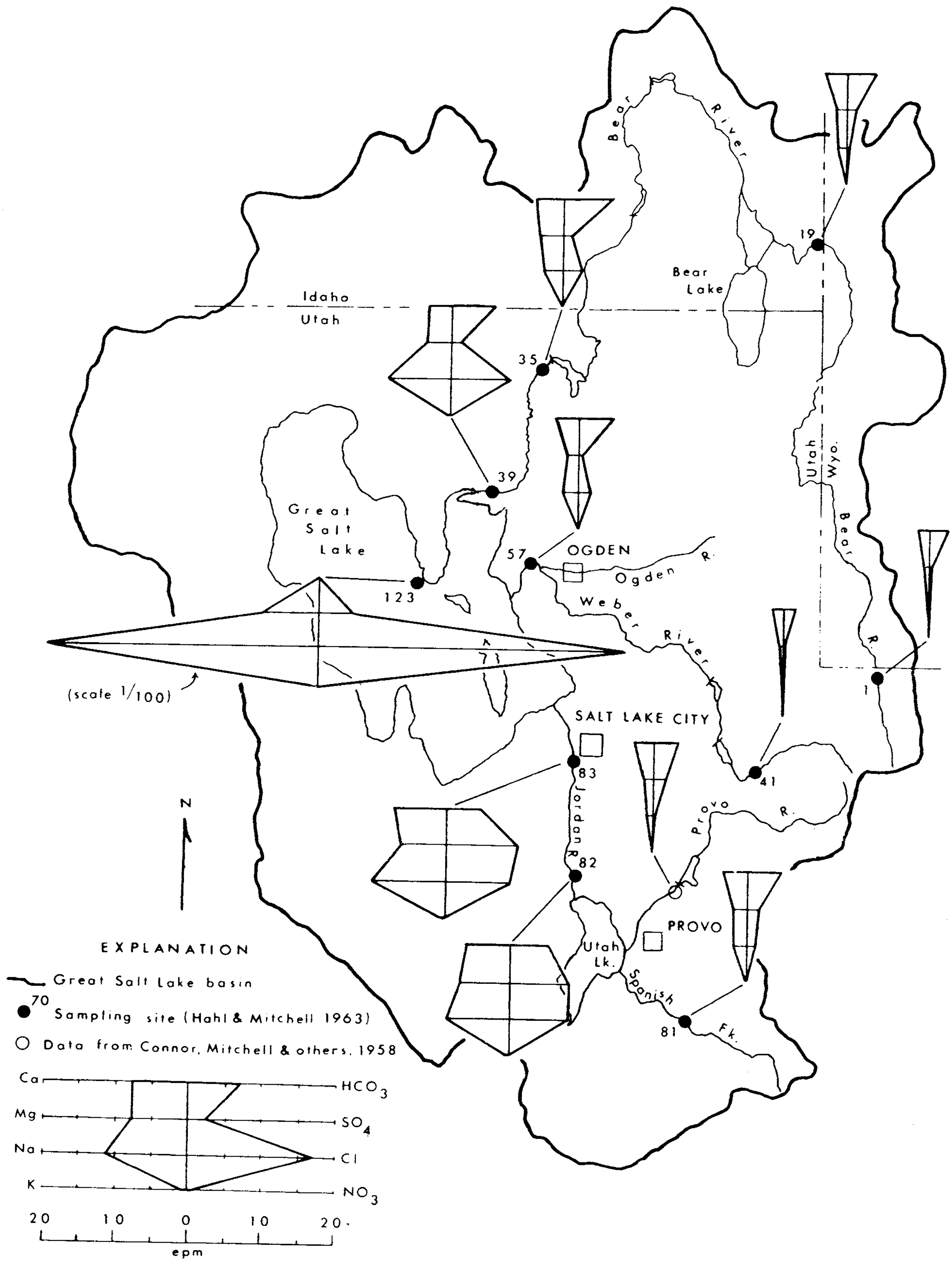

Figure 2. — Chemical quality of water in Great Salt Lake basin.

Table1. — Summary of estimates of dissolved-solids contribution by surficial inflow to the lake area during the water years 1960 and 1961.

Unit	Source	Water year	Runoff (thousands of acre-feet) 1/	Dissolved solids	
				Tons per acre foot 2/	Thousands of tons
Bear River	Bear River at Bear River Bay Bird Refuge, near Brigham City	1960	3/ 635	1.08	686
		1961	3/ 448	1.27	569
	Blue Springs Creek below Thiokol Chemical Plant, at State highway 83	1960	3	6	18
		1961	2	6	12
	Subtotal	1960	638	--	704
		1961	450	--	581
Weber River	Weber River near Plain City	1960	4/ 124	0.47	58
		1961	4/ 61	.61	37
	Sloughs and drains in the lower Weber River Delta	1960	80	.8	64
		1961	30	.9	27
	Subtotal	1960	204	--	122
		1961	91	--	64
East shore	Streams between Weber and Jordan River basins	1960	30	0.5	15
		1961	20	.6	12
	Subtotal	1960	30	--	15
		1961	20	--	12
Jordan River	Jordan River plus Surplus Canal at Salt Lake City	1960	4/ 181	1.74	315
		1961	4/ 132	1.80	238
	Subtotal	1960	181	--	315
		1961	132	--	238
Springs around the lake	Locomotive Springs area near Snowville: West Lake	1960	10	3.5	35
		1961	10	3.5	35
	Baker Springs Slough	1960	6	2.6	16
		1961	6	2.6	16
	East Lake	1960	10	10	100
		1961	10	10	100
	Springs at abandoned salt plant south of Snowville: Large spring	1960	.7	100	70
		1961	.7	100	70
	Small spring	1960	.3	85	26
		1961	.3	85	26
	Big Spring at Timpie	1960	5	11	55
		1961	4	11	44
	Misc. springs	1960	10	5	50
		1961	7	5	35
	Subtotal	1960	42	--	352
		1961	38	--	326
Drains and sewage canals	Sewage from some communities between Salt Lake City and Ogden	1960	4/ 15	3	45
		1961	4/ 15	3	45
	Salt Lake City sewage canal at Cudahy Lane, near North Salt Lake	1960	4/ 32	3.0	96
		1961	4/ 32	3.0	96
	Kennecott drain at U. S. Highway 40, near Saltair	1960	70	4.7	329
		1961	50	5.3	265
	Garfield Smelter drain at U. S. Highway 40, near Saltair	1960	3	7.8	23
		1961	3	8	24
	Misc. drains	1960	10	3	30
		1961	7	4	28
	Subtotal	1960	130	--	523
		1961	107	--	458
Lake area	Total	1960	1,225	--	2,031
		1961	838	--	1,679

1/ Estimated unless otherwise indicated.
2/ Calculated from data in Hahl and Mitchell (1963).
3/ Estimated from streamflow records for gaging station at Collinston, Utah.
4/ Measured at gaging station or from pumpage records.

equating ground water inflow to surface-water inflow, precipitation, evaporation, and changes in lake volume. Attempts to use this method to estimate subsurface inflow to Great Salt Lake were unsuccessful, however, because evaporation-rate and other climatological data for the entire 1,000 square miles of lake surface are only approximate. Also, there is evidence that evaporation occurs from the beach areas, which were about 500 square miles in surface area during the study. In addition, a mass-transfer study of the lake by D. R. Dickson (oral communication, 1961) indicates that water vapor from the air can enter the lake brine without first condensing because, at times, the vapor pressure in the air is greater than the vapor pressure of the brine.

The method used to estimate the ground-water inflow was based on a reconciliation of the following: insight gained through performing the calculations mentioned in the preceding paragraph, extrapolation of data presented by J. H. Feth (written communication, 1962), consideration of some recent work done by E. L. Peck (oral communication, 1962), and the work done by T. C. Adams (1932). The annual ground-water inflow to the lake area, based on the above reconciliation, is estimated at about half a million acre feet. Assuming an average concentration of about 700 parts per million (ppm) of dissolved solids, the resultant subsurface load into the lake area is, then, about half a million tons annually. This subsurface load is about one-fifth of the total dissolved-solids load contributed to the lake area annually during the period of study.

The contributions of water and dissolved minerals to the lake by the different units during the two-year study period (as given in Table 1) are, in Table 2, expressed as percentages of the total; and the weighted-average concentrations and water types are given. As shown in Table 2, the Bear River unit contributed about half of the water and about a third of the minerals to the lake area, whereas the springs around the lake contributed only one twenty-fifth of the water but more than one-sixth of the minerals.

