Hydrology and Geochemistry of Abert, Summer, and Goose Lakes, and Other Closed-Basin Lakes in South-Central Oregon

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GEOLOGICAL SURVEY PROFESSIONAL PAPER 502-B

U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

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By KENNETH N. PHILLIPS *and* A. S. VAN DENBURGH

CLOSED-BASIN INVESTIGATIONS

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*A description of several broad,
shallow lakes of differing
salinity, and an evaluation of factors
affecting their hydrologic and chemical
character*

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CONTENTS

ILLUSTRATIONS

TABLES

CLOSED-BASIN INVESTIGATIONS

HYDROLOGY AND GEOCHEMISTRY OF ABERT, SUMMER, AND GOOSE LAKES, AND OTHER CLOSED-BASIN LAKES IN SOUTH-CENTRAL OREGON

By KENNETH N. PHILLIPS and A. S. VAN DENBURGH

ABSTRACT

Topographically enclosed fault-block basins in the semidesert region of south-central Oregon contain lakes whose volumes have fluctuated in response to changes in water supply (precipitation plus inflow) and water loss. Most of the lakebeds are impermeable, and the water is dissipated only by evaporation or, for some lakes, occasional overflow. Solutes carried into the closed lakes by springs and small streams tend to be accumulated in solution, or removed from the lake water by organic and inorganic processes to become a part of the lakebed sedimentary deposits. The most soluble salts can be removed only by overflow, by incorporation within the lake-bottom and peripheral muds as interstitial brines, or by wind transport of precipitated evaporite minerals in periods of dryness.

Physical, hydrologic, and chemical data for the lakes studied are summarized in the following table.

Summary of physical, hydrologic, and chemical data for the lakes

	Lake Abert	Summer Lake	Goose Lake	Silver Lake	Harney Basin		Warner basin		
					Malheur Lake [1]	Harney Lake	Crump Lake	Hart Lake	Bluejoint Lake
Drainage area, including lake sq mi	860	390	1,140	520	2,150	5,280	700	900	1,920
Altitude (ft):									
Overflow	4,390	4,390	4,716	4,310.4	4,093.5±	4,114±	4,474.4	4,473	4,800+
Low point in lake bed	4,243.5+	4,144+	4,692	4,299+	4,088.8	4,079.7	4,468	4,463.5	4,455
Highest observed lake level [2]	4,260.5	4,149	4,707.8	4,309.0	4,095.4	4,087.6	4,476.4	4,474.5	(3)
Lowest observed lake level [2]	Dry	Dry	Dry	Dry	Dry	Dry	4,470.6	Dry	Dry.
Highest known Pleistocene lake level	4,520	4,520	4,720±	4,520	4,114+	4,114+	4,750 to 4,800		
Lake area at high level [2] sq mi	64	[4]71	181	16±	103	47	12+	12	(3)
Lake volume at high level [2] 10^3 acre-ft	496	(3)	1,270	60±	240	176	(3)	56	(3)
Estimated average annual quantity:									
Lake-surface precipitation in.	12	11	14	11	9	9	10	8	8
Evaporation in.	39	40	42	38	42	41	44	44	44
Inflow 10^3 acre-ft	55	65	165	(3)	100±	60±	70±	80±	(3)
Overflow [2] 10^3 acre-ft	0	0	0	0	20±	0	60±	30±	0
Dissolved-solids content:									
Maximum determined ppm	95,000	36,900	2,700	698	[5]484	[6]22,400	500	[5]781	[6]3,630
Minimum determined ppm	18,700	1,800	600	300	[5]258	(6)	101	[5]230	(6)
Principal constituents [7]	Na $ClCO_3$	Na $ClCO_3$ HCO_3	Na HCO_3	(8)	CaNa HCO_3	Na Cl	CaNa HCO_3	Na HCO_3	Na HCO_3

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[1] Area and volume shown for Malheur Lake at high levels include Mud lake.
[2] For period 1924–63.
[3] Not determined.
[4] Measured within meander line (est alt 4,152–4,155 ft).
[5] Only two reliable determinations are available.
[6] Only one reliable determination is available.
[7] On basis of equivalents per million. Listed constituents are calcium (Ca), sodium (Na), chloride (Cl), carbonate (CO_3), and bicarbonate (HCO_3).
[8] Variable.

Lake Abert, 25 miles north of Lakeview, is at present (1968) the largest landlocked saline water body in the Pacific Northwest. Inflow to the lake is almost entirely from the Chewaucan River, which drains about 60 percent of the total tributary area. The lake was dry in the summer of 1924 and again during other dry years through 1937. At its highest observed level, in 1958, the lake drowned juniper trees as much as 55 years old.

Summer Lake, 25 miles northwest of Lake Abert, is the shallow evaporating sump for inflow from the spring-fed Ana River and small snow-fed streams that rise on adjacent Winter Ridge. The flow of Ana Springs (believed to be nourished by ground water from nearby Fort Rock basin) has decreased from 160–170 cubic feet per second in 1904 to about 90 cubic feet per second, owing in large part to impoundment of the river and submergence of the spring orifices in 1923. Because of the decreased discharge from springs and the increased use of water for irrigation, the total flow now reaching Summer Lake, including precipitation, is only about 60 percent of that prior to 1923, and the average lake level is now several feet lower. The lakebed has been almost entirely dry late in the summers of many years since 1923.

Goose Lake, which straddles the Oregon-California border south of Lakeview, Oreg., is fed mostly by streams draining areas in Oregon. The lake overflowed briefly into the North Fork Pit River in 1868 and 1881, but storage and diversion of sufficient water for irrigation of about 35,000 acres has subsequently decreased the inflow; thus, future overflow is unlikely. The lakebed was dry in the summers of 1926 and 1929–34.

Silver Lake, in the Fort Rock basin, is fed mostly by Silver Creek and other streams that enter by way of Paulina Marsh. Overflow last occurred in 1905, and use of water for irrigation has decreased the likelihood of future overflow. The lake apparently loses water to unsaturated zones beneath its bed. Silver Lake was dry from 1922 to 1950, refilled to its highest recent level in 1958, and became dry again in August 1961.

Malheur Lake, 20 miles southeast of Burns, receives most of its inflow from the Silvies and Donner und Blitzen Rivers. In wet years, the lake merges with small Mud Lake and, at a slightly higher level, overflows into Harney Lake, the lowest point in Harney Basin. Malheur Lake was dry in 1934, and nearly dry in 1926, 1931–33, 1961, and 1962. A single wet season after a drought produces more inflow than the capacity of Malheur and Mud Lakes, causing overflow. In addition to this occasional overflow, Harney Lake receives intermittent runoff from several small streams.

Warner basin, northeast of Lakeview, contains a 40-mile chain of lakes that includes Crump Lake at the south (upstream) end and Bluejoint Lake at the north low point. Most runoff occurs in the south end of the basin, and much of it is used for irrigation of about 40,000 acres, so that lakes downstream from Hart Lake (below Crump Lake) remain dry or almost dry except in wet years.

For all but the freshest closed lakes, sodium and potassium are by far the most abundant cations. Measured epm (equivalents per million) percentages for the two ions together range from 46 percent of the cations in Crump Lake at 322 ppm (parts per million) of dissolved solids to 99.99 percent in Lake Abert at 20,000–80,000 ppm. The sodium to potassium epm ratio also increases with average solute concentration from 15:1 and less in Crump Lake to 50:1 in Lake Abert.

Among the anions, carbonate bicarbonate ranks either first or a close second in all the lakes, with the relative (percentage) amounts decreasing as dissolved-solids concentration increases (the epm-percentage ranges from about 80 in Crump Lake to about 40 in Lake Abert). The decrease is largely the result of calcium carbonate precipitation and differences in the chemical character of inflow to the more dilute lakes, and the result of several factors including mineral reaction and wind removal of efflorescent playa salts from the more saline lakes. The abundance of chloride is opposite to that of carbonate bicarbonate (from about 10 epm-percent of the anions in dilute Crump Lake to almost 60 percent in Abert), and most of the same factors that account for carbon depletion with increasing concentration also explain the relative enrichment of chloride. Sulfate is not a principal component in any of the lakes (it makes up a mere 2 epm-percent of the anions in Lake Abert), even though its abundance is comparable to that of chloride in most inflow. Sulfate depletion seems largely the result of bacterial reduction within the lake-bottom muds.

Among the minor constituents, silica is generally the most abundant, at solute concentrations of less than 50,000–100,000 ppm. As much as 200 ppm of silica has been measured in Abert and Summer Lakes, with the upper limit being imposed by mineral equilibria and, perhaps, biologic controls. Calcium and magnesium are among the most abundant constituents of stream and dilute lake waters, but they are nearly absent from the more saline lakes again because of mineral reactions and possible biologic controls.

Bromide is more abundant than fluoride in the most saline lakes, despite the opposite situation in inflow. In Lake Abert, the epm-percentage for bromide relative to total anions is 0.12 (103 ppm measured at a total solute concentration of about 60,000 ppm), in contrast to only 0.04 percent for fluoride. The amount of bromide relative to chloride in Lake Abert is greater than in any other Western closed-basin lake.

The biologic nutrient orthophosphate is plentiful in the more saline closed-basin lakes, owing mostly to the absence of calcium. Maximum measured concentrations of orthophosphate in Goose, Summer, and Abert Lakes have been 12, 41, and 101 ppm, which represent 0.54, 0.25, and 0.14 percent of the total solute concentrations, respectively. The amounts present in these lakes seem little affected by biologic controls.

Boron also is an abundant minor element in the saltier lakes (its relative amount (or percentage) in Lake Abert is about the same as that of orthophosphate), though some other Western closed-basin lakes contain even higher percentages.

Of the 17 trace elements looked for in samples from Goose, Summer, and Abert Lakes, only aluminum, iron, molybdenum, nickel, and vanadium consistently occurred in concentrations that exceeded the lower quantitative limits.

Lake Abert contained about 8 million tons of dissolved solids in 1939, and almost 14 million tons in 1961. The increment was derived mostly from salts stored in peripheral and lake-bottom sedimentary deposits that were inundated as the lake level rose from near-dryness in 1938 to the record high level in 1958. The average solute contribution of the Chewaucan River, the principal source of inflow, is about 120 ppm, made up mostly of silica, calcium, sodium, and bicarbonate. Peripheral seeps and springs are sources of sodium, bicarbonate, and chloride, but much of their contribution may have been recycled.

Ana Springs, the principal tributaries to Summer Lake, yield about 160 ppm of dissolved solids—mostly silica, sodium, and bicarbonate. During periods of low lake level or dryness since 1923, large amounts of efflorescent salts have been removed from the lakebed and peripheral mud flats by gusty winds. Concurrently, chloride and sulfate have been enriched in the lake relative to carbonate-bicarbonate, due at least in part to selective windborne removal of the more powdery efflorescent evaporite salts of the latter. Goose Lake underwent a similar chemical change while losing two-thirds of its initial (1912) 3-million-ton solute load during periods of desiccation in the 1920's and 1930's.

As Silver Lake receded to near dryness between May 1959 and June 1961, the dissolved salts increased only twofold—from 370 to

698 ppm. In contrast, sodium and chloride were enriched at least tenfold, owing to depletion of the other components through organic and inorganic reactions as the lake contracted. These reactions, coupled with the escape of solutes by leakage, caused an estimated 97-percent depletion of dissolved solids during the 25-month period.

INTRODUCTION

LOCATION OF STUDY AREA

This study concerns several lakes that occupy topographically closed basins within the northwestern lobe of the Great Basin in south-central Oregon, and one (Goose Lake), in the usually closed northeastern extremity of the adjoining Sacramento River basin, astride the Oregon-California boundary (fig. 1). At high-water levels, the lakes have a combined surface area of about 490 square miles; their drainage basins cover about 10,000 square miles.

PURPOSE AND SCOPE OF REPORT

The study, culminating in this report, was made to bring together all available hydrologic and geochemical data on several topographically enclosed lakes and their tributaries; to show the variations of water level, area, volume, and chemical character of the lakes within historic time; and, insofar as practicable, to correlate such variations with climatic or other causal factors. The report, then, represents a reconnaissance effort to evaluate the generalized hydrologic and geochemical regimen of the selected lakes.

The hydrologic study included determination of the approximate magnitudes of the water-budget elements for each lake—precipitation, runoff, and spring flow as sources of supply, and evaporation, overflow, and possible leakage as means of disposition. Some of the quantities were measured directly; some were ascertained by correlation with published records of precipitation or runoff; some were computed as residuals in the water budget; and the others could only be estimated.

Geochemical aspects of the study included determination of the chemical character of the lakes and their inflow, and evaluation of the possible sources of dissolved solids and the mechanisms of geochemical evolution.

The hydrologic part of the study was made by Kenneth N. Phillips, assisted by Roy B. Sanderson, then district engineer for the Surface Water Branch of the Water Resources Division, and members of his staff in Portland, Oreg. Hydrologic data through September 30, 1963, were used. The geochemical part of the study, including chemical analysis of most water samples, was conducted by A. S. Van Denburgh. Field sampling was done between April 1961 and June 1963.

ACKNOWLEDGMENTS

Many individuals were helpful in the study. The writers are especially grateful to Glenn E. Tyler and P. M. Smith, watermasters for the Oregon State Engineer, who rendered valuable assistance in the field; A. B. Claggett, superintendent of the Summer Lake State Game Management Area, for information on water levels of Silver and Summer Lakes; S. T. Harding, consulting engineer, for supplying the results from his field observations and his unpublished notes on the hydrology of Abert and Goose Lakes; and Dr. D. B. Lawrence, for results from his observations of tree rings and water levels at Lake Abert.

Within the U.S. Geological Survey, George T. Hirashima checked most of the hydrologic computations; Keith V. Slack identified and commented upon specimens of Lake Abert biota, and many other members of the staff contributed valuable suggestions. Allen G. Hely and Blair F. Jones were principal reviewers of the manuscript.

GENERAL FEATURES OF THE LAKES AND THEIR BASINS

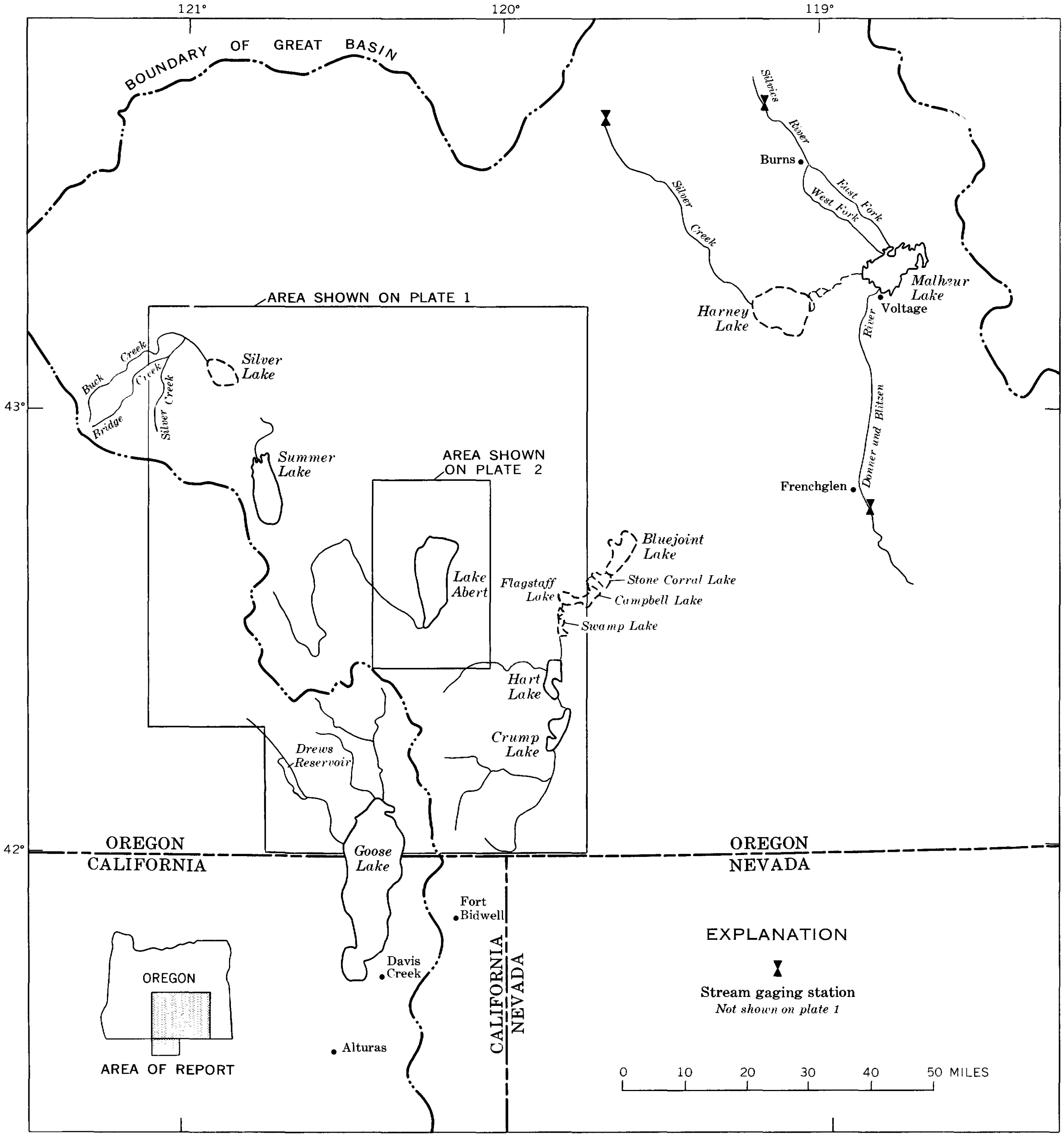
Among the lakes studied, only four—Abert, Summer, Harney, and Bluejoint—occupy impermeable basins deep enough to be truly closed. Such water bodies neither leak nor overflow; consequently, they lose water only by evaporation. All the other lakes studied—Goose, Silver, Malheur, Crump, and Hart—are freshened by rare to frequent overflow. The hydrologic and chemical data for Silver Lake suggest that it leaks as well.

General features of the lakes and their basins are summarized in table 1.

PHYSIOGRAPHIC AND GEOLOGIC SETTING

All the lakes lie within a semidesert, volcanic terrane, whose skyline is dominated by many fault-scarp ridges. Prominent among the scarps are Winter Ridge, overlooking Summer Lake on the west; Abert Rim, bordering Lake Abert to the east; the Warner Mountains, east of Goose Lake; and Hart Mountain, east of Warner basin (pl. 1). These elevated blocks form small mountain ranges whose axes trend generally north south. Between these ranges lie the lake basins.

The lakes themselves are characteristically shallow, and they occupy broad, extremely flat basin floors that are underlain by thick accumulations of generally fine grained sedimentary material. Several lakebeds are so flat that a sudden, strong wind can cause a large part of the lake water to be temporarily spread out over many acres of peripheral playa surface at altitudes slightly higher than the undisturbed lake level.



Base by U.S. Geological Survey

FIGURE 1.—Location of lakes discussed in this report.

CLIMATE

The study area lies in a belt of prevailing westerly winds. Convectional air movements give rise to local gusts at times. Air temperatures in the area are like those of other high plateaus in the Western United States, ranging from more than 90°F in summer to less than −10°F in winter. Table 2 shows the seasonal variation in average monthly temperature at Valley Falls, which is generally representative of conditions on the valley floors. In clear weather, the nighttime loss of heat by radiation is rapid,

TABLE 1.—*Summary of physical, hydrologic, and chemical data for the lakes*

	Lake Abert	Summer Lake	Goose Lake	Silver Lake	Harney Basin		Warner basin		
					Malheur Lake [1]	Harney Lake	Crump Lake	Hart Lake	Bluejoint Lake
Drainage area, including lake__sq mi__	860	390	1,140	520	2,150	5,280	700	900	1,920
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Low point in lake bed__________	4,243.5+	4,144+	4,692	4,299+	4,088.8	4,079.7	4,468	4,463.5	4,455
Highest observed lake level [2]____	4,260.5	4,149	4,707.8	4,309.0	4,095.4	4,087.6	4,476.4	4,474.5	(3)
Lowest observed lake level [2]_____	Dry	Dry	Dry	Dry	Dry	Dry	4,470.6	Dry	Dry
Highest known Pleistocene lake level______________________	4,520	4,520	4,720±	4,520	4,114+	4,114+	4,750 to 4,800		
Lake area at high level [2]_____sq mi__	64	[4] 71	181	16±	103	47	12+	12	(3)
Lake volume at high level [2] 10^3 acre-ft__	496	(3)	1,270	60±	240	176	(3)	56	(3)
Estimated average annual quantity:									
Lake-surface precipitation__in.__	12	11	14	11	9	9	10	8	8
Evaporation_______________in.__	39	40	42	38	42	41	44	44	44
Inflow _____________10^3 acre-ft__	55	65	165	(3)	100±	60±	70±	80±	(3)
Overflow [2]__________10^3 acre-ft__	0	0	0	0	20±	0	60±	30±	0
Dissolved-solids content:									
Maximum determined____ppm__	95,000	36,900	2,700	698	[5] 484	[6] 22,400	500	[5] 781	[6] 3,630
Minimum determined____ppm__	18,700	1,800	600	300	[5] 258	(6)	101	[5] 230	(6)
Principal constituents [7]_________	Na ClCO$_3$	Na ClCO$_3$ HCO$_3$	Na HCO$_3$	(8)	CaNa HCO$_3$	Na Cl	CaNa HCO$_3$	Na HCO$_3$	Na HCO$_3$

[1] Area and volume shown for Malheur Lake at high levels include Mud Lake.

[2] For period 1924–63.

[3] Not determined.

[4] Measured within meander line (est alt 4,152–4,155 ft).

[5] Only two reliable determinations are available.

[6] Only one reliable determination is available.

[7] On basis of equivalents per million. Listed constituents are calcium (Ca), sodium (Na), chloride (Cl), carbonate (CO_3), and bicarbonate (HCO_3).

[8] Variable.

and the daily range in temperature often exceeds 50°F. Frost may occur on any clear night in summer.

Relative humidity in summer also has a high diurnal range—typically 10 to 30 percent at midday, and approaching 100 percent at night. Evaporation is high on the clear, windy days typical of the dry period from May to October, but is low at night because of the marked drop in temperature and corresponding rise in relative humidity. The evaporation loss from lake surfaces is increased by occasional strong winds that spread the water over wide areas of flat beach. Table 1 summarizes estimated lake-surface evaporation rates.

TABLE 2.—*Monthly temperature and precipitation at Valley Falls, Oreg.*

[Data from records of the U.S. Weather Bur.]

	Average temperature 1931–60 (°F)	Precipitation (in.)		
		1914–63		Average for 1931–60
		Maximum	Minimum	
January________________	29.7	3.51	0.20	1.41
February_______________	33.1	3.07	.10	1.31
March_________________	38.1	2.23	.11	1.12
April__________________	45.1	2.90	.13	.96
May__________________	51.6	3.91	.00	1.43
June__________________	57.7	5.53	.00	1.38
July__________________	65.9	2.28	.00	.30
August________________	63.8	2.61	.00	.29
September_____________	56.7	2.71	.00	.57
October_______________	47.9	6.13	.00	1.11
November______________	37.6	2.71	.00	.99
December______________	32.6	3.76	.20	1.50
Year average_______	46.7	(1)	(2)	12.37

[1] Maximum annual precipitation during the period 1914–63, recorded in 1963, was 18.46 in.

[2] Minimum annual precipitation during the period 1914–63, recorded in 1924, was 6.43 in.

Average annual precipitation in the study area ranges from more than 20 inches at high altitudes within several of the tributary areas to 8 inches or less in the more arid parts. The amount may vary greatly in short distances because of changes in altitude or topographic orientation with respect to prevailing winds. Table 2 shows the seasonal pattern at Valley Falls, Oreg. Much of the precipitation occurs as snow, and runoff is delayed until melting takes place, commonly in the spring. Lake-surface precipitation ranges from 8 to 14 inches in an average year (table 1), and is a significant part of the total water supply.

The frost-free season is short, which limits agricultural activity. Livestock is pastured on open desert or mountain range during the summer and is fed locally grown hay in winter. The hay crops are produced mostly on lands irrigated with water supplied from surface streams, but ground water is also used in places.

INFLOW TO THE LAKES

The quantity of surface runoff into the lakes differs widely. Over a long period, most of the water entering Abert, Crump, Goose, Malheur, and Silver Lakes is runoff from mountainous areas that are 1,000 to 5,000 feet higher than the lakes. In dry years, however, the streams dwindle to small flows and (or) the water is diverted for irrigation before reaching the lakes. Bluejoint, Harney, and Hart Lakes are indirectly dependent on surface runoff because most of their supply consists of overflow from upstream lakes.

In contrast, most of the inflow to Summer Lake is supplied by a prolific spring system. Much smaller springs and seeps occur along or near fault zones beside Abert, Goose, Harney, and Summer Lakes. Their temperatures are well above the mean annual air temperature. Some of these springs, though too small to be important sources of water supply to the lakes, may nevertheless provide a significant amount of the incoming dissolved-solids load.

The surface- and ground-water flow entering the lakes cannot be measured accurately; therefore, records of precipitation, runoff, and lake level were used to estimate the approximate inflow (table 1). The probable accuracy of such estimates and the relative importance of such inflow as a part of the gross water supply for the lakes are summarized below:

Lake	Average annual inflow (percentage of gross water supply)	Probable accuracy (percent ±)
Abert	65	10
Crump	95	25
Goose	65	20
Hart	95	25
Malheur	60	25
Summer	70	15

OUTFLOW FROM THE LAKES

At present, evapotranspiration dissipates the entire inflow to Abert, Bluejoint, Goose, Harney, and Summer Lakes and a large proportion of the inflow to the other lakes (the proportion is least for Crump Lake and is greatest for Silver Lake).

No leakage occurs from Abert, Goose, Harney, and Summer Lakes, as all these water bodies overlie beds of fine-grained, virtually impermeable lacustrine deposits. Also, they are bordered by many peripheral springs and seeps—evidences of ground-water gradients that slope toward the lakes, rather than away from them.

Silver Lake apparently loses some water by leakage. The lack of peripheral springs and the absence of excessive mineralization in the lakebed soil are consistent with the indications of loss by seepage. Crump, Hart, and Malheur Lakes may lose some water by lateral seepage into peat deposits that border parts of each lake.

Some lakes never approach the level of surface overflow under present-day conditions. For example, the divide between Abert and Summer Lakes is more than 100 feet higher than either lake has been in historic time (table 1). At the other extreme are the lakes, such as Crump and Malheur, which overflow during most wet years. The other lakes studied fall somewhere between the two extremes. Goose and Silver Lakes have had virtually no overflow since 1868 and 1905, respectively, and future occurrences are doubtful under present conditions of climate and agricultural land use.

WATER-LEVEL FLUCTUATIONS

The water levels of the lakes fluctuate in response to changes in water supply and water loss. The peak of the annual cycle typically occurs in the spring, near the end of the period of greatest precipitation and runoff. During the following dry, warm summer, lake levels recede, reaching their annual minimum by the late summer or early autumn. In periods of greater than average precipitation and runoff, lake levels gradually rise until evaporation losses from the increased surface areas equal the augmented supply. In protracted periods of dryness, the water levels fall until some lakebeds are completely dry.

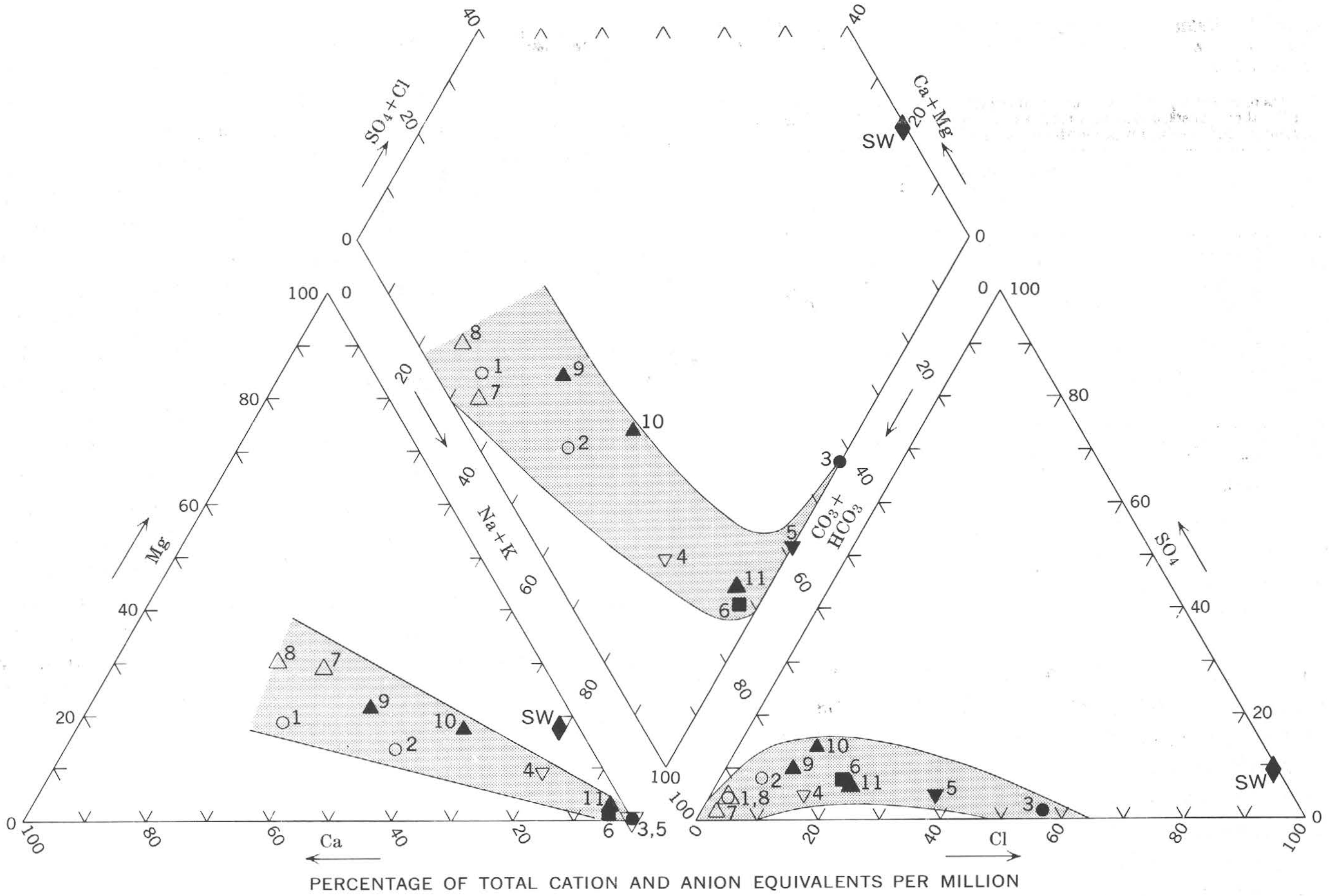
In this century the lake levels, with but few exceptions, have been highest during the early 1900's and the 1950's, and lowest (many lakes went dry) in the 1920's and 1930's. A general indication of extremes of wetness and dryness during the last few centuries is provided by studies of tree growth. Records of tree growth since 1455 were published by Antevs (1938, p. 66–85), along with historical records of precipitation, runoff, and lake level. Periods of maximum and minimum tree growth and of precipitation match well, except for some periods of retarded tree growth that may have resulted from insect attack, disease, or other unusual factors. Since 1455 the greatest rates of tree growth through 1934 occurred in the periods 1790–92, 1805–25, and 1907–09; the lowest growth rates were in 1842–49 and 1918–34. According to a similar study by Keen (1937), the period 1918–34 was the driest in at least 650 years.

During Pleistocene time, large lakes occupied the deep Abert-Summer, Warner, and Fort Rock basins, where they left shoreline deposits more than 200 feet above the present-day lake beds. During the same period, lakes in the much shallower Goose and Harney basins doubtless overflowed into the Pit and Malheur Rivers, respectively.

CHEMICAL CHARACTERISTICS

Chemically, the lake waters range from highly dilute—fresher than water used for irrigation and municipal supply throughout much of the United States—to highly saline. In general, the dilute waters are those of lakes freshened by an overflow that ranges from rare to almost seasonal, whereas the most saline waters are those of true closed lakes, where only the water, but not its solute content, is lost by evaporation.

The character of components dissolved in the lakes and their inflow is also wide in range. The more dilute water bodies contain mostly silica, calcium, sodium, and bicarbonate, whereas the highly saline accumulations consist mostly of sodium, carbonate bicarbonate, and chloride. The wide range in chemical character is recorded in table 3 and is shown graphically in figure 2, in which diagrams depict (1) the distribution of major dissolved constituents,



No.	Sample site	Dissolved solids (parts per million)
	LAKE ABERT BASIN	
1	Chewaucan River near Valley Falls	94
2	do	193
3	Lake Abert	55,900
	SUMMER LAKE BASIN	
4	Ana River at gage	158
5	Summer Lake	7,200
	GOOSE LAKE BASIN	
6	Goose Lake	1,270
	WARNER BASIN	
7	Deep Creek at gage	85
8	Honey Creek at gage	135
9	Crump Lake	322
10	Hart Lake	781
11	Bluejoint Lake	3,630
SW	Sea water	34,500

FIGURE 2.—Relative abundance of major dissolved constituents of lakes and their tributaries in south-central Oregon. Solid symbols represent lakes; matching-shaped open symbols represent the respective tributary streams.

by showing points on two trilinear plots, and (2) the overall chemical character of the water, by showing a single point on a diamond-shaped grid.

The characteristic seasonal pattern of changes in dissolved-solids concentration is approximately as follows: Snowmelt runoff during late winter and early spring increases the lake volume and dilutes the more saline lake water, while adding a small increment of dissolved solids (for several of the lakes, the runoff during some years is sufficient to cause overflow, which removes solutes from the lake). During the hot summer and early fall, high evaporation rates and a lack of significant inflow cause a lowering of lake level and an increase in dissolved-solids concentration—that is, water is lost, but the salts remain. The evaporation rate decreases greatly during the cold, late fall and winter. This decrease, in combination with small amounts of inflow and often significant amounts of precipitation on the lake, causes a stationary or a rising lake level, as well as a relatively constant or a slightly decreasing dissolved-solids concentration.

For a shallow lake that neither overflows nor dries frequently, the short-term (several-year) relation between the dissolved-solids concentration and the lake level is nearly constant at most times because the shallow water

TABLE 3.—*Relative amounts of major and minor constituents in representative samples from Abert, Summer, Goose, Hart, and Crump Lakes*

[Amounts of dissolved solids and of hardness reported in parts per million. Amounts of all other constituents reported as a percentage of total dissolved solids; maximum and minimum percentages for each are in italic]

	Lake Abert	Summer Lake	Goose Lake	Hart Lake	Crump Lake
Dissolved-solids content	40,800	7,200	1,270	781	322
Silica (SiO_2)	*0.38*	1.5	4.6	4.5	*12*
Calcium (Ca)	<*.005*	.04	1.0	6.7	*11*
Magnesium (Mg)	<.005	*.004*	.32	3.8	*4.3*
Sodium (Na)	*40*	39	35	25	*17*
Potassium (K)	*1.3*	1.6	*2.8*	2.0	2.0
Bicarbonate (HCO_3)*	*5.8*	13	29	33	*38*
Carbonate (CO_3)	16	*17*	7.4	5.5	*1.9*
Sulfate (SO_4)	*1.8*	4.8	6.5	*12*	8.1
Chloride (Cl)	*35*	22	12	7.9	*6.2*
Fluoride (F)	*.01*	.08	.07	*.27*	.25
Bromide (Br)	*.17*	.11	*.07*	-------	------
Orthophosphate (PO_4)	*.14*	.25	*.54*	-------	.31
Boron (B)	*.14*	*.47*	.30	-------	------
Hardness as $CaCO_3$	8	8	49	252	144
pH	9.7	9.6	9.1	8.8	8.4
Sampling date	4-26-61	4-25-61	6-12-62	4-27-61	4-27-61

* Calculated as carbonate.

body remains almost homogeneous, and the dissolved tonnage is virtually constant. The relationship is temporarily destroyed during periods of abundant inflow and precipitation on the lake surface, when the dilute incoming water is stratified above the more saline lake water. This stratification remains until wind action again homogenizes the lake-water body.

In lakes that frequently overflow or are dry, the relation between lake level and dissolved-solids concentration changes with time because the salts are depleted during overflow and are either lost or temporarily stored during desiccation. Figure 3 shows schematically the effect of occasional overflow: the accumulation of salts in a lake during periods when the basin remains closed is offset by loss of salts during overflow, and the lake thus tends to remain dilute. A similar illustration could be used to show the solute-depletion effect of occasional desiccation.

EFFECTS OF MAN'S ACTIVITIES

The hydrologic and chemical character of a lake may be artificially altered in several ways by the activities of man. For the lakes in the study area, some activities can be eliminated from consideration. For example, no attempts at weather modification were made, and there are no transbasin diversions of streamflow. Water is diverted only from Hart Lake, and no sewers or mineralized industrial effluents discharge into any of the lakes or their tributaries. The use of saltlicks, fertilizers, insecticides, and herbicides is confined to small areas and probably has had a minor effect on the total tonnage of dissolved salts in the lakes. The activities to be considered, therefore, are storage on tributaries, diversion for irrigation, and drainage of swampland.

In the basin of Lake Abert there is, as yet (1968), no upstream storage reservoir. Drainage of the Chewaucan Marsh during the period 1901–15 released some water which previously would have been lost by evapotranspiration from the swampy area, but the concurrent development of irrigation probably resulted in consumptive use of about an equal amount, so that the average inflow to Lake Abert was not changed significantly. In a series of dry years, however, Lake Abert might now receive less inflow than it did under natural conditions; therefore, it is more likely to become dry than it was before the marsh was drained and irrigation was practiced. The same general situation is true of the Harney and Warner basins, as well.

In Goose Lake basin, Drews Reservoir (storage capacity, 62,500 acre-ft) and Cottonwood Reservoir (storage capacity, 7,540 acre-ft) were built in 1911 and 1921, respectively. Several small reservoirs and many stock ponds also exist. Evaporation from these reservoirs and diversion of streamflow may deplete the average inflow to Goose Lake by about one-third. Because of this depletion, the lake is not likely to repeat the brief overflows to the Pit River that occurred in 1868 and 1881; thus, it may now be a true closed-basin lake.

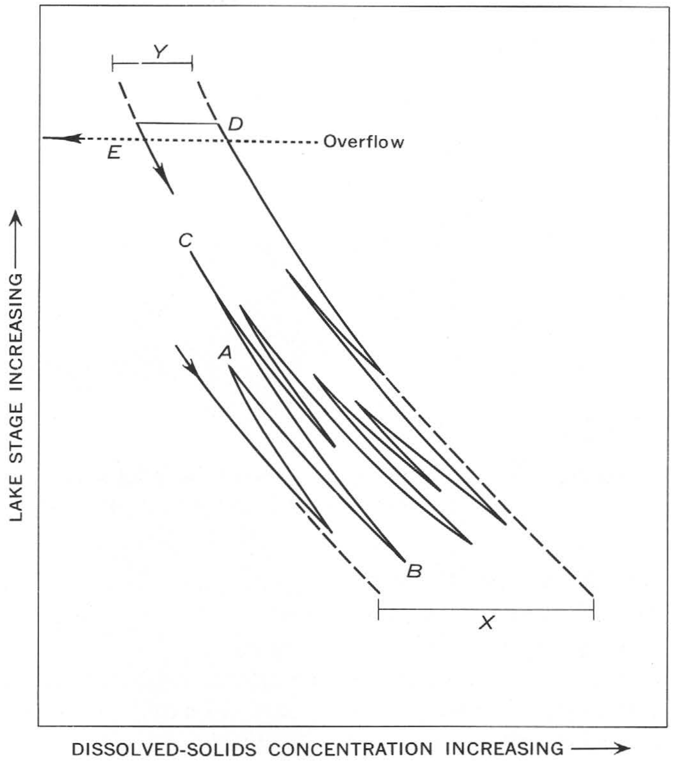


FIGURE 3.—Relation between dissolved-solids concentration and stage of a lake that occasionally overflows. *A–B–C*, seasonal cycle; *D*, lake reaches overflow stage; *D–E*, lake overflows, losing dissolved solids; *E*, termination of overflow, and start of normal cycle. *X*, dissolved-solids increment, gained prior to overflow; and *Y*, dissolved-solids decrement, lost during overflow.

The inflow to Silver Lake is materially reduced in most years by upstream storage and irrigation. Although Silver Lake has not overflowed to Thorn Lake since 1905, a slight extension of the wet period 1952–58 would have raised the lake to the level of its former overflow channel. Hence, the depletion of potential inflow has been effective in maintaining a dry lakebed in a period of drought (1922–50), but was much less effective in limiting the rise of the lake in a period of great runoff (1952–58) simply because the reduction in wet years is a smaller part of the total runoff, and because the lake volume at overflow is small (about 75,000 acre-ft).

Normally, the level of Summer Lake is now several feet lower than it was 40 to 50 years ago. Part of that reduction is apparently due to a natural decrease in flow from the springs that feed the Ana River, but most of the change seems to be the result of man's activities, including the increased agricultural irrigation, the flooding of a wildfowl-management area, the drilling of artesian wells that tap the aquifer feeding the Ana River, and back pressure on the large springs that were flooded by completion of the irrigation dam in 1923.

In such basins as those of Summer, Goose, and Silver Lakes, where development and construction by man have reduced the amount of streamflow runoff, the lakes characteristically contain larger concentrations of dissolved solids than they would under natural conditions.

LAKE ABERT

Lake Abert is a large, shallow body of water that occupies the lowest part of an 860-square-mile closed basin about 25 miles north of Lakeview (pls. 1, 2). Slopes around the lake range from nearly flat to precipitous. At the southern end the Chewaucan River, the lake's principal tributary, leaves the plain of Chewaucan Marsh and drops about 12 feet over a fault scarp to the lake level. West of the lake the surface of a tilted fault block slopes upward to Coglan Buttes, whereas to the north the mud flats near the lake merge into a hilly terrane. Along the entire east shore, steep talus slopes and near-vertical volcanic rock faces rise to the nearly flat crest of Abert Rim, 1,500 to 2,200 feet above the lake and only 1 mile distant from it (fig. 4). The spectacular cliffs and steep slopes of the narrow tributary belt fringing the east shore are an expression of faulting on a grand scale.

FIGURE 4.—Southward view from the east shore of Lake Abert, January 12, 1962. Snow-covered Abert Rim in background. Vegetation boundary indicates high water level of 1958. Dark areas near lakeshore show peripheral seeps melting recently fallen snow.