The two years for which data were obtained were years of relatively low precipitation. In wet years the relative magnitude of contributions from the different units may be materially different. Though the Bear River will probably continue to be the major contributor, a relatively small increase in discharge from springs and drains may result in a greatly increased mineral contribution because of their high dissolved-solids concentration. Also, springs and drains around the lake that were dry during the study period may contribute substantial amounts of minerals during wet years.

Table 2. — Relative importance of the six units as contributors to the lake area, October 1959 - September 1961.

Unit	Percentage		Weighted average dissolved-solids concentration		Water type [1]
	Runoff	Load	Parts per million	Tons per acre foot	
Bear River	53	35	870	1.2	Sodium chloride bicarbonate
Weber River	14	5	460	.6	Calcium sodium magnesium bicarbonate
East shore	2	1	400	.5	" " "
Jordan River	15	15	1,300	1.8	Sodium calcium magnesium sulfate chloride
Springs around the lake	4	18	6,200	8.4	Sodium chloride
Drains and sewage canals	12	26	3,000	4.1	" "

[1] Based on relative concentrations (in epm) of major constituents.

The water type as shown in Table 2 was determined by computing equivalents per million (epm) for the data in Table 3, and then selecting the predominant cations and anions. In the absence of a single predominant value, multiple cations and anions were listed, each in the order of its magnitude. Most water entering the lake area was of the sodium chloride type.

About two-thirds of the total inflow, however, had a dissolved-solids concentration less than 900 ppm (as a two-year weighted average) and was generally of the bicarbonate type. In 1960, for example, more than 700,000 acre feet of surface water, suitable for irrigation and as industrial cooling water, entered the lake area through Bear and Weber River units. With treatment, this water could be made suitable for other uses, also.

Loads of Dissolved Constituents

Table 3 shows the discharge-weighted average concentration of dissolved constituents in water entering the lake area from each of the units for each year of the study. A discharge-weighted average of the aggregate inflow was also computed for each year and represents the overall concentration of each dissolved constituent entering the lake area.

An average annual load of 1.9 million tons of dissolved minerals entered the lake area during the two-year period. The loads of dissolved constituents delivered by each of the units are shown in Table 4. Of the 3.7 million tons contributed during the two-year period, sodium and chloride accounted for almost 60 percent. The percentage composition, by weight, of the dissolved solids in the surficial inflow during 1960 and 1961 water years is as follows:

Silica, SiO_2	1.3
Calcium, Ca	7.1
Magnesium, Mg	3.7
Sodium, Na	22.7
Potassium, K	1.5
Bicarbonate as carbonate, CO_3	12.8
Sulfate, SO_4	14.3
Chloride, Cl	36.3
Nitrate, NO_3	.3
Total	100.0

Table 3. —Estimated weighted-average concentration of dissolved constituents in water discharged by each unit.

(Dissolved constituents in parts per million)

Unit	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Nitrate (NO_3)	Dissolved solids [a]
1960 water year										
Bear River	16	65	39	174	15	346	64	263	2.8	810
Weber River	14	58	24	63	12	313	46	63	3.8	440
East shore	12	58	24	43	8	320	38	32	7.0	380
Jordan River	17	144	67	183	18	207	474	273	7.7	1,280
Springs around the lake	20	130	100	2,020	70	340	380	3,290	7.0	6,200
Drains and sewage canals	24	180	74	680	35	520	500	1,200	4.0	3,000
Weighted average	17	90	46	270	19	338	178	428	4.1	1,220
1961 water year										
Bear River	15	68	42	222	17	366	69	334	3.1	950
Weber River	17	66	34	69	10	379	54	70	7.0	510
East shore	15	70	26	52	7	350	50	40	7.0	440
Jordan River	19	157	68	185	15	245	459	290	6.6	1,320
Springs around the lake	20	130	100	2,070	70	350	390	3,340	7.0	6,300
Drains and sewage canals	35	200	87	720	37	450	550	1,280	3.0	3,100
Weighted average	19	102	53	343	21	358	205	548	4.3	1,470

[a] Computed from Table 1.

Table 4. — Estimated loads of dissolved constituents contributed to the lake area.

(Thousands of tons)

Unit	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate as carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Nitrate (NO_3)	Dissolved solids a/
1960 water year										
Bear River	14	56	34	151	13	148	56	228	2.4	704
Weber River	3.9	16	6.7	17	3.3	43	13	17	1.1	122
East shore	.5	2.4	1.0	1.8	.3	6.4	1.6	1.3	.3	15
Jordan River	4.2	35	16	45	4.4	25	117	67	1.9	315
Springs around the lake	1.1	7.1	5.7	115	4.0	9.7	22	188	.4	352
Drains and sewage canals	4.2	32	13	120	6.2	45	88	212	.7	523
Total tons	27.9	148.5	76.4	449.8	31.2	277.1	297.6	713.3	6.8	2,031
1961 water year										
Bear River	9.2	42	26	136	10	110	42	204	1.9	581
Weber River	2.1	8.2	4.2	8.5	1.2	23	6.7	8.7	.9	64
East shore	.4	1.9	.7	1.4	.2	4.7	1.4	1.1	.2	12
Jordan River	3.4	28	12	33	2.7	22	82	52	1.2	238
Springs around the lake	1.0	6.7	5.2	107	3.6	8.9	20	173	.4	326
Drains and sewage canals	5.1	29	13	105	5.4	32	80	186	.4	458
Total tons	21.2	115.8	61.1	390.9	23.1	200.6	232.1	624.8	5.0	1,679

a/ Data from Table 1.

The percentage of the total load for each constituent contributed to the lake area by each unit, calculated from the data in Table 4, is listed in Table 5. Comparison of the data shows that the Bear River unit contributes the greatest load of dissolved minerals, and with respect to the individual constituents, it is the largest single contributor of all constituents with the exception of sulfate. Sulfate is contributed principally by the units comprised of the Jordan River and the drains and sewage canals. The two units combined deliver 69 percent of the total sulfate load contributed to the lake. Chloride is contributed almost equally by the units comprising the springs, the drains and sewage canals, and the Bear River. The differences in the constituent load contribution of each unit reflect the effects of the various uses of the water prior to entering the lake. In the Bear River unit the water is generally of the bicarbonate type and is used for irrigation and the generation of hydro-electric power; whereas the Jordan River unit and the unit consisting of drains and sewage canals are greatly affected by industrial and municipal wastes, and are usually high in sulfate and chloride content. Together these three units contributed approximately three-fourths of the water, total load, and load of each of the major constituents contributed to the lake area by surficial sources.

As water moves from the lake area boundary to the lake itself several factors influence its chemical characteristics. Among these factors are impoundment in bird refuges of a large part of the surficial flow entering the lake area, and traversal of this flow across the bay lying eastward of a line through Antelope Island and the Promontory Mountains before it enters the lake body (Fig. 1). At or below the lake area boundary much of the runoff from the Bear, Weber, and Jordan Rivers is impounded in bird refuges. Generally, this runoff is not released in large amounts from the bird refuges except during the winter and early spring. The floor of the bay eastward of Promontory Point and Antelope Island ranges from 4,195 to 4,200 feet above mean sea level (msl), and, since 1851, this bay has been at least partly dry during two periods, 1900-1907 and 1931-1963 (Fig. 3). During parts of each of the water years 1934-1945 and 1959 the bay was completely dry except for the river channels extending below the bird refuges and leading to the lake body. In 1960 the bay dried up and remained dry throughout the 1961 and 1962 water years. Thus, during the period of study most of the surficial inflow was impounded and had to traverse as much as 15 miles of salt marshes and barren lake bed via the extended river channels before reaching the brine. For example, the Bear River traverses about 15 miles of the dry Bear River Bay below the refuge, flows through the 600 foot opening in the railroad fill, and then flows across another few miles of lake shore before entering the lake proper.

Table 5. — Percentage of load dissolved constituents contributed to the lake area during the water years 1960-61.