TABLE 4.—*Approximate area and volume of Lake Abert*

[Data are based chiefly on soundings made May 19 and 20, 1959, when lake level was at an altitude of 4,258.9 ft, on outline of the lake at lower levels, as shown by aerial photographs, and on recent topographic mapping]

Altitude (ft)	Area (acres)	Volume (acre-ft)	Altitude (ft)	Area (acres)	Volume (acre-ft)
4,243.5+	0	0	4,253	35,300	206,000
4,244	240	100	4,254	36,300	242,000
4,245	8,000	3,200	4,255	37,300	279,000
4,246	12,400	13,300	4,256	38,200	316,000
4,247	19,100	28,900	4,257	39,000	355,000
4,248	24,800	50,900	4,258	39,700	394,000
4,249	28,100	77,300	4,259	40,300	434,000
4,250	30,500	107,000	4,260	40,800	475,000
4,251	32,400	138,000	4,261	41,300	516,000
4,252	33,900	171,000			

AREA, VOLUME, AND LAKE-LEVEL FLUCTUATIONS

At high stages, Lake Abert is about 16 miles long and 6 miles wide, and has a maximum depth of more than 15 feet. The lakebed configuration is shown in figure 5, and the area and volume of the lake at various altitudes are listed in table 4.

Lake-level records (table 20) are fragmentary prior to 1950. Since 1950 the level has been observed several times each year (fig. 6), and from September 1961 to May 1963, a continuous record of stage was made. Some levels were deduced from general descriptions of the areal extent and from photographs of the lake. The extreme range since 1843 is well substantiated, as follows:

1. The lake was completely dry in the summer of 1924 for the first time since the area was settled in the 1870's, and it was nearly or completely dry in 1926, 1930, 1931, 1933, 1934, and 1937.
2. The lake level rose to an altitude of 4,260.5 feet above mean sea level in June 1958—the highest level attained since the area was settled by permanent residents. All herbs, shrubs, and trees with root crowns at or below that level were killed by flooding (fig. 4).

The shores of Lake Abert were searched for trees whose growth records might give some indication of the lake

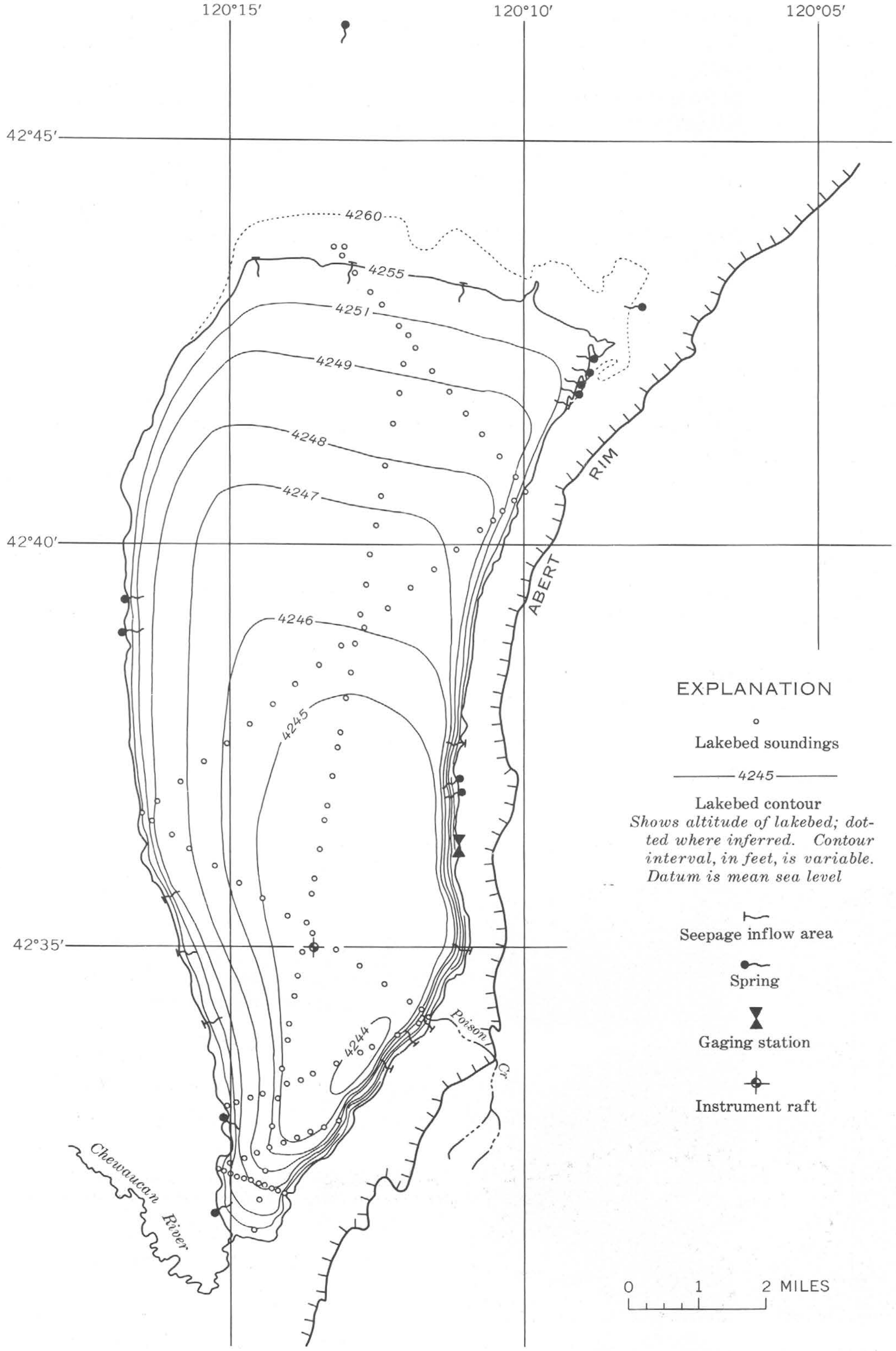


Figure 5.—Lakebed contours of Lake Abert. Dotted contour, indicated as inferred in explanation, is from preliminary topographic mapping.

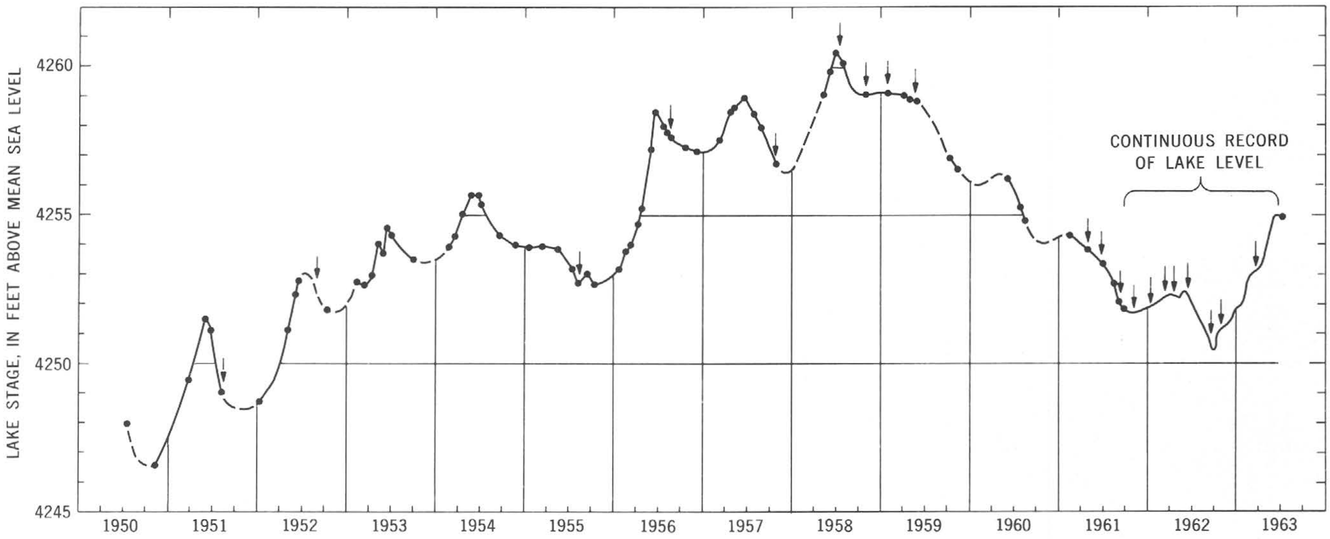


FIGURE 6.—Seasonal variations in stage of Lake Abert, June 1950–June 1963. (Altitude of the lowest point in the basin is 4,243.5+ feet above mean sea level.) Arrows indicate times when samples were collected for chemical analysis (table 28). Dashed parts of hydrograph indicate periods for which lake levels are inferred.

levels prior to the first regular observations. The only such trees are a few isolated junipers along the southeast shore. Those with root crowns at or below an altitude of 4,260.5 feet were drowned by the saline water when the lake rose to that level in 1958. The largest drowned tree—whose root crown was at an altitude of 4,260.3 feet—was cut down, and the annual growth rings on the stump were counted. The ring count showed that the tree had germinated in the year 1903, or shortly before. Cores taken from other nearby, slightly smaller trees, at a level 0.4 foot higher, showed that they had germinated about 1908 to 1910. The largest, oldest living tree near the lake measured 21 inches in diameter in 1959, and its base was at an altitude of 4,264.3 feet. A core taken 1 foot above the tree base showed 64 annual rings; hence, that tree germinated before 1895. Certainly, the lake level was lower than the bases of these trees during, and immediately preceding, their lifetimes.

FIGURE 7.—Northeastward view from the southeast shore of Lake Abert, July 3, 1963. Dashed line represents maximum lake level, at 4,260.5 feet, which was attained in June 1958. Herbs and shrubs (but no trees) below (or left of) that line have germinated and grown since the saline water receded. Stump in foreground is that of an older generation tree (juniper?) that died 250 (±200) years ago.

A solitary, older generation tree stump 3 feet high was found adjacent to the lake, with its root crown at an altitude of 4,260.2 feet. The stump, which was measured 11 inches above the ground surface, was 13 to 14 inches in diameter (fig. 7). A cross section of the stump showed 2 inches of decay in the center, as well as 26 wide, uniform growth rings outside the decayed area. The tree was estimated to have been only about 35 years old when it died. The tree apparently grew in a period when ground moisture was adequate for its needs, and it may have been drowned by submergence in the early 1800's or in the 1860's. A carbon–14 age determination, made in 1964, showed that it had died about 250 (±200) years ago (U.S. Geol. Survey lab. sample W–1398). The presence of this stump at the altitude of 4,260.2 feet and the similarity of its annual growth rings to those of present-generation trees growing nearby indicate that Lake Abert was below that level for a period of at least 35 years when the inflow was not affected by man's activities.

A distinct beach line of rounded coarse gravel and cobbles at an altitude of 4,269.7 feet marks a still-stand of Lake Abert that is 9.2 feet higher than the highest observed level. The beach line occurs at many places along the east

FIGURE 8.—Northward view from east shore of Lake Abert near site of lake gage. Rod is held at edge of the well-defined beach line (alt 4,269.7 ft), formed sometime prior to 1895.

shore (fig. 8). Notes of the Eastern Oregon Railroad survey, in 1907, along the west shore refer to a high water level at an altitude of 4,269 feet (railroad survey adjusted +10.7 ft to 1929 standard datum), presumed to be the same strand line.

Sage, greasewood, other desert vegetation, and a few juniper trees have become established below the high beach. The oldest cored trees below the line germinated about 1895, but the beach line was probably formed long before that. The cobbles are not weathered, and in many places no soil has accumulated over them. Their appearance suggests youth, and the high lake level they mark may well have occurred within the last two centuries. Unusually rapid tree growth near Lakeview during the period 1805–25 indicates that precipitation in that period was greater than any period of equal length in the last four centuries (Antevs, 1938, p. 66), and Lake Abert may then have formed the prominent beach line.

Fragments of beaches or strand lines, not yet covered by windblown dust or by talus, are present at levels several feet higher than the well-defined beach at an altitude of 4,269.7 feet, the higher beaches being less well defined and apparently somewhat older than the lowest one. Such beaches have been noted on the east shore near the present lake gage at altitudes of 4,273.8 and 4,276.3 feet, and 3 miles farther north, at 4,271.2 and 4,273.2 feet. Their age is not known, but it is probably not more than a few thousand years.

Beach deposits far above the present-day lake attest to the existence of a much larger lake in this basin in Pleistocene time (pl. 1). Allison (1946, p. 64) referred to that body of water at its high level as Lake Chewaucan, and stated (1954, p. 1331) that it attained a maximum altitude of 4,520 feet. At that level, the present Chewaucan Marsh, near Paisley, was covered by water more than 200 feet deep, and the water surface was almost 280 feet above the present bed of Lake Abert and 370 feet above that of Summer Lake. Lake Chewaucan at its maximum level covered 480 square miles, or 38 percent of the combined drainage basins (1,250 sq mi at present, and probably about the same then). Even at its maximum altitude of 4,520 feet, Lake Chewaucan did not overflow.

WATER SUPPLY

The water of Lake Abert is derived from four sources—precipitation on the lake, small peripheral springs, ephemeral streams that drain arid areas fringing the lake, and the Chewaucan River. None of these sources can be measured precisely, but the total water supply can be approximated fairly accurately.

LAKE-SURFACE PRECIPITATION

Extended records of precipitation near the lake are available only at Valley Falls (alt 4,326 ft), which is 10 miles south of midlake (pl. 2). Annual precipitation at Valley Falls has averaged about 12 inches during the period 1915–63. Precipitation on the lake itself may be a little less than at Valley Falls, but for the studies herein, it is assumed to be about the same.

SPRINGS

Many springs emerge along the shores on all sides of the lake (figs. 4, 5). Most of them are mere seeps that maintain small spots of green growth or saturated ground, making no material contribution to the water supply of the lake; others discharge up to about 1 cfs (cubic feet per second). The largest spring is about 4 miles north of Lake Abert (32/21–26D). Its measured flow was 1.04 cfs on July 23, 1950, and 1.96 cfs on November 13, 1962. Its water and that of other seeps and springs irrigate hay crops on lands bordering the lake, and a part of the flow is thus consumptively used. The total combined flow of all seeps and springs reaching Lake Abert, along with that of the minor local surface streams, averages an estimated 10 cfs, or 7,000 acre-feet per year. That estimate is based on an inspection of the springs in 1962 (total observed spring flow, 4.9 cfs), when the lake level was about 4,251 feet in altitude, coupled with a study of inflow data and changes in lake level.

No seeps of significant size were thought to enter the lake below an altitude of 4,251 feet at the time of inspection in 1962. No such seeps were reported by local residents, who had seen the lakebed dry in the late 1920's and early 1930's. However, one such observer—Bert Harber of Lakeview—did describe the flow of springs at the Pike Ranch, along the northeast shore, as a wide wet streak that meandered southward for several miles across the lakebed until dissipated by evaporation and seepage (oral commun., 1962).

The many springs that rise along the great fault zone near the northeast shore have, within a distance of 8 miles, a combined flow of about 3 cfs (1962), far more than is to be expected from the small semiarid area topographically tributary to them. At sites 102 and 103 (pl. 2; table 30), the spring flow temperatures were, respectively, 66° and 71° F, about 20° F higher than mean air temperature. On the opposite shore, other springs (sites 104, 106) in a lesser fault zone flow at temperatures of 68° and 66° F. The discharge of all these springs apparently rises from considerable depth. The similarity in temperature and the lack of adequate drainage area to account for those near the northeast shore suggest a common source, perhaps outside the area topographically tributary to the lake.

STREAMS

In most years the Chewaucan River supplies most of the water reaching Lake Abert. At the gaging station near Paisley, where the river leaves the forested mountains, the flow was measured during water years 1913–21 (Oct. 1912 to Sept. 1921) and water years 1925–63. The average flow for those 48 years of record is 136 cfs (98,500 acre-ft per yr). For this study, the average annual flows for water years 1922–24 were estimated, on the basis of records for Silvies River near Burns and Camas Creek near Lakeview, as 80, 60, and 25 cfs, respectively. The average flow for the 51-year period 1913–63, determined from these estimates, is 131 cfs (94,900 acre-ft per yr).

The drainage area of the Chewaucan River is 275 square miles at the gaging station near Paisley, 430 square miles at the former gaging station at Hotchkiss Ford, and 490 square miles at the mouth. As of 1963, diversions from the reach between gaging stations supplied irrigation water to 32,000 acres, and diversions below Hotchkiss Ford, to about 8,700 acres. The principal crop is wild hay.

Table 5 shows the depletion of streamflow between the gaging stations during 1915–18 and 1920, caused chiefly by irrigation diversions.

TABLE 5.—*Annual discharge of Chewaucan River near Paisley and Chewaucan River at Hotchkiss Ford, 1915–18 and 1920*

[Drainage area: Chewaucan River near Paisley, 275 sq mi; Chewaucan River at Hotchkiss Ford, 430 sq mi]

Water year	Discharge of Chewaucan River (acre-ft)		Depletion (acre-ft)
	Near Paisley	At Hotchkiss Ford	
1915	63,800	15,300	48,500
1916	106,000	51,700	54,300
1917	118,000	65,600	52,400
1918	57,700	23,100	34,600
1920	45,400	7,990	37,400

The use of water from the Chewaucan River for irrigation began about 1884; drainage of marshes and irrigation development continued until about 1915. As yet, no upstream storage reservoirs have been built on the river, but one is now (1968) under serious consideration. Such storage development would decrease the average annual inflow to Lake Abert.

Streamflow into Lake Abert was not directly measured. Records of Chewaucan River near Paisley are the only long-term data in the basin. Between that gaging station and the lake, evapotranspiration from Chewaucan Marsh significantly reduced the inflow to Lake Abert prior to the beginning of irrigation. The amount of that natural depletion is not known, but over a period of years it was probably similar to the average depletion for the presently irrigated 41,000 acres. The present net depletion may be about 1.6 acre-feet per acre irrigated. In many dry years the supply available is not adequate to irrigate the entire 41,000 acres, just as the supply was in many years not adequate to flood the entire marsh under natural conditions. Thus, the average annual discharge now reaching Lake Abert probably is about as great as it was under natural conditions. In periods of drought, however, the small available flows may now be controlled and consumed more effectively by irrigation than they were by dissipation in the natural marsh, thereby increasing the frequency with which the lake dries during such periods.

The average annual inflow to Lake Abert from the Chewaucan River may be about 48,000 acre-feet (51 percent of the quantity measured 32 miles upstream, near Paisley), on the basis of water-budget computations (p. B15).

WATER LOSS

EVAPORATION

Evaporation from Lake Abert was computed by the mass-transfer method described by Harbeck (1962). The basic equation is

$$E=Nu(e_0-e_a),$$

in which

E = evaporation rate, in inches per day;
N = coefficient of proportionality (termed "the mass-transfer coefficient");
u = windspeed, in miles per hour;
e_0 = saturation vapor pressure, in millibars, for the water-surface temperature; and
e_a = vapor pressure of the airmass, in millibars.

The difference in vapor pressure (e_0-e_a) is commonly expressed as Δe. The product $u\Delta e$ for any period is an index of evaporation loss.

For periods with no precipitation and only minimal inflow, the evaporation loss from the lake (E) is equal to

TABLE 6.—*Monthly wind movement, temperature, relative humidity, and evaporation losses at Lake Abert, and temperature and precipitation at Valley Falls, October 1961 and April to October 1962*

[Wind movement measured at midlake 2 meters above water surface; temperature of lake at surface measured at midlake. Air temperature and relative humidity measured 1 mile south of lake]

Month	Wind movement (mi)		Average temperature (°F)		Relative humidity (percent)	Computed evaporation loss (in.)[1]	Valley Falls (3 mi SSW of lake)	
	Total	Average per hour	At lake surface	Air			Temperature (°F)	Precipitation (in.)
1961								
October[2]	6,750	10.4	50.2	47.5	61.7	3.53	46.0	0.66
1962								
April[3]	3,390	11.8	54.0	48.9	60.2	4.66	49.8	.64
May	6,760	9.1	54.0	51.2	67.2	3.50	50.8	3.91
June	5,500	7.6	65.3	61.3	57.5	5.44	59.2	.08
July	4,820	6.5	71.5	63.4	52.6	7.00	64.3	.00
August	6,420	8.6	67.6	62.2	51.6	7.69	64.6	.23
September	5,050	7.0	63.9	58.4	52.4	5.19	59.9	.16
October	5,960	8.0	50.8	46.1	79.6	2.09	48.8	6.13

[1] Not adjusted for lake-water density.

[2] Data except those for Valley Falls cover period October 1–27 only; values are estimated for remainder of month.

[3] Data except those for Valley Falls cover period April 19–30 only; values are estimated for remainder of month.

the fall in lake level, adjusted slightly for the effects of inflow. If windspeeds (u) and vapor-pressure differences (Δe) for the same periods are known, the relation between E and $u\Delta e$ can be defined and the coefficient N determined. Then, the evaporation can be computed for any period for which windspeed and vapor-pressure data are available.

The following data were collected for Lake Abert:

1. A continuous record of lake stage at a point on the east shore 10 miles northeast of Valley Falls.
2. Computed or estimated inflow from the Chewaucan River and from springs.
3. A continuous record of wind movement 2 meters above the lake surface at the midlake raft (fig. 9; data summarized in table 6).
4. A continuous record of lake-surface temperature at the raft (summarized in table 6).
5. Continuous records of temperature and relative humidity of the air 1 mile south of the lake and 2 miles northeast of Valley Falls (table 6).

To ascertain the mass-transfer coefficient, N, for Lake Abert, the average daily fall in stage (ΔH) was taken from the recorder trace for selected periods when there was little or no precipitation and comparatively little inflow to the lake. These values of ΔH, adjusted for effects of inflow, are equivalent to the loss by evaporation and were plotted against the product of average windspeed and difference in vapor pressure, $u\Delta e$, for concurrent periods. The resulting plot (fig. 10) defines a straight line on arithmetic coordinate paper that passes practically through the origin, with a slope (N) of 0.00216. This value of N was rounded to 0.0022 for the computing of the monthly evaporation losses listed in table 6.

For the 6-month period of complete record, May–October 1962, the total computed evaporation loss was 30.9 inches. That value must be corrected for effects of lake-water density, which averaged about 1.05 g/ml (grams per milliliter) at 20° C during the period. Assuming about a 1 percent evaporation reduction for each 0.01 density unit above 1.00 (C. H. Lee, in Harbeck, 1955, p. 1), the 30.9-inch computed value would be equivalent to 32.5 inches from a fresh-water body. The 6-month total for 1962 was then adjusted to an average full-year value by comparison with U.S. Weather Bureau records for the Medford Experiment Station, 135 miles to the west—the nearest site with a long-term year-round record (1943–63). There, the measured evaporation for May–October 1962 was 78.6 percent of the full-year value, which

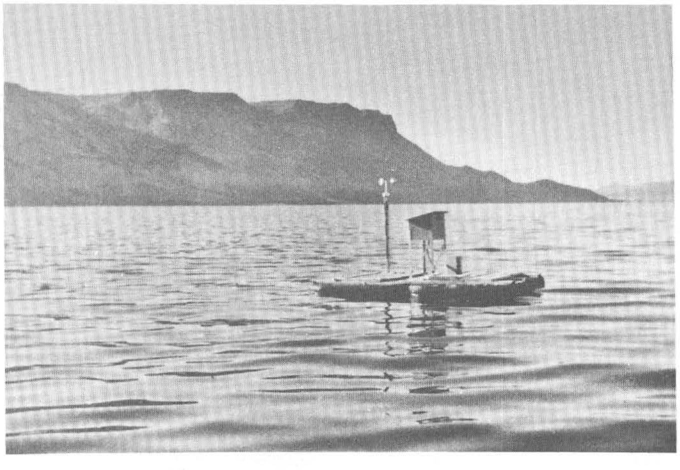


FIGURE 9.—Anchored instrument raft on Lake Abert, September 17, 1962. Abert Rim is in background. Midlake raft housed equipment for measuring wind velocity and lake-surface temperature, as part of evaporation study.

in turn was 102.3 percent of the 21-year average. On the basis of these data, the estimated long-term fresh-water evaporation rate at Lake Abert would be about 40.3 inches (3.36 ft) per year. Assuming the average density to be about 1.04 grams per milliliter at 20° C, the actual lake-surface evaporation rate is probably about 38.7 inches (3.22 ft) per year.

LEAKAGE

Lake Abert does not leak. The lakebed is lower than any other adjacent valley floor except that of Summer Lake. Furthermore, Lake Abert is surrounded by springs and seeps (fig. 5) that indicate a ground-water gradient toward, rather than away from, the lake.

OVERFLOW

The lowest topographic divide, which separates the Abert and Summer Lake basins 2 miles north of Paisley, is about 140 feet higher than the bed of Lake Abert. No overflow has occurred there within historic time. During the Pleistocene period, however, inflow to Lake Abert was sufficient to cause overflow, which filled the adjacent Summer Lake basin, forming Lake Chewaucan. At its maximum level, the large Pleistocene lake covered the present-day divide to a depth of about 130 feet. Overflow from Lake Abert has occurred since that time, as evidenced by a channelway that meanders generally northwestward from the divide to an altitude of about 4,330 feet. The time and quantity of the most recent overflow to Summer Lake by way of this channelway are unknown.

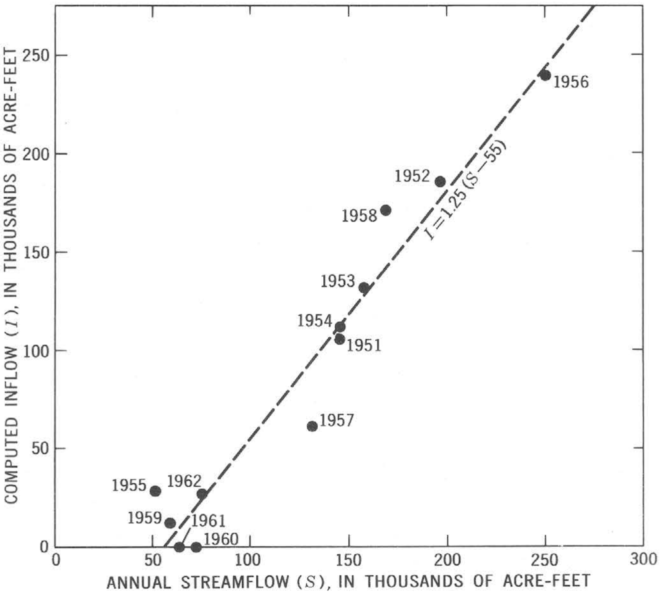


FIGURE 10.—Relation between fall in stage (ΔH) and the product $u\Delta e$ at Lake Abert near Valley Falls during May–October 1962. Symbols: u = average wind velocity, in miles per hour; Δe = difference, in millibars, between vapor pressure of saturated air over lake water and vapor pressure of incoming air. Slope of line ($\Delta H/u\Delta e$) is mass-transfer coefficient (N).

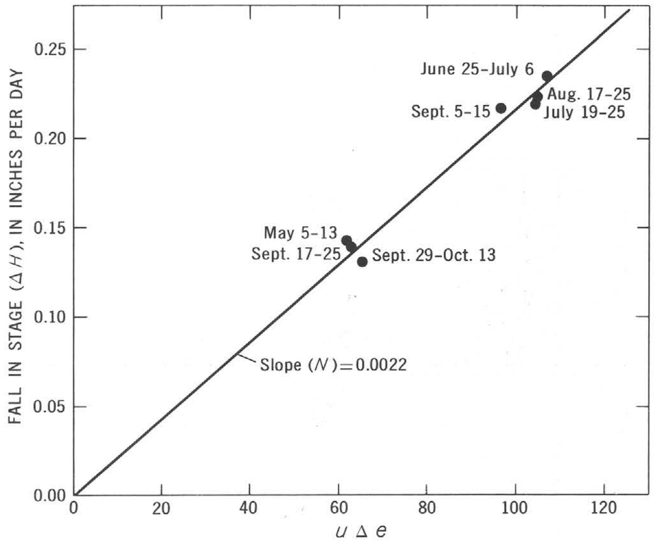


FIGURE 11.—Relation between annual streamflow of Chewaucan River near Paisley and computed inflow to Lake Abert, water years 1951–62.

WATER BUDGET FOR THE LAKE

A generalized relationship between the annual streamflow, or discharge, of Chewaucan River near Paisley and the total annual inflow to Lake Abert has been defined by a study of the water budget of the lake for the water years 1951–62. For those years, the altitude of the lake surface on September 30 is known or has been closely approximated by interpolation between observations. The annual inflow was computed as equal to the change in volume of the lake (computed from water-level data and table 4) plus the volume of water evaporated (3.22 ft, multiplied by the average surface area) minus the volume of precipitation on the lake (observed precipitation at Valley Falls, multiplied by the average area).

The net yearly inflow so computed for water years 1951–62 is plotted against the concurrent yearly discharge at the station near Paisley in figure 11. The relationship in that figure is expressed by a straight-line equation:

$$\text{Annual inflow } (I)\text{, in acre-feet} = (1.25)\ [\text{Paisley streamflow } (S) - 55{,}000 \text{ acre-ft}].$$

However, the inflow is assumed to be never less than 7,000 acre-feet per year because of the peripheral springs and local runoff. This relationship may not give accurate results for any given year, but it probably provides a fairly accurate estimate over a period of several years.

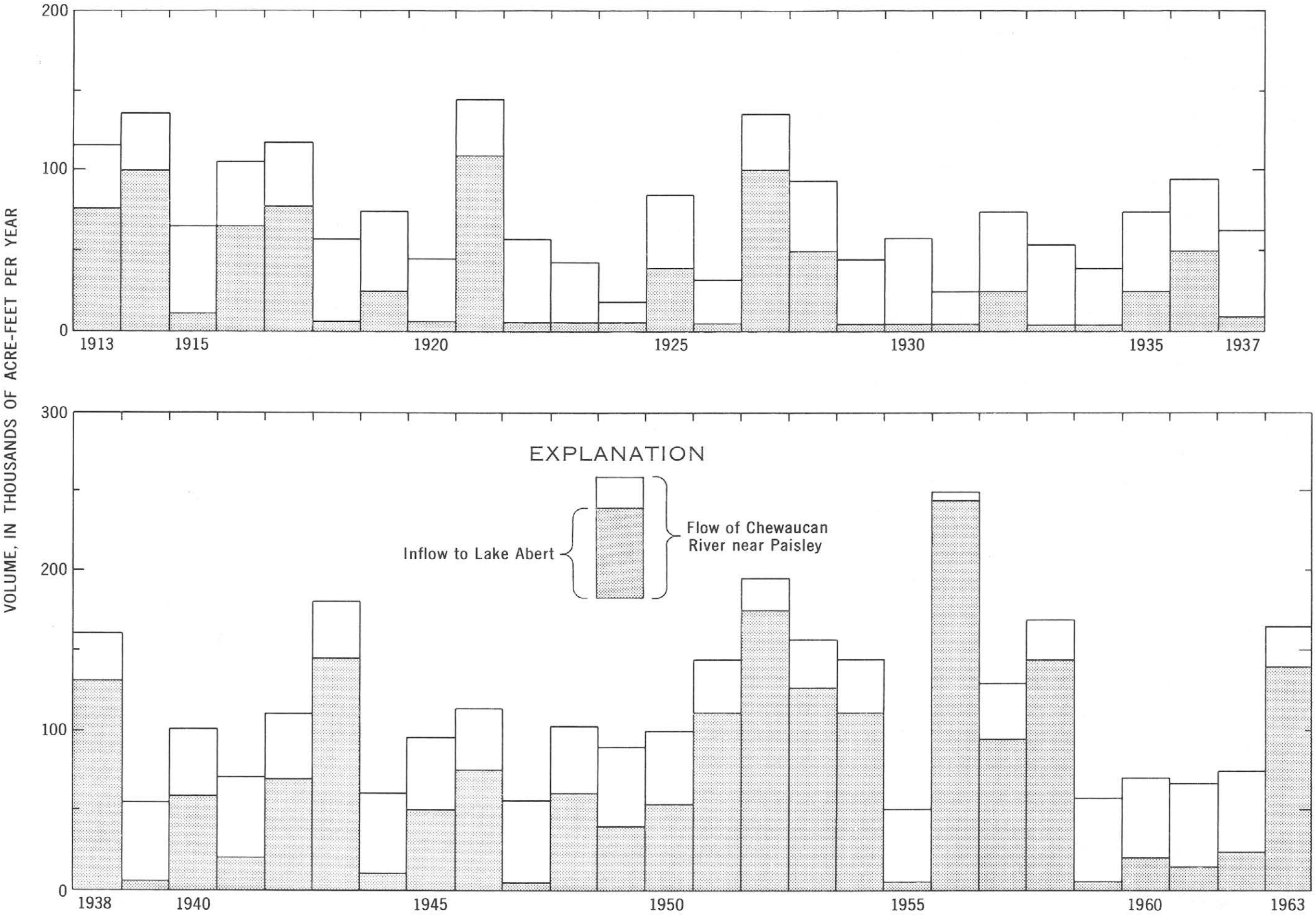


FIGURE 12.—Annual flow of Chewaucan River near Paisley and computed inflow to Lake Abert, water years 1913–63.

The equation was used to compute the annual inflow to Lake Abert in the period 1913–63 (fig. 12). For the entire period, the computed annual inflow averaged about 55,000 acre-feet. Of this amount, about 48,000 acre-feet per year may have been contributed by the Chewaucan River.

This generalized water budget was tested for validity by synthesizing a record of the stage of Lake Abert for May 31 (near-maximum) and September 30 (near-minimum) of each year from the first accurately known lake stage, at an altitude of 4,154.2 feet on October 4, 1915, to September 30, 1963. In this computation, the lake was assumed to have been dry whenever the stage fell to an altitude of 4,243.5 feet. No additional adjustments were applied to make the synthesized record agree with later observations. According to this computation, the lake should have been dry or practically dry in 1924, 1926, 1930, 1931, 1933, 1934, and 1937, which is in complete agreement with a news account of 1924 and with the oral statements of reliable local witnesses. The computed annual low stage for September 30 was compared with the known lake stages in 18 years of the 48-year period, and the greatest difference was 1 foot, in 1961. The good agreement between computed and observed lake stages warrants the conclusion that the computed values are probably within 1 foot of actual lake stages in years when no observation was made. Extension of the estimates to periods before 1915 is not possible, however, because earlier records of precipitation at Valley Falls and runoff at Paisley are lacking. The computed record of lake-level fluctuation since 1915 is shown graphically in figure 13.

The budget equation also shows that Lake Abert could again reach the level at an altitude of 4,269.7 feet indicated by distinct beach deposits (p. B11), provided that there is no large additional upstream diversion or storage. At the high level, the lake covers about 50,000 acres, and its volume is about 1 million acre-feet. The net evaporation loss would offset an average annual inflow of 110,000 acre-feet, which would be attained with an annual discharge at Paisley of 143,000 acre-feet—about 50 percent more than the average flow in the period 1912–63. If the water year 1956 (250,000 acre-ft of discharge at Paisley) had been followed by 4 more years of equally heavy dis-

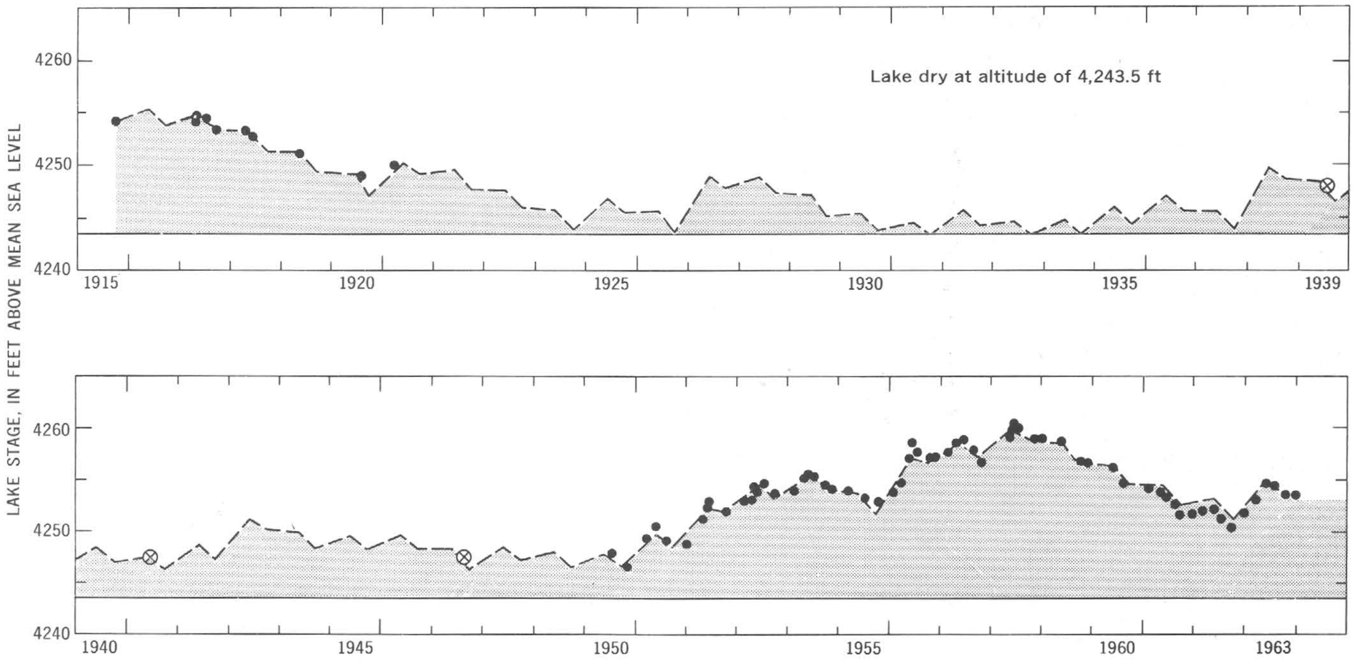


FIGURE 13.—Variations in the stage of Lake Abert, 1915–63. Dashed line connects water levels on May 31 and September 30, computed by annual water-budget method and projected from the observed water level on October 4, 1915. Dots represent observed water levels, obtained from gage reading or by leveling; small circled crosses represent less accurate observations.

charge, Lake Abert would have risen above the old high level. The average annual discharge at Paisley in the period 1951–58 (156,000 acre-ft) would also have raised the lake to that level if continued for an additional 15 years.

GEOCHEMISTRY

GENERAL CHEMICAL CHARACTER OF THE LAKE

In 1963 Lake Abert contained about 13 million tons of dissolved solids, covered an area of about 55 square miles, and was the largest landlocked saline water body in the Pacific Northwest. The dissolved-solids content of the lake fluctuates considerably, but generally ranges from 20,000 to 80,000 ppm. The three most abundant dissolved constituents—sodium, carbonate, and chloride—make up about 90 percent of the dissolved solids. Potassium, bicarbonate, and sulfate account for more than 9 of the remaining 10 percent. Although silica, bromide, orthophosphate, and boron constitute less than 1 percent, these constituents occur in large parts-per-million concentrations. (See table 3.) Concentrations of calcium and magnesium in the lake are unusually small; combined, they probably remain less than 5 ppm at most times.

Among the trace elements, iron, aluminum, vanadium, molybdenum, nickel, lead, and cobalt are present in measurable parts-per-billion concentrations, generally in the above-listed order of abundance (table 29).

VARIATIONS IN DISSOLVED-SOLIDS CONCENTRATION

The dissolved-solids content of samples collected from Lake Abert since 1882 has ranged from 18,700 ppm (July 8, 1958) to 95,000 ppm (July 21, 1939). The estimated (unrecorded) minimum salt content during the entire 80-year period—about 18,000 ppm—occurred in 1958 during the highest historically observed lake stage (alt 4,260.5 ft above mean sea level). In contrast, amounts greater than 100,000 ppm doubtless occurred during periods of near dryness between 1924 and 1937.

Except at near-dryness stage, the relation between dissolved-solids concentration and lake level is almost constant for Lake Abert over periods of several years, such as 1958–62 (fig. 14). This is because of the nearly unchanging solute tonnage in the lake during such periods (table 7) and because the shallow water body remains virtually homogeneous when inflow is negligible. (For example, note data on pl. 2.)

Concurrent records of lake stage and dissolved-solids concentration for Lake Abert prior to 1939 are not available. Hence, accurate comparisons of dissolved-solids tonnages in the lake before and after the long period of near dryness (1924–37) are not possible. Table 7 summarizes available tonnage information subsequent to 1938. The data show that the quantity of salts in the lake increased by about 75 percent—from about 8 million tons to almost 14 million tons—during the 22-year period 1939–61. Apparently, most of the accumulation occurred between

TABLE 7.—*Dissolved-solids tonnage in Lake Abert, 1939–63*

Date	Analysis No. (table 28)	Lake level (ft above mean sea level)	Lake volume (10^3 acre-ft)	Dissolved-solids content (ppm)	Load (10^6 tons)[1]
7-21-39	5a	4,248.2	56	95,000	7.8
8- -52	5b	4,252.7	196	35,000	9.6
8-12-55	2a	4,252.8	198	40,400	11.2
7- 9-58	1a	4,260.5	496	18,700	12.8
1-29-59	1b	4,259.2	442	20,500	12.5
5-20-59	6a	4,258.9	430	21,700	12.8
4-26-61	1c	4,253.86	237	40,800	13.6
6-27-61	1d	4,253.31	217	45,000	13.7
9- 7-61	1e	4,252.04	174	55,400	13.7
1-12-62	1f	4,251.81	165	55,900	13.1
3-13-62	1g	4,252.14	177	52,000	13.0
4-18-62	1h	4,252.30	181	52,000	13.3
9-17-62	8a	4,250.70	129	71,000	13.1
10-30-62	1j	4,251.19	145	63,000	13.0
3-19-63	1k	4,253.08	208	45,000	13.1

[1] Error probably less than about 0.5 million tons. Additional analyses are available (table 28), but accuracy of analytical results is questionable because sample-collection sites were subject to dilution by inflow from the Chewaucan River or from peripheral seeps.

1952 and 1958, when the lake rose from an altitude of about 4,250 feet to almost 4,261 feet (equivalent to a fivefold volume increase and an almost 45-percent lake-area expansion). During the 13-year period prior to 1952, the lake stage had only fluctuated from an altitude of about 4,246 feet to about 4,252 feet. During the present study (Apr. 1961–Mar. 1963), the salt tonnage in solution has remained almost constant, averaging 13.3 million tons (table 7). Possible reasons for accumulation of the large dissolved-solids increment (about 4 million tons) between 1952 and 1961 are discussed in the section on sources of dissolved solids.

Despite a lack of data on solute loss from Lake Abert during times of desiccation between 1924 and 1937, the major solute losses from Summer and Goose Lakes (p. B28, B34) imply a similar occurrence at Lake Abert as well. However, if the changes in chemical character of Summer and Goose Lakes were largely the result of salt depletion during periods of desiccation (p. B28), the lack of chemical change in Lake Abert (table 9) may mean that loss of salts from the Abert playa between 1924 and 1937 was not great. This possibility is further supported by the large tonnage increase in the lake between 1939 and 1961. The great increase implies that much of the salts given up by the lake during desiccation remained accessible for later re-solution, and were not removed from the vicinity of the playa, or even from the basin.

CHANGES IN CHEMICAL CHARACTER

The amounts of many dissolved constituents in Lake Abert have remained virtually unchanged relative to one another during the period of study, despite the large variations in dissolved-solids content. However, the relative (percentage) concentrations of two major constituents, several minor constituents, and all the identified trace elements fluctuated significantly. Among the major constituents, the amounts of carbonate and bicarbonate vary relative to one another, even though their combined concentration (calculated as carbonate) remained about 22 percent of the dissolved-solids content. This trend is characteristic of Summer and Goose Lakes as well, and it is discussed in more detail on page B45.

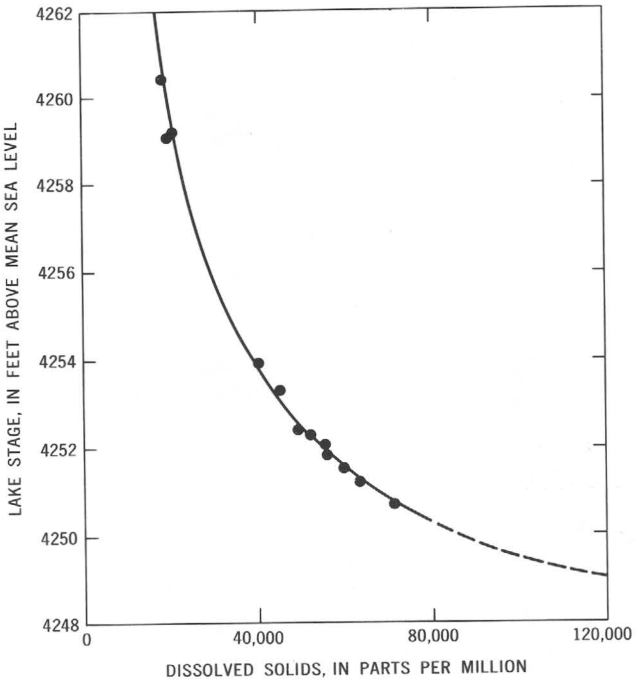


FIGURE 14.—Relation between dissolved-solids concentration and stage of Lake Abert, July 1958–October 1962.

Another characteristic of the three adjacent lakes is a seasonal variation in the relative concentrations of silica and orthophosphate; the variations are different from lake to lake, however. On the basis of 2 years of record at Lake Abert (during which the measured concentrations of silica and orthophosphate ranged from 130 to 201 ppm and from 55 to 101 ppm, respectively), relative amounts of the two nutrients apparently tend to reach peak values during the summer (June–August) when water temperatures are highest (fig. 15). The smallest relative amounts were found between December and March. The range in fluctuation of silica relative to dissolved-solids content is wide—from 0.248 to 0.385 percent between April 1961 and October 1962, equivalent to a range from 31,000 to 51,000 tons of silica.[1] The larger percentages occurred at times of lesser dissolved-solids content. Fluctuations in the relative

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[1] Percentages are easily translated into tonnages, because, if the percentage for any constituent and the total solute tonnage in the lake remain constant regardless of a changing concentration, the constant percentage is equivalent to a constant tonnage. For example, Lake Abert now contains about 13 million tons of dissolved solids. If silica were to remain at 0.248 percent of the dissolved-solids concentration, even though that concentration changed from 30,000 to 60,000 ppm because of a 50-percent lake-volume decrease, the silica tonnage would remain at 31,000.

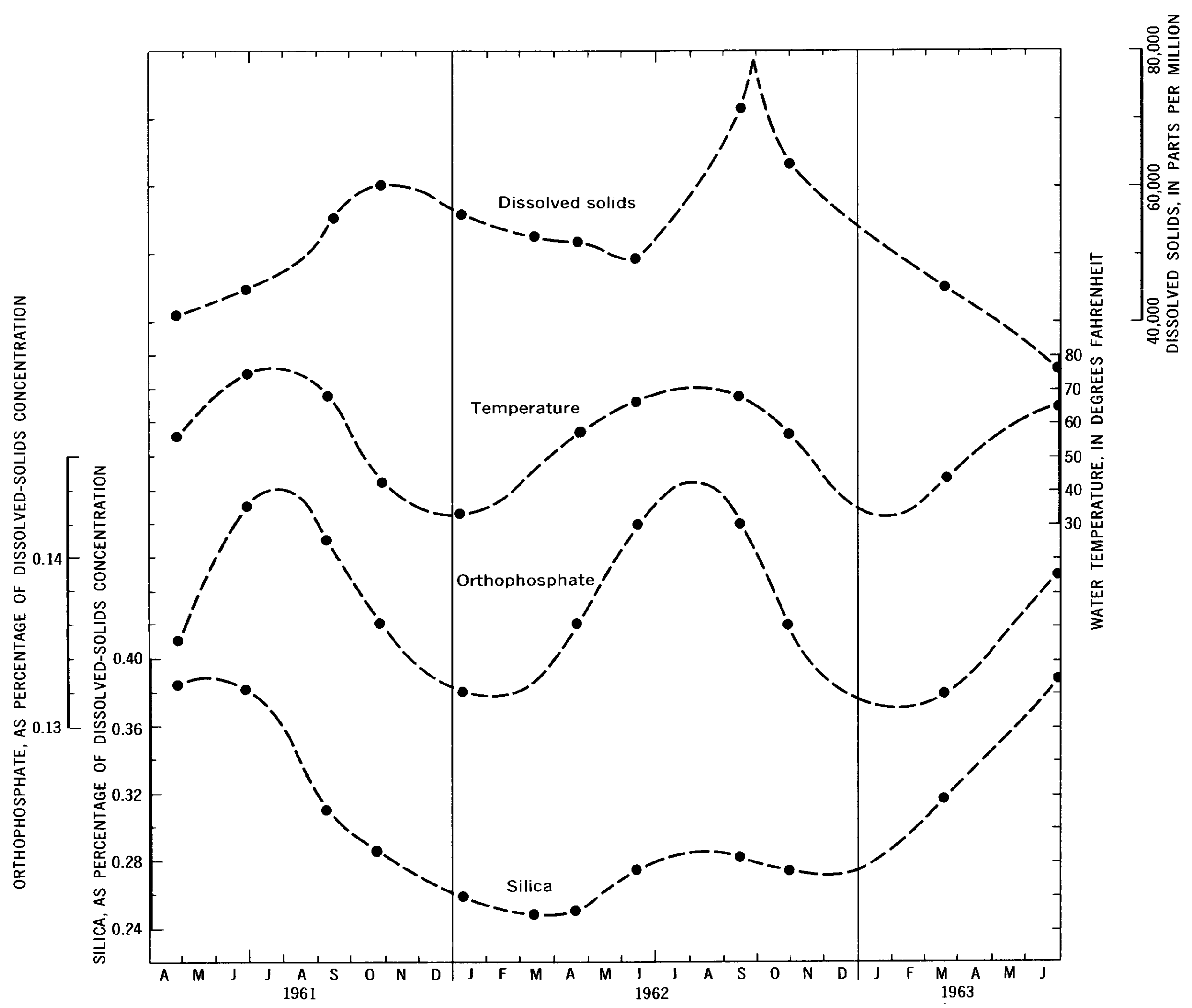

FIGURE 15.—Changes in dissolved-solids concentration, temperature, and relative amounts of silica and orthophosphate in Lake Abert, April 1961–July 1963.

amount of orthophosphate in the lake are smaller and more uniform from season to season than those for silica; the estimated seasonal range (fig. 15) was from 0.132 to 0.144 percent orthophosphate, equivalent to a variation from 16,800 to 18,300 tons. The orthophosphate fluctuations closely follow those of water temperature in Lake Abert—a correlation that does not apply for Summer Lake (fig. 24) or Goose Lake (fig. 28).

Seasonal fluctuations of silica and orthophosphate in the three lakes are discussed in more detail on pages B48 and B51.

Changes in the absolute (parts per billion) and relative (percentage) amounts of trace elements in Lake Abert are erratic (tables 8, 29). No consistent pattern of either seasonal fluctuation or variation with changing dissolved-

TABLE 8.—*Relative (percentage) amounts of five trace elements in Lake Abert and the Chewaucan River*

[All data from table 29. Relative amounts expressed as a percentage of dissolved-solids content, multiplied by 10^5]

Element	Lake Abert			Chewaucan River near Valley Falls
	January 12, 1962	June 12, 1962	September 17, 1962	June 12, 1962
Cobalt (Co)	<0.4	<1.0	1.2	78
Lead (Pb)	<.4	<1.0	3.2	<75
Molybdenum (Mo)	>8.6	2.6	4.4	21
Nickel (Ni)	≧.1	3.5	2.4	150
Vanadium (V)	>8.6	16	≧6.6	300
Dissolved-solids content, in parts per million	55,800	49,100	71,200	193

TABLE 9.—*Relative abundance of major dissolved constituents in Lake Abert, 1912 and 1962*

Constituent	Percentage of total dissolved-solids content	
	February 1912 [1]	January 12, 1962
Sodium (Na)	38.9	39.3
Potassium (K)	1.7	1.3
Carbonate (CO_3) plus bicarbonate (HCO_3) [2]	20.8	22.2
Sulfate (SO_4)	1.9	1.8
Chloride (Cl)	36.1	34.5
Dissolved-solids content, in parts per million	[3] 29,600	55,900

[1] Data after Van Winkle (1914, p. 119, analysis 4).
[2] Calculated as carbonate.
[3] Corrected for estimated concentrations of fluoride, bromide, orthophosphate, and boron; bicarbonate recalculated as carbonate; dissolved-solids content of sample may have been significantly less than lake average at time of collection, owing to dilution by inflow at south end of lake.

solids concentration is evident. Some of the apparently erratic change may be the result of variable reliability of the data, as discussed on page B56.

No major long-term net changes were noted in the relative abundance of anions at Lake Abert, whereas such changes did occur in Summer Lake (table 12) and Goose Lake (table 14). Analyses of samples collected from Lake Abert in 1912 and 1962 (table 9) show only minor net changes, perhaps within limits of analytical error. The data suggest that sulfate plus chloride may have decreased from 38.0 to 36.3 percent of the dissolved-solids concentration during the 51-year period; this decrease represents only 4 percent of the original value, in contrast to increases of 29 and 21 percent for Goose and Summer Lakes during a comparable period.

BIOLOGIC CONTROLS ON CHEMICAL QUALITY

The biologic assemblage in Lake Abert doubtless exerts controls on, and is also controlled by, the amounts of certain constituents in the lake water, such as silica, calcium, magnesium, sulfate, nitrate, orthophosphate, and probably several of the trace elements. Brine shrimp (*Artemia salina*) abound in the water during certain periods of the year, and at such times one can hardly dip a single cupful of the lake water without getting several specimens. In early autumn, the lakeshores are lined with small windrows of larval skins discarded by emerging adult brine flies. In summer vast numbers of algae (*Cladophora*) float freely in the water and cover much of the lake bottom, their filaments clustered into balls formed by the action of waves in the warm shallow water. Several other kinds of plankton, including diatoms and *Anabaena*, may also be present in significant populations. The important inorganic chemical constituents of three of the above biologic organisms are summarized below (data after Welch, 1952, p. 274, 275, 304). No information is available regarding the major inorganic constituents of the brine shrimp, but such crustaceans probably contain significant amounts of phosphorus and calcium, plus lesser amounts of silica and magnesium (K. V. Slack, written commun., 1962).

Organism	Percentage of dry weight of sample				
	Ash	Silica (SiO_2)	Phosphorus (as PO_4)	Calcium (Ca)	Magnesium (Mg)
Cladophora [1]	26.5	7.1	1.0	2.4	1.0
Diatoms [2]	39.5	30.8	----	----	----
Anabaena [3]	7.2	1.0	1.6	1.0	.4

[1] Welch (1952, table 29, p. 304).
[2] Welch (1952, table 22, p. 274); collected at Lake Mendota, Wis.
[3] Welch (1952, table 23, p. 275); collected at Lake Mendota, Wis.

The chemical data suggest that assimilation of certain constituents during periods of population growth, and at least partial release of these constituents after death, may affect the amounts dissolved in the lakes. However, the variations in orthophosphate tonnage, and to a lesser degree silica tonnage (as shown by relative quantities in fig. 15), seem to contradict results expected on the basis of incomplete knowledge of biologic activity in the lakes. The possible importance of biologic influences on seasonal fluctuations of silica and orthophosphate are discussed in more detail on pages B48 and B51.

The amount of sulfate in Lake Abert may be influenced by anerobic sulfate-reducing bacteria within the lake-bottom muds. This subject is discussed briefly on page B46.

SOURCES OF DISSOLVED SOLIDS

The Chewaucan River and precipitation are, by far, the two most important sources of water for Lake Abert, but they may not be the most important source of dissolved salts. Numerous small springs rise along or near the periphery of the lake (figs. 4, 5), and although their combined discharge is small (an estimated 10 cfs), their total dissolved-solids contribution to the lake and adjacent playa may be more than that from surface inflow and precipitation. A significant amount of salts may also be contributed to the lake by wind transport of alkali dust from other parts of the basin and from outside the basin. In addition, the recovery of salts lost during periods of lake dryness or of near dryness is a significant short-term source.

The several potential sources of dissolved or dissolvable salts are discussed below.

CHEWAUCAN RIVER

Unfortunately, the only available chemical-quality data for the river near its mouth are analyses of 16 samples collected during the period January 1959–November 1962 (analyses 14a–14p, table 28). For these analyses, the relation between specific conductance, in micromhos, and dissolved-solids content, in parts per million, is expressed by the equation:

$$\text{Dissolved solids} = (0.583 \times \text{specific conductance}) + 25.$$

The dissolved-solids concentration in the Chewaucan River near its mouth is poorly related to discharge (fig. 16). Nonetheless, the data suggest that the average concentration may be near 120 ppm. The principal constituents of the river, regardless of the amount of dissolved solids, are silica, calcium, sodium, and bicarbonate. However, as the concentration of dissolved solids increases, the amounts of sodium, sulfate, and chloride increase relative to calcium and bicarbonate, whereas the relative percentage of silica decreases considerably (fig. 17). The calcium content, in parts per million, is generally three to four times that of magnesium (fig. 18).

Much of the dissolved-solids load carried by the Chewaucan River apparently is derived in the mountainous area upstream from Paisley. Data from three samples collected in April 1962 (table 10) show that, although dissolved-solids content increased by 67 percent in the 31-mile reach from the gaging station above Paisley to the river mouth near Valley Falls, the discharge decreased by 58 percent; therefore, the load decreased from 71 to 49 tons per day. Most of the decrease was due to loss of silica. In contrast, the amount of chloride increased from 0.2 to 2.6 tons per day in the same reach. Thus, most of the chloride (a major constituent in Lake Abert) in the Chewaucan River accumulates between Paisley and the mouth. Windblown alkali dust, metabolic animal-waste products, and, perhaps, flow from springs are principal sources of the chloride. In addition, residual salts from pluvial Lake Chewaucan may also contribute some chloride to the river.

TABLE 10.—*Changes in chemical character of Chewaucan River between Paisley and Valley Falls*

	Chewaucan River station		
	Above Paisley	At The Narrows	Near Valley Falls
River miles upstream from mouth [1]	32	16	1
Date of collection	4-16-62	4-16-62	4-18-62
Discharge cfs	419	194	[2] 175
Dissolved solids: [3]			
Parts per million	65	70	105
Tons per day	73	36	49
Silica (SiO_2):			
Parts per million	30	30	32
Tons per day	33	16	15
Sodium (Na):			
Parts per million	4.9	6.4	15
Tons per day	5.5	3.3	7.1
Chloride (Cl):			
Parts per million	.2	.8	5.5
Tons per day	.2	.4	2.6

[1] Approximate; does not include the numerous meanders between Valley Falls and The Narrows.
[2] Estimated discharge; others are measured.
[3] Estimated using specific conductance.

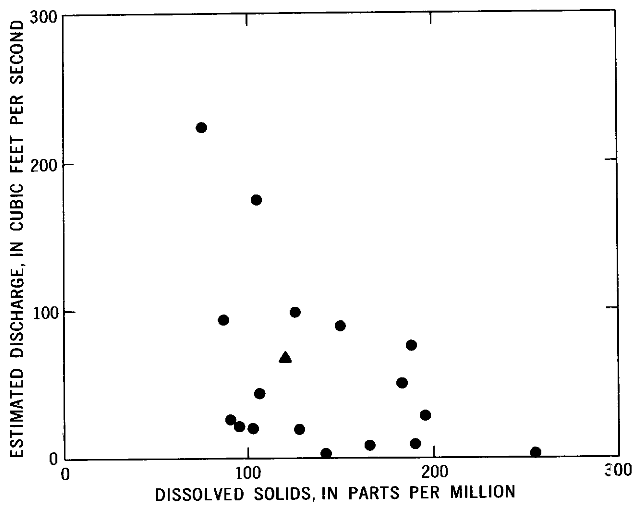

FIGURE 16.—Dissolved-solids concentration versus estimated discharge of Chewaucan River near Valley Falls. Triangle indicates estimated average discharge (66 cfs) and dissolved-solids concentration (120 ppm).

The chemical contrast between water of the Chewaucan River and of Lake Abert shows that most of the incoming silica, calcium, and magnesium, as well as lesser proportions of bicarbonate, must be removed from solution soon after mixing with the lake water. For example, the annual contribution of silica to Lake Abert from the river probably is about 2,000 tons. Yet, the entire silica load in the lake has not exceeded 51,000 tons in the period of intensive study, and the river alone seems to deliver that much in less than 30 years. The possible mechanisms for depletion of silica and other constituents are discussed in the section entitled "Geochemical Trends and Processes" (p. B42).

The relations between trace-element concentrations in the Chewaucan River and in the lake (table 8) are uncertain because the analytical results are of questionable accuracy (p. B56) and, also, because only one analysis is available for the river water. Nonetheless, the data in table 8 were recalculated to provide an order-of-magnitude comparison of quantities in the lake and its principal inflow:

Element	Lake Abert [1] (lb, rounded)	Chewaucan River [2] (lb per yr, rounded)	Theoretical number of years to accumulate Lake Abert load
Cobalt (Co)	3,000	100	30
Lead (Pb)	8,000	<100	>80
Molybdenum (Mo)	>20,000	30	>700
Nickel (Ni)	9,000	200	40
Vanadium (V)	40,000	500	80

[1] Based on largest percentage values in table 8.
[2] Based on percentage values in table 8, and an estimated average annual load of about 8,000 tons.

The calculations suggest that large amounts of incoming trace elements are removed from solution. This is indicated

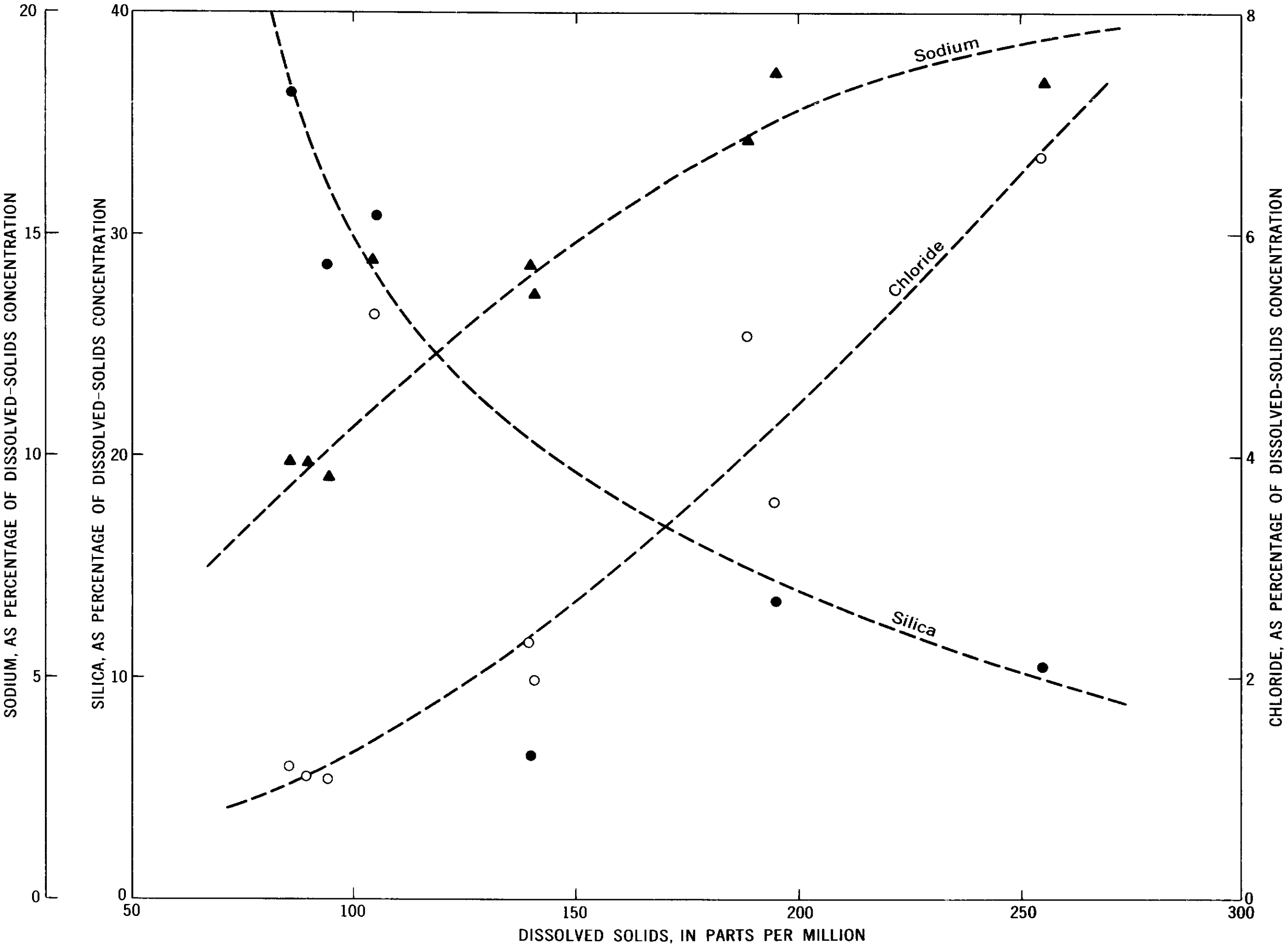

FIGURE 17.—Relation between dissolved-solids concentration and the relative amounts of silica, sodium, and chloride in discharge of Chewaucan River near Valley Falls. Solid circles represent silica; solid triangles, sodium; open circles, chloride.

by the very short replenishment period that would theoretically be necessary for accumulation of each constituent in the lake.

PERIPHERAL SPRINGS

Most water from springs adjacent to the lake (fig. 5) chemically resembles a dilute version of the lake water; sodium, bicarbonate, and chloride are the principal constituents, even though the dissolved-solids content is less than 1,000 ppm (analyses 104 and 106, table 30). The resemblance is not as great for peripheral spring water that contains less than about 300 ppm of dissolved solids (analyses 101 and 105, table 30); and the only available analysis of nearby well water shows almost no chemical resemblance to the lake (analysis 114, table 31).

A part of the dissolved solids in peripheral spring flow may represent salts recycled from the lake or from lacustrine deposits underlying the lake. This is suggested by the large dissolved-solids content in the discharge from two of the sampled springs that are closest to the lakeshore (analyses 104 and 106, table 30), and by the similarity of chloride percentages in these two spring waters and in the lake (32 and 34 percent for the spring waters, compared with 35 percent for Lake Abert; all other peripheral ground-water samples contained less than 25 percent chloride). If an appreciable amount of the dissolved solids contributed by peripheral spring flow does represent recycled salts, then the Chewaucan River may be the primary source of solutes now present in Lake Abert.

The solute contribution of springs adjacent to Lake Abert is difficult to assess because (1) the combined flow rate of the springs has been estimated during only one period (July–November 1962), and the rate may vary considerably with fluctuations of annual precipitation; (2) the overall chemical character of the spring flow can be only approximated, mostly on the basis of analyses of six samples collected June 9, 1962; (3) the amount of dissolved solids in the spring discharge that actually

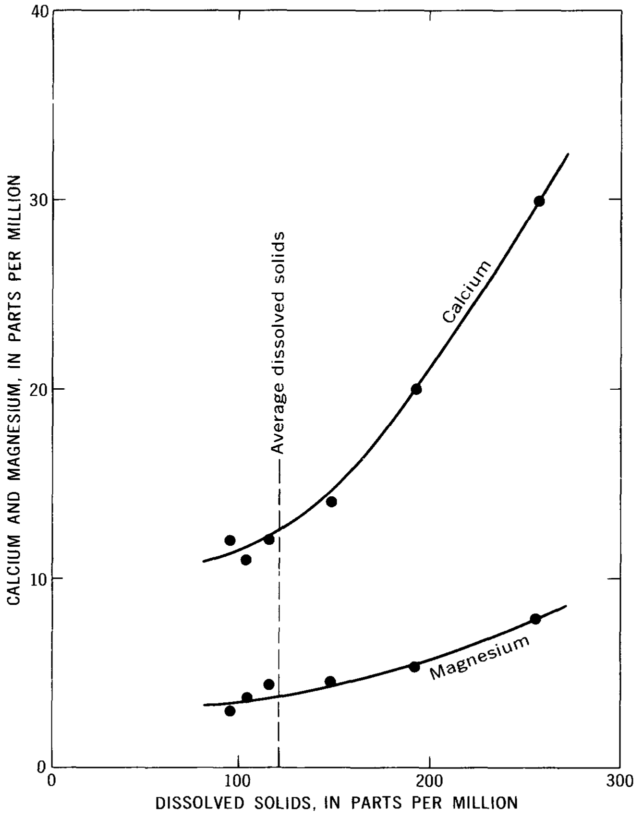

FIGURE 18.—Relation between dissolved-solids concentration and amounts of calcium and magnesium in discharge of Chewaucan River near Valley Falls.

represents recycled salts from the lake and lakebed is uncertain; and (4) the amount of spring-derived soluble material removed from the northern playa by wind before reaching the lake is unknown. Nonetheless, data in table 30 suggest that the annual contribution of major lake constituents (sodium chloride and carbonate-bicarbonate) by the peripheral springs may be greater than that of the Chewaucan River, even though the total spring discharge is far less than the streamflow.

PRECIPITATION

Almost no information is available on the chemical character of precipitation in the Lake Abert basin. Only one example of precipitation, a fresh-snow sample, has been collected within the basin. Because the snow cover was sampled at the same time as the nearby lake, the amount of dissolved solids in the snow sample may reflect slight contamination during handling of the two samples; yet, the snow sample contained only 4 ppm of dissolved solids—principally sodium, bicarbonate, and chloride. The snow presumably fell after the air had been cleared of dust by earlier precipitation; thus, the dissolved-solids content may be similar in magnitude to that of incoming precipitation unaltered chemically by the alkali environment.

Rain and snowfall within the Lake Abert basin undoubtedly contains more than 4 ppm of dissolved solids at many times during the year, owing to the pickup of soluble substances in atmospheric dust. Although some of these solutes may represent recycled material derived within the basin, much undoubtedly is brought into the basin by air movements. Nonetheless, the direct solute contribution of precipitation on the lake surface certainly must be far less than that of the streams and peripheral springs.

WIND-TRANSPORTED SALTS

The most difficult parameter to evaluate, even semiquantitively, is the net contribution of windblown salts. Alkali dust clouds have been observed traveling east into the Abert basin from adjacent Summer Lake (R. W. Childreth, U.S. Geol. Survey, oral commun., 1962). However, violent winds also pick up large amounts of salts from the flat playa north of Lake Abert, and, although much of this material is dropped within the basin, an unknown amount is carried beyond the basin. Also, the rate of eolian salt removal undoubtedly is accelerated during periods of low lake stage, when broader lakebed areas are exposed to wind action. Thus, an average annual gain (or loss) of salts by wind action cannot be estimated.

RE-SOLUTION OF LAKEBED SALTS

Most of the 75-percent solute-tonnage increase in Lake Abert during the period 1939–61 (p. B17) probably results from recovery of salts formerly isolated from the lake during the 14-year period of dryness and near-dryness (1924–37). The subject of solute storage within playa deposits peripheral to Abert and Summer Lakes is planned to be covered in considerably greater detail in a paper on the solute balance in the combined basin (Van Denburgh, unpub. data).

OTHER SOURCES OF DISSOLVED SOLIDS

Several other sources of dissolved solids must be considered, even though their average annual contributions are insignificant compared with those from the Chewaucan River and peripheral springs. Poison Creek, which heads on the Abert Rim plateau and courses down the steep scarp to the lake (location 35/21–1; pl. 2), is the only peripheral stream other than the Chewaucan River that supports even a small discharge during much of the year. Surface flow at the U.S. Highway 395 culvert is usually less than 1 cfs, but underflow in the broad alluvial fan augments the surface discharge by rising in an almost continuous line of seeps on the fan toe adjacent to the lakeshore. Chemical analyses of streamflow samples collected at the culvert in June and October 1962 (analyses 15a and 15b, table 28) show that the chemical character of Poison Creek is similar to that of Chewaucan River above Paisley throughout the year.

Overland flow during short periods of heavy rainfall may be a significant contributor of salts to the lake, especially because of the alkaline soils throughout most of the basin. However, the magnitude of contributed solute tonnage is unknown. The flow of ephemeral streams doubtless contributes salts to the lake either directly as inflow or indirectly by percolation to the ground-water aquifers feeding the peripheral springs.

SUMMER LAKE

Summer Lake is a shallow body of water that lies on the surface of a deep valley fill of alluvial and lacustrine deposits in a closed fault-block basin. The fill is reported to be more than 1,000 feet deep in places (Brown, 1957, p. 4). Southeast of Summer Lake, near Paisley, the basin is separated from Chewaucan Marsh by the lacustral-alluvial fan of the Chewaucan River (pl. 1). To the north it is separated from Fort Rock valley by a fault-scarred ridge that trends east-west. The south and west sides of the basin are formed by a great composite fault scarp that rises steeply along the crest of Winter Ridge (Walker, 1963). Less prominent scarps occur along the east edge. Winter Ridge is timbered; other parts of the basin are arid and support only desert-type vegetation.

AREA, VOLUME, AND LAKE-LEVEL FLUCTUATIONS

Summer Lake is very broad and shallow. At high stages (alt 4,149–4,151 ft) the lake is about 15 miles long, north to south, and about 5 miles wide, covering an area of about 60 square miles, yet its maximum depth is only 5–7 feet. Within the meander line (alt 4,152–4,155 ft) the area of the lake is about 45,000 acres; the corresponding volume may be 300,000 acre-feet or more. At an altitude of 4,146 feet, the lake area is about 25,000 acres, and its estimated volume about 25,000 acre-feet. At any stage, and especially at low levels, the wetted area may suddenly be increased significantly by the gusty winds that frequently sweep over the basin.

The fragmentary records of lake level are given in table 21, and seasonal fluctuations during the period 1959–62 are shown in figure 19. The records have been obtained almost entirely by leveling from reference marks. At times the lake level is affected by wind.

The highest stage of record (alt 4,151.4 ft) occurred in February, March, and April 1905, a time when precipitation and runoff were abundant, and the use of water for irrigation had not been fully developed. The highest stage attained in recent years through 1963 was at an altitude of about 4,149 feet in the spring of 1952, when the water level was just below the shoulder of State Highway 31 at the "sunken grade" southwest of the lake (A. B. Claggett, Oregon State Game Comm., oral commun., 1961).

At times the lake has been practically dry. The water area was reduced to about 10 acres in the late summer of 1950, and again in August 1961 (A. B. Claggett, oral commun., 1961) and in 1962. The lowest level actually observed was at an altitude of 4,144.86 feet on September 30, 1961; at lower stages, leveling is impracticable because of the wide mudflats around the lake. The lowest part of the lakebed probably is slightly above 4,144 feet in altitude, which is lower than any other point within about 70 miles.

At many sites around the lake, well-preserved shoreline deposits at altitudes up to 4,520 feet (370 ft above present lake level) attest the existence in Pleistocene time of a much larger pluvial lake, known as Lake Chewaucan (p. B12).

WATER SUPPLY

Summer Lake is fed by lake-surface precipitation, small streams that course down the steep slopes west and south of the lake, intermittent runoff from the east, and many springs, both large and small.

LAKE-SURFACE PRECIPITATION

Records of precipitation have been kept since April 1957 by the U.S. Weather Bureau at a station in the shadow of Winter Ridge, 1 mile south of Summer Lake Post Office and about 1 mile northwest of the lake. For the years 1958–62, the average annual precipitation was 12.4 inches. In these same 5 years, the precipitation at Valley Falls was about 3 percent more than the long-term average, suggesting that the average at the Summer Lake station is probably about 12.0 inches per year. The lakewide average is probably a little less—perhaps about 11 inches.

SPRINGS

The largest and least variable source of inflow to Summer Lake is a group of springs called Ana Springs, which rise north of the lake in at least five separate clusters (location 30/17-6E) and feed the Ana River, a stream about 5 miles long. According to Brown (1957, p. 1), "The waters of the springs rise by artesian pressure from lava-rock aquifers through about 150 feet of overlying thinly bedded lake deposits * * *." The springs may be fed by groundwater flow from the adjacent Silver Lake valley (p. B39).

An unpublished engineering report by Barr and Cunningham, Engineering Consultants, in 1920 indicates that the five large springs have their openings into the channel of the Ana River at the following altitudes: springs 1 and 2, 4,198 feet; springs 3–5, 4,175 feet (the

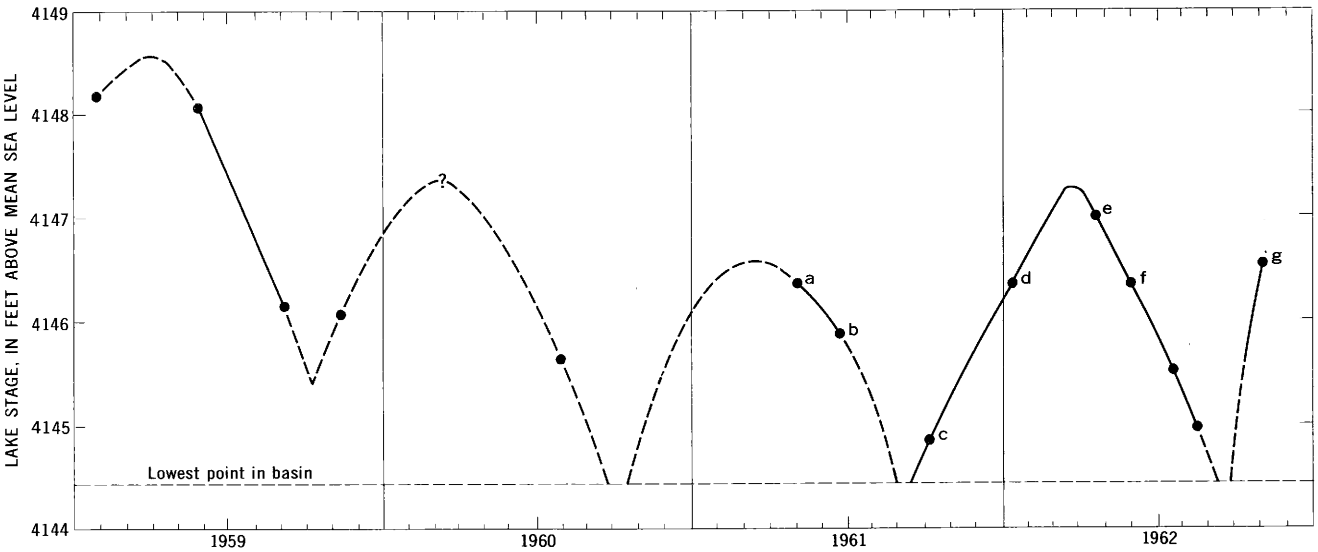

FIGURE 19.—Seasonal variations in the stage of Summer Lake, 1959–62. Lettered points correspond to samples from site 16 (table 28). Dashed where approximated.

base level used presumably was the sea-level datum prior to the 1929 adjustment, which probably would make the altitudes in error by less than 1 foot relative to present-day datum). Several years prior to 1920, a temporary dam was built below spring No. 2 to raise the water level about 10 feet. That dam was still in existence in 1920, and the flow at the dam was then thought by Barr and Cunningham to be undiminished by the submergence.

In 1922–23 an earthen dam with a metal outlet pipe near its base was built across the Ana River below the five springs to divert part of the flow into Summer Lake Canal for irrigation (Brown, 1957, p. 6). Shortly thereafter, slumping of the earthfill caused collapse of the outlet pipe, and a new and higher pipe was installed in 1926. As constructed and now operated, the pool over the springs is maintained at about 4,221 feet in altitude from May to September each year, and at about 4,214 feet from October to April. The pool therefore produces a hydraulic back pressure on the springs of 16 to 39 feet in winter and 23 to 46 feet in summer.

TABLE 11.—*Measured discharge of Ana River near Summer Lake between 1904 and 1962*

[Data not available for all years]

Year	Month	Discharge (cfs)	Year	Month	Discharge (cfs)
1904	July, November	[1] 164	1929	February	100
1905	March, April, June	[1] 148	1930	February-March	[1] 96
1906	April	141	1931		[3] 89
1909	January, May	[1] 142	1932		[3] 91
1910	September	141	1933		[3] 92
1912	February	140	1934		[3] 91
1914	August, December	[1] 134	1935		[3] 88
1915	May, October	[1] 133	1936		[3] 93
1917	April	132	1937		[3] 97
1918	April	124	1938		[3] 100
1919	March, August	[1] 120	1951		[3] 84–[4] 94
1920	March, August	[1] 114	1952		[3] 85–[4] 91
1921	March, August, October	[1] 127	1953		[3] 86–[4] 90
			1954		[3] 83–[4] 87
1922	April 4	130	1955		[3] 87–[4] 95
	August 17	[2] 106	1956		[3] 81–[4] 91
1923	January 29	[2] 109	1957		[3] 86–[4] 97
1924	September	124	1958		[3] 90–[4] 102
1925	January	126	1959		[3] 86–[4] 98
1926	January	[2] 109	1960		[3] 90–[4] 97
1927	March	91	1961		[3] 83–[4] 93
1928	April	106	1962		[3] 90–[4] 99

[1] Average of two or three gagings.

[2] Springs submerged by pool upstream from temporary dam at times in 1922–23, and continuously from permanent dam since 1926.

[3] Average summer flow; includes diversion in canal. Springs under full pressure from reservoir.

[4] Average flow the following winter; no flow in canal. Reservoir level about 7 feet lower than in summer season.

The combined discharge of the five springs, as measured below the dam and including the flow in Summer Lake Canal, is given in table 11. Records are fragmentary through 1950, and are continuous after June 1951. For the 12 water years of complete record, 1952–63, the combined discharge averaged about 91 cfs (66,000 acre-ft per yr).

The data in table 11 indicate that submergence of the springs reduces their flow. A rather abrupt drop of about 20 cfs accompanied first submergences by the pool in 1922 and in 1926. From 1951 to 1962, the flow in November and December was always 4 to 12 cfs (avg, 9 cfs) more than in the preceding summer season. This difference is due to the lowering of the pool level by about 7 feet after the irrigation season each year. The observed decrease in flow of Ana Springs may be partly offset by an increase in flow of other springs, but which springs are thus affected has not been determined.

Downstream from the dam and the gaging station, several other small springs appear in the Ana River channel. The effect of the dam on the flow of these springs is not known.

Flow of the Ana River is not affected by seasonal variations in local precipitation, but it doubtless responds slowly to long-term changes in precipitation. For example, table 11 shows a gradual decrease in discharge from about 160 cfs in 1904 to about 125 cfs 20 years later—presumably due mostly to natural causes.

The records since 1926 in table 11 include flow in a large diversion canal at the dam, several hundred feet upstream from the point where discharge measurements are made. That canal diverts about 11,000 acre-feet per year, mostly in the period May to September. Several smaller agricultural diversions are downstream, the largest one supplies irrigation water to about 1,000 acres. Considerably larger diversions have been made to maintain a suitable marsh habitat for wild ducks and geese in an area reclaimed from the bed of Summer Lake, above the level of the lake in recent years. That wildfowl area is flooded during the entire year, as much as a third of the riverflow being diverted for that purpose (A. B. Claggett, Oregon State Game Comm., written commun., 1964). The fresh water of the Ana River has been used to flush out salts from this portion of the former lakebed since the 1920's or 1930's. This use is possible because the lake now occupies a smaller area than it did when less of the tributary flow was used for irrigation.

In addition to those springs which feed the Ana River, there are many smaller springs scattered throughout Summer Lake basin. Many of them occur along the faultline west of the lake. At the Thousand Springs Ranch, 6 miles southeast of Ana Springs, many seeps supply the water used to irrigate fields of wild hay. Most of the smaller springs are used for irrigation; hence, in the summer they do not contribute materially to Summer Lake. South of Summer Lake there is at least one small hot spring, with a flow of about 0.05 cfs, which Waring (1908, p. 55) called Woodward Spring. Now, this spring is better known as Summer Lake Hot Spring (location 33/17–12A).

STREAMS

Summer Lake is fed by many small streams that tumble down the steep slopes west and south of the lake. No attempt was made to estimate the contribution of these streams, partly because their summer flows have been almost entirely diverted for irrigation for many years.

To the east, runoff presumably has reached the lake occasionally following heavy showers. The magnitude of this runoff is unknown.

WATER LOSS

EVAPORATION, LEAKAGE, AND OVERFLOW

Short-term records at the Summer Lake weather station, about 1 mile northwest of the lake, suggest that potential evaporation from a fresh-water body there is about 40 inches per year. Wind on the lake sometimes increases the wetted area subject to evaporation. On the other hand, the salinity of the lake water tends to reduce evaporation slightly. In the absence of conclusive data, the loss from the lake is estimated to be 40 inches per year.

Summer Lake does not leak. The presence of many springs around the shores of the lake indicates that the water table slopes toward the lake, rather than away from it, and the lakebed is lower than any other point within 70 miles.

The lowest topographic divide in the Summer Lake basin, 2 miles north of Paisley, is about 240 feet above the lakebed, and the volume capacity of the basin below that divide (about 25 million acre-ft) is more than enough to contain all flow generated within the basin.