Constituent	Unit						Total
	Bear River	Weber River	East Shore	Jordan River	Springs	Drains and canals	
Silica, SiO_2	47	12	2	15	5	19	100
Calcium, Ca	37	9	2	24	5	23	100
Magnesium, Mg	44	8	1	20	8	19	100
Sodium, Na	34	3	1	9	27	27	100
Potassium, K	42	8	1	13	15	21	100
Bicarbonate as carbonate, CO_3..	54	14	2	10	4	16	100
Sulfate, SO_4	18	4	1	37	8	32	100
Chloride, Cl	32	2	1	9	27	30	100
Nitrate, NO_3	37	17	4	26	7	9	100
Dissolved solids	35	5	1	15	18	26	100

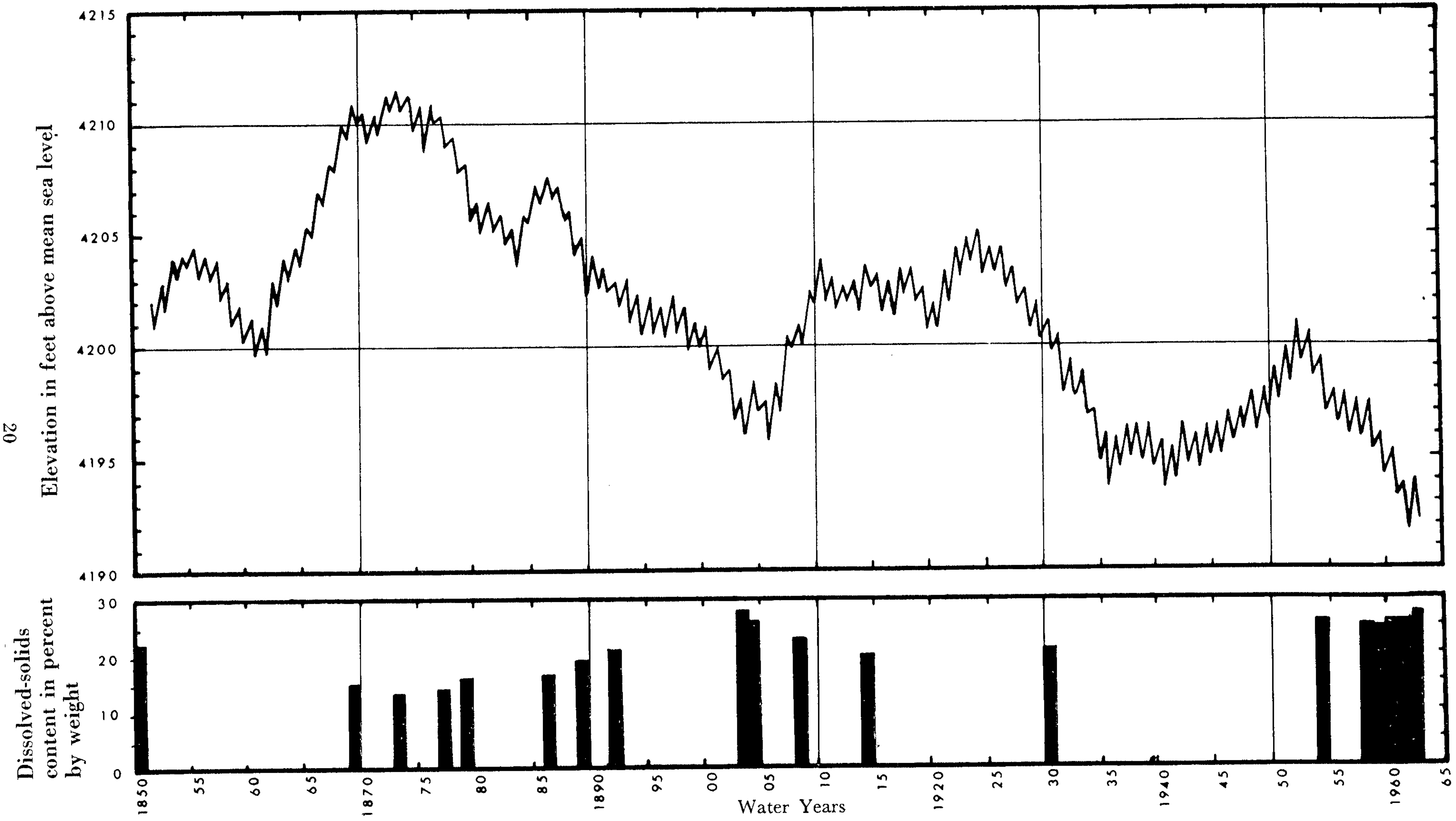

Figure 3. — Hydrograph of Great Salt Lake showing yearly maximum and minimum elevations of lake surface, 1851-1962, and the dissolved-solids content of the brine.

Impoundment and traversal of barren lake shore subjects surficial inflow to evaporation and transpiration and to contact with soluble-salt deposits. The effect would be to increase the dissolved-solids content of the inflow; however, definitive studies have not been made to determine the magnitude of the resulting increase or change in chemical character.

GREAT SALT LAKE

Factors Influencing the Chemical Characteristics of the Brine

When the pioneers arrived in the Jordan Valley in 1847 the surface of Great Salt Lake was about 4,200 feet above msl (Fig. 3). Irrigation and other water-resources development started at that time and both continually expanded through the years. In spite of increased water development, the lake surface rose above the 4,200 foot mark in two separate periods since the high lake stages of 1865-1890. Since 1924, however, precipitation on and runoff from the headwater areas of the Bear, Weber, and Jordan Rivers have been much less than in earlier years of record, as illustrated in Figures 4 and 5. This decrease in precipitation and runoff also occurred throughout the Wasatch Range and is the primary cause of the downward trend in lake volume since 1924; of secondary importance is the water-resources development that has occurred in the drainage basin. The amount of precipitation in the headwaters will continue to determine the ultimate lake stage.

The dissolved-solids content of the brine has ranged from about 15 percent during the high lake stages of the 1870's to about 28 percent during the low lake stages of the early 1900's and 1960's (Fig. 3). The histograms showing dissolved-solids content in Figure 3 were developed from data in Clarke (1924), Richardson (1906, p. 34), and Hahl and Mitchell (1963, p. 38-40). The histograms represent single measurements of dissolved-solids content during the indicated water years, except for those for the years 1896, 1904, 1960, and 1961 which represent averages of several measurements.

In Figure 3 lake-stage data for 1851-1950 were taken from the compilation report of the U.S. Geological Survey (1960, p. 24-25); for 1951-1960, from the U.S. Geological Survey annual reports in the series "Surface water supply of the United States, Part 10, The Great Basin", and for 1961 and 1962 from annual reports of the U.S. Geological Survey (1961b, 1962).

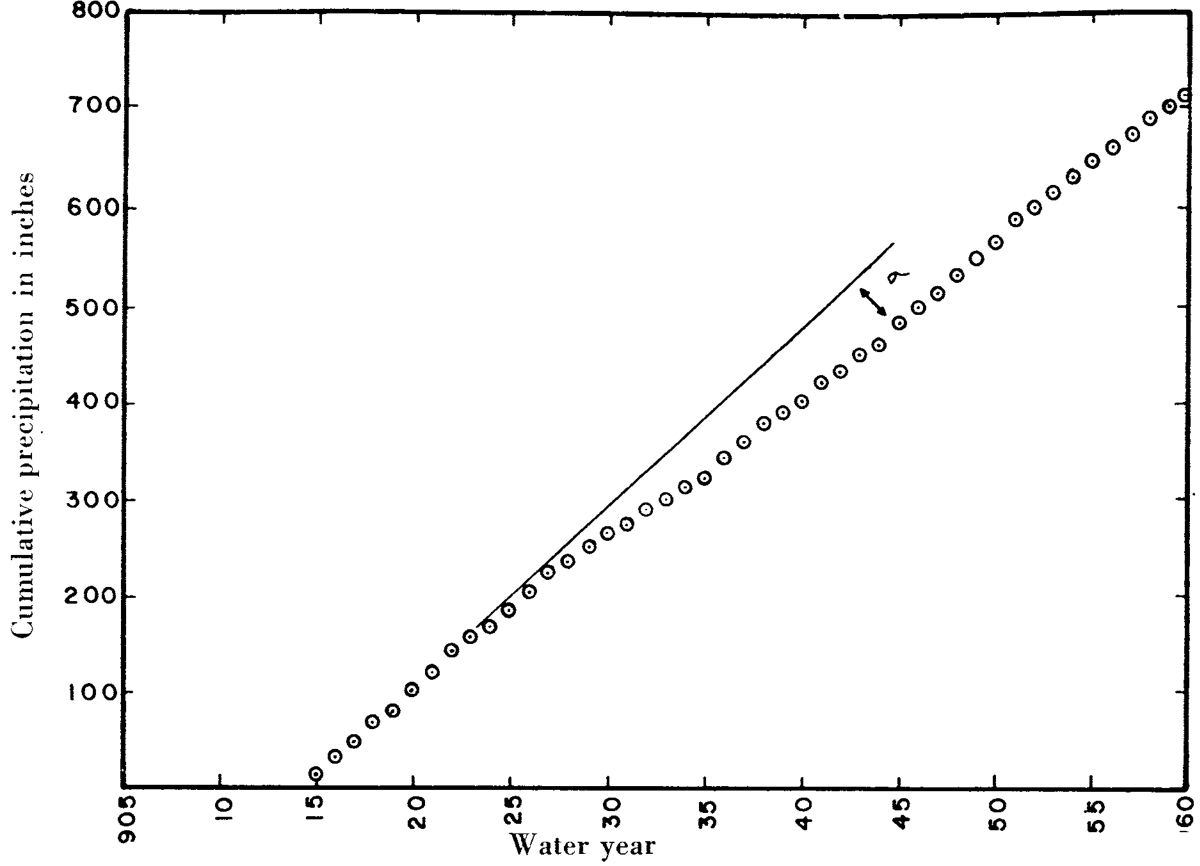

Figure 4. — Deviation (σ) from 1915-23 precipitation rate at Heber, Utah.