WATER BUDGET FOR THE LAKE

The observed variations in water level (table 21) permit a rough approximation of the average annual water budget for Summer Lake:

Approximation of annual water budget for Summer Lake for the periods 1904–22 and 1923–63

[Data reported in thousands of acre-feet per year]

Source or disposition of water	Period 1904–22	Period 1923–63
a. Inflow from the Ana River	100	70
b. Inflow from other sources	20	20
c. Net depletion by irrigation	10	25
d. Total dissipated by net evaporation $(a+b-c)$	110	65
Area of lake corresponding to item *d* 10^3 acres	46	27
Approximate lake level corresponding to item *d* ft	>4,150	4,146–4,147

In the above table, the lake-surface areas required to dissipate the estimated inflow were estimated on the basis of (1) an average annual precipitation of 11 inches, and (2) a loss by evaporation of 40 inches (net evaporation, therefore, is 29 in., or 2.4 ft); the comparable lake altitudes are those believed to provide such surface areas. The two estimated lake levels are supported by the few observations. Most of the observed levels prior to 1923 were above an altitude of 4,150 feet; since then, lake-surface altitudes have ranged about equally above and below 4,146½ feet (table 21). The change is ascribed to the reduction in flow of the Ana River (which began even prior to 1923) and to the increased use of water both for irrigation and for flooding areas reserved for waterfowl. At the lower levels during recent decades, the lake area has been accordingly smaller, and the resultant decrease in evaporation volume has offset both the decreased flow into and the precipitation on the lake.

GEOCHEMISTRY

GENERAL CHEMICAL CHARACTER OF THE LAKE

Summer Lake is similar chemically to Lake Abert, its neighbor to the east. Sodium, bicarbonate, carbonate, and chloride are the principal constituents, whereas calcium and magnesium are almost lacking (table 3; fig. 2). Concentrations of silica, potassium, sulfate, orthophosphate, and boron are appreciable, but the five constituents make up only about 10 percent of the total dissolved-solids content. Compared with Lake Abert, Summer Lake contains significantly greater proportions of silica, bicarbonate, sulfate, fluoride, orthophosphate, and boron, whereas proportions in Summer Lake of chloride and bromide are significantly less, and the proportions of sodium, potassium, and carbonate are about the same (table 3).

Positively identified trace elements, as indicated by the analysis of a sample collected June 12, 1962, include aluminum, molybdenum, cobalt, iron, nickel, and vanadium, in that order of abundance (table 29). However, the sample was very turbid at the time of collection, and the analytical results, thus, may not be accurate. (See discussion, p. B56.)

VARIATIONS IN DISSOLVED-SOLIDS CONCENTRATION

The dissolved-solids concentration in Summer Lake varies considerably with time. The largest recorded value is about 37,000 ppm, for a sample collected in 1901 (Van Winkle, 1914, p. 119), though even greater concentrations are doubtless present at the lower levels near dryness. The smallest measured value is 1,800 ppm for a sample collected October 30, 1962. On a short-term basis, the concentration tends to vary inversely with stage—that is, with lake volume. When the lake is nearly dry or is refilling rapidly, however, the above relation is not consistent. For example, the lake dried almost completely in the late summer of 1961, and during at least the first 4 months after appreciable inflow resumed in September 1961, the dissolved-solids content of the lake at the sampling site remained less than the predryness content at comparable lake levels (fig. 20). Perhaps part of this difference was because the samples collected along the lake periphery during the first several months of refilling were not chemically representative of the entire lake, owing to areal differences in concentration prior to thorough mixing of the lake water with inflow. More importantly, however, the incoming water probably did not immediately recover all the salts previously lost during desiccation. In reference to figures 19 and 20, the lake dried almost completely after collection of sample 16b and had just started to fill when sample 16c was collected. During the period between collection of samples 16c and 16e, the lake regained much of the dissolved-solids tonnage lost during desiccation.

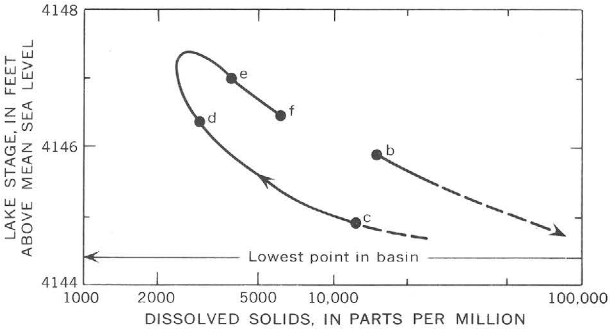

FIGURE 20.—Cycle of dissolved-solids concentration and lake stage, in part hypothesized, for Summer Lake between June 1961 (point b) and June 1962 (point f). Lettered points correspond to samples from site 16 (table 28).

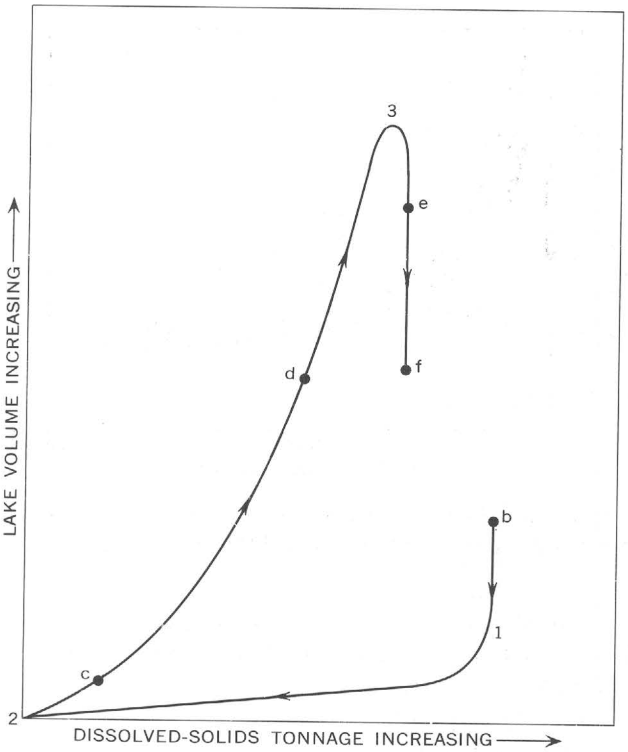

FIGURE 21.—Hypothetical relation between lake volume and dissolved-solids tonnage for Summer Lake between June 1961 (point b) and June 1962 (point f). Lettered points correspond to samples from site 16 (table 28).

The theoretical relation between lake volume and dissolved-solids tonnage during the period April 1961 to June 1962 is shown schematically in figure 21. The lake volume decreased with no major loss of salts until it reached hypothetical volume 1. Continued volume decrease below that level was accompanied by solute depletion until, at point 2, the lake basin became dry or nearly so, and depletion was virtually complete. When the basin subsequently began to fill, the depleted salts were slowly regained until, at point 3, the tonnage approached

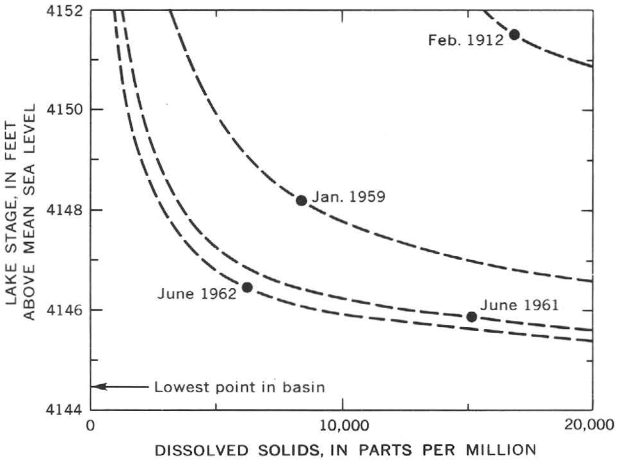

FIGURE 22.—Relations between dissolved-solids concentration and stage of Summer Lake in 1912, 1959, and parts of 1961–62.

the predesiccation quantity. (The relations depicted for Summer Lake in figures 20 and 21 resemble in some ways the general relations suggested by Langbein (1961, p. 10) in figure 9 of his report, parts *B* and *C*.)

Physical, rather than chemical, reasons probably explain the slow recovery of depleted solutes. Wind action at low lake stages prior to desiccation may have blown the relatively small residual brine over large areas of the flat surrounding playa, isolating parts of it at altitudes as much as several feet above the normal lake level for that volume. Thus, the isolated salts would not be recovered until the lake had again reached the higher levels. Actually, the recovery of solutes entrapped as interstitial brines, even in the lowest central areas of the playa, is probably a slow process because of the low permeability of the fine-grained host sediments.

Figure 22 shows that a spectacular net solute loss occurred in the Summer Lake basin between 1912 and 1962. Van Winkle's February 1912 analysis (1914, p. 120) indicated a dissolved-solids concentration of 16,800 ppm at an estimated lake level of 4,151.5 (±1.0 ft),[2] whereas the estimated 1961–62 dissolved-solids concentration at the same lake stage would have been only 1,000–1,500 ppm. The difference represents a 93-percent net solute depletion in the 50-year period (fig. 22).

Most of the solute loss doubtless occurred during periods of basin dryness or near dryness after 1926. Prior to impoundment and extensive use of water from Ana Springs for irrigation in the 1920's, Summer Lake probably contained water at almost all times, owing to an abundant and consistent inflow. However, after construction of the Ana River dam in 1926, depletion of the potential water supply due to impoundment and irrigation, coupled with a period of drought, resulted in a shrinking lake volume. Complete or nearly complete desiccation occurred during many of the summers from 1929 to 1951. Although the entrapment of solutes within the playa muds at levels not attained by the lake since the early 1900's accounts for much of the observed depletion, eolian transport of powdery evaporite salts during these periods of basin dryness or near dryness probably has been a significant means of solute removal from the Summer Lake playa. Wind action is violent within the basin at many times throughout each year. During the summer months, when the lakebed is dry or almost dry, billowing white clouds of alkali dust rise above the playa (fig. 23) and are carried to remote parts of the basin, or even outside the basin.

Wind transport of solutes is not restricted to periods of dryness or near dryness, however. Even at times of moderate lake stage, gusts blow water out over the flat surrounding playa, especially to the east, where some of the water and its dissolved solids are stranded and lost from the main body. Subsequent evaporation of this stranded water leaves a powdery efflorescent deposit that is readily eroded from the playa and blown away. Nonetheless, removal of salts by wind probably has been more commonplace since 1926 than during any other period within the last several thousand years.

CHANGES IN CHEMICAL CHARACTER

The relative amounts of most constituents, expressed as percentage of the total dissolved-solids content, apparently remained almost unchanged during the 2-year period of intensive study, despite the large fluctuations in the amount of dissolved solids. However, silica and orthophosphate exhibited significant seasonal fluctuations in

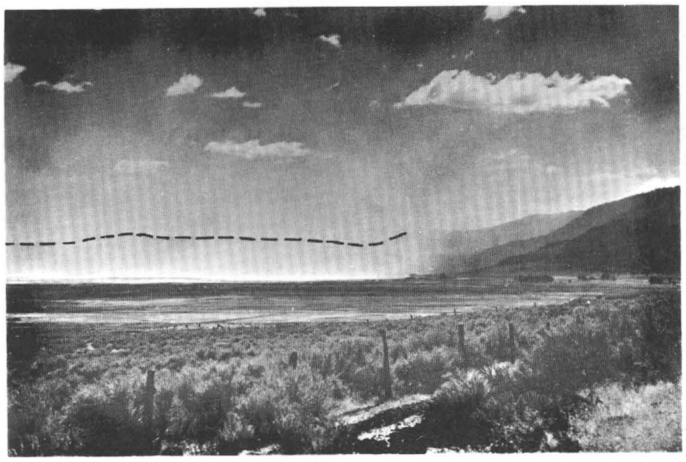

FIGURE 23.—Southward view toward dry Summer Lake playa, September 8, 1961. Clouds of wind-transported alkali dust are shown rising from the playa surface and being carried southwestward. Dashed line marks crest of 3,000- to 3,700-ft ridge obscured by dust clouds.

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[2] Measured lake level on Nov. 10, 1912, was at an altitude of 4,151.3 ft. Level in Feb. 1912—prior to most spring snowmelt inflow or summer evaporation—is assumed to have been within about 1 ft of the November value.

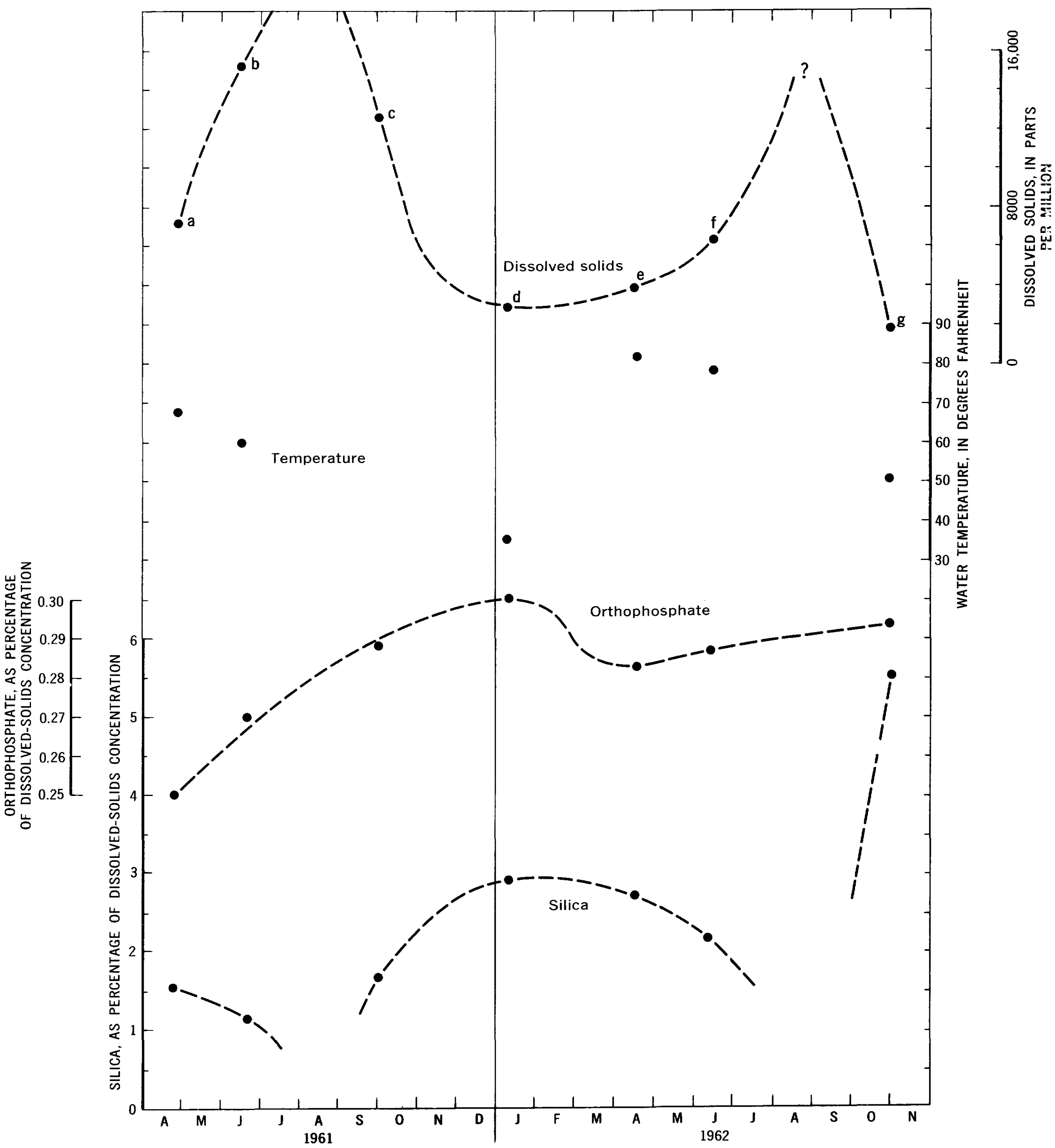

FIGURE 24.—Variations in dissolved-solids concentration, temperature, and relative amounts of silica and orthophosphate in Summer Lake, April 1961–October 1962. Lettered points correspond to samples from site 16 (table 28).

relative concentration (fig. 24). As in Goose and Abert Lakes, the relative amount of silica in Summer Lake varies more than that of orthophosphate. On the basis of seven samples collected between April 1961 and October 1962, the extremes, expressed as percentages of the dissolved-solids content, are 1.14 and 5.53 percent for silica, but only 0.25 and 0.30 percent for orthophosphate (absolute extremes ranged from 86 to 207 ppm and from 5.2 to 41 ppm, respectively). During the brief study, maximum relative concentrations of both constituents occurred in January, whereas minimum amount of silica occurred about July, and that of orthophosphate, about March.

The amount of silica in Summer Lake tends to vary inversely with the dissolved-solids content (fig. 24), whereas orthophosphate shows little if any relation to dissolved solids. Seasonal fluctuations of silica and orthophosphate are discussed in more detail on pages B48 and B51.

The concentrations of several other minor constituents may also have varied slightly relative to total dissolved-solids content during the 2-year period of study, but the data available and the analytical methods used did not define such fluctuations.

Changes in the amount of carbonate relative to bicarbonate apparently accompany changing concentration of dissolved solids in Summer Lake, even though the total amount of carbonate plus bicarbonate (expressed as carbonate) remains at about 30 percent of the total dissolved solids. This characteristic was also observed in other lakes, and the probable causes are discussed on page B46.

A long-term net increase in the amounts of sulfate and chloride relative to those of carbonate and bicarbonate occurred during the 49-year period 1912–61. (See table 12.) The amount of sulfate plus chloride increased from 22 to 27 percent of the total dissolved-solids content, whereas the percentage of carbonate plus bicarbonate decreased by a like amount during the same period. The percentages of sulfate and chloride each increased by about one-fifth of their 1912 values.

The relative enrichment of sulfate and chloride is attributed, at least in part, to the wind removal of efflorescent salts from the lake playa. During final stages of desiccation, winds probably blew the saline water out over the surrounding playa, and spread it in thin sheets that facilitated rapid evaporation. Some brine was undoubtedly trapped on the playa at altitudes as much as several feet higher than the lowest point in the basin. These isolated parts of the brine would tend to evaporate, leaving an efflorescent deposit of salts underlain by moist playa sediment. The thin layer of salts may have contained a large percentage of powdery, less hygroscopic sodium carbonate bicarbonate minerals, whereas much of the residual sulfate and chloride (plus accompanying sodium) would form the crustier parts of the surface deposit, or would remain near surface within the moist sediment. Wind action could then remove the powdery efflorescenses rich in sodium, carbonate, and bicarbonate, leaving the surface and near-surface of the playa slightly enriched in sulfate and chloride relative to carbonate and bicarbonate. Thus, when the lake basin filled again, and the remaining solutes were redissolved, the resulting lake water would become slightly enriched in sulfate and chloride.

TABLE 12.—*Changes in the relative amounts of six major constituents in Summer Lake between 1912 and 1961*

Constituent	Percentage of total dissolved-solids content	
	February 1912 [1]	April 25, 1961
Sodium (Na)	39.2	39.3
Potassium (K)	1.6	1.6
Carbonate (CO_3) plus bicarbonate (HCO_3) [2]	35.2	30.0
Sulfate (SO_4)	4.1	4.8
Chloride (Cl)	18.1	22.1
Dissolved-solids content, in parts per million	[3] 16,800	7,200

[1] Data after Van Winkle (1914, p. 120, analysis 7).

[2] Calculated as carbonate.

[3] Corrected for estimated concentrations of fluoride, bromide, orthophosphate, and boron; bicarbonate recalculated as carbonate.

The depletion of silica in Summer Lake is almost as pronounced as that in neighboring Lake Abert. Silica comprises 23 percent of the dissolved-solids content in the Ana River, whereas it makes up only about 2.5 percent (measured range, 1.5 to 5.5 percent) of the dissolved-salt tonnage in Summer Lake. Silica in the several lakes is discussed in more detail on page B47.

SOURCES OF DISSOLVED SOLIDS

Most of the salts dissolved in Summer Lake have, at least during postpluvial time, come from the Ana Springs via the Ana River (analyses 20a–20f, table 28). Because of the relatively consistent discharge from these springs, a large amount of dissolved material presumably has been added to the lake during the last few thousand years. More than half of the 160 ppm increment consists of the major dissolved constituents of Summer Lake—sodium plus equivalent chloride and bicarbonate.

The amount of incoming calcium and magnesium that is available for removal from solution by organic and inorganic processes is somewhat less in Summer Lake than in Lake Abert because most of the flow into Summer Lake contains only small concentrations of these two constituents. In the Ana River, for example, calcium plus magnesium make up only about 5 percent of the total load, in contrast to about 14 percent for the Chewaucan River.

Other, lesser sources of dissolved solids include small springs north, west, and south of the lake, streams draining the relatively small area west and south of the lake, and occasional thundershower runoff from the east. The quantity and character of solutes derived from these sources have not been evaluated.

GOOSE LAKE

Goose Lake is situated immediately west of the Basin and Range physiographic province, in Modoc County, Calif., and Lake County, Oreg. (fig. 1). Its rarely occurring overflow is tributary to the North Fork Pit River in the Sacramento River basin. Although most of the lake itself lies in California, most of its valley and almost two-thirds of the total drainage basin are in Oregon. Among lakes in semiarid zones, Goose Lake is noteworthy in that it currently occupies an unusually large part, 13 percent, of its total drainage basin.

The lake lies in a semiarid plain, almost completely surrounded by mountains and wooded ridges. Immediately to the east, the Warner Mountains in California and their northern extension include peaks in each State that rise to altitudes of more than 8,000 feet within 5 or 6 miles of the 4,700-foot lake. To the north, a rather broad plain rises gradually through rolling slopes that are referred to locally as the Fremont Mountains (pl. 1), which reach an altitude of about 7,000 feet. Similar but slightly lower wooded ridges lie within 10 miles of the west shore. At the south end of Goose Lake, a low gravelly terrace or old lake beach separates the lake from a marshy meadow in an old river channel that winds southward to the headwaters of the North Fork Pit River.

AREA, VOLUME, AND LAKE-LEVEL FLUCTUATIONS

At overflow stage (alt 4,716 ft), Goose Lake covers 194 square miles; it has a maximum depth of 24 feet, a length of 28 miles, and a maximum width of 10 miles. Surveys of the bed and outlet of Goose Lake were made in 1959 by the California Department of Water Resources. The results are shown in figure 25, and the area and volume are given in table 13. Goose Lake has varied greatly in area and volume within historic time, as shown by the data in table 22 and by the pattern of fluctuations since 1958 (fig. 26). Similar variations have undoubtedly occurred for thousands of years. Even before any water was stored or diverted for irrigation, the historical records attest to conditions ranging from near desiccation to overflow. For example, on a visit in 1882, Russell (1884, p. 456) found the lake to be 15 feet deep over a former road crossing 4 or 5 miles from the south end. That road was undoubtedly at the site of the present causeway

TABLE 13.—*Area and volume of Goose Lake*

[Area and volume data are rounded to three significant figures]

Altitude (ft)	Area (acres)			Volume (acre-ft)
	Oregon	California	Total	
4,692.0	0	0	0	0
4,692.5	210	6,180	6,390	1,060
4,693.0	3,290	12,500	15,800	6,620
4,693.5	5,620	19,200	24,800	16,800
4,694.0	8,960	29,400	38,400	32,600
4,694.5	12,800	34,200	47,000	54,000
4,695.0	17,100	38,000	55,100	79,500
4,696.0	21,300	46,100	67,400	141,000
4,697.0	25,500	52,700	78,200	214,000
4,698.0	27,400	56,100	83,500	294,000
4,699.0	28,400	59,000	87,400	380,000
4,700.0	29,900	62,000	91,900	470,000
4,704[1]	33,900	73,700	108,000	862,000
4,716	43,600	80,600	124,000	2,250,000

[1] Lake at an altitude of 4,704 feet during survey made by the California Department of Water Resources in 1959.

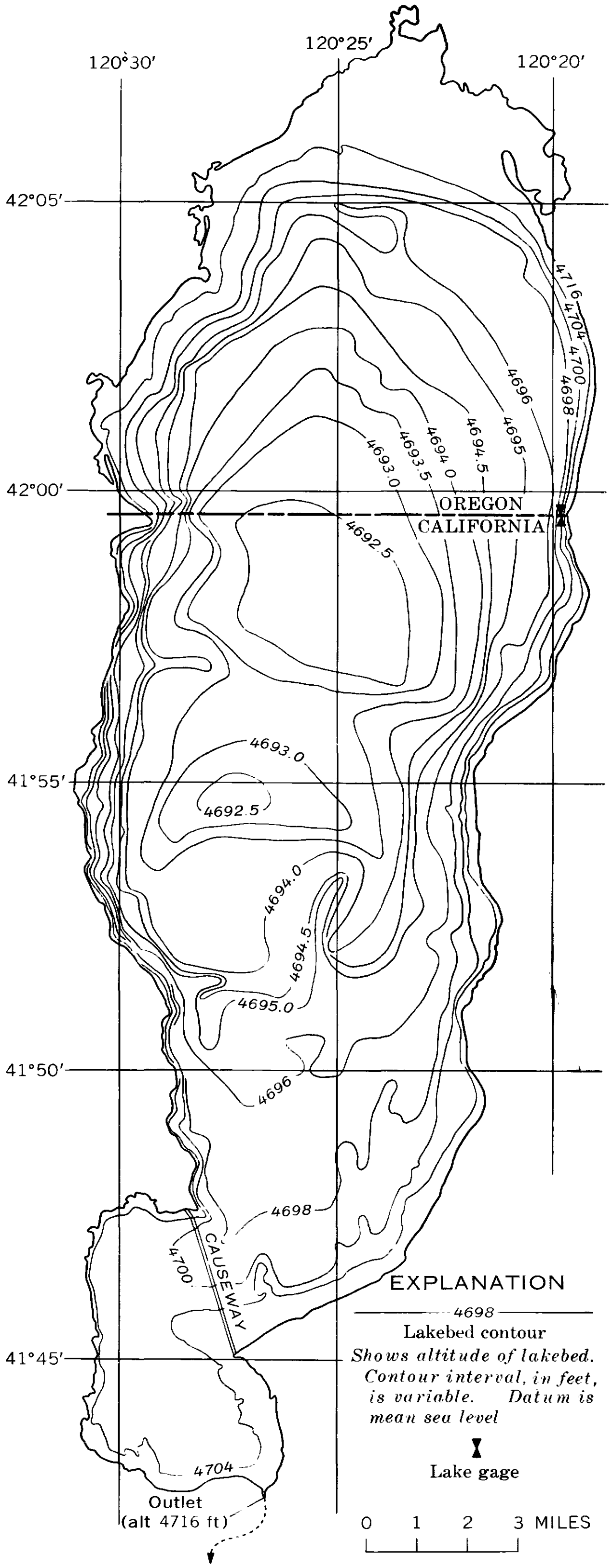

FIGURE 25.—Lakebed contours of Goose Lake. Map furnished by California Department of Water Resources.

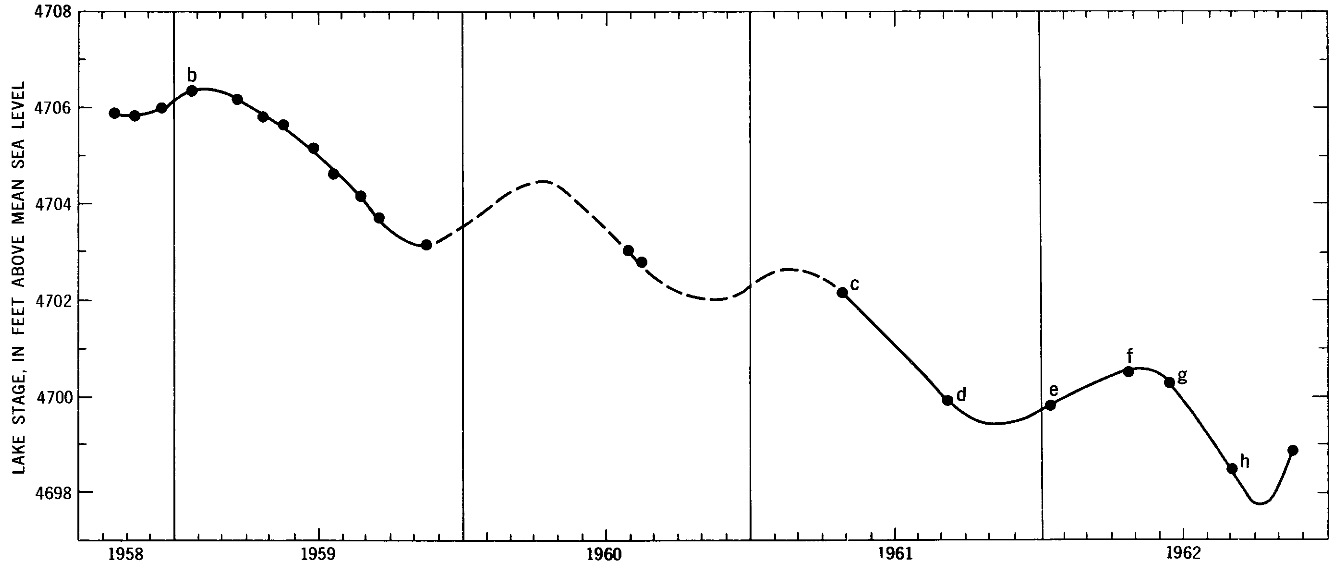

FIGURE 26.—Seasonal variations in the stage of Goose Lake, October 1958 to November 1962. Dashed where approximated. Lettered points correspond to samples from site 21 (table 28).

across the lake, where the lowest lakebed altitude was about 4,699.5 feet. Russell recognized that the high level he observed was not permanent, and predicted—though the lake had no historical record of dryness—that in a series of arid seasons the lake would "unquestionably evaporate completely * * *." It did indeed become dry in 1926 and was virtually dry in the late summer of each year during the period 1929–34. The desiccation in 1926 exposed ruts of another pioneer road that crossed the lake at an altitude of about 4,694 feet several miles farther north of the present causeway.

Some early records of lake level (table 22) are based on descriptive narratives and diaries of travelers that give estimates of the size of the lake or of its stage in reference to the outlet level. (See Harding, 1965, p. 24, 26, 27, 32.) Accuracy of these descriptions depends on the ability of the observers to estimate those factors.

WATER SUPPLY

Goose Lake derives its water supply from lake-surface precipitation, stream inflow, and small peripheral springs.

LAKE-SURFACE PRECIPITATION AND SPRINGS

Rain and snow at Lakeview, about 12 miles north of midlake, averaged 14.1 inches per year during the nearly complete period of record 1885–1963. Records of precipitation at Davis Creek, Calif., and at a site west of Goose Lake, obtained during the period 1959–61 by California State Department of Water Resources, correspond closely to records at Lakeview; hence, the average annual precipitation on Goose Lake is assumed to be about 14 inches.

No large springs emerge from the bed of Goose Lake, but several small springs are said to maintain soggy areas (Harding, 1965, p. 27, 47). Many small seeps and springs line the east shore of the lake; some of them are thermal, and others are fed by percolating irrigation water. Their total flow is a very small part of the water budget for the lake.

STREAMS

The largest streams in the Goose Lake basin are Drews, Cottonwood, and Thomas Creeks, all in Oregon. Their summer flows are now diverted for irrigation, and in some years very little of their flows reach Goose Lake. The annual flow of these streams is extremely variable. For example, on Drews Creek, during the discontinuous-record period of 32 water years, the flow ranged from about 5,000 acre-feet in 1931 to 163,000 acre-feet in 1956.

The available records for Drews, Cottonwood, and Thomas Creeks, summarized below, have been obtained

Average annual flow at gaging stations on streams tributary to Goose Lake

Stream	Drainage area (sq mi)	Altitude of gage (ft)	Total record		Concurrent record, water years 1913–17, 1928–30 (acre-ft)
			Period (water yr)	Acre-feet	
Drews Creek [1]	212	4,835	1913–30, 1938, 1940–41, 1947, 1954–63.	49,400	47,600
Cottonwood Creek [2]	32.9	5,007	1910–19, 1925–35, 1939–42, 1947–63.	15,300	16,400
Thomas Creek	30	4,800	1913–17, 1928–31	9,480	10,400
Total (rounded)	275	--------	----------------	74,200	74,400

[1] Adjusted for diversion by North Drews Canal and change in contents of Drews Reservoir.

[2] Not adjusted for change in volume of Cottonwood Reservoir (ordinarily empty on Sept. 30).

near the points where those streams leave the wooded hills and enter the alluvial plain; hence, the data are not an index of flow into Goose Lake, except that in very wet years much of the observed streamflow does reach the lake because it exceeds the needs for storage and irrigation. The runoff per square mile from the lower, drier plain is believed to be less, and that from the Warner Mountains greater, than the quantities measured at these stations.

The average annual discharge of all streams tributary to Goose Lake is estimated as 250,000 acre-feet, unadjusted for the effects of irrigation.

Irrigation began in a small way when the valley was first settled in the 1870's. Water has been stored since 1911 in Drews Reservoir (capacity 62,500 acre-ft) and since 1921 in Cottonwood Reservoir (capacity 4,160 acre-ft, until enlarged, in 1962, to capacity of 7,540 acre-ft), upstream from the two gaging stations. Harding (1965, p. 39) estimated the acreage irrigated and the resulting average annual streamflow depletion (including loss by evaporation from surface-storage reservoirs) as follows:

Estimated effect of irrigation on inflow to Goose Lake during years of adequate streamflow

Period	Average area irrigated (acres)	Average net annual streamflow depletion (acre-ft)
1882–89	5,000	10,000
1890–1904	10,000	20,000
1905–11	15,000	30,000
1912–19	20,000	45,000
1920–25	25,000	62,500
1926–35	30,000	68,500
1936–60	35,000	85,000

Thus, for the period since 1935, assuming that the average total streamflow has been 250,000 acre-feet per year, annual inflow to the lake has averaged about 85,000 acre-feet less, or about 165,000 acre feet.

WATER LOSS

EVAPORATION AND LEAKAGE

The average annual evaporation loss from Goose Lake is believed to be about 42 inches. That estimate is based on observed seasonal fluctuations of the lake level in dry years (fig. 26), and on studies of evaporation at Eagle Lake in California and at Klamath and Abert Lakes in Oregon.

Goose Lake was at one time suspected of leaking into the headwaters of the North Fork Pit River (Van Winkle, 1914, p. 38). When the lake was being reduced to dryness in the 1920's and was refilling in the 1930's, no evidence of any such leakage was noted, and no known variations in the base flow of streams in the Pit River basin can be correlated with changes in the level of Goose Lake. In dry seasons, the rate of fall of the lake level is no more than would be expected from evaporation alone. There is good reason to believe, then, that the lakebed is watertight, and that all inflow is dissipated by evaporation, except for small volumes of overflow at rare intervals.

OVERFLOW

Loss by overflow within the last 100–150 years has been rare and small. Goose Lake overflowed in 1868, after two or more very wet years. The quantity of water lost is not known, but it probably was only a small part of the stream discharge reaching the lake in that year. The lake overflowed again in 1881 for about 2 hours because of the temporary effect of a strong wind from the north. The volume of overflow in that year was insignificant. Other reports of overflow in 1862, 1869, 1871, 1875, 1898, and 1910 cannot be verified and are thought to be erroneous (Harding, 1965, p. 31–33); the events of 1868 and 1881 are believed to be the only instances of overflow since 1832.

Earlier overflow probably was more frequent and of greater volume than that in the last hundred years. Terraces or strand lines many miles long have been formed by the action of waves and ice at altitudes ranging from 4,716 to 4,720 feet. (The railroad grade along the east shore is built on such a terrace at the State line.) Strand lines of such magnitude are evidence that the lake attained overflow level for an extended period. Likewise, the relatively low concentration of dissolved salts in Goose Lake, as compared with those in waters of true closed lakes, also suggests that part of the inflow has in the past been dissipated by outflow, rather than by evaporation.

The probability of overflow in the future has been greatly reduced by the consumptive use of about 85,000 acre-feet of water per year from tributary streams. In the past, the lake has approached overflow only when two or three very wet years occurred in succession after the lake had previously attained at least a moderate level. In 1958, when other closed lakes reached or approached record high levels, about 1 million additional acre-feet (six times the average annual inflow) would have been required to cause overflow. Under present-day climatic and agricultural conditions, then, Goose Lake can be considered a true closed lake, rather than one that occasionally overflows.

WATER BUDGET FOR THE LAKE

Goose Lake receives an average annual precipitation of about 14 inches, but it loses about 42 inches annually by evaporation. Its tributary springs and streams provide an average annual discharge of about 250,000 acre-feet, of which about 165,000 acre-feet is inflow to the lake.

For the present degree of streamflow depletion by irrigation, the average calculated lake level is at an altitude of about 4,697 feet (lake volume, 214,000 acre-ft), a stage at which the lake area provides an average net evaporation loss of about 165,000 acre-feet per year, which offsets the average net inflow. Similar climatic conditions prior to any depletion for irrigation would have provided runoff to maintain the lake at a calculated average level at an altitude of about 4,705 feet (lake volume, 950,000 acre-ft).

GEOCHEMISTRY

GENERAL CHEMICAL CHARACTER OF THE LAKE

Goose Lake is chemically similar to Abert and Summer Lakes, but is characteristically much more dilute. The principal dissolved constituents in Goose Lake are sodium, carbonate plus bicarbonate, and chloride (table 3; fig. 2). Silica, potassium, and sulfate are less abundant, but collectively they are about 14 percent of the total dissolved-solids content. Orthophosphate and boron occur in significant concentrations. Only small amounts of calcium and magnesium are present in the lake: their combined concentration usually makes up only 1 or 2 percent of the dissolved-solids content. The calcium to magnesium ratio ranges from 3:1 to 4:1.

Positively identified trace elements present in a lake sample collected June 12, 1962, include vanadium, aluminum, molybdenum, iron, and nickel, in that order of abundance (table 29). (See remarks regarding the reliability of trace-element data, p. B56.)

VARIATIONS IN DISSOLVED-SOLIDS CONCENTRATION

The measured or estimated dissolved-solids concentration in 16 samples collected from Goose Lake during the period 1953–62 has ranged from about 600 to about 2,800 ppm. A plot of dissolved-solids concentration versus lake stage (fig. 27) indicates a reasonably consistent relation. The moderate scatter of points is due to small amounts of dilute inflow near sampling sites and to other slight chemical heterogeneities throughout the lake. For example, samples collected by Harding on July 9, 1958, at three different lakeshore sites contained 600 to 740 ppm of dissolved solids (analyses 21a, 22e, and 23d, table 28), whereas the estimated average solute content at that lake level was 650–700 ppm.

Figure 27 shows that the rate of change of concentration with changing lake stage is slow above altitudes of about 4,702 feet, and rapid at altitudes below that level, as the lake volume diminishes. Because Goose Lake is nearly homogeneous except during periods of appreciable inflow, seasonal fluctuations in the dissolved-solids concentration at most sites are related to changes in lake volume.

An average value of about 1 million tons for the solute load in Goose Lake during the period 1953–62 is indicated by the relations between lake stage, volume, and dissolved-solids concentration (tables 13, 28). A long-term decrease in dissolved-solids tonnage is indicated by comparing the relation between lake stage and solute concentration for recent samples with that calculated for a 1912 sample analyzed by Van Winkle (1914, p. 39). Figure 27 shows that 1,010 ppm of dissolved solids, which corresponded to an estimated lake stage at an altitude of about 4,714 feet in 1912, would also have occurred at a stage at an altitude of about 4,702 feet during the period 1953–62. If the 1912 sample is assumed to represent the average lakewide dissolved-solids concentration at that time,[3] it indicates a tonnage of about 3 million tons—three times the calculated tonnage for 1953–62.

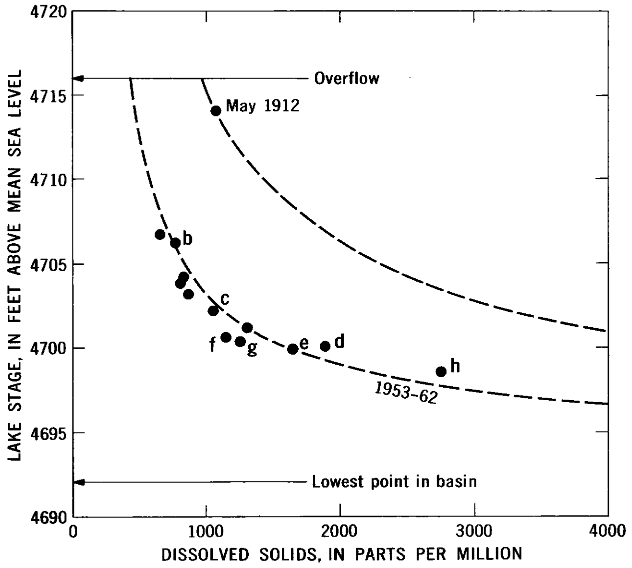

FIGURE 27.—Relation between dissolved-solids concentration and stage of Goose Lake, 1912 and 1953–62. Lettered points correspond to samples from site 21 (table 28).

The spectacular loss of dissolvable solids can probably be attributed in part to removal of salts from the lakebed by winds during periods when the basin dried completely or almost completely in the summers of 1926 and 1929–34. This theory is supported by newspaper accounts of alkali duststorms on August 26, 1926, and July 16, 1931 (S. T. Harding, written commun., 1962). Additional unrecorded periods of less spectacular wind undoubtedly occurred during the seven dry years. A large amount of windblown salts, if not actually removed from the basin, has at least been isolated from rapid return to the lake as part of surface runoff. Entrapment of salts within the broad mudflats surrounding the lake undoubtedly also accounts for some of the depletion. Recovery of the lost salts in Goose Lake will be a slow and incomplete process, as indicated by the lack of any noticeable increase in solute tonnage during the period 1953–62.

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[3] The dissolved-solids concentration and the lake stage in 1912 compare favorably with similar values—about 1,100 ppm at an altitude of about 4,715 ft—reported for a sample collected in August 1904 (Harding, 1965, p. 50). Even though the accuracy of certain individual determinations in the 1904 analysis is questionable, the reported value for total dissolved-solids concentration probably is of sufficient accuracy to verify the relation in 1912.

CHANGES IN CHEMICAL CHARACTER

The relative (percentage) amounts of most dissolved constituents in Goose Lake have not changed significantly since 1953. Only the ratio of carbonate to bicarbonate and the relative quantities of silica, calcium plus magnesium, and orthophosphate have fluctuated with any certainty during the 10-year period. The relation of carbonate to bicarbonate is discussed on page B45.