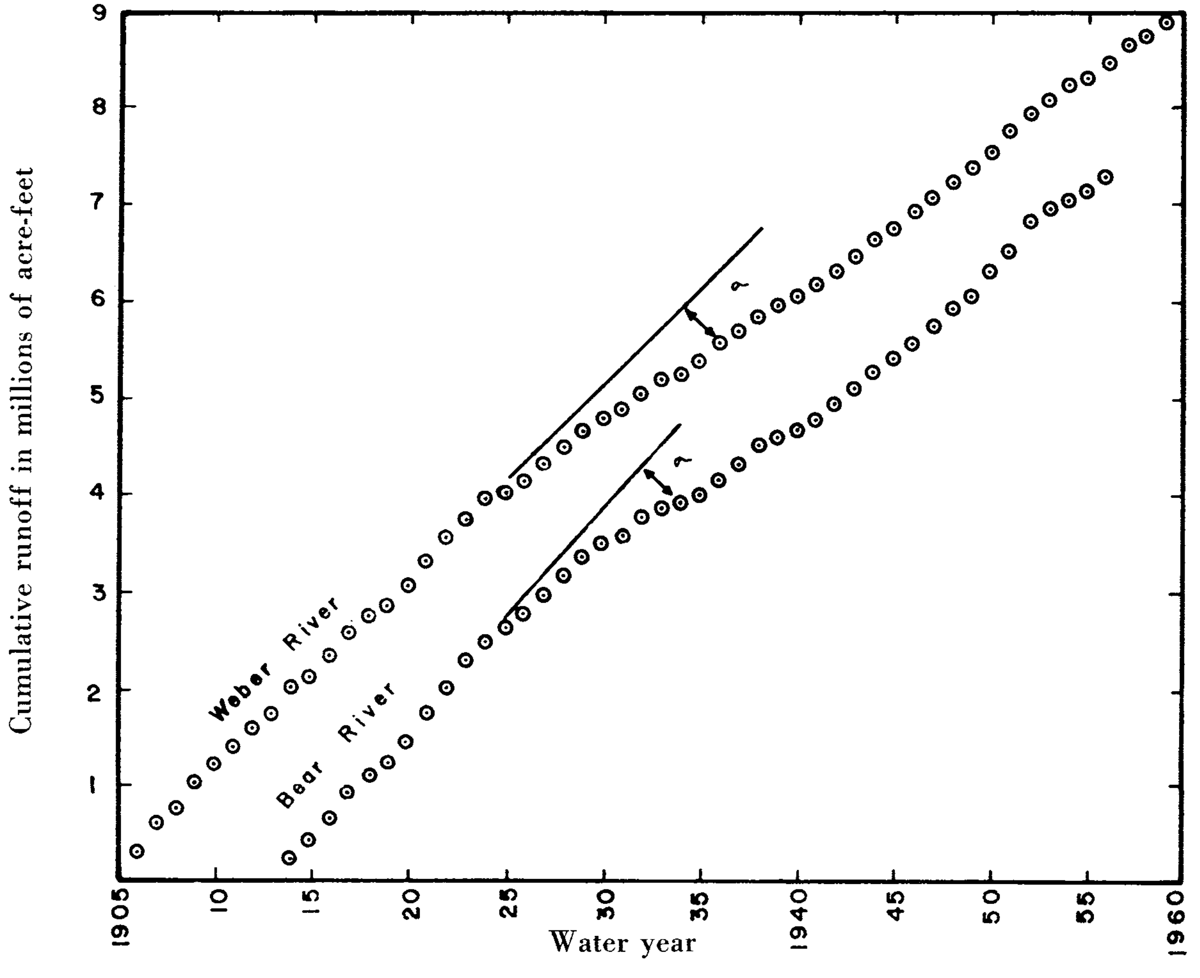

Figure 5. — Deviation (σ) from 1906-24 runoff rate of the Bear River near Evanston, Wyo., and of the Weber River near Oakley, Utah.

The present study of the lake brine took place when the lake was at or near its lowest historical level. The lake was about 25 feet deep at its deepest point during the current study; in contrast, it was about 45 feet deep in 1873. Furthermore, whereas the surface area of the lake varied during the study from about 900 to 1,100 square miles; at the maximum historical level in 1873, the surface area was about 2,400 square miles. The corresponding volumes of brine in the lake were about 10 million and 30 million acre feet, respectively (U.S. Geological Survey, unpublished data, 1961c).

The Southern Pacific Company constructed a causeway across the lake during the late 1950's parallel to the old trestle between Promontory Point and Lakeside. This causeway is a fill composed of rock from the Promontory and Lakeside Mountains. Free movement of brine between the northern part of the lake and the southern part is restricted to only two openings in the fill (see Fig. 1); the bases of these openings are about 15 feet above the lake bed at an altitude of about 4,184 feet above msl, and the openings are 15 feet wide and are located over one of the deepest parts of the lake. Flow through these two openings is reported to be northward except when the wind is from the north. On January 22, 1963, the air was still and the combined flow through these openings was northward at about 400 cubic feet per second (cfs).

Chemical Characteristics of the Brine

The lake south of the railroad fill is fed mainly by relatively fresh water from the major tributaries, whereas since 1957, the lake north of the fill has been fed mainly by brine discharging through the two openings in the fill. Analyses of samples of the brine taken the same day but on opposite sides of the fill show that the dissolved-solids content of brine from the north side is slightly higher than that of brine from the south side (Hahl and Mitchell, 1963, p. 42). The lake bottom to the north is at least partly covered with salt crystals several inches thick, whereas the lake bottom to the south is sandy. Therefore, because brine on the north side of the fill appears to be more nearly saturated than the brine on the south side, and because inflow northward through the openings in the fill is highly mineralized compared to inflow for the remainder of the lake, the dissolved-solids concentration of the northern arm probably will change slowly with time whereas the concentration of the brine to the south could change seasonally. The amount of seasonal change in concentration of the southern part of the lake is determined by the amount of inflow from the major tributaries. Years of low runoff will result in a lake of small volume which approaches saturation; years of high runoff will produce the reverse effect. For low lake levels, the seasonal change of concentration, expressed in weight percent, is illustrated in Figure 6.