The abundance of calcium and, perhaps to a lesser extent, magnesium is controlled largely by the solubility of alkaline-earth carbonate minerals. The relative quantities also may be influenced by the actions of calcium-utilizing biota, and by reactions that may occur between the alkaline-earth ions—especially magnesium—and certain clay minerals present on the lake bottom. The several processes are discussed in more detail on pages B49–B50.

Amounts of the biologic nutrients silica and orthophosphate vary appreciably relative to the dissolved-solids content in Goose Lake. (See fig. 28.) Silica varies the most. For six samples collected between April 1961 and September 1962, the absolute concentration varied from 50 to 80 ppm, while the relative amount, expressed as a percentage of the dissolved-solids content, ranged from 2.9 to 5.6 percent. This is equivalent to a range in silica content of 29,000 to 56,000 tons. (See footnote 1, p. B18.) Variations in orthophosphate content are less pronounced. Relative amounts in five samples ranged from 0.44 to 0.54 percent of the dissolved-salt content (absolute range, from 5.3 to 12 ppm). On the basis of only 16 months of record, the largest relative amounts of both constituents characteristically seem to occur during the spring, and the smallest amounts occur sometime between August and November.

Figure 28 shows that the relative amounts of silica and orthophosphate in Goose Lake tend to vary inversely with dissolved-solids concentration but seem unrelated to water temperature. A more thorough discussion of silica and orthophosphate is presented on pages B48 and B51, respectively.

A significant net change in the distribution of major anions occurred in Goose Lake during the period 1912–62. (See table 14.) The amount of sulfate plus chloride increased from 15 percent to 20 percent of the sum of the six most abundant constituents (sodium, potassium, carbonate, bicarbonate, sulfate, and chloride), whereas the relative amount of carbonate plus bicarbonate (calculated as carbonate) decreased by a similar percentage; sodium plus potassium remained at about 41 percent during the 50-year period.

As at Summer Lake, the change may have occurred during periods of desiccation (in 1926 and 1929–34 at Goose Lake), owing largely to eolian removal of efflorescent salts from the lake playa (p. B28).

TABLE 14.—*Changes in the relative amounts of six major constituents in Goose Lake between 1912 and 1962*

Constituent	Percentage of the six-constituent parts-per-million sum	
	May 12, 1912 [1]	June 12, 1962
Sodium (Na)	37.2	38.0
Potassium (K)	3.6	3.0
Carbonate (CO_3) plus bicarbonate (HCO_3) [2]	43.8	39.0
Sulfate (SO_4)	4.8	7.0
Chloride (Cl)	10.6	12.9
Dissolved-solids content, in parts per million	1,060	1,270

[1] Data after Van Winkle (1914, p. 39).
[2] Calculated as carbonate.

It may at first seem anomalous that the relative amounts of sulfate and chloride together have increased by almost one-third in just 50 years, especially when they amounted to only about 15 percent of the major-constituent sum at the start of the 50-year period (table 14). The principal reason may be as follows: The lake probably dried only rarely during the last few thousand years, but in this century storage and diversion of runoff for irrigation have reduced inflow almost 35 percent. Thus, the extensive diversion of runoff, together with several years of abnormally low precipitation, caused the unusual periods of desiccation and accompanying removal of salts during 1926 and 1929–34.

Increased use of ground water during the last 50 years might be suspected as a secondary cause of the marked increases in sulfate and chloride. However, the available chemical analyses (tables 30, 31) indicate that most ground water in the basin is not a source of significant amounts of sulfate and chloride relative to bicarbonate (even assuming the elimination of some bicarbonate due to precipitation of alkaline-earth carbonate minerals). Exceptions include certain hot-spring and well waters located within, and adjacent to, fault zones along the eastern limits of the valley. Although this ground water contains large relative concentrations of sulfate and chloride (for example, analyses 109 and 110, table 30), the aggregate discharge probably is too small for the solute contribution to have a significant short-term (50-year) effect on the chemical character of Goose Lake.

SOURCES OF DISSOLVED SOLIDS

Surface inflow probably has been the largest long-term source of the dissolved solids in Goose Lake. Unfortunately, little information on the chemical character of this inflow is available (table 28). Presumably, though, most of the streamflow reaching Goose Lake chemically resembles the flow of the Chewaucan River in the adjacent Lake Abert basin (p. B20). Streams such as Thomas

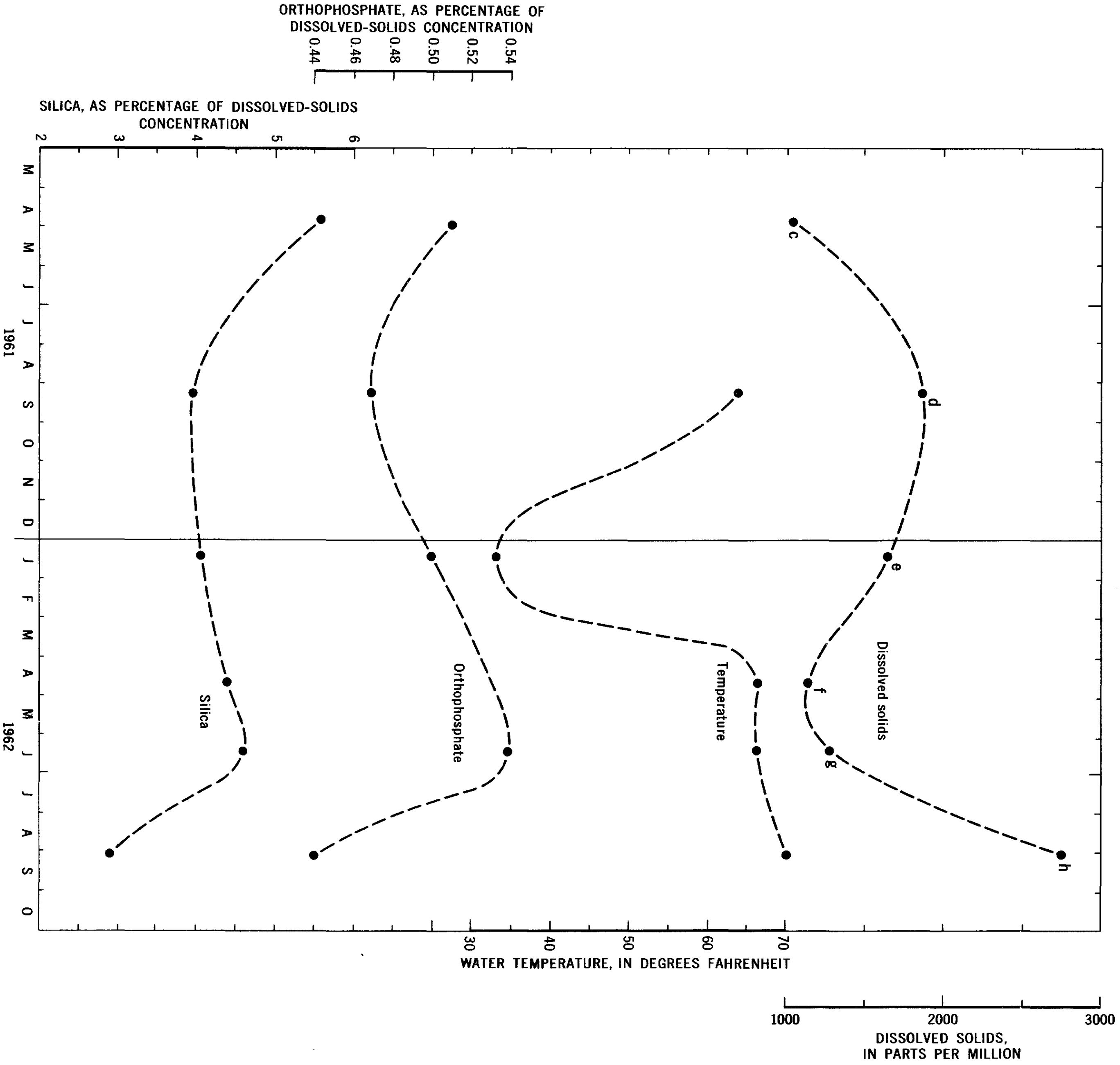

FIGURE 28.—Changes in dissolved-solids concentration, water temperature, and relative amounts of silica and orthophosphate in Goose Lake, April 1961–September 1962. Lettered points correspond to samples from site 21 (table 28).

Creek, which pass through, and are used in, sizable irrigated areas, probably contribute water to Goose Lake that is not much more dilute than the Chewaucan River inflow to Lake Abert. Other streams, which are not influenced as much by irrigation, probably contribute a characteristically more dilute inflow.

Much ground water in the basin contains considerably greater concentrations of dissolved solids than those assumed to be present in the streams (tables 30, 31).[4] Ground water may have contributed somewhat larger than usual amounts of dissolved solids to the lake during the last 50 years, owing to accelerated use for irrigation, but the long-term contribution, as spring flow, probably

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[4] Additional analyses for the Goose Lake basin in California have been published by the California Department of Water Resources (1965, p. 157, and subsequent annual reports in the same series; also, 1966, table 44).

is a relatively minor part of total dissolved-solids influx to the lake.

RECONNAISSANCE OF SEVERAL OTHER CLOSED-BASIN LAKES

Hydrologic and chemical data of varying quantity are available for several other lakes in south-central Oregon: Silver Lake in the Fort Rock basin north of Summer Lake; Malheur and Harney Lakes in the Harney Basin near Burns; and Crump, Hart, and Bluejoint Lakes in the Warner basin east of Lake Abert (pl. 1; fig. 1).

Hydrologic data for the lakes are summarized in table 1. Additional pertinent information is presented in this section.

AREA, VOLUME, AND LAKE-LEVEL FLUCTUATIONS

The approximate area and volume of Silver Lake at three altitudes are estimated below (the lake dries between altitudes of 4,299 and 4,300 ft). At an altitude of about 4,310.4 feet (area about 11,000 acres, volume about 75,000 acre-ft), the lake overflows into adjacent Thorn Lake. Records of lake level for Silver Lake are listed in table 23. The highest level observed, noted from a high-water mark made in the spring of 1904, was at an altitude of 4,311.8 feet. The highest level in recent years was at an altitude of 4,309.05 feet on June 26, 1958; after that date, the water level fell steadily until the last pools disappeared about August 11, 1961 (A. B. Claggett, Oregon State Game Comm., oral commun., 1961).

Altitude (ft)	Area (acres)	Volume (acre-ft)
4,303	6,000	10,000
4,306	8,500	32,000
4,309	10,000	60,000

Silver Lake is the remnant of a Pleistocene lake that at one time covered more than 500 square miles, including not only the present lake, but also Paulina Marsh, Thorn Lake, Fossil Lake, Christmas Lake, and Fort Rock Valley. Well-developed lake terraces were formed at several levels north of the town of Silver Lake, and waterworn notches in the lava cliffs on Fort Rock are attributed to wave action (Hubbs and Miller, 1948, p. 73). According to Allison (1940, p. 300), the lake at one time overflowed to Deschutes River, in the Columbia River basin, until the outlet was buried by more than 100 feet of lava. Allison (written commun., 1963) proposed "Fort Rock Lake" as the name of this pluvial body of water, and found the highest beach line to be at an altitude of about 4,520 feet (220 ft above the bed of Silver Lake).

Malheur and Harney Lakes occupy shallow depressions in the central plain of Harney Basin (fig. 1) and are separated by a smaller body of water known as Mud Lake. When Malheur Lake rises above an altitude of about 4,091.5 feet (maximum depth, about 2.5 ft), water begins to flow through a winding, reed-grown channel (The Narrows) westward into Mud Lake. At a somewhat higher stage, Mud Lake overflows westward through a gap in a bar locally known as the Sand Reef into Harney Lake. The bar was apparently formed by wind, waves, and ice on Harney Lake during periods of no inflow; its altitude at the inlet varies. In 1881, for instance, the Sand Reef was observed to be a temporary dam about 10 or 12 feet high, according to testimony before the U.S. Supreme Court (1932, p. 841), but in April 1942, John C. Scharff of the U.S. Fish and Wildlife Service (written commun., 1942) observed it to be 1 foot (or less) high and to be lower than the level of overflow from Mud Lake. The approximate areas and volumes of the lakes at various levels were listed by Piper, Robinson, and Park (1939, p. 20).

Malheur Lake has ranged from near dryness to a maximum observed level of 4,095.39 feet on June 9, 1952. The lake was nearly dry in 1889, 1926, 1931–35, and 1960–62; in 1934 the lakebed was planted to grain.

Harney Lake is the final evaporating sump for the basin. At times, its lakebed has been practically dry for long periods, including 1929–34, 1962, and probably other years for which no observations were reported. The highest water level of record is an altitude of 4,087.60 feet on June 16, 1943, but higher stages probably occurred in the 1950's.

Historical references abstracted from records of the U.S. Supreme Court (1932) provide a general indication of lake-level fluctuations in the Harney Basin prior to 1900; the references are summarized in table 24. Records of stage for Malheur and Harney Lakes during 1903–31 were listed by Piper, Robinson, and Park (1939, p. 129–131). In their tabulation, reported low levels at The Narrows gage do not, as implied, represent the stage of Malheur Lake, because the hydrologic connection between the lake and gage is doubtful below an altitude of about 4,092 feet, and is nonexistent below about 4,091.5 feet. At the gage near Voltage, in the channel of the Donner und Blitzen River, stages are at times somewhat higher than the level of Malheur Lake because of the effect of streamflow or wind. In addition, comparison of data at the two gages during periods of falling lake stage indicated that readings at the Voltage gage are consistently about half a foot higher than those at The Narrows, suggesting a difference in datum.

Records of stage subsequent to those reported by Piper, Robinson, and Park (1939) for Malheur and Harney Lakes are listed in tables 25 and 26, respectively.

During Pleistocene time, a large but shallow water body (maximum area, about 900 sq mi; maximum depth, 35 ft) covered present-day Malheur and Harney Lakes and overflowed occasionally into the Snake River basin via the Malheur River (information largely from Snyder and others, 1964).

The floor of Warner basin is virtually a chain of marshes, shallow intermittent lakes, and drained meadows. In downstream order, they are Pelican, Crump, Hart, Anderson, Swamp, Mugwump, Flagstaff, Campbell, Lower Campbell, Stone Corral, and Bluejoint Lakes. They vary greatly in size; all the lakes have been dry or practically dry at times (the lower ones have been dry for periods of several years), whereas during periods of high water, many of the lakes merge. From Crump Lake to Bluejoint Lake (about 30 miles), the total drop in lake-bed surface is only about 13 feet. In this report, the discussion is restricted almost entirely to Crump, Hart, and Bluejoint Lakes—the only ones for which appreciable data are available.

The area and volume of Hart Lake at several altitudes are given below (Oregon State Engineer, written commun., 1961). Similar data are not available for Crump or Bluejoint Lakes.

Altitude (ft)	Area (acres)	Volume (acre-ft)
4,463.5	0	0
4,465.0	2,600	2,100
4,467.0	4,200	8,400
4,469.0	5,800	17,800
4,471.0	6,900	30,400
[1]4,473.0	7,400	44,600

[1] Spillway altitude (lake is diked).

Records of stage for Crump, Hart, and Bluejoint Lakes are listed in table 27. In some recent years, Hart Lake has been pumped dry for irrigation before the end of summer. Large parts of it were naturally dry in 1889—when the use for irrigation was slight—and teams were driven across the lakebed from the east side of the valley to Plush (Whistler and Lewis, 1916, p. 32).

A distinct beach line was observed in 1915 around the north end of Bluejoint Lake, about 18 feet higher than the lowest point in the lakebed. The beach is thought to have been formed about 1868, on the basis of the following evidence:

1. Precipitation received at Fort Bidwell, Calif., about 60 miles southwest of the lake, in the period July 1, 1866, to June 30, 1868, was by far the greatest 2-year precipitation at that station in 75 years of record.
2. Sage brush growing below the beach line was not more than 40 years old when observed in 1914, and was distinctly younger than that above the beach line.
3. A. M. Hammersley of Lakeview stated (written commun., 1912) that the lakes were very high when his father came to the valley in 1869, which was "probably when the beach line was made."

Although Waring (1908, p. 38) cited litigation as evidence of recession of the lakes in Warner basin since about 1860, the lake outlines shown on his reconnaissance maps (pls. II, VI), made on the basis of inspection in the autumn of 1906, suggest that lake levels were not low then (Crump Lake was continuous with Hart Lake, and Flagstaff Lake covered a large area).

Extensive remnants of another prominent beach line at 4,750–4,800 feet—some 300–350 feet above the bed of Bluejoint Lake—attest to the existence of a very large lake in Warner basin in pluvial time (approximate shoreline altitude estimated from U.S. Geol. Survey $7\frac{1}{2}$-minute Bluejoint Lake East and Crump Lake quadrangles). At that level, the lake covered about 500 square miles, or 26 percent of its entire drainage basin. Russell (1884, p. 459) and Free (1914, p. 26) concluded that, even at that high level, Lake Warner did not overflow—a conclusion that was later questioned by Van Winkle (1914, p. 118). Hubbs and Miller (1948, p. 65, 151) found the faunal evidence to be confusing, but they concluded that, at its highest level, pluvial Lake Warner was probably closed. Information presented by Van Winkle (1914, p. 111), adjusted to the present-day datum (table 27, headnote), suggests that the lowest topographic divide is above an altitude of 4,800 feet, and presumably above the high shoreline.

WATER SUPPLY

Estimates of average lake-surface precipitation are listed in table 1.

Ground water contributes little or no inflow to any of the lakes except Harney Lake. Springs in the Warm Spring Valley, west of Harney Lake, discharge 30 to 40 cfs, which reaches the lake when not used for irrigation.

Principal sources of inflow to the several lakes are as follows:

Lake	Source of inflow
Silver Lake basin	
Silver Lake	Silver, Bridge, and Buck Creeks, by way of Paulina Marsh.
Harney Basin	
Malheur Lake	The Silvies and Donner und Blitzen Rivers, plus other smaller streams northeast of Burns.
Harney Lake	Silver and Warm Spring Creeks, plus overflow from Malheur Lake.
Warner basin	
Crump Lake	Twentymile and Deep Creeks.
Hart Lake	Honey Creek, plus overflow from Crump Lake.
Bluejoint Lake	Overflow from upstream lakes.

Table 15 summarizes the records of discharge for those of the streams that are gaged. The gaging stations are upstream from irrigated and (or) marshy areas, as well as reservoirs, that deplete the flow considerably. In fact, in dry years these areas consume all, or almost all, the potential inflow.

At Silver Lake the approximate annual inflow is related in a general way to the flow of Silver Creek, as shown in figure 29. The figure suggests that negligible surface runoff reaches the lake in water years when the measured flow of

Silver Creek during December–June totals less than about 30,000 acre-feet. In wetter years the inflow is about twice the amount by which the 7-month total exceeds 30,000 acre-feet. On the basis of this general relation, the long-term record for Silver Creek suggests that appreciable flow has reached the lake during only a few years (probably less than 12 of the 53 years of record), which makes any estimate of average annual inflow almost meaningless.

At Malheur Lake the inflow from all streams probably averages about 100,000 acre-feet per year, though it varies so much from year to year that, as for Silver Lake, an average figure has little meaning. At Harney Lake the annual inflow in addition to periodic overflow from Malheur Lake may average about 40,000 acre-feet—also highly variable from year to year.

Estimates of average yearly inflow to Crump and Hart Lakes in the Warner basin are listed in table 1. Observations at Bluejoint Lake and streamflow data for Twentymile, Deep, and Honey Creeks suggest that the lake generally receives inflow when the gaged discharge exceeds about 200,000 acre-feet per year.

WATER LOSS

Estimated evaporation rates at the lakes are listed in table 1. The data are based largely on the generalized map of Kohler, Nordenson, and Baker (1959, pl. 2).

As early as 1908, Waring (p. 41) suggested that the bed of Silver Lake may leak, and hydrologic evidence supports this suggestion. Ground water may move from the Silver Lake basin toward Summer Lake (Hampton, 1964, p. 18), perhaps along southeast-trending fault zones, such as that marked by the spectacular scarp east of Silver Lake. (Much of this interbasin ground-water flow may feed the prolific Ana Springs, which rise 7 miles southeast of the lake, at a point on a projection of the scarp mentioned above. See pl. 1.) Almost all surface inflow enters Silver Lake from the northwest, and peripheral springs—indicators of ground-water gradients toward the lake—are absent from the south and east sides of the lake basin. In 1948, following a long period of lake dryness, the ground-water level was at least 10 feet below land surface in wells on the eastern part of the lakebed. By December 1954, after the lake had filled to a maximum depth of at least 4 feet, the water levels in two such wells had risen more than 10 feet (E. R. Hampton, U.S. Geol. Survey, oral commun., 1963). Because the amount of recharge from areas south of Silver Lake seems inadequate to have produced such a pronounced rise in water level, seepage from the lake itself is considered to have been the principal source (other contributing factors may have been loading effects of the lake-water body, pressure response to recharge northwest of the lake, and leakage into the wells from the lake).

TABLE 15.—*Average annual discharge at gaging stations on principal streams in Silver Lake, Harney, and Warner basins*

Stream	Drainage area above gage (sq mi)[1]	Total full-year record		Concurrent record, by basin (acre-ft)
		Period (water yr)	Acre-feet	
		Silver Lake basin		
Silver Creek	180	1906, 1910–27, 1930–63.	19,400	----------
		Harney Basin		
Silvies River	934	1904–5, 1910–12, 1918–21, 1923–63.	117,000	140,000
Donner und Blitzen River	200	1912–13, 1915–16, 1918–21, 1939–63.	87,900	85,300
Silver Creek	228	1952–63	32,400	32,400
Total (rounded)	1,360	----------------	237,000	258,000
		Warner basin		
Twentymile Creek	194	1911–15, 1919, 1941–44, 1946–63.	35,800	37,800
Deep Creek	249	1923, 1930–63	86,200	98,900
Honey Creek	170	1911–14, 1931–63	19,800	21,900
Total (rounded)	610	----------------	142,000	159,000

[1] Gage locations are shown in figure 1 and on plate 1.

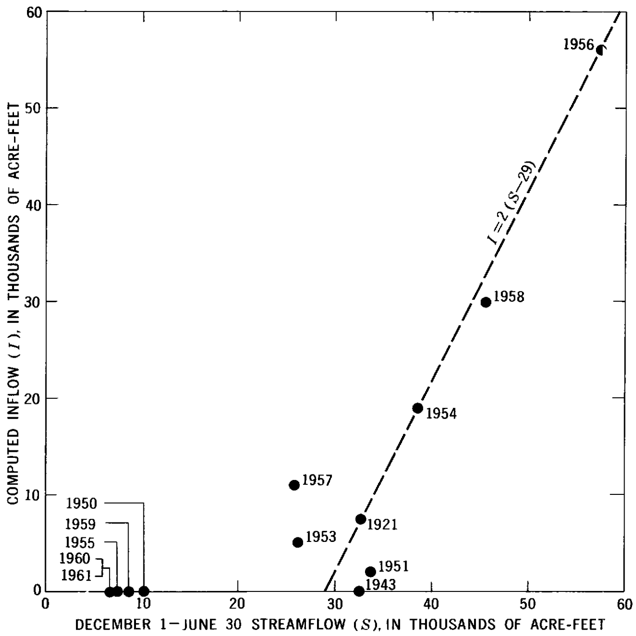

FIGURE 29.—Relation between seasonal (Dec. 1–June 30) streamflow of Silver Creek near the town of Silver Lake and computed inflow to Silver Lake, listed by water year.

That leakage occurs is further supported by records of lake level and precipitation for the periods from November 1 to April 30 in 1958–59 and 1959–60. No inflow occurred in these two periods, and the lake declined from its high level of 1958. Evaporation during each 6-month period was estimated to have been about 20 percent of the annual total (Kohler and others, 1959, pl. 4). At Medford Weather Station, about 110 miles southwest of Silver Lake, pan evaporation for these same two periods was 19 and 20 percent of the annual totals for water years 1959 and

1960, respectively. Thus, assuming the average annual evaporation at the lake to have been about 38 inches, unaffected by local or temporary abnormalities, the total for each November–April period would be about 7.6 inches. The following calculations show that lake-level declines during the two 6-month periods—including allowances for lake-surface precipitation—were, respectively, about 4.7 and 3.1 inches greater than the decrements ascribed to evaporation alone. The two quantities are considered to represent seepage, and the apparent difference between them presumably is due, at least in part, to decreased head as the lake level declined about 2½ feet between April and November 1959. The two calculated rates of seepage, projected over the entire period between the modern-day lake-level maximum in May 1958 and dryness in August 1961, suggest that total leakage during the 37-month period may have been about 10,000 acre-feet. This quantity represents almost 20 percent of the net lake-volume decrease during the same period (from about 60,000 acre-ft in May 1958 to dryness in Aug. 1961).

Estimate of lake-level decline due to seepage loss from Silver Lake for the periods November 1 to April 30 in 1958–59 and 1959–60

[NOTE.—Silver Lake received no inflow during either given period]

Water budget for Silver Lake	Quantity (inches)	
	Nov. 1, 1958–Apr. 30, 1959	Nov. 1, 1959–Apr. 30, 1960
a. Precipitation [1]	4.3	6.1
b. Drop in lake level	8.0	4.6
c. Lake-level drop plus precipitation (*a*+*b*)	12.3	10.7
d. Estimated evaporation	7.6	7.6
e. Estimated lake-level decline due to seepage loss (*c*−*d*)	4.7	3.1

[1] Average of precipitation totals recorded at The Poplars and Summer Lake weather stations, 20 miles north and 13 miles southwest of Silver Lake, respectively.

Additional evidence for leakage from Silver Lake is provided by chemical data (p. B41).

The shallow depression occupied by Malheur Lake is bordered by a flat plain that in places has extensive surface and near-surface deposits of peat derived from the decomposition of tules and other marsh-loving vegetation (Piper and others, 1939, p. 30). Crump and Hart Lakes occupy a similar environment. Although no direct evidence of lateral leakage from any of these lakes exists, seepage into the peat beds may occur under some conditions as the lakes rise, and much of the seepage probably does not return to the water bodies as their levels fall.

Harney Lake certainly does not leak, and Bluejoint Lake probably does not.

All the lakes except Harney and Bluejoint have overflowed within the last century, although the overflow frequency is wide in range. Silver Lake has not overflowed since 1905, presumably due in large part to the diversion of potential inflow for consumptive agricultural use. In contrast, overflow from Malheur, Crump, and Hart Lakes is frequent. At Malheur Lake, for example, the average annual inflow is about 100,000 acre-feet, yet the lake's capacity (including Mud Lake) at overflow is only about 120,000 acre-feet. Thus, overflow to Harney Lake can occur in a somewhat wetter than average year, even following a dry year.

Crump Lake overflows during many years, whereas outflow from Hart Lake and other downstream water bodies in the Warner basin is less common. Comparison of records for Hart Lake with streamflow data for Twentymile, Deep, and Honey Creeks suggests that overflow from the lake generally is small or nonexistent when the combined discharge at the three stream gages is less than about 100,000 acre-feet per year (somewhat below average). In relatively dry years, however, the water that reaches Hart Lake is pumped to irrigate nearby marshlands for crops of wild hay, and in some years the lake is pumped dry by late summer. Such pumpage is equivalent, in effect, to outflow in removing the water and its dissolved salts from the lake.

GEOCHEMISTRY

Analyses of lakes, streams, and ground water in the Silver Lake, Harney, and Warner basins are listed in tables 28, 30, and 31 (for the Harney Basin, many ground-water analyses, plus five additional stream analyses, were listed by Piper and others, 1939, p. 114–119). The small number of available lake-water analyses permit only a few specific comments.

At Silver Lake, the only available chemical-quality data, except for a single partial analysis by Van Winkle (1914, p. 117), were obtained during 1959–61, a period of virtually uninterrupted lake-level decline. The chemical character of the lake varied considerably during that period. In January and May of 1959, at a relatively high stage (alt about 4,307 ft), the lake contained 320 and 370 ppm of dissolved solids, respectively (analyses 31b and 31c, table 28), which consisted almost entirely of calcium, magnesium, sodium (in that order of abundance), bicarbonate, and probably silica (amount not determined). Concentrations of chloride were small—1.0 and 4.0 ppm, respectively. In contrast, on June 20, 1961, just prior to desiccation, the lake contained almost 700 ppm of dissolved solids, principally sodium, carbonate, and bicarbonate, with 40 ppm of chloride (analysis 31e, table 28).

Between April 25 and June 20, 1961, a marked change in chemical character accompanied the drop in lake level from an altitude of 4,300.85 to 4,300.32 feet (analyses 31d and 31e, table 28). In April (analyses 31d), principal components of the 686-ppm solute load were sodium, calcium, magnesium, and bicarbonate; the pH was 8.5. Although the dissolved-solids content had increased slightly to 698 ppm (analyses 31e) by June 20, the pH had increased to 9.7, and sodium plus chloride were enriched appreciably, while most other constituents were depleted (table 16). The amount of change can be estimated by comparing the pairs of sodium and chloride values. Chloride and, to a lesser extent, sodium can be used as indicators of concentration or dilution, because under many circumstances these two ions (especially chloride) do not enter appreciably into short-term reactions with other constituents of their environment. During the 2-month period in 1961, sodium in Silver Lake increased from 137 to 234 ppm (about 70 percent), and chloride increased from 21 to 40 ppm (about 90 percent). Thus, assuming an average increase of about 80 percent, the dissolved-solids content on June 20 should theoretically have been 1,234 rather than 698 ppm. (See table 16.) Much of the difference (about 220 ppm) apparently represents precipitation of calcium carbonate when the lake water became saturated with respect to the carbonate mineral as a result of (1) an increased pH due to lake-bottom plant growth, and (2) concentration of the lake water due to evapotranspiration (the more detailed aspects of carbonate-mineral equilibria are discussed on p. B49). However, significant amounts of silica, magnesium, and potassium also were lost during the same period.

An even greater loss of dissolved solids occurred at Silver Lake between May 1959 and June 1961. Again using sodium and chloride as indicators, the estimated dissolved-solids content would have increased from about 370 to about 3,400 ppm during the 25-month period if no solutes had been lost because of mineral precipitation or other chemical reactions. Yet, the actual value in June 1961 was only 698 ppm.

Without solute loss by any means, including leakage, the dissolved-solids content in June 1961 would have been 20,000–25,000 ppm, instead of about 700 ppm (fig. 30).

TABLE 16.—*Theoretical and actual changes in the chemical character of Silver Lake, April 25–June 20, 1961*

[≈, about, or approx.]

Constituent	Concentrations, in parts per million: Initial values, 4-25-61	Theoretical new values based on 80-percent increase [a]	Actual new values, 6-20-61	Loss	Percentage loss
Silica (SiO_2)	22	40	19	21	52
Calcium (Ca)	59	106	16	90	85
Magnesium (Mg)	44	79	18	61	77
Sodium (Na)	137	246	234	≈0	≈0
Potassium (K)	28	50	32	18	36
Carbonate (CO_3) plus bicarbonate (HCO_3) [b]	373	671	335	336	50
Chloride (Cl)	21	38	40	≈0	≈0
Sulfate (SO_4) plus fluoride (F) plus orthophosphate (PO_4)	2.3	4.1	4.2	≈0	≈0
Dissolved-solids content	686	1,234	698	530	43
pH	8.5	-----------	9.7	-------	--------

[a] 80 percent of initial value. Does not allow for solutes lost by lake-bottom leakage.

[b] Expressed as carbonate.

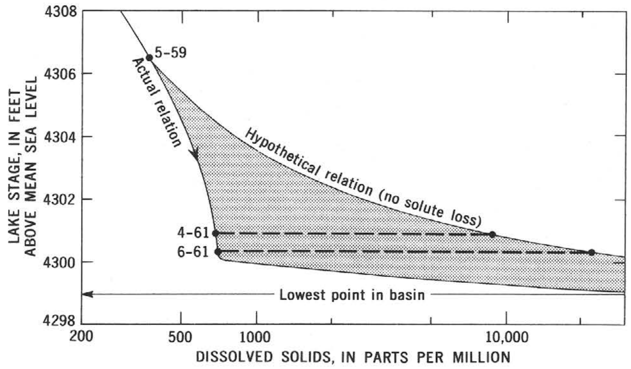

FIGURE 30.—Comparison of estimated relation between dissolved-solids concentration and stage of Silver Lake, 1959–61, with and without solute loss due to mineral precipitation, other chemical reactions, and lake-bottom leakage.

Thus, the various mechanisms of depletion caused an estimated 97-percent loss of solutes during the 25-month period.

Malheur Lake is characteristically dilute because of solute depletion by overflow, whereas Harney Lake is saline because it is the final accumulation sump for salts in the basin. The two analyses of Malheur Lake (samples collected in 1912 and 1961) are significantly different. Most of the difference is caused by (1) year-to-year changes in the lake's stored-solute tonnage due to varying income and depletion by overflow, and (2) controls on the amount of calcium by calcium carbonate solubility. However, these factors do not explain the pronounced increase in relative amounts of sulfate (from two times the chloride content in 1912 to eleven times in 1961). This increase may be due instead to agricultural application of gypsum (calcium sulfate) as an alkali-soil conditioner, whereas it probably is not due to increased ground-water use in the basin (the sulfate to chloride ratio in sampled ground water characteristically is 2:1 or less, according to the data of Piper, Robinson, and Park, 1939, p. 114–118).

In Warner basin, the chemical contrasts among Crump, Hart, and Bluejoint Lakes during infrequent periods when all contain water probably are similar to those shown by analyses made in 1912 (Van Winkle, 1914, p. 113). Each lake at a successively lower level has a successively greater concentration of dissolved solids because (1) the major streams in the valley feed the upstream lakes; (2) subsequent evaporation causes an increase in solute concentration; and (3) the lake-to-lake passage of water carries salts to, and accumulates them in, the lowest (northernmost) basins in the chain of lakes. Bluejoint Lake is the lowest point—the accumulation sump—in Warner basin. By assuming at least a modest long-term supply of dissolved solids to the lake, especially prior to extensive diversion and impoundment of upstream flow for irrigation, the relatively small solute concentration in 1912 (3,630 ppm) suggests prior depletion of solutes. Most of the salts may have been dissipated by wind during periods of desiccation, and some salt reportedly was removed for use by livestock (Van Winkle, 1914, p. 112). The effectiveness of depletion is evident by the ability of the dry lakebed to support crops of salt-tolerant wild hay in years when little water reaches the northern parts of Warner basin.

GEOCHEMICAL TRENDS AND PROCESSES

This section discusses the lake-to-lake similarities and contrasts in chemical character and the governing geochemical processes. The discussion includes consideration of the major dissolved constituents and properties, the minor components, and the trace elements.

MAJOR CONSTITUENTS AND PROPERTIES

DISSOLVED-SOLIDS CONCENTRATION

A wide range of dissolved-solids concentration occurs in the lakes studied. For example, Crump Lake contained about 120 ppm of dissolved solids during a period of overflow in 1962, whereas true closed-basin lakes, such as Lake Abert, contain more than 100,000 ppm during periods of near dryness. The tonnages of stored solutes are similarly wide in range.

Five major factors determine the amount of dissolved solids in lakes that occupy arid and semiarid, topographically enclosed basins:

1. The amount of solutes contributed to the lake by inflow.
2. The relative abundance of "stable" incoming constituents, such as sodium, chloride, and much of the carbonate plus bicarbonate. These constituents tend to be retained in the lakes, rather than lost through organic and inorganic chemical reactions. (This factor is important in all but the most dilute lakes.)
3. The amount of overflow or leakage. Regardless of how many tons of dissolved solids are added to a lake annually, the long-term accumulation of salts is either diminished or prevented because of loss during overflow or leakage.
4. The frequency of lake desiccation, which, in turn, is related to both the quantity and the year-to-year regularity of inflow. The amount of dissolved salts is dependent on the frequency of desiccation because deflation during the dry periods can remove large amounts of salts from a saline-lake basin.
5. The areal extent and the solute content of peripheral mudflats, which were at one time inundated, but which now lie outside the reach of lake water. If the marginal area at a particular time is sizable, a large solute tonnage can be entrapped within the playa muds. This last factor is most applicable to true closed-basin lakes.

The relative importance of each of the above factors is different in every lake; consequently, no two lakes have the same geochemical characteristics. For example, Lake Abert never overflows and rarely dries completely. Because of this, its solute loss is relatively slight, and the lake contains a large tonnage of dissolved solids, even though the principal lake constituents probably constitute less than one-half of the total income. Summer Lake, by contrast, does not overflow, but it has dried frequently in recent years. The resultant dissolved-solids tonnage in Summer Lake is small, as compared with that in Lake Abert, despite a moderate amount of inflow that contributes salts consisting largely of the principal constituents of the lake. The effect of recurrent desiccation at Summer Lake thus overshadows the factors favoring solute accumulation.

A different geochemical situation is characteristic of Goose Lake; it dries about as frequently as Lake Abert but has overflowed on rare occasions (the topographic divide is only 24 feet above the lowest point in the basin). Although the overflow has not removed significant amounts of dissolved solids during the last 100 years, it certainly must have done so prehistorically, before agricultural development of the valley began depleting potential inflow. In addition, large quantities of salts were blown off the central basin floor during desiccation in 1926 and in 1929–34. Surface-water flow into the lake doubtless contains only modest amounts of Goose Lake's major constituents (sodium, bicarbonate, and chloride). The relatively small amount of dissolved solids in Goose Lake, therefore, has resulted from desiccation, from a presumably significant prehistoric overflow, and from a deficiency of stable incoming constituents.

Whereas Lake Abert provides an example of effective salt accumulation, Crump Lake represents the opposite extreme. Crump Lake occupies a very shallow basin that frequently overflows for several months during normal and wet years. Thus, the lake is not closed in the usual sense, but represents, instead, a transition between closed lakes and those that overflow every year. As a result, the lake contains only a small amount of solutes in spite of a rather large annual increment. The solute balance in Crump Lake illustrates the potential dominance of overflow.

SPECIFIC CONDUCTANCE

Specific conductance is a measure of the ability of a solution to conduct electric current, which, in turn, depends on the number of ions in solution (the dissolved-solids concentration). A consistent relation exists between the specific conductance and the dissolved-solids concentration of most lakes and streams throughout the semidesert area of south-central Oregon. In the specific-conductance range from 300 to 20,000 micromhos, the dissolved-solids content, in parts per million, is generally about 65 percent of the specific conductance. Above about 20,000 micromhos, the dissolved-solids content increases more rapidly than specific conductance, owing to decreased ionic mobility. Below 300 micromhos, the dissolved-solids value approaches that of specific conductance because of the increasing relative abundance of undissociated (nonionic) silica (fig. 34); the two values are equal at about 60 micromhos.

DENSITY

The relation between increasing dissolved-solids concentration and increasing density for saline lake waters in south-central Oregon is consistent throughout the range of available values, and can be described by the following equations, in which D is the density (in grams per milliliter at 20° C), and X and X_1 are the dissolved-solids content, in parts per million and milligrams per liter, respectively:

$$D=(8.3\times10^{-7})X+0.998;$$

$$D=0.499+\sqrt{0.249+(8.3\times10^{-7})X_1}.$$

SODIUM AND POTASSIUM

Sodium and potassium are by far the most abundant cations in almost all closed lakes of south-central Oregon. In Lake Abert, for example, the two alkali metals account for 99.99 percent of the positive ions, on the basis of equivalents per million. (By comparison, the two constituents make up 79 epm-percent of the cations in sea water.) Only in dilute lakes does sodium plus potassium amount to less than 50 epm-percent of the cations. For instance, on April 27, 1961, Crump Lake contained only 322 ppm of dissolved solids, and the value for sodium plus potassium was 46 epm-percent.

The increased importance of sodium and potassium relative to calcium and magnesium in the more concentrated lake waters reflects the loss of alkaline-earth cations (p. B49–B50) and the resultant alkali enrichment.

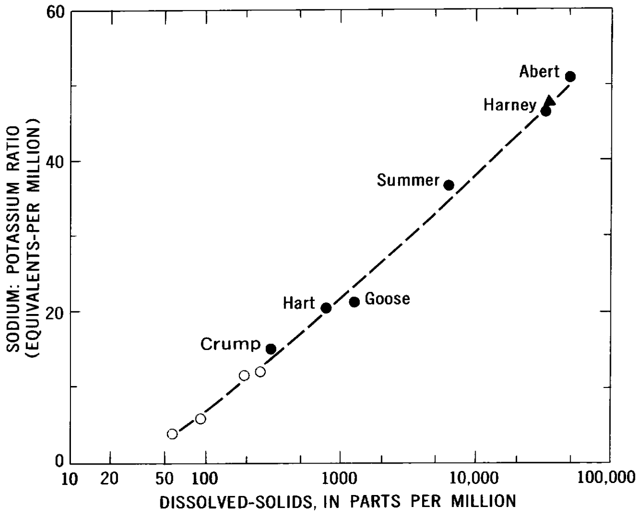

FIGURE 31.—Relation between sodium to potassium ratio and dissolved-solids concentration in surface waters of south-central Oregon. Triangle indicates ratio in sea water. Open circles represent the Chewaucan River; solid circles represent lakes as indicated.

The sodium and potassium content in streams tributary to the lakes is variable. In mountainous upstream reaches the two ions generally account for only 25 to 35 epm-percent of total cations (dissolved-solids content is characteristically less than 100 ppm). However, many of the streams pour forth from the mountainous headwaters onto marshy flatlands before flowing into the lakes. In these flat downstream reaches, the dissolved-solids content and the relative amount of sodium plus potassium increase, especially during periods of low flow. As an example, data for the Chewaucan River, the principal tributary to Lake Abert, indicate that the average dissolved-solids content at the river mouth is about 120 ppm, and the epm-percentage for sodium plus potassium relative to total cations probably averages about 40 (observed range, 35–54 percent). In contrast, values for the river about 30 miles upstream, near Paisley, are about 65 ppm of dissolved solids and only 35 epm-percent sodium plus potassium.

Widespread silicic extrusive rocks in the various basins are an ample source of sodium and potassium. (See Walker, 1963.) The two constituents are among the major elements released to solution as a result of alteration of silicate minerals (the chemical equation on p. B50 is an example of this type of alteration).

The relation between sodium and potassium in the surface waters of south-central Oregon is surprisingly consistent. (See fig. 31.) The amount of potassium relative to sodium decreases with the increase in dissolved-solids content. In dilute samples from the Chewaucan River, the epm-percentage of sodium is only about five times that of potassium, whereas in Goose Lake (dissolved-solids content, about 1,000 ppm) sodium is 20 times as abundant as potassium, and in Lake Abert (about 50,000 ppm) it is 50 times as abundant.