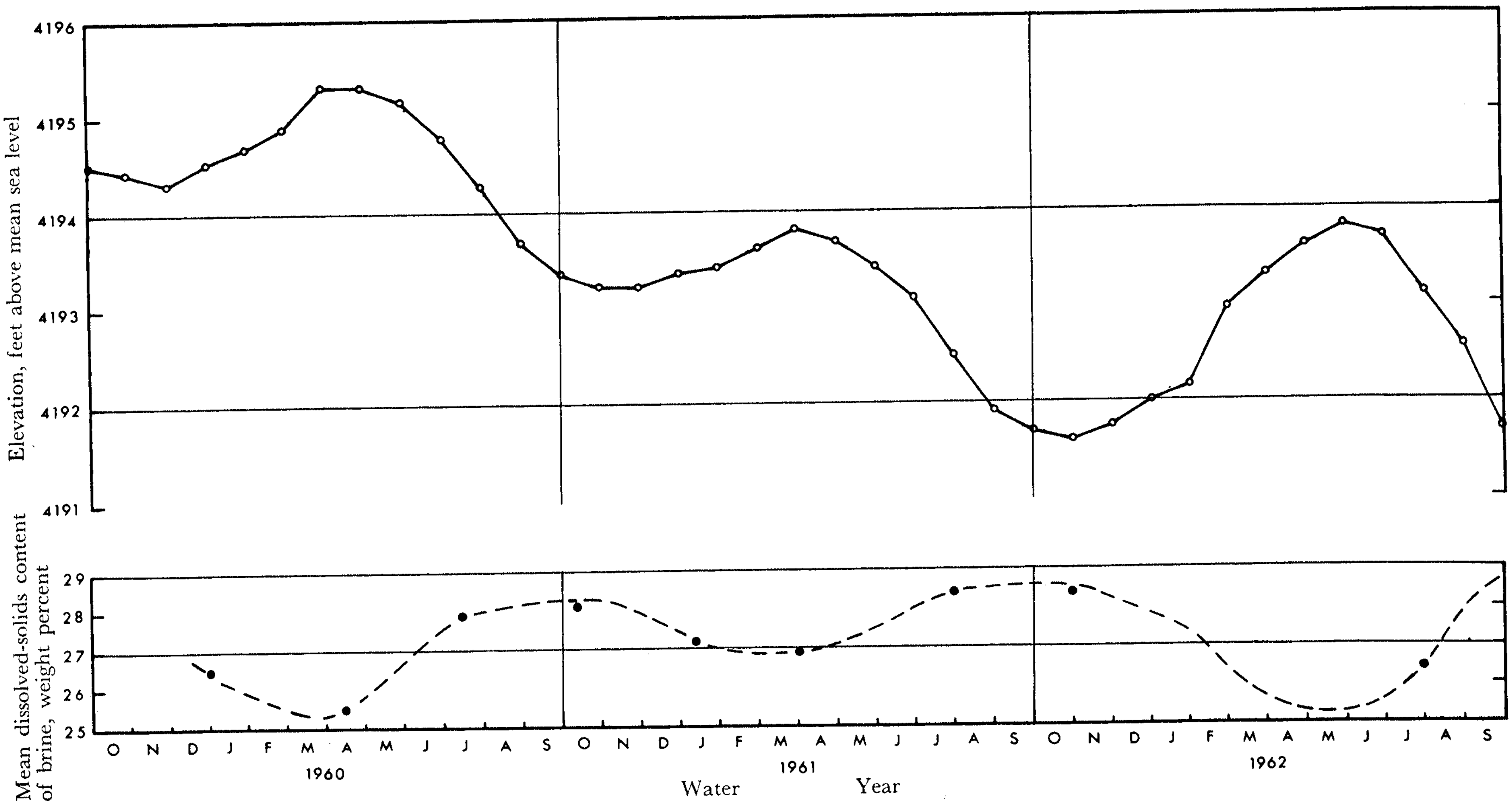

Figure 6. — Fluctuations of water-surface elevation of Great Salt Lake and dissolved-solids content of the brine during the water years 1960-62.

The concentrations shown in Figure 6 were determined by evaporating a known weight of brine and drying the residue at 180° C for 2 hours. Dissolved-solids concentrations determined in this manner include some water of hydration along with most of the dissolved constituents; in contrast, the dissolved-solids concentration calculated as the sum of the determined constituents includes neither water of hydration nor those dissolved constituents that were not individually determined. Therefore, the "residue" values are generally several percent higher than the "calculated" values. For a brine, such as that of Great Salt Lake, the calculated dissolved-solids concentration is believed to be the more accurate of the two provided all of the major dissolved constituents are determined. The residue values were used in Figure 6, however, because they were available for all of the analyses.

The average volume of brine in Great Salt Lake during the period October 1959 to September 1961 was about 10 million acre feet. The average dissolved-solids concentration (calculated) of the brine for the same period was 266,000 ppm after allowance is made for the slightly higher dissolved-solids concentration of the northern arm. Thus, the brine contained an average of about 4.4 billion tons of dissolved minerals during the period. No great differences in concentration were noted from point to point about the main lake body, and on the basis of few data no mineral stratification of the brine was noted. Because the lake is shallow, the circulation caused by wind, seasonal temperature changes, and evaporation is probably sufficient to produce the uniform chemical characteristics of the brine.

Even though the dissolved-solids content of the brine changes with time (see Figs. 3 and 6), the chemical composition of the dissolved solids has remained practically constant over the last century. Analyses of samples collected between 1850 and 1913 (Richardson, 1906, p. 34, and Clarke, 1924, p. 157) and those collected more recently (Hahl and Mitchell, 1963, p. 42) are given in Table 6. Despite the differences in analytical methods, in sampling points, and in lake volume and mineralization, the percentage composition of the dissolved solids remained almost constant and was predominantly sodium and chloride with lesser amounts of sulfate, magnesium, and potassium and with even lesser amounts of calcium, bicarbonate, and other constituents. A comparison of extremes observed and of average concentrations of individual constituents dissolved in the brine is given in Table 7. These data are further compared in Table 7 with the discharge-weighted average concentrations of surficial inflow.

The solubility of Glauber's salt ($Na_2SO_4 \cdot 10H_2O$) is decreased about tenfold with a change in temperature from 90° F to 20° F. A temperature change from about 90° F to 20° F is an annual occurrence for

Table 6. — Percentage composition (by weight) of the dissolved solids in Great Salt Lake brine.

Constituent	1850 1/	1869 2/	August 1892 1/	October 1913 2/	March 1930 3/	April 1960 3/	November 1961 3/
Silica, SiO_2	....	....	....	....	....	0.002	0.003
Iron, Fe	....	....	....	....	....	.00002	.00004
Calcium, Ca	....	0.17	1.05	0.16	0.17	.12	.10
Magnesium, Mg	0.27	2.52	1.23	2.76	2.75	2.91	3.49
Sodium, Na	38.29	33.15	33.22	33.17	32.90	32.70	31.53
Potassium, K	....	1.60	1.71	1.66	1.61	1.61	1.95
Bicarbonate as carbonate, CO_3	....	....	....	.09	.05	.06	.07
Sulfate, SO_4	5.57	6.57	6.57	6.68	5.47	6.60	8.21
Chloride, Cl	55.87	55.99	56.22	55.48	57.05	55.86	54.59
Nitrate, NO_3	....	....	....	....	....	.03	.06
Boron, B	....	....	....	....	....	.01	....
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Dissolved solids, in percent by weight of the brine	22.28	14.994	22.83	20.349	21.0	24.7	26.9

1/ Computed from data reported by Richardson (1906, p. 34).

2/ Reported by Clarke (1924).

3/ From Hahl and Mitchell (1963, p. 38); analyses for samples collected at Promontory Point south of RR fill (site 123 on fig. 1).

Table 7. — Concentrations of dissolved constituents in Great Salt Lake brine and surficial inflow.

(Concentrations in parts per million unless otherwise indicated)

Constituent or property	Great Salt Lake			Surficial inflow
	Maxium 1/	Minium 2/	Average 2/	Discharge-weighted average 3/
Silica, SiO_2	7.0	4.2	5.3	18
Aluminum, Al	2.6	2.5	....	.....
Iron, Fe	.11	.02	.04	.....
Calcium, Ca	463	265	319	94
Magnesium, Mg	9,440	6,920	8,050	49
Sodium, Na	92,200	77,800	85,700	300
Potassium, K	5,570	3,810	4,550	20
Lithium, Li	56	29	....	.....
Bicarbonate, HCO_3	398	266	327	344
Sulfate, SO_4	22,600	12,100	17,400	188
Chloride, Cl	158,000	133,000	147,000	475
Fluoride, F	7.4	5.9	......	.....
Iodide, I	.60	.26	.41	.....
Nitrate, NO_3	154	61	82	4.1
Boron, B	36	21	......	.....
Dissolved solids, calculated	285,000	240,000	263,000	1,320
Density, g/ml at 20°C	1.221	1.186	1.208	1.000

1/ Extremes observed from analyses of samples collected at sites 122, 123, 124, 131, 132 (see Fig. 1) during June 1959-November 1961.

2/ Average of anlyses of samples collected at sites 123 (south of fill), 131, and 132 (see Fig. 1) in April, July, and October 1960 and January-February 1961.

3/ For water years 1960 and 1961, and from data in tables 1 and 3.

the lake brine (Table 8). As a result, large amounts of Glauber's salt are precipitated and washed up on the beaches each winter to be redissolved with warmer weather and spring rains. Seasonal fluctuations in the concentration of sodium and sulfate ions in the brine are illustrated in Figure 7. Spring runoff also causes a marked dilution of the brine, whereas summer evaporation reconcentrates the brine after which the cycle repeats itself with the onset of cold weather. (See chloride curve in Fig. 7.) Eardley (1962) reports that a wedge-shaped bed of Glauber's salt with a maximum thickness of at least 32 feet lies interbedded with the soft lake-bottom clays west of Promontory Point along the railroad fill.

The saturation point of the brine with respect to the major constituents has not been determined. The relationships of density to dissolved-solids concentration and to lake volume, however, indicate that a dissolved-solids content of between 28 and 29 percent by weight is required to precipitate sodium chloride.