The decrease in potassium relative to sodium with an increase in dissolved-solids content reflects an actual rather than apparent loss of potassium. The potassium probably is depleted by chemical reaction with clay minerals on the lake bottom.

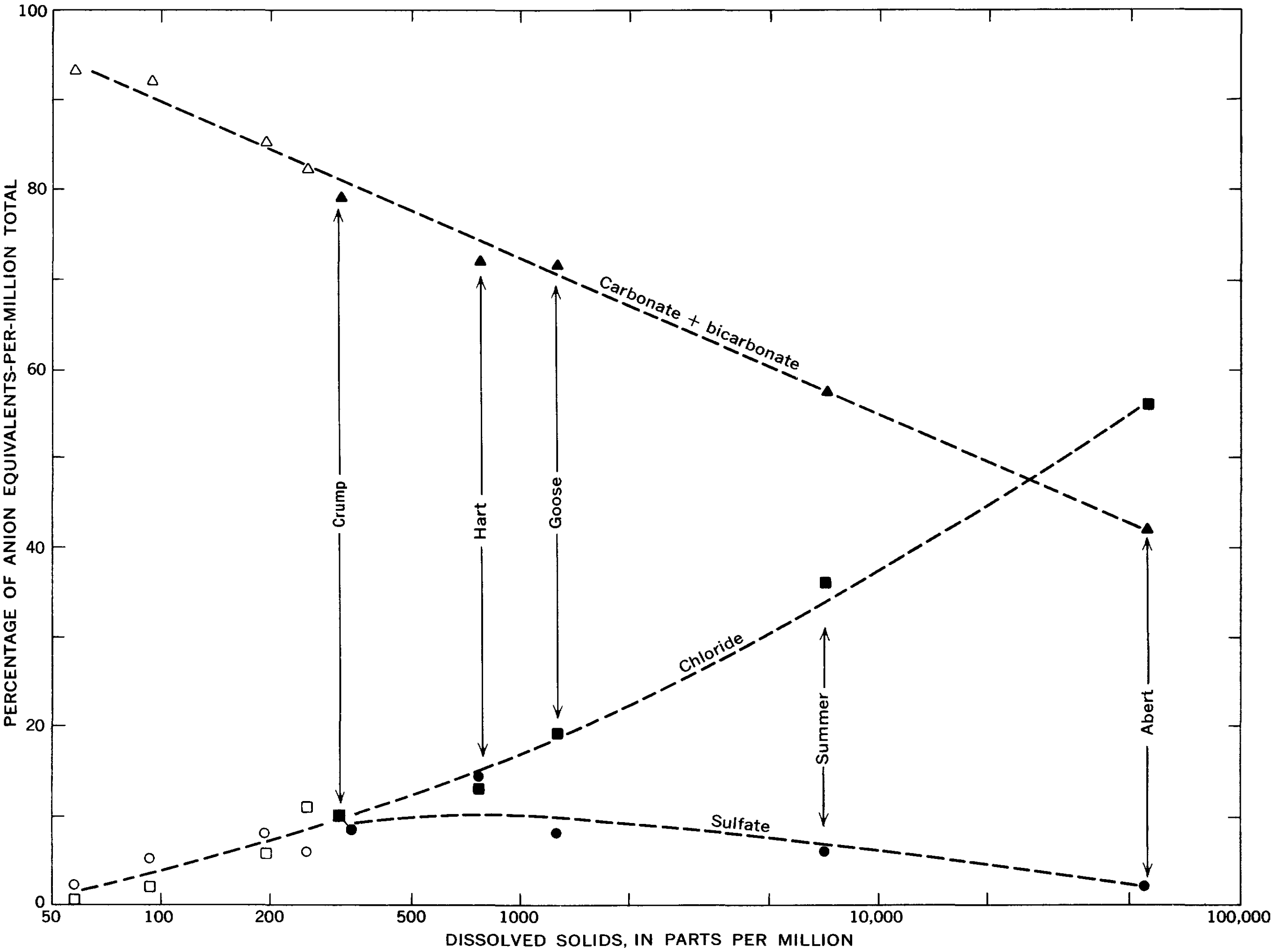

FIGURE 32.—Changes in the distribution of major anions with increase in dissolved-solids concentration in surface waters of south-central Oregon. Open symbols represent the Chewaucan River; solid symbols represent lakes.

CARBONATE, BICARBONATE, AND pH

The combined amount of carbonate plus bicarbonate ranks either first or a close second among the anions of almost all closed lakes in south-central Oregon. However, the relative amount tends to be least in those lakes having the greatest dissolved-solids concentrations (fig. 32).

The straight-line relation between carbonate bicarbonate abundance and dissolved-solids content, as shown in figure 32, is in part fortuitous. At dissolved-solids content greater than 1,000 ppm, this trend may be explained partly by the varied effectiveness of long-term eolian removal of efflorescent carbonate bicarbonate evaporite salts from the lake playas in preference to the generally more hygroscopic salts of sulfate and chloride (p. B30; fig. 23). However, another significant reason probably is a basin-to-basin difference in the character of chemically important inflow.

The amount of calcium relative to that of carbonate bicarbonate in the inflow exerts an equally important influence on the anionic character in the lakes. Calcium contributed to the lakes by inflow is depleted by precipitation of carbonate minerals. Therefore, if the incoming amount of calcium is comparable to that of carbonate plus bicarbonate, the loss of calcium and equivalent carbonate will leave a lake water with only small amounts of residual alkalinity. This, in turn, will result in a pronounced enrichment in chloride and sulfate relative to carbonate plus bicarbonate. Conversely, if calcium is a minor constituent in inflow, whereas bicarbonate is by far the most abundant anion, as in the Summer Lake basin, for example, carbon species will remain as the principal anionic constituents in the lake water.

Bicarbonate is by far the most abundant anion in nearly all stream waters of the region. In the analyses of 20 samples from 15 streams, bicarbonate (plus carbonate, where present) ranged from 35 to 97 percent and averaged 87 percent of the negative ions, on the basis of equivalents

TABLE 17.—*Carbonate-bicarbonate and calcium in stream waters*

[Data from table 28]

Stream	Location	Discharge (cfs)	Dissolved-solids content (ppm)	Percentage of anion or cation epm total		
				Carbonate plus bicarbonate	Calcium	Carbonate plus bicarbonate in excess of calcium
Lake Abert basin						
Chewaucan River	33/18-26E (upstream)	48	81	95	39	56
		210	58	93	43	50
		144	66	97	43	54
Do	35/21-21P (downstream)	2	255	82	34	48
		22	94	92	46	46
		28	193	85	32	53
Poison Creek	35/21-1C	2	73	85	43	42
Summer Lake basin						
Ana River	30/17-6SE¼	92	158	79	11	68
Goose Lake basin						
Warner Creek	39/20-8R	3	525	35	15	20
Drews Creek	40/19-18P	15	94	95	38	57
Dry Creek	41/19-7B	12	115	93	53	40
Davis Creek	45N/14E-16J	25	60	92	54	38
Willow Creek	47N/14E-22Q	5	111	91	40	51
Lassen Creek	47N/14E-27L	15	65	81	36	45
Pine Creek	48N/15E-32L	52	56	79	46	33
Silver Lake basin						
Silver Creek	28/14-28SW¼	23	66	94	47	47
Malheur Lake basin						
Donner und Blitzen River	32/32½-8SW¼	43	85	90	36	54
Silvies River	22/30-8SW¼	9	120	93	42	51
Warner basin						
Deep Creek	39/23-15NW¼	20	90	94	36	58
Honey Creek	36/24-29NE¼	1	135	93	43	50
Average			125	87	39	48

per million (table 17). Calcium is also an important inflow constituent. For the same 20 samples, the alkaline earth ranged from 11 to 54 epm-percent and averaged 39 percent of the cations. However, the abundant carbon species overshadow the calcium (last column, table 17), and an appreciable amount of carbonate bicarbonate therefore remains in the lakes even after great losses due to the precipitation of alkaline-earth carbonate minerals.

Several reactions in addition to the depletion of incoming calcium tend to affect the carbonate plus bicarbonate content of closed-basin lakes. Ion-exchange mechanisms involving clay minerals within the lacustrine sediments can indirectly deplete carbonate. When sodium from the lake water replaces calcium on the clay-mineral exchange site, the released calcium combines with carbonate, as shown in the following idealized reaction:

$$\text{Ca clay}+2\text{Na}^{+1}+\text{CO}_3^{-2}\rightarrow\text{Na clay}+\text{CaCO}_3.$$

Two other reactions tend to add rather than deplete carbonate plus bicarbonate. Anaerobic decomposition of organic matter by sulfate-reducing bacteria, according to the type of reaction discussed on page B46, yields bicarbonate. Similarly, the inorganic breakdown of silicate minerals (p. B50) produces bicarbonate, rather than hydroxyl ions (OH^{-1}), if carbon dioxide enters the reaction along with water.

The relative importance of these several reactions is unknown, but all of them probably occur within or beneath the saline lakes. The trend of decreasing carbonate plus bicarbonate abundance with increasing average salinity (fig. 32) suggests, however, that the depletion mechanisms as a group are more effective overall than the bicarbonate-producing reactions.

The amount of carbonate relative to bicarbonate in the lakes of south-central Oregon differs widely. Compared on the basis of equivalents per million, the measured carbonate to bicarbonate ratio has ranged from less than 0.05:1 in Crump Lake to about 4:1 in Lake Abert. Relative amounts of the two carbon species are closely related to pH, a property that also varies among the lakes (from 8.4 in Crump Lake to 9.7 in Lake Abert). Both pH and the carbonate to bicarbonate ratio are invariably

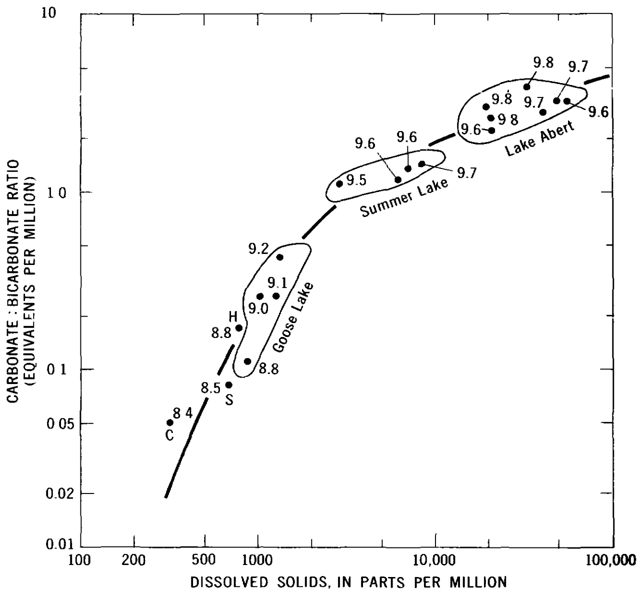

FIGURE 33.—Variations in pH and carbonate to bicarbonate ratio relative to dissolved-solids concentration in lakes of south-central Oregon. Numbers indicate pH. Letters indicate: C, Crump Lake; H, Hart Lake; S, Silver Lake. Ratio and pH values are based on laboratory determinations.

greater in the lakes that contain larger concentrations of dissolved solids, as shown in figure 33. (See remarks regarding the reliability of carbonate plus bicarbonate and pH data on p. B56.)

This tendency is associated with decreased hydrolysis of the carbonate ion (CO_3^{-2}) in solutions containing greater concentrations of carbonate and bicarbonate (Glasstone, 1942, p. 375), and therefore dissolved solids.

SULFATE

Sulfate is not a principal constituent of closed lakes in south-central Oregon; relative amounts rarely exceed 10 epm-percent of the negative ions, regardless of dissolved-solids content. In fact, the percentage of sulfate characteristically is smallest in lakes that contain the largest concentrations of dissolved solids (fig. 32).

Measured concentrations of sulfate have ranged from 26 ppm in Crump Lake (Apr. 1961; 322 ppm of dissolved solids) to 1,000 ppm in Lake Abert (July 1939; 95,000 ppm of dissolved solids). Of course, the maximum range has been much greater; Crump Lake doubtless contains less than 10 ppm of sulfate during periods of overflow, whereas concentrations greater than 10,000 ppm may occur in some lakes immediately before and after periods of desiccation.

Adequate chemical-quality data are not available for principal tributary streams near their mouths. Available data suggest, however, that most of the streams probably contribute sulfate to the lakes in concentrations about equal to or greater than those of chloride (table 28).

The amount of sulfate in spring flow ranges widely, in terms of concentration and relation to accompanying amounts of chloride. Discharge of the Ana Springs system, principal source of dissolved solids for Summer Lake, contains about 6 ppm of sulfate and has a chloride to sulfate epm ratio of approximately 3:1, compared to about 6:1 for the lake itself. At Lake Abert, sampled peripheral springs yield sulfate in the 25- to 50-ppm range, with chloride to sulfate ratios from 3:1 to 9:1. In contrast, the lake itself contains 26 times more chloride than sulfate.

The data for streams and springs indicate a discrepancy between the relative amounts of sulfate and chloride contributed to the lakes and the relative amounts in the lakes themselves, with the discrepancy greatest in the most saline lakes. Thus, incoming sulfate apparently is depleted, rather than accumulated within the lakes. The most probable mechanism of depletion is bacterial sulfate reduction within the lake-bottom muds. Anaerobic decomposition of organic matter by bacteria generally is accompanied by reduction of sulfate, according to a reaction of the following type:

$$2CH_2O + SO_4^{-2} + CO_3^{-2} \rightarrow HS^{-1} + 3HCO_3^{-1},$$

where organic matter such as carbohydrates is generalized as CH_2O (Berner, 1966, p. 22). In shallow lakes, such as Summer and Abert, some of the reduced sulphur species produced by such reactions may be lost to the atmosphere, while other increments may combine with iron to form iron sulfide minerals within the lake-bottom muds.

CHLORIDE

Chloride is the most abundant or second most abundant anion in nearly all closed-basin lakes in south-central Oregon, even though it is a minor constituent of stream waters in the area (fig. 32). In lakes that rarely if ever overflow, chloride invariably makes up at least 20 epm-percent and in some lakes as much as 60 epm-percent of the negative ions. The greatest relative (percentage) amounts occur in lakes that characteristically contain more than 5,000 ppm of dissolved solids (Abert, Harney, and Summer Lakes among those studied). This increase with increasing dissolved-solids concentration is comparable to that suggested by Langbein (1961, p. 12) for closed lakes in general.

The relative amounts of chloride in closed-basin lakes can be used as a clue to the hydrochemical history of the lakes and their basins because chloride, more than almost any other constituent, is immune to the influence of most biologic, oxidation-reduction, and mineral-alteration phenomena, and it does not enter into mineral-precipitation reactions, except during the final stages of lake desiccation.

Relative chloride concentrations indicate the following with regard to the closed-basin lakes of south-central Oregon:

1. For lakes that characteristically contain more than about 1,000 ppm of dissolved solids:
   a. If chloride is more than about 50 epm-percent of the anions, the principal source of dissolved solids may be a chloride-rich ground-water supply; or, chloride may have undergone a long-term enrichment relative to carbonate plus bicarbonate; or, the amount of incoming calcium may be adequate to remove much of the incoming carbonate plus bicarbonate, thereby enriching chloride. The abundance of chloride can generally be attributed to a combination of these factors, with the importance of each differing from lake to lake.
   b. If the relative amount of chloride in the lake is small, streamflow containing only minor amounts of chloride may be the most important source of dissolved solids; or, most inflow may contain only small amounts of calcium relative to sodium, thereby diminishing the importance of chloride enrichment by the precipitation of alkaline-earth carbonates.
2. For closed lakes that characteristically contain less than about 1,000 ppm of dissolved solids, the conclusions that can be drawn from relative chloride content are, in general, similar to those above, but not as definitive. In such lake waters, calcium can be a major constituent, and if so, the relative amount of chloride is less than it would be in the same lake if the dissolved-solids content were greater. For example, on April 27, 1961, Crump Lake contained 322 ppm of dissolved solids, and calcium amounted to 32 epm-percent of the cations, whereas chloride totaled only 10 epm-percent of the anions. If the calcium and equivalent carbonate were removed from Crump Lake by mineral precipitation, chloride would increase to 15 epm-percent of the anions.

The concentration of chloride in stream waters varies with dissolved-solids content and downstream location. Except where chloride-rich ground water contributes significantly to surface flow, the amount of chloride present upstream from the flat marshy basin floors characteristically is 2 ppm or less, which in turn represents about 5 epm-percent or less of the total anions. Little is known about the chloride content of stream water as it enters the lakes after flowing through the marshy lowland areas. The chloride increment derived from these lowland areas is uncertain, but may be significant in several, if not all, of the valleys. In the Lake Abert basin, for example, the amount of chloride in the Chewaucan River near Paisley, upstream from Chewaucan Marsh, rarely exceeds about 1 ppm, but concentrations of as much as 17 ppm (11 epm-percent of the anions) have been measured at the mouth near Valley Falls.

Even though the proportion of incoming chloride is increased in the lake, owing to the precipitation of alkaline-earth carbonate minerals, the chloride tonnages added to the lakes annually by stream inflow are, nonetheless, small compared with the amounts that have accumulated in the more concentrated lake waters.

Ground-water inflow undoubtedly is a significant chloride contributor in several of the closed basins, but its quantitative importance relative to streamflow is difficult to assess.

The ultimate source of chloride now present in the lakes is uncertain. Chloride derived from outside the study area is atmospherically transported into the region and contributed to the basins as dry fallout or as a constituent of precipitation. However, the amount of chloride thus introduced may be small, compared with the amount originating within the region.

The most important long-term source of "new" chloride may be related to volcanism, which was prevalent within, and adjacent to, the closed-basin area throughout most of Tertiary and Quaternary time.

Much of the chloride presently contributed to the lakes by ground and surface water has been recycled from within, or adjacent to, the specific basin. Recycled chloride in surface water is derived from wind-deposited dust on the land surface and from evaporite salts leached at and near the land surface, whereas part of the chloride contributed by spring flow is acquired from soluble salts in buried lakebed deposits and from salts leached within and below the soil zone by downward-percolating water.

MINOR CONSTITUENTS

Minor constituents studied include silica; calcium and magnesium; fluoride; bromide; nitrate; orthophosphate; and boron. In waters of more dilute lakes (those containing less than about 1,000 ppm of dissolved solids), calcium, magnesium, and silica constitute a large part of the dissolved-solids content. However, these constituents are of only minor abundance in the true closed-basin lakes, and their occurrence is thus considered along with that of the consistently minor components.

SILICA

Unusually large concentrations of silica occur in the closed-basin lakes of south-central Oregon. Most lake waters throughout the world contain 5 to 35 ppm of silica, and concentrations greater than 50 ppm are rare. In contrast, Abert and Summer Lakes are known to have contained more than 200 ppm of silica at times (table 28).

The characteristically large amounts of accumulated silica in the more saline, closed lakes of the study area might be expected simply on the basis of plentiful supplies—25 to 40 ppm—provided by tributary streams. Yet the amount of silica now present in the lakes is only a small fraction of the long-term amount introduced by surface and ground water. For example, the average annual increment of silica contributed to Lake Abert by the Chewaucan River is about 2,000 tons, meaning that the present silica load in Lake Abert (30,000–50,000 tons)

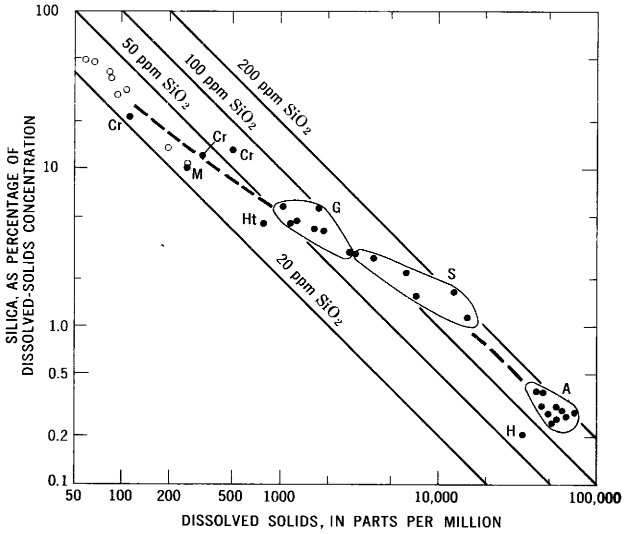

FIGURE 34.—Relation between silica and dissolved-solids concentration in surface waters of south-central Oregon. A, Lake Abert; Cr, Crump Lake; G, Goose Lake; H, Harney Lake; Ht, Hart Lake; M, Malheur Lake; S, Summer Lake; open circles, Chewaucan River.

would theoretically accumulate in less than 30 years, assuming that no silica depletion occurs. The large concentrations of silica in the saline lakes are therefore not related to accumulation time. Instead, most of the incoming silica has been removed from the lake waters, as shown in figure 34. With increasing dissolved-solids content, silica constitutes a smaller and smaller percentage of the dissolved material, even though the absolute silica concentration increases from about 30 ppm in the dilute stream waters to 200 ppm or more in the most saline lakes. In addition to the variations from lake to lake, the silica tonnage in true closed-basin lakes varies seasonally.

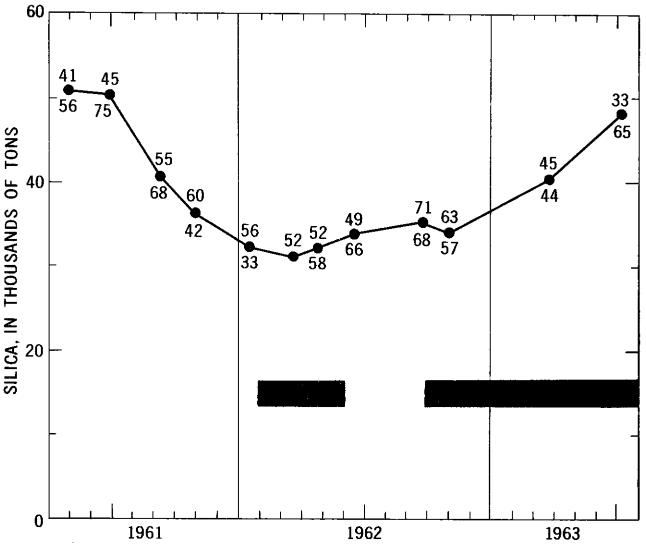

FIGURE 35.—Seasonal variations of silica tonnage in Lake Abert, 1961–63. Numbers above circles indicate dissolved-solids concentration, in thousands of parts per million; those below indicate water temperature, in degrees Fahrenheit. Horizontal bars indicate periods of appreciable inflow (more than about 50 cfs).

Two factors can be important in controlling the amount of dissolved silica: the growth and decay of silica-using organisms and the reactions between silica-rich minerals and lake water. The importance of biologic controls on the amount of silica in the lakes is uncertain. Diatoms, the potentially most important silica users, are present in Lake Abert at least (p. B20), but their abundance, bloom periods, silica requirements, and decomposition rates are unknown. Seasonal fluctuations in dissolved-silica tonnage at the lake might be expected to mirror the activities of silica-rich biota. However, the data (fig. 35) are inconclusive—no consistent seasonal pattern is shown. During the 9-month period October 1962 to June 1963, the amount of silica in Lake Abert increased by 14,000 tons (a remarkable 40 percent of the initial tonnage), whereas only a 6,600-ton increment is attributable to inflow during that period (table 18). The difference, about 7,400 tons, must have been derived mostly from decomposition of silica-rich organic material in the lake, or perhaps from dissolution or alteration of inorganic deposits on the lake bottom. The 7,400-ton increment, accumulated during only 9 months, seems too large to be ascribed to the short-term breakdown or dissolution of silicate minerals. An analogous net loss of dissolved silica, about 20,000 tons, which occurred during the 9-month period July 1961 to March 1962 (fig. 35), also seems too great to have resulted from formation or alteration of silicates. Diatoms, which are the most important silica users, often become dominant in the late fall, winter, and early spring (K. V. Slack, U.S. Geol. Survey, written commun., 1964). Yet, biologic extraction of such a large amount of silica during the frigid, latter half of the period July 1961 to March 1962 (average air temperature 31° F at Valley Falls) seems uncertain. Thus, although organic processes apparently help to control the amount of dissolved silica in the lakes, their exact nature and relative importance are as yet unknown.

TABLE 18.—*Silica budget for Lake Abert, October 1, 1962–June 30, 1963*

a.	Lake-volume increase (tables 4, 20)	acre-ft	153,000
b.	Evaporation (est. 22 in.)	acre-ft	64,000
c.	Direct precipitation (est. 19 in.)	acre-ft	55,000
d.	Net volume increase attributable to inflow ($a+b-c$)	acre-ft	162,000
e.	Silica increment (fig. 35)	tons	14,000
f.	Assume all inflow is from the Chewaucan River, containing 30 ppm SiO_2; therefore, silica increment	tons	6,600
g.	Increment necessarily derived from organic or inorganic lake-bottom sediment ($e-f$)	tons	7,400

Quartz exerts no control on silica in the lakes, primarily due to the sluggishness of its equilibrium reactions, compared to those of amorphous silica. Calculations by Jones, Rettig, and Eugster (1967, fig. 1) indicate that amorphous forms of silica at 77° F should be soluble to the extent of about 110 ppm when the pH is less than 8.5. At higher pH, however, the dissociation of silicic acid causes a pronounced solubility increase: about 300 ppm of silica should be soluble at pH 9.7. Thus, the solubility controls exerted by amorphous silica should permit concentrations in the 150- to 200-ppm range in Abert and Summer Lakes (pH, 9.5–9.8) except at low temperatures.

The exact nature and extent of interactions between the lake water and silica-rich lake-bottom materials are unknown. At Lake Abert, bottom sediments include large amounts of an amorphous to montmorillonoid material which may have formed authigenically in contact with the lake water (B. F. Jones, U.S. Geol. Survey, oral commun., 1965), thereby providing a means of silica depletion.

At Summer and Goose Lakes, but not at Lake Abert, the seasonal fluctuations of silica tonnage are inverse to those of dissolved-solids concentration (figs. 15, 24, 28; footnote 1 on p. B18). This relation may result in part from restraints imposed on the concentration of silica by mineral equilibria.

CALCIUM AND MAGNESIUM

Calcium and magnesium, two of the most abundant constituents of most waters and rock-forming minerals, are present in only minute quantities in the saline lakes of the study area. In Lake Abert, for example, the two components usually total less than 5 ppm and constitute less than 0.02 epm-percent of the cations. The dearth of calcium and magnesium might seem strange in view of the great abundance of the two constituents in most stream waters of the study area. Excluding the Ana River, which is fed almost entirely by the Ana Springs, the alkaline-earth content of sampled streams in the study area ranged from 20 to 72 epm-percent of total cations. The average was about 60 percent, two-thirds of which was calcium.

Perhaps the most important reason for calcium depletion is the precipitation of calcium carbonate minerals. The chain of events that cause the loss of calcium is illustrated by assuming that a lake water originally contains about 200 ppm of dissolved salts (including major proportions of calcium and bicarbonate). As the calcium and dissolved-solids concentrations increase owing to accumulation of incoming salts and evaporation, the concentration of carbonate and its abundance relative to bicarbonate also increase (fig. 33). Finally, the solubility limits of alkaline-earth carbonates are exceeded, and the calcium plus the accompanying carbonate begin to drop out of solution. This decreased tolerance for calcium in solution as the dissolved-solids concentration, pH, and relative proportion of carbonate increase is shown in general terms by the following data for Goose Lake (from table 28).[5]

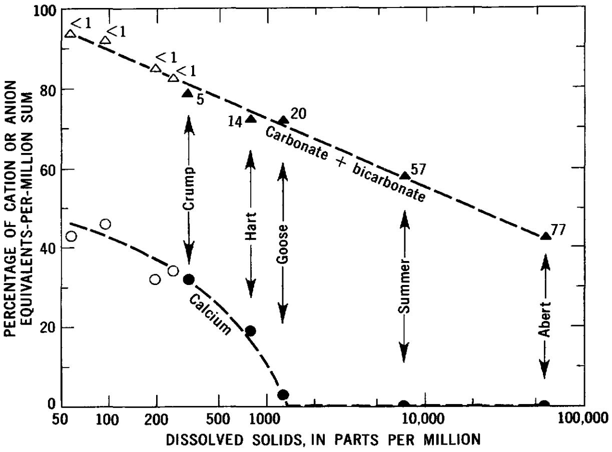

FIGURE 36.—Changes in the relative amounts of calcium and carbonate plus bicarbonate with increasing dissolved-solids concentration in surface waters of south-central Oregon. Open symbols represent the Chewaucan River; solid symbols represent lakes. Numbers indicate carbonate abundance, as percentage of carbonate plus bicarbonate on the basis of equivalents per million.

Dissolved solids (ppm)	pH	Relative abundance, as percentage of dissolved-solids concentration	
		Carbonate	Calcium
823	8.9	6.0	1.7
868	8.8	3.5	1.5
1,040	9.0	7.6	1.7
1,270	9.1	7.4	1.0
1,340	9.2	11	.9

With continued salinity increase, the losses also continue until almost all calcium has been removed; this is possible because during the final stages of depletion, the carbon species are present in concentrations far greater than those of calcium (fig. 36). The last stages of depletion occur at a dissolved-solids content of about 1,500 ppm or less. Figure 36 also shows, by inference, the characteristic "path" of calcium depletion with increasing dissolved-solids content in lakes of the study area.

Depletion of calcium and carbonate is accelerated considerably at a high pH, such as that of Abert and Summer Lakes (9.5–9.8). Under these conditions, however, the actual precipitation of carbonate minerals (represented by reaction 1, below) tends to lower the pH, because hydroxyl ions (OH^{-1}) are consumed during the

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[5] See remarks regarding the reliability of carbonate, bicarbonate, and pH data on p. B56.

resulting replenishment of carbonate (reaction 2);

$$CO_3^{-2}+Ca^{+2}\rightarrow CaCO_3, \quad \text{and} \qquad (1)$$

$$HCO_3+OH^{-1}\rightarrow CO_3^{-2}+H_2O. \qquad (2)$$

Hence, the high pH must be maintained by chemical reactions other than carbonate precipitation. The two most important phenomena that can increase the pH of a lake water are hydrochemical alteration of silicate minerals and photosynthetic activities of aquatic plant life—especially algae. Both of these actions can be considered to produce hydroxyl ions, particularly where the counterbalancing uptake of carbon dioxide is sluggish. Silicate alteration is exemplified by the transformation of feldspar to clay minerals, such as albite to kaolinite:

$$2NaAlSi_3O_8+11H_2O \rightarrow Al_2Si_2O_5(OH)_4+4H_4SiO_4+2Na^{+1}+2OH^{-1}.$$

Photosynthesis can be characterized by the following reaction, in which carbon is extracted from the lake water to produce cell material (here generalized as carbohydrate):

$$HCO_3^{-1}+H_2O\rightarrow CH_2O+O_2+OH^{-1}.$$

Depletion of magnesium is not a simple matter of carbonate precipitation. Recent work by B. F. Jones (Jones and Van Denburgh, 1966, p. 443) on the mineralogy of lake-bottom sediments at Lake Abert indicates that much of the magnesium apparently combines with silica to form an amorphous or poorly defined montmorillonoid magnesian silicate.

Inorganic reactions certainly are not the only means of alkaline-earth depletion. Biota in the lakes undoubtedly require and utilize significant amounts of calcium and magnesium as nutrients. For example, the several major biologic species at Lake Abert use the alkaline earths (p. B20); similarly, some of the calcium that enters Summer Lake is assimilated as shell-building material by tiny ostracoda (a subclass of Crustacea), which are abundant in the lake-bottom deposits according to William Taft (oral commun., 1962). Although much of the biologic depletion is only temporary, some of it, at least, is permanent, as indicated by organic components of the lake-bottom sediment.

A striking example of alkaline-earth removal from a south-central Oregon lake is provided by two samples from Silver Lake (analyses 31c, d, table 28). Between April 25 and June 20, 1961, at least three-fourths of the calcium and magnesium and one-half of the carbonate and bicarbonate were lost from the lake during a period of evaporation and decreasing lake volume. (See p. B41; table 16.)

FLUORIDE

The minor-halide content of the lakes and their inflow was not studied in detail. Only fluoride was determined consistently in samples of lake, stream, and ground waters. Concentrations of fluoride showed an unusually small variation compared with those of chloride, the major halogen. Dilute stream and ground waters characteristically contain from 0.7 ppm to less than 0.1 ppm of fluoride, yet concentrations ranging from about 1 ppm to not much more than 5 ppm are characteristic of the closed lakes. The largest measured amount—13 ppm—was from Harney Lake, sampled at a stage of near-dryness (analysis 34b, table 28).

The relative quantities of fluoride in saline lakes of the study area are thus less than might be expected, compared with the relative amounts contributed by inflow. Specifically, the Chewaucan and Ana Rivers—the principal sources of flow into Abert and Summer Lakes, respectively—have chloride to fluoride epm ratios ranging from 25:1 to 3:1, whereas ratios for the two lakes are about 1,400:1 and 150:1, respectively. The disposition of fluoride is similar to that of many other constituents (silica, calcium, magnesium, potassium, the carbon species, and sulfate) that are removed from solution as components of organic and inorganic material in the lakes. Fluoride is a trace constituent of biota (Rankama and Sahama, 1950, p. 761), and it also is sorbed, or actually incorporated, in certain authigenic minerals—both silicates and nonsilicates.

Sources of fluoride doubtless include chemical alteration of hydrous silicate minerals, deep-circulating ground water, and, in the past, volcanic emanations.

BROMIDE

Bromide is undoubtedly far less plentiful than fluoride in dilute waters (Livingstone, 1963, p. 41–42), but it is far more abundant in the most saline lakes. Measured bromide content ranged from about 1 ppm in Goose Lake to 103 ppm in Lake Abert (table 28).

Bromide is hydrologically one of the most mobile ions—that is, like chloride, it is immune to the influence of most organic and inorganic chemical reactions. Although many other dissolved constituents may be waylaid at various stages in a hydrologic sequence, bromide moves largely unhindered to the endpoint, or accumulation sump, of the sequence. Thus, bromide is amassed at the lowest parts of true closed basins, and the lake waters that occupy such depressions are enriched in bromide. As with chloride, the relative amount of enrichment is a reasonably good measure of the long-term effectiveness of solute accumulation. For example, bromide and chloride, respectively, make up 0.17 and 35 percent of the dissolved-solids content in Lake Abert (table 3), but only about 0.04 and 12 percent in Goose Lake. This reflects, at least in part, the greater efficiency of long-term accumulation in Lake Abert.

Because bromide and chloride are extremely mobile in almost any hydrologic environment, the relation between amounts of the two halides can be used to characterize a particular lake water and to evaluate the potential sources of dissolved solids. For example, the chloride to bromide ratios (in equivalents per million) for Abert and Summer Lakes are 470:1 and 500:1, respectively. In contrast, other closed-basin lakes in the Western United States contain considerably smaller amounts of bromide relative to chloride, as shown by the following ratios (from data of Whitehead and Feth, 1961, table 1):

Closed-basin lake	*Chloride to bromide ratio (epm)*
Big Borax Lake, Calif	680:1
Pyramid Lake, Nev	800:1
Mono Lake, Calif	920:1
Big Soda Lake, Nev	950:1
Walker Lake, Nev	1,000:1
Great Salt Lake, Utah	3,700:1

Ocean water also contains less bromide relative to chloride than do the two Oregon lakes; the average ratio for sea water is about 660:1 (from data of Sverdrup and others, 1942, p. 176). On the basis of limited data, the chloride to bromide ratio of most volcanic emanations apparently ranges from about that of sea water to more than 10 times that of sea water (White and Waring, 1963, p. K5). At the other extreme, the ratio for igneous and sedimentary rocks is less than 350:1, according to data of Turekian and Wedepohl (1961, table 2).

These data suggest that rock alteration may be a significant source of bromide in Abert and Summer Lakes, despite the fact that bromide is such a minor component of most rock-forming minerals. For example, its average abundance in igneous rocks is less than one-hundredth of that of fluoride (Turekian and Wedepohl, 1961, table 2).

NITRATE

The nitrate content of most surface waters throughout the world is less than 5 ppm (Livingstone, 1963), and lakes in the study area are no exception. Measured concentrations ranged from 0.9 ppm in Silver Lake to 7.8 ppm in Goose Lake (table 28). The nitrate content of streams draining into the lakes is generally less than 1.0 ppm, as is that of most spring waters in the study area. (See comments on the reliability of nitrate data, p. B56.)

ORTHOPHOSPHATE

Most surface waters throughout the world contain less than 1 ppm of orthophosphate, as indicated by the data of Livingstone (1963). In contrast, the more saline lakes of south-central Oregon characteristically contain much more than 1 ppm; maximum measured amounts of orthophosphate in Goose, Summer, and Abert Lakes are 12, 41, and 101 ppm, respectively. (Table 3 shows, however, that the relative amount decreases, rather than increases, with increasing solute concentration.)

The data available on the orthophosphate content of streams draining into the lakes are only meager. The Chewaucan River, which chemically may resemble most stream inflow, averages 0.2–0.3 ppm. Thus, orthophosphate apparently is enriched (accumulated) in the closed-basin lakes to a considerably greater degree than are silica and nitrate, the two other most abundant biologic nutrients. For example, the orthophosphate tonnage in Lake Abert (about 18,000 tons) is more than 1,000 times the 17-ton average annual contribution estimated for the Chewaucan River (assumed on the basis of a stream input of almost 48,000 acre-feet per year, with an orthophosphate content of 0.25 ppm), whereas the silica and nitrate tonnages in the lake are less than 50 times the annual stream input.

Large concentrations of orthophosphate are made possible in the true closed-basin lakes by a dearth of calcium. Calcium phosphate minerals are even less soluble than the calcium carbonates, but a great abundance of carbonate ion in the lake waters prohibits all but trace amounts of calcium, and the near absence of calcium, in turn, permits the accumulation of orthophosphate.

Seasonal fluctuations in relative amounts of orthophosphate were noted in Abert, Summer, and Goose Lakes, the only lakes for which seasonal data are available (figs. 15, 24, 28). However, the pattern of variation is different from lake to lake. Greatest and smallest amounts of orthophosphate occurred in Lake Abert during summer and winter, respectively, whereas in Summer and Goose Lakes they occurred erratically during the $1\frac{1}{2}$-year study period. Because of the importance of orthophosphate as a biologic nutrient, its fluctuations may be due primarily to seasonal variations in the rates of biotic growth in the lakes. However, fluctuations within Lake Abert seem to contradict those to be expected on the basis of observed biotic blooms. For example, amounts of dissolved orthophosphate increased during the period March–July, yet during the same period a large biologic-population increase was observed in the lake. In 1962, the March–July increase was about 1,500 tons—only 10 percent of the initial 15,000-ton load, but far more than the amount contributed by ground water and surface inflow (estimated to be only 10 tons). For the average lake volume during the period (about 170,000 acre-ft), the orthophosphate increment represented a sizable increase in concentration (6–7 ppm). The apparent conflict between orthophosphate gains and biologic blooms at Lake Abert may be explained at least in part by the accelerated liberation of orthophosphate by decomposing organisms on the lake bottom as the water temperature increases during the spring and early summer (fig. 15).

At Summer and Goose Lakes, not enough is known about the nature, extent, and timing of biologic activity to evaluate its influences on orthophosphate. The seasonal variations at Goose Lake (fig. 28) show no apparent relation to water temperature; rather, a crude inverse relation apparently exists between orthophosphate tonnage and dissolved-solids content. Because Goose Lake contains calcium in more than trace amounts (table 28), the controls imposed by calcium phosphate insolubility may help to govern the orthophosphate content.

BORON

Although boron comprises less than one-half of 1 percent of the dissolved-solids content in the more saline Oregon lakes, the concentrations of this constituent are nonetheless large. Maximum measured amounts of boron in Goose, Summer, and Abert Lakes are 4.8, 34, and 85 ppm, respectively. Large concentrations are not restricted to lakes of the study area, however. Boron is an abundant minor-element component of closed-basin lakes throughout the Western United States (Whitehead and Feth, 1961, table 1); several lakes in the Western States contain even greater relative and absolute amounts than do the lakes in south-central Oregon.

The only available information on the boron content of streams in the study area is the analysis of a sample collected August 7, 1963, from Chewaucan River at Valley Falls (dissolved-solids content, 102 ppm; discharge, about 20 cfs), which shows only 0.08 ppm of boron.

The boron content of ground water is not much better known. Hot springs in the study area contribute some boron; measured concentrations in four samples ranged from 1.0 to 9.9 ppm (table 30). No data are available for nonthermal and warm springs—except Ana Springs, which yields about 0.5 ppm boron (analysis 20b, table 28). Sampled well waters not associated with hot-spring activity characteristically contained less than 1 ppm, and some contained almost none (table 31).

The abundance of boron in the saline lakes of south-central Oregon is attributable to an adequate supply of the constituent and to its solubility in the very soft waters that are characteristic of the lakes. Not all the boron that enters the lakes necessarily remains in solution, however. Boron, though a mobile component in many hydrochemical environments, is not immune to incorporation within organic and clay-mineral phases (Rankama and Sahama, 1950, p. 488; Oborin and Zalkind, 1964; Harder, 1964).

The ultimate source of boron in the lakes is conjectural; however, the volcanic environment of the closed basins and the characteristic association of boron (as well as chloride and fluoride) with volcanic activity suggests such a source. An extensive part of the Western United States—which includes the study area—may be peculiar in this regard. White (1957, p. 1679) stated that "Data on the boron content of glassy volcanic rocks * * * and of thermal waters * * * suggest that California, western Nevada, and southern Oregon constitute a high-boron province."

TRACE ELEMENTS

Only meager data are available on the trace-element content of closed lakes and their tributaries in south-central Oregon. Spectrographic analyses for 17 elements were performed on samples collected June 12, 1962, from Summer and Goose Lakes and from the Chewaucan River, and collected January 12, June 12, and September 17, 1962, from Lake Abert (table 29).

Among the 17 trace elements tested for in the lake-water samples, only five—aluminum, iron, molybdenum, nickel, and vanadium—occurred in amounts consistently greater than the lower limits of quantitative determination. Other elements whose concentrations were measurable in one or two of the five lake-water samples are cobalt, manganese, lead, and titanium. Largest measured amounts, in parts per billion, of the nine constituents are tabulated below:

[>, greater than; ≈, about, or nearly equal to]

Element	*Parts per billion*
Aluminum (Al)	270
Cobalt (Co)	19
Iron (Fe)	>96
Lead (Pb)	23
Manganese (Mn)	≈4.8
Molybdenum (Mo)	>48
Nickel (Ni)	17
Titanium (Ti)	≈1.9
Vanadium (V)	77

Maximum concentrations for all but one of the nine constituents occurred in Lake Abert (the exception, 19 ppb of cobalt, occurred in Summer Lake).