Comparison of the concentrations of dissolved constituents in the brine to those in the influent waters (see Table 7) opens many interesting approaches for further study. The deficiency of silica in the brine, for example, is probably attributable to diatoms growing in the lake rather than chemical factors. Woolley and Marsell (1946, p. 105) report in their annotated bibliography that earlier investigators found 62 diatoms in the brine. Differences in concentrations of some of the other minor constituents in the brine as compared to those in the inflow may not parallel differences in concentration of the major constituents. Further study of the inflow of minor constituents to the lake and in the brine itself during and after periods of very high and of median runoff would help to define the extremes of concentrations of minor constituents and, thus, might aid in studying lake cycles by keying cyclic events to specific dissolved constituents. Because the dissolved-solids concentration of surficial inflow is only about one two-hundredths of that of the brine. The dissolved-solids concentration of the brine is essentially unaffected by the minerals being delivered to the lake by surficial inflow. The effect of inflow is, however, to change the stage and volume of the lake, thus, inflow acts as a diluent. With increasing lake stage the dissolved-solids concentration of the brine decreases, whereas the tons of minerals dissolved in the brine increase. This increase in total dissolved minerals results mainly from re-solution of salts that were precipitated on the lake bed and near shore during a previous period when the lake stage was decreasing. Therefore, the chemical characteristics of the brine are mainly controlled by the minerals dissolved in the brine and the soluble salts on the lake bed which are available for solution. Physiographic features of the lake bed, as well as the aquatic life

Table 8. — Temperature, in °F, of Great Salt Lake brine, 1958-1963.

Date	Salt Lake County Boat Harbor (site # 131)	Solar Salt Plant Intake (site # 132)	Promontory Point (site #123)	
			South of RR fill	North of RR fill
Oct. 11, 1960	62	53	....	....
Oct. 12	....	....	60	....
Oct. 16, 1962	....	....	60	59
Nov. 8, 1961	....	....	49	....
Jan. 5, 1960	....	23	....	34
Jan. 10, 1961	....	29	....	....
Jan. 11	....	....	37	....
Jan. 22, 1963	....	....	25	29
Feb. 29, 1960	34	43	....	....
Apr. 6, 1958	48	....	....	....
Apr. 12, 1960	60	67	57	....
Apr. 19	....	....	53	53
Apr. 4, 1961	60	58	....	....
Apr. 6,	....	....	55	....
June 26, 1959	....	83	....	....
June 29	....	....	....	72
July 8, 1960	78	80	....	....
July 19	....	....	85	85
July 25, 1961	89	89	....	....
Sept. 29, 1959	....	55	....	....
Sept. 30	....	....	....	60

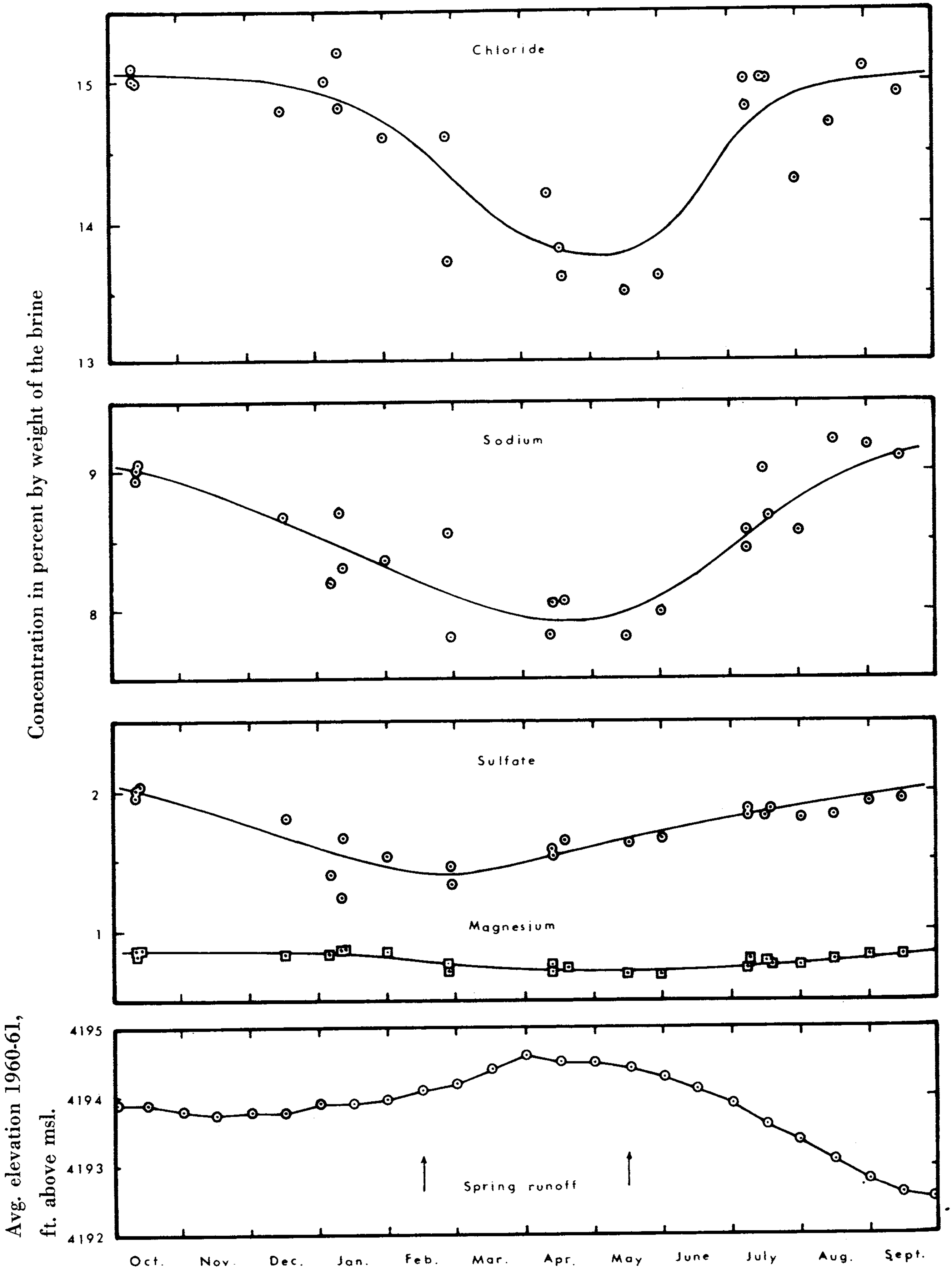

Figure 7. — Seasonal fluctuations in stage and concentration of some dissolved constituents in Great Salt Lake brine during the water years 1960-1961.

in the brine, also affect the dissolved-solids concentration and chemical character of the brine.

SUMMARY AND CONCLUSIONS

Most of the surficial water entering the Great Salt Lake area comes from tributaries originating in the Uinta Mountains. East of the Wasatch Range water in the streams is of the calcium bicarbonate type and generally contains less than about 400 ppm of dissolved solids. By the time the streams enter the lake area, however, water use and solution of minerals from rocks and soils in that part of the drainage basin west of the Wasatch Range cause the water to become more highly mineralized and to be of the sulfate or chloride type.

The estimate of 1.9 million tons of dissolved minerals that entered the lake area annually during the water years 1960 and 1961 was based entirely on the dissolved solids transported by surficial sources. An assumed annual load carried by subsurface water was about a half a million tons. Almost 60 percent (by weight) of the load contributed by surficial sources was sodium and chloride.

About one-third of the surficial load and half of the water entering the lake area came from the Bear River unit; about half the load and about one-seventh of the water was contributed by the two units which include springs, drains, and sewage canals; and about 15 percent of each the water and the load was contributed by the Jordan River unit. Together, the three units--Bear River, Jordan River, and drains and sewage canals--delivered about three-fourths of the dissolved minerals and three-fourths of the water which entered the lake area during the two-year period.

Great Salt Lake contained about 4.4 billion tons of dissolved minerals and had a dissolved-solids concentration of 24 to 28 percent (by weight) during the water years 1960 and 1961. Even though the concentration has doubled over the past century, the percent composition of the dissolved solids has remained fairly constant. Seasonal fluctuations in the concentrations of sodium, chloride, magnesium, and sulfate, however, are attributed to inflow of runoff in the spring and to temperature changes. During 1958-63 brine temperatures as low as 23° F and as high as 89° F were observed.