Six elements were abundant enough to be determined quantitatively in the lone sample from the Chewaucan River (table 29), although the relative abundances may not be at all representative because the dissolved-solids content (193 ppm) is about 1.6 times the estimated average. Nonetheless, the amounts may suggest the general order of magnitude in stream inflow compared with that in the lakes themselves.

A comparison of the relative amounts (expressed as percentages of the total dissolved-solids content) of several trace elements in the samples collected in June 1962 from the Chewaucan River and from Goose, Summer, and Abert Lakes is given in table 19. The analyses, which are arranged in order of increasing dissolved-solids content, show few consistent trends of trace-element enrichment or depletion. (The same is true for the analyses of

TABLE 19.—*Relative amounts of six trace elements in samples from Chewaucan River near Valley Falls and Goose, Summer, and Abert Lakes, June 12, 1962*

[Element data shown as percentage of dissolved solids multiplied by 10^5. All data recalculated from table 29. <, less than]

Constituent	Chewaucan River near Valley Falls	Goose Lake	Summer Lake	Lake Abert
Aluminum (Al)	460	87	270	16
Cobalt (Co)	78	<11	30	<1.0
Iron (Fe)	3,300	40	24	18
Molybdenum (Mo)	21	50	70	2.6
Nickel (Ni)	150	13	3.0	3.5
Vanadium (V)	300	110	2.6	16
Dissolved-solids content, in parts per million	193	1,270	6,270	49,100

three Lake Abert samples of different dissolved-solids content. See table 8.) The lack of clear and consistent trends may reflect the basin-to-basin differences in the chemical character of inflow or the different rates and forms of biologic and non-biologic reactions within the lakes. (See, also, discussion on reliability of trace-element data, p. B56.)

On the assumption that data in tables 8 and 19 are at least semiquantitatively representative of the trace-element content of the lakes and stream, several general characteristics are indicated by the percentages. Five of the elements are substantially depleted as the dissolved-solids content increases from 193 ppm (Chewaucan River near Valley Falls) to 1,270 ppm (Goose Lake); only molybdenum is enriched. Relative (percentage) amounts of all six trace elements are significantly less in saline Lake Abert than in either Chewaucan River near Valley Falls or comparatively dilute Goose Lake. Depletion mechanisms doubtless include (1) biologic uptake as trace nutrients (cobalt, iron, molybdenum, and vanadium, among others) (Hutchinson, 1957, p. 824, 826; Oborn, 1960, p. 111; Rankama and Sahama, 1950, p. 598–600), (2) precipitation in a reducing environment (cobalt, iron, and vanadium, among others), and (3) diagenetic mineral alteration (aluminum).

LOCATION SYSTEM

The location method used in this report is based on the rectangular system of land division. For example, in the symbol 33/21–2M, the two numbers preceding the dash indicate the township and range south and east, respectively, of the Williamette base line and meridian (T. 33 S., R. 21 E.) in Oregon. The last number after the dash indicates the section (sec. 2), and the letter "M" denotes the specific 40-acre tract among the 16 tracts within section 2, using letter designations, as shown in figure 37.

Location symbols for the California part of Goose Lake basin indicate the township and range north and east of the Mount Diablo base line and meridian. They are distinguished from locations in Oregon by inclusion of the letters "N" (north) and "E" (east) as parts of the symbol (for example, 45N/14E–16J).

RECORDS OF LAKE-SURFACE ALTITUDE

Data for studied lakes are presented as follows: Lake Abert (table 20), Summer Lake (table 21), Goose Lake (table 22), Silver Lake (table 23), Malheur and Harney Lakes before 1900 (table 24), Malheur Lake after 1900 (table 25), Harney Lake after 1900 (table 26), and Crump, Hart, and Bluejoint Lakes (table 27).

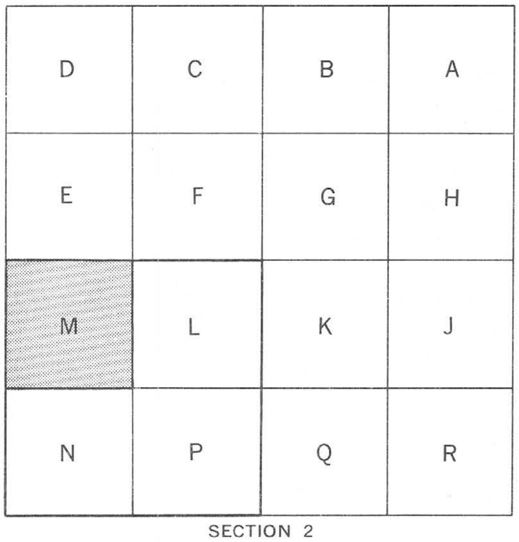

FIGURE 37.—Rectangular system of land division, showing letter designations of the sixteen 40-acre tracts within a given 1-square-mile section. For example, the location 33/21–2M referred to in text (patterned tract shown above) is the NW¼SW¼ sec. 2, T. 33 S., R. 21 E., in Oregon.

CHEMICAL ANALYSES

METHODS OF ANALYSIS

Analytical determinations performed during the period of intensive reconnaissance study, April 1961–June 1963, are, for the most part, those used for standard water analysis by the U.S. Geological Survey (Rainwater and Thatcher, 1960). Colorimetric determinations employed a Beckman model "B" spectrophotometer, and flame-photometric determinations utilized a similar instrument with a flame attachment. The ranges of values determined in the Geological Survey's Portland, Oreg., laboratory for the constituents and properties of closed-basin waters of south-central Oregon during the study are as follows:

[Data reported in parts per million except as indicated]

Constituent or property	Smallest value	Largest value
Silica (SiO_2)	9.1	207
Calcium (Ca)	1.4	59
Magnesium (Mg)	.3	44
Sodium (Na)	3.2	28,400
Potassium (K)	1.6	752
Bicarbonate (HCO_3)	35	5,930
Carbonate (CO_3)	0	9,460
Sulfate (SO_4)	.2	990
Chloride (Cl)	.0	25,000
Fluoride (F)	.0	13
Bromide (Br)	1	101
Nitrate (NO_3)	.6	1.2
Orthophosphate (PO_4)	.12	101
Boron (B)	.51	85
Specific conductance (micromhos at 25° C)	56	85,100
pH	6.8	9.7
Density at 20° C	---	1.058

The actual methods used and the refinements made necessary by the unusual character of the more saline samples are summarized below. Reference is made throughout to the detailed analytical procedures described by Rainwater and Thatcher.

Silica.—Silica content was determined colorimetrically (Rainwater and Thatcher, 1960, p. 259) on all samples containing less than 100 ppm of SiO_2, whereas gravimetric procedures (Rainwater and Thatcher, 1960, p. 261) were used for most concentrations exceeding that value (Abert and Summer Lakes). All samples were filtered through 0.45-micron Millipor pads as soon as possible after collection (usually within 1 week), and were stored in polyethylene bottles to prevent silica pickup from the conventional borosilicate glass containers. When dilutions were necessary prior to colorimetric determination, they were made immediately before the analysis was made because a significant amount of silica pickup was noted in the dilutions stored in conventional volumetric flasks, owing to the caustic high-pH nature of the more saline waters. (Of course, the error introduced by such pickup would be magnified even more by the dilution factor.)

Refinements employed as part of the gravimetric determination were as follows:

1. 100-ml sample aliquots were used, even though the resulting dissolved material totaled as much as 8 grams. The abundance of salts necessitated extreme care, but did not seem to alter the analytical accuracy of the determination.
2. Silica was determined colorimetrically from the residual filtrate (produced by means of step 8 of Rainwater and Thatcher's procedure), and the measured quantity was a significant part (3 to 10 percent) of the total silica. However, because of low silica concentrations in the presence of abundant orthophosphate in the filtrates (measured PO_4 concentrations in Lake Abert were as much as 101 ppm during the period of study), an arithmetic correction was necessary to allow for enhancement of the molybdate-blue color from orthophosphate. Using cells with a 10-mm optical depth, the amount of enhancement was found to be about 0.13 absorbency units per milligram of orthophosphate in the 10-ml aliquot. Thus, if the initial 100-ml portion contained 8.0 mg of PO_4 (equivalent to 80 mg/l in the original water sample) and the filtrate were diluted to 250 ml, a 10-ml aliquot thereof would contain 0.32 mg of PO_4, and the absorbency-correction factor would be -0.042 units. A correction of this type is unusual, necessary only when the concentrations of orthophosphate are large; most natural waters contain less than 1 ppm of orthophosphate and do not require gravimetric techniques for the determination of silica.

Calcium and magnesium.—Determinations for calcium and magnesium were made by using normal complexometric procedures (Rainwater and Thatcher, 1960, p. 127, 174, 197) for samples containing less than 10,000 ppm of dissolved solids. However, the reliability of values, especially for calcium, at salinities exceeding about 2,000 ppm is questionable. Above 10,000 ppm, the complexometric determination for calcium plus magnesium (results of which are expressed as hardness, in terms of parts per million of calcium carbonate) seems to give good semiquantitative results. This method, therefore, was used on several samples in preference to the expensive, time-consuming permanganimetric and pyrophosphate methods (Rainwater and Thatcher, 1960, p. 129, 198). In fact, the more costly methods were used only on sample 1f (table 28).

Sodium and potassium.—Sodium and potassium were measured using conventional flame-photometric techniques (Rainwater and Thatcher, 1960, p. 55). Samples were diluted when necessary to bring the amounts of sodium and potassium below 50 and 10 ppm, respectively. As with the determination of silica, dilutions were made shortly before analysis to prevent sodium pickup from the sodium borosilicate glass of volumetric flasks. Because the emission intensity of the potassium flame is enhanced by accompanying sodium, the amount of sodium in standards, blanks, and samples or dilutions thereof was augmented, as necessary, to obtain a constant background. This was accomplished by adding as much as 5.00 ml of a 2,000-ppm sodium standard to 25.00 ml of the sample, dilution, standard, or blank. The final aliquot volume was then brought to 30.00 ml by the addition of distilled water.

Each sample or dilution thereof was analyzed in combination with standards containing slightly smaller and greater sodium or potassium concentrations. This technique of close bracketing helped to ensure the accuracy of results, and it permits calculations to be made from simple proportionalities.

Carbonate, bicarbonate, and pH.—Carbonate, bicarbonate, and pH were determined in the laboratory by use of the conventional potentiometric method (Rainwater and Thatcher, 1960, p. 94) and a Beckman pH meter (model H–2). For samples containing more than about 75 epm of carbon species, a sulfuric-acid standard of 10 times the usual ($0.01639N$) strength was employed as the titrant.

Sulfate.—Sulfate was determined by one of two methods, depending on the amount present in, and the chemical character of, the sample. For dilute waters the visual thorin method (Rainwater and Thatcher, 1960, p. 279) was employed. However, modifications of the procedure listed by Rainwater and Thatcher (1960, p. 280) were used by the U.S. Geological Survey's Portland laboratory for the routine determination of sulfate. The following modifications were made (keyed to the procedural steps listed by Rainwater and Thatcher):

Step 1.—The cation ion-exchange resin was first washed with distilled water before rinsing with sample.

Step 2.—(Identical with the second procedural step of Rainwater and Thatcher, 1960, p. 283.)

Step 3.—A volume of deionized sample (10-ml maximum) containing less than 5 mg of sulfate was pipeted into a porcelain evaporating dish. Excessive amounts of chloride interfere with a visual determination: a maximum of 1,000 ppm chloride is tolerated, but below that amount, the chloride-to-sulfate ratio must be less than 20:1. Where the chloride content of reconnaissance samples did not meet the qualifications, sulfate was determined gravimetrically (Rainwater and Thatcher, 1960, p. 283).

Steps 4, 5, and 6.—Ethyl alcohol, rather than dioxane, was used as the organic medium. It was combined and stored with the thorin indicator solution (1.3 ml of 0.2 percent thorin to 1.0 liter of alcohol), rather than added separately at the time of determination. Forty milliliters of the alcoholic indicator solution was added to the deionized sample of step 3 above, and the pH was then adjusted to about 4.5, using a pH meter and 0.1 or 0.5 normal sodium hydroxide, or 2-percent hydrochloric acid.

Step 7.—A blank was carried through the entire procedure and titrated with samples. Its titration volume (generally less than 0.06 ml) was subtracted from the sample titration volumes for more accurate low-concentration results.

Chloride.—Concentrations of chloride were measured using the Mohr volumetric method (Rainwater and Thatcher, 1960, p. 141). For samples containing only a small amount of chloride (less than 10 ppm), the determinations were made on 100-ml aliquots evaporated to about 50 ml. Where chloride concentrations exceeded about 1,500 ppm, dilutions were made to maintain the amount of chloride in a 25-ml aliquot at 40 mg or less.

Fluoride.—Determination of fluoride was by the colorimetric Zirconium-Eriochrome Cyanine R method (Rainwater and Thatcher, 1960, p. 163). Preliminary dilutions were made, when necessary, to keep the dissolved-solids content of samples below about 8,000 ppm.

Bromide.—The concentrations of bromide plus iodide and of iodide alone were initially determined by the conventional oxidation method (Rainwater and Thatcher, 1960, p. 121). The determination of bromide plus iodide is considered accurate, but later determinations of iodide alone (in 1964), by the more accurate photometric method, showed that actual concentrations of iodide were far less than those indicated by the oxidation technique. (For example, results of the oxidation method gave an iodide concentration of about 3 ppm in Lake Abert, whereas the photometric method indicated only 0.2–0.5 ppm.) Therefore, bromide values listed in table 28 represent the concentration of bromide plus iodide (oxidation method), corrected for the small amounts of iodide that later were shown to be typical.

Nitrate.—The nitrate content in dilute samples was measured colorimetrically by use of the phenoldisulfonic acid method (Rainwater and Thatcher, 1960, p. 216), whereas the more conventional reduction technique (p. 219) was used for those samples containing more than 50 ppm of chloride.

Orthophosphate.—Orthophosphate was determined colorimetrically by use of the phosphomolybdate method (Rainwater and Thatcher, 1960, p. 245). However, several minor refinements of the basic procedure described by Rainwater and Thatcher (1960, p. 247) were employed to increase the analytical accuracy. To prevent deterioration, all reagents were prepared with extreme care immediately prior to analysis, and were then carefully added to the sample aliquots by means of pipets. (Use of volumetric pipets aided accuracy by reducing the small variations in reagent volume which cause sizable differences in sample absorbency.) The digestion period between the addition of the molybdate and stannous chloride reagents was kept at 7.0 minutes. Finally, the determination of sample absorbency was made exactly 20 minutes after the stannous chloride reagent had been added. Exact timing was vital, for the absorbency "plateau" that follows color development but precedes color deterioration was characteristically attained during the period between about 15 and 25 minutes after the stannous chloride had been added.

Boron.—Concentrations of boron were determined by the colorimetric dianthrimide method (Rainwater and Thatcher, 1960, p. 113).

Specific conductance.—Measurements of specific conductance were made using the Wheatstone bridge method (Rainwater and Thatcher, 1960, p. 275) and a U.S. Geological Survey instrument. The conductivity cell had a constant of 0.345.

Trace elements.—Trace element contents of six samples (table 29) were determined by means of the spectrochemical separation-concentration technique perfected by William D. Silvey of the U.S. Geological Survey (Silvey and Brennan, 1962). The analyses were performed by Silvey and his coworkers in the U.S. Geological Survey laboratory at Sacramento, Calif.

ACCURACY OF ANALYTICAL RESULTS

The overall accuracy of chemical analyses performed as part of this study is good; however, several minor points deserve mention. Chloride concentrations smaller than 1 ppm are of only semiquantitative accuracy when determined by the conventional Mohr volumetric method, due to the very small titration volumes. The difficulty of accurate determination is compounded by natural water color, which is intensified during evaporation of a 100-ml aliquot to 50 ml prior to titration.

After the reconnaissance analytical work had been completed, analysts discovered that even the very small chloride concentrations (much less than the 50-ppm maximum indicated on p. B55) interfered with the accurate determination of nitrate by the phenoldisulfonic method. Thus, the apparent nitrate values shown in table 28 for samples 14b, 31d, 31e, and perhaps for several earlier samples as well, may be somewhat less than the amounts of nitrate actually present.

The chemical changes that occurred within samples during the interim between the time they were collected and analyzed may also have caused some inaccurate analytical results. Several of the potentially most important chemical changes are discussed briefly below.

The determination of large silica concentrations in high-pH waters, such as those of Abert and Summer Lakes, is subject to some error because the solubility of amorphous silica is strongly dependent on temperature (Morey and others, 1964, fig. 1). Thus, any turbid sample collected at a relatively low temperature (35°–50° F) and later filtered at laboratory temperature may have gained a significant amount of dissolved silica in the interim. The effect was minimized by filtering the samples in the laboratory as soon after collection as possible. (Field filtration was difficult or impossible with available equipment, owing to the very fine grained particles in turbid suspension.)

All considerations of pH and of carbonate to bicarbonate ratios, based on data shown in table 28, are necessarily tentative because the analytical determinations were performed in the laboratory as much as 1 month after sample collection. Both parameters are subject to rapid change, owing to their variability with temperature change and with partial pressure of CO_2, biologic activity, and reactions between the water sample and accompanying sediment. Similar caution should be applied to the interpretation of the laboratory-determined values given for calcium in saline samples with high pH and abundant carbonate because of possible loss or gain of alkaline-earth carbonates in solution due to solubility considerations.

Nitrate and orthophosphate were determined on samples that were neither treated with preservative at the sampling site nor refrigerated between collection and analysis. Thus, because of biologic activity in the samples after collection, the amounts of nitrate and orthophosphate reported for streams and dilute lake waters may not accurately reflect the amounts actually present at the time of sampling. Orthophosphate concentrations exceeding about 1 ppm in the more saline lakes probably are accurate.

Finally, the limitations imposed on the significance of spectrographic trace-element analyses (table 29) by inadequate sample-treatment techniques may be important. For example, large amounts of aluminum reported in the Summer Lake analysis may be correlated with (1) the pronounced turbidity of the sample when collected; (2) the long interval between collection and filtration (about 30 hours); and (3) the presence of a near-colloidal suspension in the sample even after vacuum filtration through 0.45-micron pore-size pads. In other words, the reported aluminum content, and perhaps that of other trace elements as well, may represent components of the fine dispersion, rather than comprising true solutes. Alternatively, elements originally present in the sample as true solutes may have subsequently been sorbed by the clay minerals in suspension, or depleted or enriched owing to biologic activity or decay within the sample under conditions of varying temperature, CO_2 pressure, and pH during the period between collection and filtration. Thus, analytical results in table 29 may not represent the exact trace-element content of the aqueous phase of a sampled water. However, they are considered to give at least a semiquantitative indication of the trace-element characteristics.

TABLES OF CHEMICAL ANALYSES

A compilation of chemical analyses is presented in tables 28–31, as follows: Table 28 gives results of analyses for the lakes and their tributary streams. Table 29 shows the trace-element content of samples from Abert, Summer, and Goose Lakes and from the Chewaucan River. Tables 30 and 31 contain representative chemical analyses of water from springs and wells in the several topographically enclosed basins. Sample-collection sites are numbered in each table (lakes and streams, 1–41; springs, 101–111; wells, 112–136), and the locations of many are shown on plates 1 and 2. In addition, location of each site is indicated by the number and letter code of the rectangular system of land division (p. B53).

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TABLES 20–31

TABLE 20.—*Altitude of water surface in Lake Abert, 1843–1963*

[All altitudes through June 1951 determined on the basis listed; those since June 1951 determined at gage on east shore of lake]

Year	Date	Altitude [1] (ft)	Basis
1843	Dec. 20	[2] 4,256	Sketch by Capt. J. C. Fremont, discoverer.
1861-62		Presumed high	Period of generally heavy runoff.
1865	Aug. 21		Large body of water (diary of George Conn, with military party).
1881		Probably high	Goose Lake filled to outlet.
1890		Probably high	Generally very wet period following dry years.
1904		Probably high	Wet year; heavy runoff.
1905	June 6		Ivan Landes set copper bolt in bedrock on southwest shore at an altitude of 4,261.23 ft; lake must have been several feet lower.
1906	October	4,251	Areal extent of lake, as shown by notes of Eastern Oregon Railroad survey, east shore.
1906	Autumn	4,251	Approximate estimate from photograph by Waring (1908, pl. X). Water about 5 ft below level of July 3, 1963.
1915	Oct. 4	4,254.2	Leveling from Landes' copper bolt.
1917	Apr. 29	4,254.2	Do.
	May 15	4,254.6	Do.
	July 8	4,254.5	Do.
	Sept. 25	4,253.5	Do.
1918	Apr. 28	4,253.5	Do.
	June 15	4,252.9	Do.
1919	May 18	4,251.1	Leveling from Landes' copper bolt; may be too low because of southwest wind.
1920	Aug. 7	4,249.1	Levels to water in river at south end of lake, allowing 0.2 ft drop to lake.
1921	Mar. 26	4,250.2	Leveling from Landes' copper bolt.
	Aug. 24	<4,249.5	Leveling from Landes' copper bolt; unable to reach lake because of mud.
1924	Aug. 14	≈4,244	Dry, (except for small pools fed by springs and Poison Creek) for first time in memory of old inhabitants (Lake County Examiner, news report).
1926, 1930, 1931, 1933, 1934, 1937.			Lake practically dry, in late summer or autumn of each year, according to local residents; confirmed by study in 1964 of water budget for previous years.
1931	October	≈4,244	Observations by Antevs (1938, p. 19).
1938			A wet year; lake probably rose moderately and has since contained water.
1939	July 15	4,248.2(±0.2)	Photograph, by S. T. Harding, of boulder later used to hold gage.
1941	June	4,247.5(±1.0)	Lake outline on map of Fremont National Forest, 1954, and comparison with soundings of 1959.
1947	Aug. 2	4,247.5(±1.0)	Aerial photograph by U.S. Forest Service of extreme south end of lake.
1950	July 21	4,248.02	Leveling from bench mark, east shore.
	Nov. 11	4,246.60	Do.
1951	Mar. 31	4,249.47	Do.
	June 5	4,250.52	Do.
	June 23	4,250.13	Leveling from bench mark, east shore. Gage set on boulders on east shore, 10 miles northeast of Valley Falls, used for all later water levels; zero at 4,247.78 ft.

Year	Date	Altitude [1] (ft)
1951	Aug. 10	4,249.10
1952	Jan. 12	4,248.80
	May 3	4,251.15
	June 4	4,252.34
	June 25	4,252.78
	Oct. 16	4,251.86
1953	Feb. 26	4,252.74
	Mar. 9	4,252.7
	Apr. 19	4,252.95
	Apr. 21	4,252.97
	May 8	4,254.03
	May 25	4,253.67
	May 30	4,253.84
	July 14	4,254.58
	July 20	4,254.49
	July 31	4,254.38
	Sept. 27	4,253.56
	Oct. 8	4,253.53
1954	Feb. 27	4,253.98
	Mar. 14	4,254.26
	Apr. 17	4,255.08
	Apr. 28	4,255.13
	May 23	4,255.64
	June 16	4,255.63
	June 26	4,255.43
	July 11	4,255.43
	Sept. 15	4,254.38
	Sept. 22	4,254.48
	Nov. 22	4,254.02
1955	Jan. 17	4,253.97
	Mar. 8	4,254.03
	May 1	4,254.08
	May 10	4,253.93
	July 9	4,253.26
	Aug. 5	4,252.78
	Sept. 16	4,253.08
	Oct. 6	4,252.78
1956	Jan. 22	4,253.28
	Feb. 12	4,253.84
	Feb. 16	4,253.84
1956	Mar. 8	4,253.88
	Apr. 4	4,254.73
	Apr. 22	4,255.30
	May 31	4,257.28
	June 2	4,257.36
	June 20	4,258.6
	July 2	4,258.2
	July 17	4,258.02
	July 28	4,257.84
	Aug. 5	4,257.68
	Aug. 13	4,257.66
	Oct. 15	4,257.28
	Nov. 30	4,257.18
1957	Mar. 2	4,257.58
	Mar. 3	4,258.28
	Apr. 22	4,258.53
	May 9	4,258.66
	June 15	4,258.98
	July 26	4,258.47
	Aug. 22	4,258.00
	Oct. 22	4,256.78
1958	May 5	4,259.12
	May 30	4,259.88
	June 22	[3] 4,260.48
	July 9	4,260.43
	July 25	4,260.23
	Nov. 7	4,259.13
1959	Jan. 30	4,259.2
	Apr. 8	4,259.12
	May 7	4,258.92
	May 19	4,258.98
	May 20	4,258.82
	Oct. 9	4,257.0
	Nov. 11	4,256.6
	Nov. 13	4,256.65
1960	June 3	4,256.25
	July 28	4,255.3
	Aug. 10	4,254.8
1961	Feb. 15	4,254.32
	Apr. 25	4,253.93
1961	June 21	4,253.41
	June 23	4,253.37
	June 27	4,253.31
	Aug. 18	4,252.72
	Sept. 7	4,252.04
	Sept. 26	4,251.9
	Sept. 29	[4] 4,251.81
	Oct. 10	4,251.69
	Oct. 20	4,251.69
	Oct. 31	4,251.67
	Nov. 10	4,251.65
	Nov. 20	4,251.62
	Nov. 30	4,251.69
	Dec. 10	4,251.77
	Dec. 20	4,251.76
	Dec. 31	4,251.86
1962	Jan. 10	4,251.87
	Jan. 20	4,251.92
	Jan. 31	4,251.93
	Feb. 10	4,252.07
	Feb. 20	4,252.23
	Feb. 28	4,252.08
	Mar. 10	4,252.24
	Mar. 20	4,252.22
	Mar. 31	4,252.23
	Apr. 10	4,252.27
	Apr. 20	4,252.31
	Apr. 30	4,252.21
	May 10	4,252.16
	May 20	4,252.17
	May 31	4,252.45
	June 10	4,252.40
	June 20	4,252.23
	June 30	4,252.03
	July 10	4,251.83
	July 20	4,251.65
	July 31	4,251.45
	Aug. 10	4,251.26
	Aug. 20	4,251.15
	Aug. 31	4,250.94
1962	Sept. 10	4,250.78
	Sept. 20	4,250.65
	Sept. 30	4,250.52
	Oct. 10	4,250.60
	Oct. 20	4,251.11
	Oct. 31	4,251.19
	Nov. 10	4,251.19
	Nov. 20	4,251.26
	Nov. 30	4,251.30
	Dec. 10	4,251.56
	Dec. 20	4,251.76
	Dec. 31	4,251.87
1963	Jan. 10	4,252.02
	Jan. 20	4,251.95
	Jan. 31	4,252.02
	Feb. 10	4,252.56
	Feb. 20	4,252.80
	Feb. 28	4,252.93
	Mar. 10	4,253.12
	Mar. 20	4,253.09
	Mar. 31	4,253.13
	Apr. 10	4,253.28
	Apr. 20	4,253.63
	Apr. 30	4,253.90
	May 10	4,254.19
	May 20	4,254.55
	May 31	4,254.83
	June 7	4,254.89
	July 3	4,254.88
	Aug. 6	4,254.47
	Aug. 14	4,254.36
	Oct. 21	4,253.58
	Nov. 12	4,253.58
	Dec. 6	4,253.72
	Dec. 26	4,253.63

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[1] Altitudes are based on the datum of 1929, later adjustments of the level net being disregarded. Many of the lake-level readings were made by personnel of U.S. Soil Conservation Service and Oregon State Engineer.

[2] Approximate minimum level in 1843 inferred from sketch showing lake covering the beaches that were exposed in 1915.

[3] Highest stage ever observed.

[4] Continuous records available from Sept. 29, 1961, to June 7, 1963.

TABLE 21.—*Altitude of water surface in Summer Lake, 1905–63*

[Observations made by U.S. Geological Survey personnel, except as indicated. Altitudes based on supplementary adjustment of level network of 1947. Levels during period January 1905–May 1959 based on copper bolt in rock at southwest corner of lake, 14 miles south of present Summer Lake Post Office (sec. 25, T. 32 S., R. 16 E.). Permanent reference marks set September 2, 1959, by leveling at Hunters Point, on west shore of lake 10 miles south of Summer Lake Post Office; later records of lake altitude obtained at this site. Altitude entries followed by the letter "a" (4,145.2a) were approximated; those followed by the letter "e" (4,144.5e) were estimated]

Date	Altitude (ft)	Remarks
1905		
Jan. 9	4,151.0	Gage and reference mark set.
Feb. 25, 26	4,151.4	Highest level ever observed.
Mar. 21, Apr. 5	4,151.4	Do.
1912		
Nov. 10	4,151.3	
1915		
Oct. 3	4,150.12	Beach line and top of alkali, alt 4,151.2 ft.
1918		
Apr. 29	4,150.48	
1920		
Mar. 26	4,149.64	
1921		
Mar. 9	4,149.42	
1929–34		
Summers	--------	Lake low but not dry (Antevs, 1938, p. 19).
1931		
Summer	--------	Lake dry; note on Fremont National Forest Map, 1932.
October	--------	Lake at lowest known level; 2 mi wide and reached a point 2 or 3 mi short of normal south end (Antevs, 1938, p. 19).
1937		
Sept. 22	--------	Lake dry except for small sump.
1941		
May 1–June 10	--------	Field party of Cadastral Engineer, Bureau of Land Management, sounded depths over lake bottom. Greatest depth of water was less than 2.5 ft; water level probably was between altitudes of 4,146 and 4,147 ft.
1944		
Sept. 1	4,146.2	Allison (1945, p. 791).
1946		
Aug. 8	4,145.2a	Deduced from aerial photograph, U.S. Forest Service, and from comparison with level notes for Sept. 30, 1961.
1948		
(No date)	--------	Nearby farmers in 1950 reported lake was dry about 1948.
1949		
September	--------	"Practically dry" (Harbeck and others, 1951, p. 29).
1950		
July 23	4,145.5a	Level party could not reach water because of mud.
Summer minimum	4,144.5e	Area about 10 acres (A. B. Claggett, Oregon State Game Comm., oral commun., 1961).
1951		
June 6	4,147.20	Recent high-water mark at an altitude of 4,148.1 ft.
1952		
April	4,149a	Highest in many years (A. B. Claggett, oral commun., 1961).
June 30	4,147.43	
1953		
Apr. 24	4,147.57	
Sept. 9	4,145.8a	Deduced from aerial photograph.
Oct. 8	4,144.91	
1954		
Apr. 28	4,147.93	
Sept. 23	4,146.03	
1955		
Mar. 10	4,146.7	
1956		
Aug. 10	4,147.71	
1957		
Apr. 23	4,148.73	
Oct. 22	4,147.25	
1959		
Jan. 30	4,148.2	By hand level.
May 4	4,148.17	
21	4,148.06	Depth 3.0 ft, ½ mi east of Hunters Point.
Sept. 2	4,146.05	
Nov. 11	4,146.08	
1960		
July 27	4,145.62	
1961		
Apr. 25	4,146.33	White crust at an altitude of 4,148.97 ft.
June 21	4,145.86	
Aug. 14	--------	Nearly dry; lake covered about 10 acres (A. B. Claggett, oral commun., 1962).
Sept. 30	4,144.86	West edge of lake about ⅔ mi east of Hunters Point.
1962		
Jan. 11	4,146.38	
Apr. 16	4,147.00	
May 28	4,146.39	High watermark for 1962 at an altitude of 4,147.0 ft.
July 26	4,145.56	
Aug. 18	4,145a	
Sept. 18	--------	Nearly dry; south edge of lake about 2 mi northeast of Hunters Point.
Oct. 30	4,146.57	
1963		
July 2	4,147.97	
Aug. 20	4,147.23	

TABLE 22.—*Altitude of water surface in Goose Lake, 1832–1963*

[Data for 1832–86 from Harding (1965), and page numbers listed in parentheses for those years refer to his report. Data for 1936–41 from S. T. Harding (written commun., 1962). Records for 1945–63 based chiefly on occasional readings of gages or on leveling from bench mark H-92 at New Pine Creel (alt 4,720.499 ft, datum of 1929). Gage used in period 1947–49 was unstable; hence, results may be in error a small fraction of a foot]

1832, October.—4,701–4,706 ft (p. 24).

1846.—About 4,695 ft (p. 26).

1849, late summer.—4,694–4,695 ft (p. 26).

1854.—About 4,698 ft (p. 26).

1868.—Slight overflow (4,716 ft; p. 32).

1872.—About 4,711 ft (p. 27).

1874.—About 4,713 ft (p. 27).

1877.—About 4,708 ft (p. 27).

1879, 1880.—About 4,711 ft (p. 27).

1881.—Brief overflow during windstorm (p. 27).

1882.—About 4,714 ft (p. 27).

1886.—About 4,713.5 ft (p. 27).

About 1895.—About 4,715 ft (C. T. Watkins, Alturas, oral commun., 1956).

1904, July.—About 4,715 ft (from survey made by U.S. Bur. Reclamation).

1914, August.—About 4,713 ft.

1914–34.—Precipitation was below average in every water year except 1925 and 1927. Lake was dry at times in each calendar year, 1926 and 1929–34 (Antevs, 1938, p. 18–19).

1936, October.—About 4,694 ft, based on news account stating that lake then contained more water than in any October during previous 5 years.

1937.—Lake reported practically dry late in year.

1938–41.—Lake level was about 4,700 ft in 1938, 4,698 ft in 1939, and 4,699 ft in 1941.

Date	Altitude
1945	
Oct. 30	4,699.71
Nov. 30	4,699.32
1946	
Mar. 22	4,700.74
Apr. 3	4,700.86
May 9	4,700.90
June 4	4,700.98
July 9	4,700.19
16	4,700.17
Aug. 9	4,699.87
Sept. 5	4,699.32
Oct. 8	4,698.93
Nov. 16	4,698.89
1947	
Mar. 15	4,699.3
Apr. 14	4,699.4
May 5	4,699.1
June 4	4,698.8
July 11	4,698.4
Aug. 9	4,697.7
Sept. 9	4,697.6
Oct. 11	4,697.3
Nov. 19	4,697.4
Dec. 11	4,697.4
1948	
Apr. 19	4,698.1
May 10	4,698.2
June 7	4,698.4
July 10	4,698.4
Aug. 5	4,697.7
Sept. 3	4,697.4
Oct. 6	4,697.5
Nov. 4	4,697.4
1949	
May 6	4,698.0
1949—Con.	
June 6	4,698.1
July 7	4,697.5
Aug. 9	4,697.4
Nov. 14	4,697.4
Dec. 6	4,697.4
17	4,697.5
1950	
Mar. 4	4,697.3
Apr. 7	4,697.5
May 8	4,697.6
June 5	4,697.7
July 6	4,697.5
Aug. 7	4,697.4
Nov. 13	<4,697
1951	
Apr. 2	4,697.8
June 21	4,698.3
1952	
June 24	4,700.96
1953	
Apr. 21	4,701.47
Oct. 7	4,701.19
8	4,701.15
1954	
Apr. 27	4,702.87
Sept. 23	4,700.85
1955	
Oct. 4	4,699.47
1956	
June 6	4,704.96
July 9	4,704.45
Aug. 11	4,703.98
1957	
Apr. 22	4,705.54
Oct. 24	4,703.94
1958	
Sept. 17	4,706.1
Oct. 16	4,705.8
Nov. 11	4,705.8
Dec. 9	4,706.0
1959	
Jan. 28	4,706.3±
Mar. 17	4,706.1±
Apr. 23	4,705.8
May 6	4,705.73
19	4,705.7
June 24	4,705.2±
July 13	4,704.8
21	4,704.7
Aug. 21	4,704.2
25	4,704.0
Sept. 16	4,703.7
Nov. 13	4,703.23
1960	
July 28	4,703.02
1961	
Apr. 26	4,702.15
June 22	4,701.51
Sept. 7	4,699.98
28	4,700.0
1962	
Jan. 13	4,699.81
Apr. 19	4,700.57
May 30	4,700.50
June 11	4,700.31
Aug. 17	4,699.4±
Sept. 3	4,698.57
Nov. 14	4,698.94
1963	
July 3	4,700.94

TABLE 23.—*Altitude of water surface in Silver Lake, 1861–1963*

[Datum used is that of 1929, with supplementary adjustment of 1947 (U.S. Coast and Geodetic Survey). Altitudes for 1905–17 were originally published in Water-Supply Papers 360, 410, and 460 (U.S. Geol. Survey, 1916, 1918, 1921), but were based on local datum 130.2 ft too high. Corrected values are shown in this table. Records for period 1905–21 were obtained in sec. 11, T. 29 S., R. 15 E., from staff gage or by leveling; those for period 1950–63 were obtained by leveling from bench mark on north shore, or from staff gage at inlet, in sec. 21, T. 28 S., R. 15 E., 5½ miles east of Silver Lake (town). Many of the readings were made by personnel of U.S. Soil Conservation Service and Oregon State Engineer. Additional readings for 1905, 1915, and 1956–60 are in files of the U.S. Geological Survey, Portland, Oreg.]

Date	Altitude (ft)
1861–1903	(1)
1904	
Floodmark	4,311.8
Sept. 17	4,310.36
1905	
Jan. 17	4,310.54
Feb. 27	4,310.8
Mar. 20	4,310.8
Apr. 6	4,310.8
May 9	4,310.7
June 8	4,310.5
1906	
Apr. 5	4,308.8
26	4,309.6
May 6	4,309.9
1908	
October	4,304.8
1912	
Nov. 11	4,307.09
1913	
Feb. 5	4,306.9
1914	
Aug. 2	4,306.47
Oct. 9	4,305.35
Nov. 2	4,305.28
1915	
July 19	4,303.90
Oct. 3	4,302.87
1916	
June 11	4,303.67
1917 [2]	
Aug. 24	4,300.78
1921 [2]	
May 10	4,302.65
15	4,302.54
Aug. 23	4,299.85
1951	
Aug. 10	4,299.21
1953	
Apr. 24	4,300.87
Oct. 9	4,300.79
1954	
Apr. 28	4,303.58
Floodmark	4,304.8
Sept. 23	4,303.32
1955	
Mar. 10	4,302.79
Oct. 7	4,300.1
1956	
May 31	4,307.9
1956—Con.	
Floodmark	4,308.9
July 28	4,307.88
Aug. 13	4,307.50
30	4,307.20
1957	
Apr. 17	4,307.34
29	4,307.34
May 15	4,307.61
31	4,307.89
June 7	4,307.74
July 24	4,306.84
Aug. 10	4,306.46
30	4,306.11
Sept. 11	4,305.91
30	4,305.80
Oct. 10	4,305.80
28	4,305.73
Nov. 12	4,305.68
27	4,305.63
Dec. 11	4,305.59
31	4,305.68
1958	
Jan. 13	4,305.76
27	4,305.68
1958—Con.	
Feb. 13	4,305.83
27	4,305.93
Mar. 14	4,306.33
31	4,306.45
Apr. 21	4,306.72
30	4,307.21
May 16	4,307.96
29	4,308.20
June 16	4,308.95
26	4,309.05
July 11	4,308.95
28	4,308.71
Aug. 19	4,308.25
Sept. 1	4,307.94
Sept. 17	4,307.74
30	4,307.63
Oct. 15	4,307.48
Nov. 7	4,307.31
19	4,307.31
Dec. 2	4,307.21
17	4,307.21
1959	
Jan. 7	4,307.15
15	4,307.18
1959—Con.	
Jan. 29	4,307.20
Feb. 10	4,307.21
27	4,307.21
Mar. 11	4,307.14
27	4,307.12
Apr. 16	4,306.85
May 4	4,306.62
7	4,306.70
20	4,306.51
June 1	4,306.37
11	4,306.19
29	4,305.86
July 15	4,305.46
29	4,305.26
Aug. 17	4,304.86
30	4,304.80
Sept. 3	4,304.56
29	4,304.42
Oct. 1	4,304.36
15	4,304.31
30	4,304.22
Nov. 11	4,304.21
27	4,304.11
Dec. 29	4,304.05
1960	
Feb. 10	4,304.24
18	4,304.11
Mar. 16	4,304.11
Apr. 3	4,304.03
May 5	4,303.81
31	4,303.59
June 17	4,303.27
July 27	4,302.59
1961	
Apr. 25	4,300.85
June 20	4,300.32
Aug. 11	Became dry.
1962	Dry.
1963	
July 4	4,300.32
September	Dry.

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[1] For the period 1861–1903 the descriptive references by Antevs (1938, pages cited below) give fragmentary data on lake extent or altitude. In 1861 (p. 12) Paulina Marsh was practically a lake, extending almost to present site of Silver Lake (town). In 1879 (p. 14) Silver Lake was 4 feet deep. In 1882 (p. 14) water had risen 6 feet since 1879, had a depth of 10 feet, and was confluent with Thorn Lake. From 1885 to 1889 (p. 15) water subsided, and lakebed became dry in 1889, exposing sagebrush presumed to have grown in an earlier dry period in the 1840's (p. 12). Heavy runoff in 1890 filled Silver Lake (p. 15), so that it overflowed into Thorn Lake and Christmas Lake Valley. In spring of 1904 (p. 16) Silver Lake filled, and overflow into Thorn Lake continued at least as late as September 17.

[2] In September or October 1917 the bed of Silver Lake became dry and was nearly or completely dry in each summer or autumn from 1917 to 1950. In summer of 1951, Paulina Marsh overflowed and several hundred acres of Silver Lake bed was flooded to shallow depth. Paulina Marsh again overflowed into Silver Lake in 1952, and the lake contained water thereafter until August 11, 1961. It was dry in 1962.

TABLE 24.—*Hydrologic references to Malheur and Harney Lakes, 1826–99*

[Data from U.S. Supreme Court (1932). All page numbers in parentheses refer to that report]

1826, November 1.—Peter Skene Ogden observed that "A small ridge * * * divides the fresh water [extension of Mud Lake] from the salt lakes [Harney Lake]. The lakes have no intercourse" (p. 1014–1059). Lack of overflow on that date does not necessarily mean that runoff in 1826 was below average; in fact, overflow to Harney Lake has never been observed as late as November 1.

1827, June 8.—Ogden again visited the area and noted that the water of Harney Lake was "very high. The waters of Sylvailles [Silvies] River and the lakes [Malheur and Mud] discharge into it" (p. 1014–1059).

1831, July.—John Work reported Harney Lake to be unusually high, possibly as compared to Ogden's report of 1826 (p. 1014–1059).

1853.—Malheur Lake was high, based on observation of depth at fords (p. 631).

1860.—Lt. Joseph Dixon prepared map showing the Silvies River flowing into Harney Lake (p. 1014–1059).

1873, December.—Malheur Lake about 2½ feet deep near midlake (p. 370).

1878.—Water near top of Sand Reef; none flowing to Harney Lake (p. 841).