The railroad fill extending from Promontory Point westward to Lakeside has isolated the northern part of the lake. Although two openings through the fill allow brine to flow from one part of the lake to the other, the dissolved-solids concentration of the brine in the northern arm probably will remain near the saturation point whereas that in the southern part will be subject to seasonal and cyclic changes dependent on the amount of runoff delivered by the major tributaries. Almost all of the dissolved solids delivered annually by surficial sources enters the lake area on its eastern side and, thus, represents inflow available to dilute only the southern arm of the lake.

The data obtained as a result of this study are of hydrologic and geologic significance in developing a better understanding of the history of Great Salt Lake. They are of significance also in evaluating plans for further development of water and mineral resources and of recreational uses of the lake and its drainage basin. As the study progressed, the need for additional investigations became apparent. Some of these needed investigations are as follows:

(1) Studies comparable to this one, but made during periods of high and of median runoff, would provide data from which a long-term estimate of loads entering the lake could be computed.

(2) Continuing records of the chemical composition of the lake brine are needed to refine correlations of dissolved-constituent concentration with lake stage, inflow, and temperature.

(3) Water and dissolved-solids budgets for the lower Bear River and the lower Jordan River Units would result in better estimates of subsurface as well as surficial inflow to the lake.

(4) Refinement of data on evaporation from and precipitation on the lake area is essential for a better understanding of the hydrology of the lake area.

(5) A reconnaissance study of the western shore of the lake to determine if ground- and surface-water sources are delivering significant amounts of dissolved minerals to the lake would establish the need, if any, for more detailed studies in this part of the lake area.

(6) A study of the amounts and chemical composition of salts precipitated in the lake bed would provide information on the degree of saturation of various minerals in the brine, the precipitation reactions that control the composition of the brine, and the rates and areas of salt accumulation on the bed.

(7) Determination of the amount and character of soluble airborne salts transported into and out of the lake area would show the effect of such a transport mechanism on the chemical characteristics of the brine and of influent streams, and would also provide information on the feasibility of reclaiming lands adjacent to the lake for agricultural purposes.

Proposals for diking Great Salt Lake need to include the economic aspects of the brine as a water and as a mineral resource. Proper evaluation of water-management plans such as, for example, creating a relatively fresh water body in Bear River Bay, freshening the eastern bays, controlling the dissolved-solids content of the southern part of the lake, and leaving the northern arm as a saturated brine require that the chemistry of the brine and the inflow be thoroughly understood. The studies outlined above will provide information essential to a fuller understanding of the hydrology of the lake and to its potential utilization.

APPENDIX

Collection of Samples

The criteria used in collecting the samples included 1) selection of sampling sites to insure adequate mixing of upstream tributary waters at the sampling section, 2) selection of the most representative sampling point with regard to the stream cross section, and 3) scheduling the sampling frequency to ascertain the yearly average concentration of dissolved constituents.

For collection of data on the chemical composition of Great Salt Lake, sites at the Salt Lake Co. boat harbor (site No. 131 on Figure 1), at the intake to Solar Salt Plant (site No. 132), and at Promontory Point (site No. 123) were selected. Data from these sites were intended to represent the chemical composition of the main lake body. Other sites on Great Salt Lake (Fig. 1) were selected to provide supplementary information.

Chemical Analysis

Samples collected for this study were analyzed according to the methods commonly used by the U.S. Geological Survey (Rainwater and Thatcher, 1960). In addition, iodide (I) was determined by an adaptation of the method developed by Rossum and Villarruz (1960). Density was determined for each sample having a specific conductance of 10,000 micromhos or greater. In the Great Salt Lake basin a specific conductance of 10,000 micromhos represents water containing about 6,000 ppm of dissolved solids.

Analysis of Great Salt Lake brine samples required that small aliquots be taken and diluted because of the high concentration of dissolved constituents. Some dilutions (Table 9) were preset by the limitations of the flame-photometric method used or by the amount of final precipitate desired, whereas other dilutions were made to facilitate the formation of complex ions with a titrant and, therefore, are not specified in Table 9. As the general understanding of brine chemistry improves, the methods for preparing and analyzing brines undoubtedly will improve. The chemical methods used in this study were tested and found to produce reasonably consistent results. However, further study to refine methods for analyzing brines, such as the Great Salt Lake brine, is warranted.

Water Discharge

Discharge records published by the U.S. Geological Survey (1961 a,b) were used in conjunction with chemical-quality data collected at or near gaging stations. Discharge was estimated at the time samples were collected at many of the ungaged sites.

The discharge of the Bear River at Corinne was assumed to represent the discharge into the bird refuge from the Bear River. A discharge record for Corinne for water years 1960 and 1961, therefore, was computed by using the 1960-61 records at Collinston in conjunction with a correlation between the records for the gaging stations on the Bear River near Collinston and at Corinne for the water years 1950-57. This computed discharge record was utilized together with the chemical-quality record for Bear River at Bear River Bay Migratory Bird Refuge to calculate the tonnage of dissolved constituents contributed to the lake area by the Bear River.

Discharge measurements for Big Spring at Timpie, Kennecott drain, and streams draining the area between the Weber and Jordan River basins were often made at the time of sampling. Because the flow of these tributaries fluctuates seasonally, an estimate of annual runoff was made using climatological data, daily discharge records for the streams above diversions, diversions into the respective drainage areas, and measurements made at the time of sampling. The estimates of annual runoff represent only the order of magnitude of the flow from these tributaries to the lake.

Due to the large number of discharge points in the Locomotive Springs area and the difficulty in measuring discharge, only poor discharge

Table 9. — Methods of preparation and analysis of Great Salt Lake brine samples.

Determination	Volume of aliquot (ml)	Method
Silica, SiO_2	10	Molybdate blue
Aluminum, Al	25	Ferron-orthophenanthroline
Iron, Fe	50	Bipyridine
Calcium, Ca	10	Versenate
Magnesium, Mg	....	Calculated from hardness and calcium determinations
Sodium, Na	(1:2500 dilution)	Flame photometric
Potasium, K	(1:200 dilution)	"
Lithium, Li	(1:200 dilution)	"
Bicarbonate, HCO_3	50	Potentiometric
Sulfate, SO_4	5	Gravimetric
Chloride, Cl	1	"
Fluoride, F	10	Zironconium-alizarin
Iodide, I	2.	Ceric arsenous
Nitrate, NO_3	.1	Phenoldisulfonic acid
Boron, B	1	Carmine
Dissolved Solids	5	Dried at 180°C for 2 hrs
Hardness	.5	Versenate
Density	25	Gravimetric

records are available. Based on several measurements made in March and July 1939 and in June and October 1962, the mean daily discharge from the area is estimated to be about 35 cfs for the period of study.

Weighted-Average Concentrations

Standard methods of correlating discharge, specific conductance, and concentrations of dissolved solids and of dissolved constituents were used to compute discharge-weighted averages. Several examples of methods used are summarized in the following paragraphs.

At the Weber River at Gateway and near Plain City, the chemical quality of the water is affected by upstream regulation and irrigation. Therefore, to compensate for the effects of use and control on the river's characteristics, the correlations were made for periods of similar runoff conditions (Fig. 8). Further refinement in the selection of the periods would tend to reduce the scatter about any one curve, but the curves as shown will give results which are subject to error of only about ten percent.

Using the periods established from the relationships of discharge to dissolved solids, concentrations of dissolved solids were then plotted versus the corresponding values of specific conductance and of the concentration of each of the ions. The resulting curves for the Weber River at Gateway are illustrated in Figure 9. The curves (Figs. 8 and 9) were used to estimate missing data; the particular curves illustrated represent the better relationships of all those used in this investigation. For the poorer relationships, consideration of events, such as sudden storm of release from a reservoir, together with climatological data and with information about the chemical quality of the water prior to and following the period in question resolved many of the irregularities.

The Jordan River at Salt Lake City was treated differently because the dissolved-solids concentration during the period of study ranged only from about 1,000 ppm during the spring to about 1,300 ppm for the remainder of each year, and because the relation of dissolved solids to water discharge was poor. Therefore, because of the uniformity of chemical quality, knowledge of the days when rain fell and discharge changed was used to determine the representativeness of each sample. Using this approach only a few days each year could not be represented by the available chemical-quality data. Estimates for the days not represented by the data were made on the basis of data collected for periods immediately prior to and following the periods of missing data. The results so determined are considered to be good.

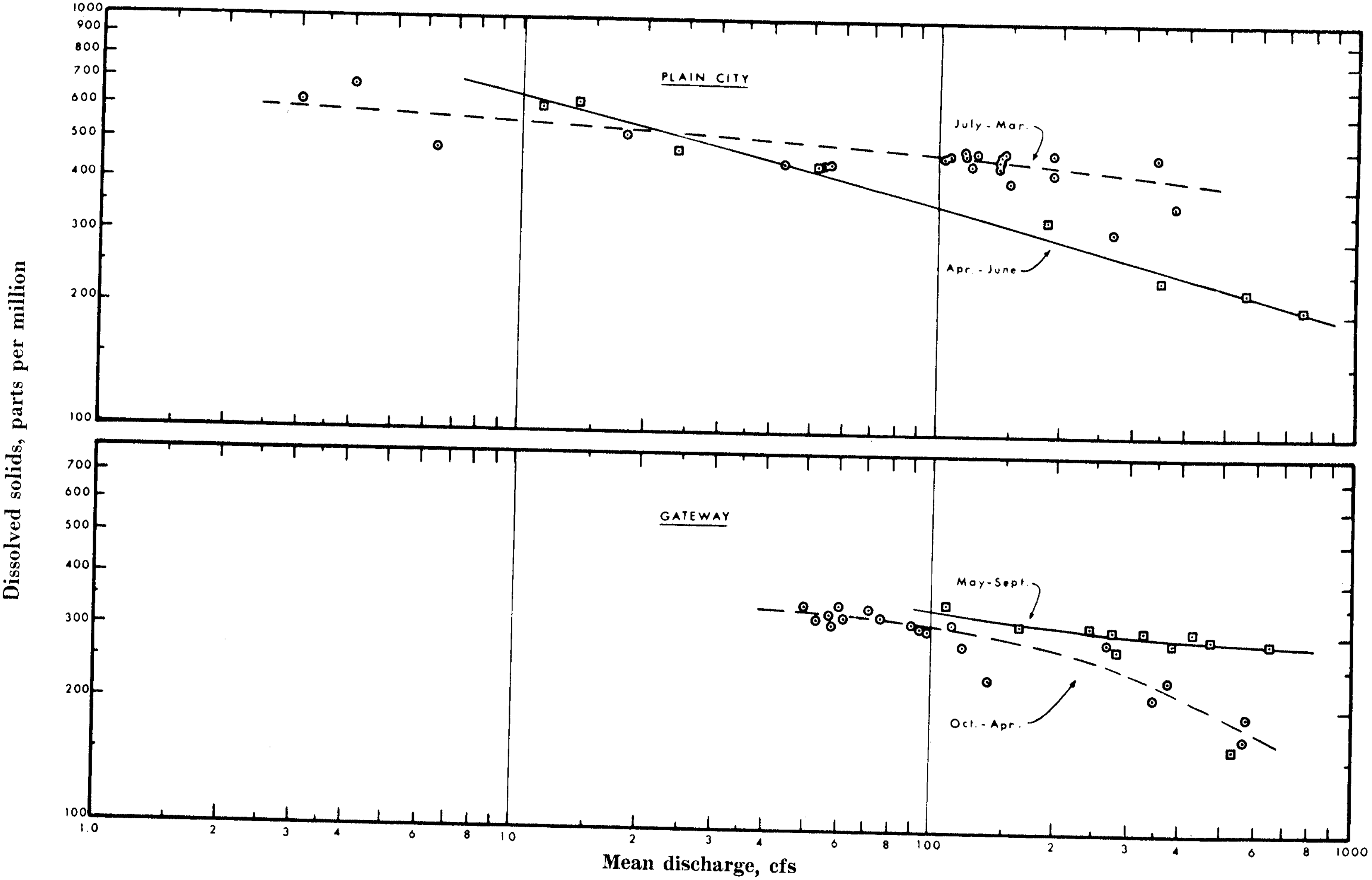

Figure 8. — Relation of dissolved-solids concentration to discharge, Weber River at Gateway and near Plain City, during the water years 1960-61.

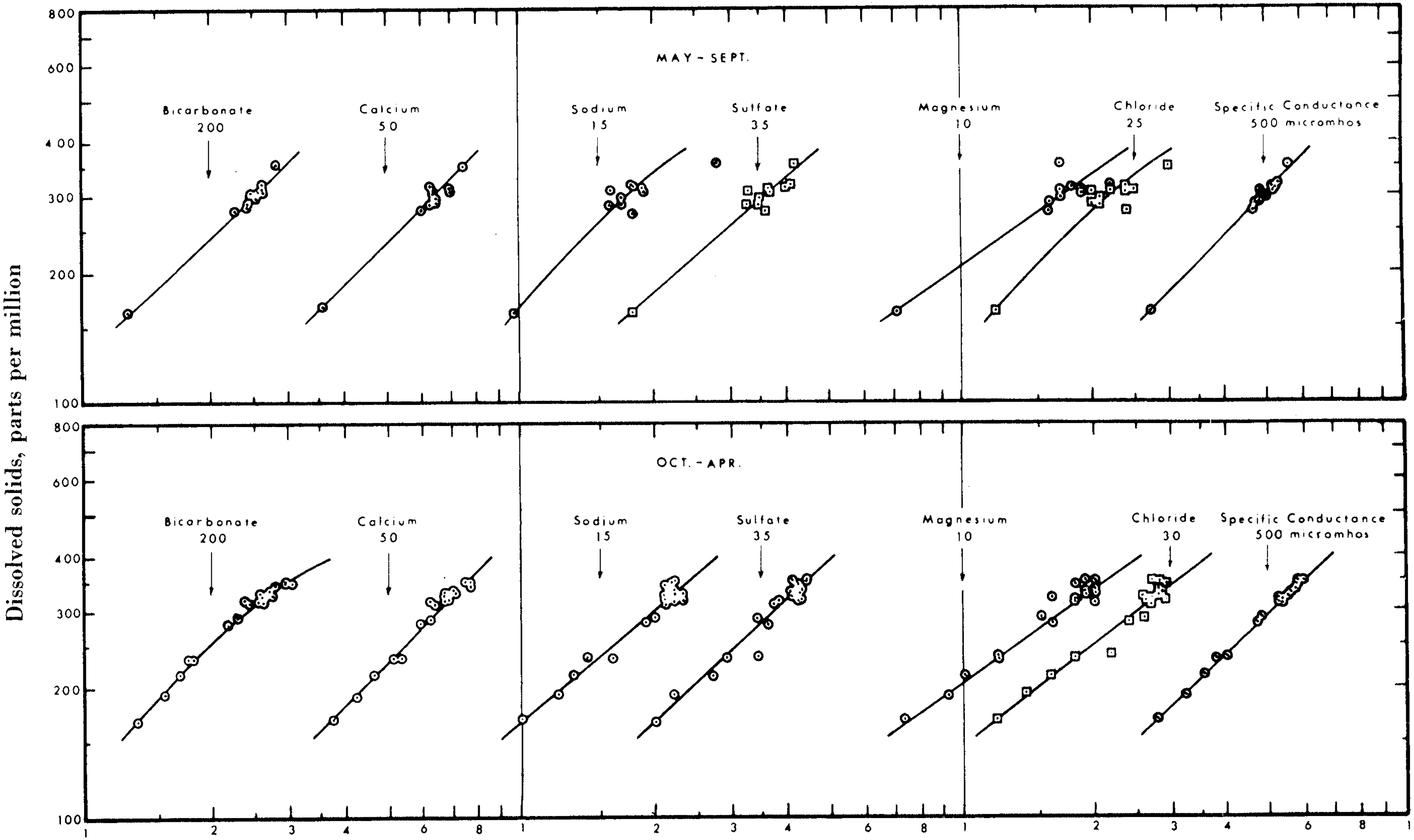

Figure 9. — Relation of dissolved-solids concentration to dissolved-constitutent concentration and to specific conductance, Weber River at Gateway during the water years 1960-1961.

The chemical quality of the water of many of the springs sampled changed very little seasonally. Therefore, the annual dissolved-solids concentrations were computed as arithmetic averages. Although these averages do not appear in the tables of basic data, they are considered to be good estimates for the period of study.

The chemical characteristics of streams draining the East shore unit fluctuated seasonally. Considering the chemical quality of the head waters, the amount and use of diversions, climatological data, the average recorded concentration of 450 ppm, and the size of the drainage area upstream from each sampling site, an average annual concentration was derived for the entire area. This average is considered to be accurate only as to its order of magnitude.

Definitions

Some of the terms used in this report are defined in the text where they first appear. Others are in general usage in the field of hydrology and are not specifically defined in this report. Geological Survey reports such as those by Hem (1959) and by Langbein and Iseri (1960) provide definitions of terms currently used in hydrology and water chemistry.

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