1879.—Water 2 or 3 feet deep east of Sand Reef; none flowing to Harney Lake (p. 832).

1881, about May 1.—Water practically to top of reef, according to witness M. H. Brenton, who, with his foot, kicked out a small trench, allowing water to start flowing to Harney Lake. Others described the flow they saw as "a little bit of a stream" to "a stream 60 to 80 feet wide" (p. 836, 841).

Early descriptions of the Sand Reef as a barrier to the flow do not correspond to observations after 1916, when reef no longer was an effective barrier.

1882–83.—Water observed flowing from Mud Lake to Harney Lake (p. 836, 837); flow probably not continuous.

1887–89.—Dry years; Malheur Lake very low in 1889 (p. 400, 401, 561, 1085).

1894.—Malheur Lake very high (p. 843, 844, 926).

1895.—Malheur Lake very high; attempt made to open larger channel at Sand Reef to lower Malheur Lake level (p. 771–774, 850).

1899.—All lakes high; water flowing to Harney Lake at Sand Reef (p. 815–818, 846–848).

TABLE 25.—*Altitude of water surface at staff gages in Malheur Lake, 1932–62*

Altitude: Altitudes reported in feet above mean sea level. Lake dries at about 4,089 ft. Records are based on reports of the Bureau of Sport Fisheries and Wildlife (Fish and Wildlife Service, U.S. Dept. of the Interior) and (prior to 1922) of the Oregon State Land Board. Several additional readings in 1943, 1944, 1948, 1951, 1952, and 1953 are in files of the U.S. Geological Survey, Portland, Oreg. For records of the period 1903–31, refer to Piper, Robinson, and Park (1939, p. 129).

Gage at Narrows Bridge: Gage referred to U.S. Geological Survey bench mark WA-314 (alt 4,095.87 ft). Doubtful connection between Malheur Lake and Narrows gage below about 4,092 ft; none below 4,091.5 ft. Previously published records below that level are not representative of level of Malheur Lake.

Gage near Voltage: Gage in channel of the Donner und Blitzen River 2½ miles north of Voltage, datum at mean sea level (leveling by Bur. Sport Fisheries and Wildlife). Water level at gage is somewhat higher than lake level at times because of river flow, wind, and obstructions, such as tule growth. For records of the period 1921–31, refer to Piper, Robinson, and Park (1939, p. 130).

Date	Altitude (ft)
Gage at Narrows Bridge	
1943	
Feb. 28	(1)
Apr. 9	4,094.12
23	4,094.42
May 5	4,094.71
25	4,094.79
30	4,094.43
June 14	4,094.51
30	4,094.29
July 20	4,093.95
Aug. 7	4,093.55
27	4,092.97
Sept. 24	4,092.75
Oct. 15	4,092.71
Nov. 3	4,092.83
1944	
Mar. 3	4,093.11
Apr. 7	4,093.00
29	4,092.79
May 22	4,092.35
June 13	4,092.26
27	4,092.35
July 11	4,092.15
28	4,091.57
1945	
June 1	4,093.20
17	4,093.57
1945—Con.	
July 2	4,093.51
23	4,093.21
Aug. 10	4,092.85
28	4,092.47
Sept. 13	4,092.17
30	4,091.93
1946	
Jan. 28	4,092.86
Mar. 11	4,092.85
31	4,092.91
Apr. 20	4,092.91
May 24	4,093.00
June 10	4,092.83
25	4,092.73
July 11	4,092.39
24	4,092.01
1947	(2)
1948	
Aug. 3	4,092.39
21	4,091.93
Sept. 3	4,091.61
1949	
Apr. 4	4,091.86
12	4,092.23
27	4,091.93
May 12	4,091.81
1949—Con.	
May 24	4,092.08
June 4	4,091.97
29	4,091.55
1950	(3)
1951	
May 14	4,091.71
30	4,092.43
June 6	4,092.51
23	4,092.13
July 9	4,091.53
1952	
Apr. 18	4,092.62
23	4,094.17
May 2	4,094.58
12	4,095.14
26	4,095.25
June 4	4,095.11
17	4,094.88
30	4,094.86
July 18	4,094.52
31	4,094.28
Aug. 13	4,093.92
30	4,093.66
Sept. 15	4,093.52
29	4,093.26
Oct. 17	4,093.06
1952—Con.	
Nov. 1	4,092.99
28	4,092.96
1953	
Jan. 23	4,092.84
Feb. 13	4,092.90
26	4,092.82
Mar. 15	4,092.76
Apr. 4	4,092.58
28	4,092.46
May 18	4,092.52
28	4,092.85
June 9	4,093.34
26	4,093.66
July 15	4,093.45
29	4,093.18
Aug. 17	4,092.76
30	4,092.46
Sept. 8	4,092.30
30	4,091.90
Oct. 28	4,091.66
Dec. 3	4,091.89
1954	
Feb. 9	4,092.22
24	4,092.24
Mar. 25	4,092.22
Apr. 18	4,092.28
1954—Con.	
May 11	4,091.87
June 25	4,091.57
1955	(3)
1956	
May 9	4,092.45
16	4,093.49
29	4,093.62
June 10	4,093.67
27	4,093.37
July 5	4,093.43
25	4,093.09
Aug. 4	4,092.97
28	4,092.33
1957	
Mar. 3	4,093.07
15	4,093.77
Apr. 18	4,094.25
30	4,094.45
May 16	4,094.57
31	4,094.90
June 2	4,094.93
15	4,094.79
30	4,094.67
July 10	4,094.45
28	4,093.97
Aug. 14	4,093.69
26	4,093.43
1957—Con.	
Sept. 16	4,092.90
30	4,092.49
Nov. 20	4,092.63
Dec. 24	4,092.79
1958	
Jan. 15	4,092.85
Feb. 3	4,092.97
16	4,093.55
Mar. 2	4,093.90
16	4,094.20
Apr. 5	4,094.20
25	4,094.28
May 2	4,094.48
16	4,094.72
21	4,094.72
30	4,094.52
June 12	4,094.48
27	4,094.27
July 10	4,093.98
29	4,093.51
Aug. 5	4,093.12
27	4,092.42
1959	
Mar. 3	4,092.08
Apr. 28	4,092.58
1960–62	(3)
Gage near Voltage	
1932–37	(4)
1938	
Mar. 9	4,091.12
26	4,091.50
Apr. 25	4,091.84
July 14	4,092.70
Aug. 26	4,092.22
Sept. 10	4,092.13
24	4,091.87
Oct. 1	4,091.80
Nov. 5	4,092.05
19	4,092.20
Dec. 10	4,092.35
1939	
Mar. 24	4,092.89
31	4,092.90
Apr. 14	4,093.00
19	4,093.00
May 9	4,092.78
21	4,092.66
June 10	4,092.34
24	4,092.18
1940	
Mar. 17	4,091.62
Apr. 18	4,091.82
May 1	4,091.92
11	4,091.85
23	4,091.78
June 9	4,091.62
July 7	4,091.12
29	4,090.74
Aug. 21	4,090.50
Sept. 12	4,090.44
1941	
Feb. 16	4,091.84
26	4,092.06
Mar. 11	4,092.20
Apr. 6	4,092.54
20	4,092.90
25	4,092.92
June 12	4,093.26
23	4,093.02
July 8	4,092.86
23	4,092.58
Aug. 7	4,092.36
21	4,092.26
Oct. ?	4,092.21
Nov. 12	4,092.28
Dec. 4	4,092.46
1942	
Jan. 9	4,092.72
Mar. 10	4,093.21
25	4,093.75
Apr. 20	4,094.28
30	4,094.82
May 5	4,094.72
18	4,094.70
1943	
Mar. 23	4,094.40
Apr. 11	4,094.71
24	4,095.24
June 1	4,094.92
17	4,094.88
July 18	4,094.51
Aug. 20	4,093.86
Sept. 6	4,093.19
29	4,093.32
Oct. 26	4,093.20
Nov. 20	4,093.32
1944	
Apr. 7	4,093.50
29	4,093.28
May 18	4,093.10
June 12	4,092.80
Aug. 8	4,092.08
Sept. 7	4,091.62
22	4,091.50
Oct. 23	4,091.36
Nov. 16	4,091.52
Dec. 15	4,091.79
1945	
Feb. 9	4,092.65
Mar. 11	4,092.76
Apr. 14	4,092.98
May 21	4,093.56
June 3	4,094.18
13	4,094.48
27	4,094.42
July 5	4,094.30
31	4,093.72
Aug. 14	4,093.40
Sept. 4	4,093.24
Oct. 10	4,092.86
Nov. 2	4,092.72
26	4,092.92
1946	
Apr. 1	4,093.52
15	4,093.60
1946—Con.	
May 2	4,093.65
9	4,093.68
28	4,093.55
June 23	4,093.30
July 15	4,093.00
Aug. 13	4,092.42
Sept. 11	4,092.00
Oct. 31	4,092.02
Nov. 24	4,092.22
1947	
Mar. 24	4,092.88
Apr. 19	4,092.78
May 26	4,092.22
June 23	4,092.12
July 17	4,091.67
Aug. 19	4,091.02
Sept. 28	4,090.84
Oct. 30	4,090.90
Nov. 25	4,091.02
1948	
Aug. 1	4,093.17
12	4,092.96
Sept. 4	4,092.62
27	4,092.47
Oct. 20	4,092.45
Nov. 15	4,092.60
1949	
Apr. 5	4,093.30
19	4,093.18
May 13	4,093.27
25	4,093.27
June 10	4,093.16
21	4,092.95
July 7	4,092.38
Aug. 12	4,091.80
Sept. 26	4,091.37
Oct. 27	4,091.31
Nov. 15	4,091.40
1950	
Mar. 24	4,092.56
Apr. 20	4,092.36
May 31	4,091.85
June 19	4,091.84
July 25	4,091.34
Aug. 23	4,090.85
Oct. 3	4,090.85
Nov. 9	4,091.10
Dec. 9	4,091.32
1950—Con.	
Dec. 24	4,091.40
1951	
Feb. 28	4,092.51
Mar. 18	4,092.62
Apr. 12	4,093.16
25	4,093.31
May 8	4,093.42
June 6	4,093.27
19	4,093.09
July 6	4,092.70
19	4,092.52
Aug. 8	4,092.07
16	4,091.96
Sept. 27	4,091.37
Oct. 31	4,091.50
Nov. 22	4,091.69
1952	
Feb. 14	4,092.56
Mar. 24	4,092.80
Apr. 13	4,093.86
24	4,094.52
May 9	4,095.10
26	4,095.32
June 9	4,095.39
20	4,095.20
July 18	4,094.92
Aug. 11	4,094.52
Sept. 4	4,094.12
Oct. 13	4,093.82
Nov. 6	4,093.59
1953	
Apr. 3	4,093.77
May 8	4,093.54
22	4,093.76
June 26	4,094.44
July 25	4,093.92
Aug. 27	4,093.42
Sept. 16	4,093.22
Oct. 12	4,092.99
Nov. 1	4,092.94
1954	
Jan. 25	4,093.32
Feb. 23	4,093.50
Apr. 10	4,093.57
May 13	4,093.17
June 30	4,092.70
July 26	4,092.23
Aug. 31	4,091.72
1954—Con.	
Sept. 13	4,091.52
Oct. 25	4,091.38
Nov. 29	4,091.46
Dec. 23	4,091.67
1955	
Mar. 17	4,092.20
Apr. 28	4,092.08
May 9	4,092.00
June 13	4,091.60
July 8	4,091.29
20	4,091.38
Aug. 11	4,091.08
29	4,090.80
Sept. 15	4,090.66
Nov. 29	4,091.02
1956	
Jan. 2	4,091.62
18	4,091.92
Mar. 23	4,092.56
Apr. 12	4,092.88
24	4,093.18
May 5	4,093.52
20	4,093.72
June 13	4,093.84
27	4,093.68
Aug. 1	4,093.12
20	4,092.82
Sept. 13	4,092.52
Oct. 9	4,092.34
Dec. 14	4,092.82
1957	
Mar. 19	4,094.22
Apr. 8	4,094.40
May 12	4,094.70
24	4,095.12
June 5	4,095.08
18	4,095.12
24	4,095.00
July 9	4,094.70
30	4,094.22
Aug. 15	4,094.00
29	4,093.72
Sept. 12	4,093.52
Oct. 2	4,093.32
Nov. 27	4,093.54
1958	
Mar. 14	4,094.66
Apr. 15	4,094.72
1958—Con.	
May 21	4,095.16
June 6	4,094.98
15	4,094.98
30	4,094.68
July 8	4,094.52
29	4,094.07
Aug. 13	4,094.01
Sept. 15	4,093.29
Oct. 12	4,093.02
Dec. 4	4,093.08
1959	
Mar. 14	4,093.02
8	4,092.90
29	4,092.56
June 17	4,092.20
July 1	4,091.98
13	4,091.62
Aug. 12	4,090.98
Sept. 2	4,090.88
16	4,090.80
Oct. 23	4,091.00
Nov. 12	4,090.82
1960	
May 10	4,091.82
19	4,091.72
July 8	4,091.10
12	4,091.20
Aug. 2	4,090.82
28	4,090.50
Sept. 5	4,090.48
Dec. 12	4,090.80
1961	
Jan. 4	4,090.82
Mar. 8	4,090.88
13	4,090.82
May 16	4,090.46
July 14	[5] 4,090.02
Sept. 5	[5] 4,090.04
Nov. 10	4,090.26
Dec. 15	4,090.22
1962	
July 16	4,090.54
23	4,090.54
Sept. 21	[5] 4,089.93
Nov. 6	4,090.78
8	4,090.64
Dec. 18	4,090.92

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[1] Measured flow from Malheur Lake to Mud Lake, 119 cfs.

[2] No records of lake stage.

[3] No water at The Narrows gage at times of inspection.

[4] No records of lake stage. Lake was very low in 1932–35 (lakebed farmed in 1934), and slightly higher in 1936–37 (J. C. Scharff, manager of Malheur National Wildlife Refuge, written commun., 1942).

[5] Lake very shallow and nearly dry.

TABLE 26.—*Altitude of water surface in Harney Lake, 1929–62*

[Altitude reported in feet above mean sea level. Lake dries at about 4,080 ft. Leveling partly estimated at times because of mud. For records of the period 1912–18, refer to Piper, Robinson, and Park (1939, p. 131)]

Date	Altitude (ft)	Remarks and source of data
1929–32	----------	Practically dry (Piper and others, 1939, p. 21).
1933–34	----------	Practically dry.[1]
1935–41	----------	No overflow from Mud Lake to Harney Lake.[1]
1942	----------	Mud Lake overflowed into Harney Lake about April 5.[1]
1943		
Apr. 9	4,084.65	(2).
22	4,085.29	County Watermaster.
May 3	4,085.84	County Watermaster.[2]
16	4,086.80	County Watermaster.
30	4,087.20	(2).
1943—Con.		
June 16	4,087.60	Highest stage of record.[2]
24	4,087.50	(2).
July 29	4,087.05	(2).
Aug. 7	4,086.90	(2).
1944–58	No records	Mud Lake overflowed to Harney Lake in 1952, 1953, 1956–58.
1959–61	No records	No overflow from Mud Lake.
August 1962	----------	Lake covered about 500 acres only 1 or 2 in. deep.[3]

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[1] J. C. Scharff, manager, Malheur National Wildlife Refuge (written commun., 1942).

[2] Leveling by Bureau of Sport Fisheries and Wildlife (U.S. Dept. Interior) from local reference mark tied to U.S. Geological Survey bench mark.

[3] Narrative report in files of Bureau of Sport Fisheries and Wildlife.

TABLE 27.—*Altitude of water surface in Crump, Hart, and Bluejoint Lakes, 1867–1963*

[Additional observations (not listed) were made at Crump Lake in 1910, 1911, 1914, 1915, 1960, 1962, 1963; and at Hart Lake in 1911–15, 1940–46, 1950–54, 1956–63. Provisional gage datums, listed in Water-Supply Paper 390 (U.S. Geological Survey, 1917, p. 276, 278), have been increased 7.3 ft as follows. Crump Lake: 1867 peak and records for 1910–22, datum at 4,471.7 ft, based on observation of overflow in 1914, which was found to occur at 4,474.4 ft (field survey, 1955). Hart Lake: Records for 1910–13, datum at approximately 4,468 ft; 1867 peak and records for 1914–38, datum at approximately 4,468.5 ft. Bluejoint Lake: 1868 peak and records for 1910–14, datum at approximately 4,454.4 ft. Datum adjustment is based on assumptions (1) that overflow level of Crump Lake (4,474.4 ft as observed in 1955 and 1962) was at same altitude as overflow level reported by Whistler and Lewis (1916, p. 17), which corresponded to 2.7 ft on Crump Lake gage used from 1910 to 1915, and (2) that computed adjustment of +7.3 ft for temporary U.S. Reclamation Service datum of Crump Lake gage is applicable also at gages used from 1910 to 1915 on Hart and Bluejoint Lakes]

Crump Lake

Date	Altitude (ft)
1867(?)	[1]4,476.9
1910	
May 21	[2]4,475.2
June 2	4,474.8
July 8	4,473.5
21	4,473.2
1911	
Jan. 4	4,473.0
Feb. 4	4,473.3
Mar. 4	4,473.5
Apr. 4	4,474.7
May 7	[2]4,475.4
June 4	4,475.3
11	[2]4,475.4
July 2	4,475.3
Aug. 6	4,473.9
Sept. 3	4,473.2
Oct. 1	4,472.8
Nov. 15	4,472.9
Dec. 1	4,473.1
1912	
Jan. 1	4,473.2
15	[2]4,473.4
1913	
Feb. 15	4,473.4
Mar. 8	4,473.4
Apr. 4	4,473.9
10	[2]4,474.0
1914	
Mar. 6	4,473.8
Apr. 1	4,475.3
1914—Con.	
May 1	[2]4,475.9
June 4	4,475.6
July 3	4,474.8
22	4,474.1
1915	
Mar. 25	4,473.4
Apr. 3	4,474.0
8	[2]4,474.2
May 5	4,474.0
25	4,473.4
Oct. 16	4,471.6
1922	
Nov. 17	4,471.5
1947	
October	4,470.6
1954	
Jan. 25	4,473.0
Apr. 18	4,474.4
Sept. 22	4,471.6
1955	
Sept. 16	4,472.0
1960	
Mar. 29	4,471.1
Apr. 21	4,472.6
May 20	4,474.9
June 7	[2]4,475.4
July 27	4,474.0
Sept. 21	4,473.2
Oct. 1	4,471.85
20	4,471.53
1961	
Apr. 27	4,472.48
Sept. 8	4,470.8
1962	
Jan. 10	4,471.35
Feb. 2	4,471.35
Mar. 12	4,472.3
Apr. 2	4,472.75
19	4,474.9
May 1	4,475.1
28	[2]4,475.2
June 8	4,475.1
July 6	4,474.37
Aug. 7	4,473.20
31	4,472.96
Oct. 1	4,472.50
Nov. 7	4,473.90
Dec. 19	4,475.1
1963	
Jan. 14	4,475.0
Feb. 5	4,476.25
Mar. 7	4,475.90
Apr. 10	4,475.85
May 15	[2]4,476.40
June 14	4,476.10
July 3	4,475.1
Aug. 23	4,473.8
29	4,473.65
Oct. 2	4,473.3

Hart Lake

Date	Altitude (ft)
1867(?)	[1]4,473.5
1910	
June 8	[2]4,471.4
July 24	4,470.8
1911	
Mar. 5	4,470.1
Apr. 2	4,471.0
30	[2]4,472.0
July 17	4,471.8
Aug. 6	4,471.5
Sept. 3	4,470.9
Oct. 1	4,470.6
Nov. 1	4,470.4
Dec. 1	4,470.4
1912	
Jan. 1	4,470.4
Feb. 1	4,470.4
Mar. 1	4,470.3
Apr. 1	4,470.3
May 3	4,470.7
June 4	4,471.6
18	[2]4,471.8
July 1	4,471.5
Aug. 4	4,471.3
Sept. 8	4,471.0
Oct. 6	4,470.9
1913	
Jan. 19	4,470.2
Feb. 2	4,470.2
Mar. 6	4,470.4
Apr. 3	[2]4,470.7
Aug. 26	4,470.6
1914	
Mar. 9	4,471.5
Apr. 7	4,472.0
17	[2]4,472.3
May 2	4,471.8
June 4	4,471.6
July 2	4,471.3
18	4,471.0
1915	
Mar. 21	4,469.8
Apr. 16	4,470.0
May 4	[2]4,470.4
Sept. 27	4,469.4
1937	
Apr. 1	4,469.2
May 15	4,470.4
June 15	4,470.9
July 1	4,470.8
Nov. 13	4,468.8
Dec. 12	4,469.1
1938	
Mar. 13	4,473.1
Apr. 25	4,473.5
May 20	4,472.8
1940	
Mar. 17	4,470.06
Apr. 16	4,471.76
May 18	[2]4,473.16
June 8	4,472.99
July 16	4,472.33
Aug. 7	4,471.91
Sept. 25	4,471.39
Oct. 21	4,471.26
Nov. 15	4,471.35
1941	
Mar. 1	4,471.64
Apr. 11	4,471.95
May 2	4,472.46
June 11	[2]4,473.39
July 1	4,473.29
Aug. 5	4,472.84
Sept. 9	4,472.63
Oct. 13	4,472.18
Nov. 10	4,472.26
Dec. 6	4,472.20
1942	
Jan. 16	4,472.51
Feb. 8	4,472.95
Mar. 8	4,473.45
Apr. 18	[2]4,473.84
May 20	4,473.62
June 26	4,473.48
July 8	4,473.54
Aug. 8	4,473.10
Sept. 11	4,472.70
Oct. 1	4,472.35
Nov. 8	4,472.07
1943	
Jan. 12	4,472.50
Feb. 13	4,473.01
Mar. 5	4,473.56
Apr. 1	[2]4,474.11
May 4	4,473.91
June 6	4,473.76
July 1	4,473.49
Aug. 2	4,473.42
Sept. 16	4,472.96
1944	
Jan. 12	4,472.72
Mar. 9	4,472.91
22	[2]4,472.96
Apr. 28	4,472.76
June 1	4,472.21
Aug. 10	4,472.34
Sept. 22	4,471.78
Nov. 17	4,471.66
1945	
Jan. 9	4,471.76
Feb. 19	4,472.24
Mar. 19	4,472.56
Apr. 18	4,472.63
May 29	[2]4,473.76
July 2	4,473.31
Aug. 10	4,473.06
Oct. 23	4,472.32
1946	
Jan. 14	4,472.21
Mar. 31	4,472.81
May 1	[2]4,473.36
June 25	4,472.96
1950	
Apr. 20	4,471.16
June 21	[2]4,473.01
July 18	4,472.76
Oct. 5	4,471.41
Nov. 4	4,471.36
1951	
Feb. 13	4,471.99
Mar. 19	4,472.66
Apr. 18	[2]4,473.81
May 24	4,473.46
June 14	4,473.16
July 12	4,472.61
Aug. 16	4,471.86
Sept. 11	4,471.48
Oct. 22	4,471.12
Dec. 6	4,471.05
1952	
Mar. 10	4,471.36
Apr. 10	4,472.98
May 7	[2]4,474.46
June 5	4,473.61
July 2	4,473.46
Aug. 11	4,473.21
Sept. 5	4,473.01
Oct. 8	4,472.81
1953	
Jan. 19	4,473.01
Mar. 4	4,473.51
Apr. 28	[2]4,473.86
May 21	4,473.61
June 15	4,473.61
July 20	4,472.96
Aug. 27	4,473.21
Sept. 20	4,472.61
Nov. 11	4,472.41
Dec. 11	4,472.56
1954	
Jan. 13	4,472.71
Feb. 2	4,472.91
Mar. 10	4,473.11
Apr. 15	4,473.51
May 11	[2]4,473.61
June 15	4,473.21
July 23	4,472.51
Aug. 19	4,472.11
Sept. 29	4,471.71
1956	
Feb. 1	4,471.71
22	4,473.36
Apr. 12	[2]4,474.01
May 10	4,473.81
July 3	4,473.21
Aug. 1	4,473.01
21	4,473.01
1957	
Feb. 20	4,473.41
1957—Con.	
Mar. 22	4,473.86
Apr. 18	[2]4,473.91
May 23	4,473.81
June 24	4,473.38
July 18	4,473.01
Oct. 6	4,471.91
1958	
Mar. 3	4,473.01
18	4,473.61
May 19	[2]4,474.01
June 24	4,473.61
July 23	4,473.51
Aug. 20	4,473.56
Sept. 18	4,473.01
1960	
Apr. 7	4,468.87
May 1	4,469.37
June 6	[2]4,469.69
July 1	4,469.15
Aug. 1	4,468.27
Sept. 1	4,467.59
Oct. 6	4,467.19
Nov. 1	4,466.85
Dec. 1	4,466.99
1961	
Jan. 1	4,466.89
Feb. 1	4,466.99
Mar. 1	4,466.91
Apr. 1	4,466.64
May 9	4,464.99
1962	
May 7	4,465.81
June 20	[2]4,468.34
July 1	4,468.12
Aug. 1	4,467.43
Sept. 1	4,466.94
Oct. 4	4,466.39
Nov. 1	4,466.93
Dec. 1	4,467.77
1963	
Jan. 1	4,469.50
Feb. 1	4,471.17
Mar. 1	4,473.87
Apr. 5	4,473.93
May 5	[2]4,474.33
June 1	4,473.85
July 1	4,473.50
Aug. 1	4,473.18
Sept. 1	4,472.82
Oct. 1	4,472.53

Bluejoint Lake[3]

Date	Altitude (ft)
1868(?)	[1]4,472.6
1910(?)	4,461.8
1911	
Mar. 21	4,459.6
Sept. 14	4,459.1
1912	
Apr. 16	4,458.5
1912—Con.	
May 31	4,458.3
1913	
Mar. 6	4,456.3
May 2	4,455.9
Aug. 26	Dry.
1914	
Mar. 8	Dry.
Apr. 7	Dry.
May 3	Dry.
June 3	Dry.
July 9	4,455.0

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[1] From watermark observed in 1914. May be too high, owing to wind. Peaks at Crump and Hart Lakes are ascribed to 1867, wettest year of record at Fort Bidwell, Calif., about 30 miles south of Crump Lake. Higher levels at Hart Lake since 1930's probably due to diking and damming of its outlet.

[2] Highest stage observed in water year.

[3] Lake reported dry in 1889, 1903, and 1906 (Whistler and Lewis, 1916, p. 32); also dry in 1915, 1918, and probably in most years during periods 1922–42 and 1944–51. Probably contained water in 1921 and all later years in which the combined runoff at gaging stations on Twentymile, Deep, and Honey Creeks exceeded about 200,000 acre-ft (1938, 1943, 1952, 1956, 1958, and 1963).

TABLE 28.—*Chemical and physical character*

General: Analyses by the U.S. Geological Survey except as follows: 1a, 2a, 5a (S. T. Harding, written commun., 1963); 3a, 5b, 18a (Stott, 1952); 10a, 10b, 19b (Allison and Mason, 1947); 21a, 22e, 23d (S. T. Harding, written commun., 1958); 22c (S. T. Harding, written commun., 1962); 22d, 23a–c, 24–30 (California Dept. of Water Resources). Analyses of samples collected in 1912 are from Van Winkle's report (1914). Analytical results reported in parts per million, except as indicated. Estimated values throughout table are indicated by "e" following the value.

Analysis: Each sample-collection site is numbered. (See locations on plates 1,2.) Analyses of samples collected at each site are arranged chronologically and lettered consecutively. Values are in parts per million, except as indicated.

Discharge or lake level: Discharges for stream-water samples in cubic feet per

Analysis No.	Collection date	Discharge (cfs) or lake level (ft)	Water temperature (°F)	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)
LAKE ABERT											
1. Lake Abert, east shore 10 miles north-											
1a	July 9, 1958	4,260.5e	----------	----------	----------	----------	7,180	----------	5,270	3,000	320
1b	Jan. 29, 1959	4,259.2	----------	----------	----------	----------	----------	----------	2,570	3,250	----------
1c	Apr. 26, 1961	4,253.86	56	157	----------	----------	16,200	536	4,820	6,600	719
1d	June 27, 1961	4,253.31	75	171	----------	----------	17,600	577	----------	----------	----------
1e	Sept. 7, 1961	4,252.04	68	172	----------	----------	21,900	716	5,850	9,290	985
1f	Jan. 12, 1962	4,251.81	33	144	1.4	0.6	22,000	752	5,930	9,460	990
1g	Mar. 13, 1962	4,252.14	----------	130	----------	----------	20,500	----------	----------	----------	----------
1h	Apr. 18, 1962	4,252.30	58	131	----------	----------	20,700	----------	----------	----------	----------
1i	June 12, 1962	4,252.36	66	136	----------	----------	19,500	654	5,290	8,460	896
1j	Oct. 30, 1962	4,251.19	57	173	----------	----------	25,300	----------	----------	----------	----------
1k	Mar. 19, 1963	4,253.08	44	142	----------	----------	17,600	----------	----------	----------	----------
2. Lake Abert, east shore about 8 miles											
2a	Aug. 12, 1955	4,252.8e	----------	----------	----------	----------	15,700	825	3,640	7,050	695
3. Lake Abert, southeast shore about 4											
3a	Aug. 1951	4,249e	----------	----------	----------	----------	23,500	835	----------	----------	----------
3b	Aug. 21, 1956	4,257.6	71	95	----------	----------	8,020	252	2,100	3,590	359
3c	Oct. 29, 1957	4,256.7	44	140	----------	----------	8,370	295	2,160	3,230	397
3d	Nov. 1, 1958	4,259.1	----------	134	1.0	1.8	7,690	296	2,120	3,120	360
3e	June 12, 1962	4,252.36	72	----------	----------	----------	----------	----------	----------	----------	----------
4. Lake Abert, southwest shore 4 miles											
4a	Apr. 26, 1961	4,153.86	56	----------	----------	----------	16,000	----------	4,650	6,460	----------
5. Lake Abert, east shore about 13 miles											
5a	July 21, 1939	4,248.2e	----------	----------	----------	----------	38,000	----------	0(?)	25,400	1,000
5b	Aug. 1952	4,252.7e	----------	----------	----------	----------	13,600	480	----------	----------	----------
6. Lake Abert, midlake 10.5 miles north-											
6a	May 20, 1959 [1]	4,258.9	----------	93	----------	----------	8,560	----------	3,020	3,240	----------
7. Lake Abert, midlake about 7.5 miles											
7a	Oct. 27, 1961	4,251.5	42	173	----------	----------	23,700	801	----------	----------	----------
7b	Apr. 18, 1962	4,252.30	57	----------	----------	----------	----------	----------	----------	----------	----------
8. Lake Abert, midlake near south end, about 5.5											
8a	Sept. 17, 1962	4,250.70	68	201	----------	----------	28,400	----------	----------	----------	----------
9. Lake Abert, off south shore 3.5 miles											
9a	Sept. 17, 1962	4,250.71	67	----------	----------	----------	----------	----------	----------	----------	----------
10. Lake Abert, east shore											
10a	Sept. 4, 1944	4,249.1e	----------	----------	----------	----------	20,200	----------	4,550	10,000	810
10b	Nov. 17, 1945	4,247.8e	----------	230	----------	----------	27,800	900	9,220	12,000	1,060
11. Lake Abert, southwest											
11a	Feb. 1912	----------	----------	96	----------	----------	11,500	502	2,500	4,920	565

See footnotes at end of table.

of lakes and their tributary streams

second (cfs). Lake levels in feet above mean sea level.

Silica: Most silica concentrations greater than 100 ppm were determined gravimetrically. Colorimetric values greater than 100 ppm are indicated by "c" following the value.

Bicarbonate, carbonate, and pH: All determinations were made in the laboratory rather than at the sampling sites. Carbonate:bicarbonate ratios and pH values are subject to change during the time between collection and analysis of samples. (See p. B56.)

Dissolved solids (calculated): Values, in parts per million, represent the summation of the concentrations of all constituents determined in a comprehensive analysis (bicarbonate is recalculated as carbonate by using the factor 0.492); dissolved-solids contents are estimated for partial analyses.

Chloride (Cl)	Fluoride (F)	Bromide (Br)	Nitrate (NO_3)	Orthophosphate (PO_4)	Boron (B)	Dissolved solids (calculated)	Hardness as $CaCO_3$	Percent sodium	Specific conductance (micromhos at 25° C)	pH	Density at 20° C
BASIN											
northeast of Valley Falls (34/21–24Q)											
5,140	----------	----------	----------	----------	----------	18,700e	----------	----------	----------	----------	1.014e
7,040	----------	----------	----------	----------	----------	20,500e	----------	----------	28,600	9.8	1.016e
14,100	5.6	70	----------	55	58	40,800	8	98	53,700	9.7	1.032
15,500	6.2	76	----------	64	64	45,000e	----------	98	58,500	----------	1.034
19,200	7.8	95	----------	78	80	55,400	----------	98	70,200	9.7	1.044
19,300	7.5	95	1	74	80	55,900	6	98	71,300	9.6	1.045
18,100	----------	----------	----------	----------	----------	52,000e	----------	----------	67,300	----------	1.041
17,900	----------	----------	----------	71	----------	52,000e	----------	----------	67,200	----------	1.041
16,700	----------	----------	----------	70	----------	49,200e	----------	98	64,800	9.7	1.040
22,000	----------	----------	----------	86	----------	63,000e	----------	----------	76,800	----------	1.051
15,500	----------	----------	----------	59	----------	45,000e	----------	----------	54,200	----------	1.032
northeast of Valley Falls (34/21–36)											
14,000	----------	----------	----------	----------	----------	40,400e	----------	97	----------	----------	1.032e
miles northeast of Valley Falls (35/21–15)											
----------	----------	----------	----------	----------	----------	60,000e	----------	98	----------	----------	1.047e
7,760	----------	----------	----------	----------	----------	21,200e	5	98	29,100	9.9	1.012
7,440	13	36	3.8	33	32	21,100	9	98	30,500	9.8	1.016
6,780	----------	----------	3.5	----------	----------	19,500e	10	98	28,800	9.8	1.013
----------	----------	----------	----------	----------	----------	----------	----------	----------	60,900	----------	----------
north-northeast of Valley Falls (35/21–16C)											
13,900	----------	----------	----------	----------	----------	----------	----------	----------	52,500	9.7	1.032
north-northeast of Valley Falls (34/21–1)											
28,500	----------	----------	----------	----------	----------	95,000e	----------	----------	----------	----------	1.077e
----------	----------	----------	----------	----------	----------	35,000e	----------	98	----------	----------	1.027e
northeast of Valley Falls (34/21–15A)											
7,570	----------	----------	----------	----------	----------	21,700e	----------	----------	30,700	9.6	1.014
northeast of Valley Falls (34/21–35NW¼)											
20,800	8.0	103	----------	81	85	60,000e	----------	98	76,000	----------	1.048
----------	----------	----------	----------	----------	----------	----------	----------	----------	66,400	----------	----------
miles northeast of Valley Falls (35/21–10NW¼)											
25,000	----------	----------	----------	101	----------	71,000e	----------	----------	85,100	----------	1.058
northeast of Valley Falls (35/21–21B)											
----------	----------	----------	----------	----------	----------	----------	----------	----------	84,700	----------	----------
(exact site unknown)											
16,600	----------	----------	----------	----------	----------	51,000e	----------	----------	----------	----------	1.040e
22,900	----------	----------	----------	----------	----------	70,000e	----------	98	----------	----------	1.055e
shore (exact site unknown)											
10,700	----------	----------	1.0	----------	----------	29,600e	----------	97	----------	----------	1.025

TABLE 28.—*Chemical and physical character of*

Analysis No.	Collection date	Discharge (cfs) or lake level (ft)	Water temperature (°F)	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)
LAKE ABERT											
12. Chewaucan River at or near Paisley (33/18–24L and											
12a	Jan. 28–Feb. 6, 1912 [2]	66	----------	34	8.3	0.4	[3] 11	----------	43	0	4.1
12b	June 6–15, 1912 [2]	613	----------	17	4.6	1.5	[3] 6.9	----------	28	0	6.7
12c	Aug. 11, 1911–Aug. 14, 1912 [4]	----------	----------	29	7.6	1.9	6.8	2.5	44	0	4.5
12d	Apr. 2, 1951	321	----------	----------	----------	----------	----------	----------	53	0	11
12e	Aug. 21, 1956	48	59	33	7.5	2.9	6.5	2.1	53	0	1.2
12f	May 19, 1959	210	45	28	5.0	1.7	3.4	1.6	34	0	.5
12g	Apr. 25, 1961	144	53	31	6.0	1.9	4.6	1.6	42	0	.2
12h	Apr. 16, 1962	419	48	30	----------	----------	4.9	----------	----------	----------	----------
13. Chewaucan River at The Narrows (34/20–30B)											
13a	Apr. 16, 1962	194	----------	30	----------	----------	6.4	----------	----------	----------	----------
14. Chewaucan River at falls 2.5 miles northeast of Valley											
14a	Jan. 29, 1959	----------	35	----------	----------	----------	----------	----------	82	0	----------
14b	Apr. 26, 1961	2e	49	27	30	7.9	47	6.8	216	0	12
14c	June 23, 1961	75e	----------	----------	----------	----------	32	----------	----------	----------	----------
14d	Sept. 8, 1961	2e	58	----------	----------	----------	19	----------	----------	----------	----------
14e	Sept. 30, 1961	20e	53	----------	----------	----------	----------	----------	----------	----------	----------
14f	Oct. 27, 1961	22e	42	27	12	2.9	8.9	2.8	73	0	3.2
14g	Jan. 11, 1962	25e	----------	----------	----------	----------	8.6	----------	----------	----------	----------
14h	Apr. 17, 1962	175e	55	----------	----------	----------	----------	----------	----------	----------	----------
14i	Apr. 18, 1962	175e	55	32	----------	----------	15	----------	----------	----------	----------
14j	Apr. 19, 1962	180e	53	----------	----------	----------	----------	----------	----------	----------	----------
14k	June 9, 1962	50e	69	----------	----------	----------	----------	----------	----------	----------	----------
14l	June 12, 1962	28e	69	26	20	5.3	36	5.5	162	0	12
14m	July 26, 1962	8e	71	----------	----------	----------	----------	----------	----------	----------	----------
14n	Sept. 16, 1962	1e	59	9.1	----------	----------	20	----------	----------	----------	----------
14o	Oct. 30, 1962	95e	49	31	----------	----------	8.4	----------	----------	----------	----------
14p	Nov. 13, 1962	225e	43	----------	----------	----------	----------	----------	----------	----------	----------
15. Poison Creek, at highway 7.5 miles											
15a	June 10, 1962	3e	52	29	7.0	1.6	6.5	1.8	45	0	3.0
15b	Oct. 30, 1962	.15e	50	28	----------	----------	6.2	----------	----------	----------	----------
SUMMER LAKE											
16. Summer Lake, west shore 10 miles south											
16a	Apr. 25, 1961	4,146.32	68	110	2.5	0.3	2,830	115	1,880	1,230	348
16b	June 21, 1961	4,145.86	60	173c	----------	----------	5,930	----------	----------	----------	----------
16c	Sept. 30, 1961	4,144.86	----------	207c	----------	----------	4,900	----------	----------	----------	----------
16d	Jan. 11, 1962	4,146.40	35	86	2.0	.3	1,160	----------	900	486	----------
16e	Apr. 16, 1962	4,147.00	82	105c	----------	----------	1,540	----------	----------	----------	----------
16f	June 12, 1962	4,146.43	78	137	2.0	.6	2,430	114	1,800	1,030	293
16g	Oct. 30, 1962	4,146.57	50	98	----------	----------	712	----------	----------	----------	----------
17. Summer Lake, west shore 14.5 miles south											
17a	Jan. 30, 1959	4,148.2	40	----------	----------	----------	----------	----------	2,150	1,500	----------
18. Summer Lake, west shore 9 miles south											
18a	Aug. 1952	4,146.8e	----------	----------	----------	----------	3,250	160	1,950	1,640	----------
19. Summer Lake, probably west											
19a	Feb. 1912	4,151.5e	----------	104	----------	----------	6,570	265	2,850	4,510	694
19b	Sept. 1, 1944	4,146.2	----------	230	----------	----------	10,800	300	3,650	7,000	1,520
20. Ana River, 2 miles northeast of											
20a	Feb. 1912	140	----------	37	4.9	4.4	[3] 39	----------	86	9	8.1
20b	Dec. 3, 1948	100	52	37	5.2	3.1	[5] 39	3.2	80	14	6.7
20c	Apr. 2, 1951	84	----------	----------	----------	----------	----------	----------	110	0	6.9
20d	Aug. 21, 1956	78	63	39	6.4	1.9	39	3.6	106	0	5.4
20e	Jan. 30, 1959	102	56	----------	----------	----------	----------	----------	104	2	----------
20f	Apr. 25, 1961	92	58	36	5.0	2.3	39	3.6	91	9	5.8

See footnotes at end of table.

lakes and their tributary streams—Continued

Chloride (Cl)	Fluoride (F)	Bromide (Br)	Nitrate (NO_3)	Orthophosphate (PO_4)	Boron (B)	Dissolved solids (calculated)	Hardness as $CaCO_3$	Percent sodium	Specific conductance (micromhos at 25° C)	pH	Density at 20° C
BASIN—Continued											
33/18–26E) about 32 river miles upstream from mouth											
1.3	---	---	0.3	---	---	80	22	---	---	---	---
.4	---	---	.3	---	---	51	18	---	---	---	---
.5	---	---	.3	---	---	75	27	33	---	---	---
1.0	---	---	---	---	---	75e	25	---	85	6.9	---
1.2	---	---	.3	---	---	81	31	30	104	7.4	---
.0	0.4	---	.5	---	---	58	20	30	57	7.2	---
.0	---	---	---	---	---	66	23	29	69	7.4	---
.2	---	---	---	---	---	65e	---	---	65	---	---
about 16 river miles upstream from mouth											
0.8	---	---	---	---	---	70e	---	---	77	---	---
Falls (35/21–21P) about 1 river mile upstream from mouth											
2.0	---	---	---	---	---	105e	44	---	127	7.3	---
17	0.4	---	0.6	0.24	---	255	108	47	402	7.9	---
9.5	---	---	---	---	---	185e	---	---	285	---	---
2.8	---	---	---	---	---	140e	---	---	202	---	---
---	---	---	---	---	---	125e	---	---	180	---	---
1.0	.1	---	---	.15	---	94	42	30	124	7.7	---
1.0	---	---	---	---	---	90e	---	---	111	---	---
---	---	---	---	---	---	---	---	---	138	---	---
5.5	---	---	---	---	---	105e	---	---	139	---	---
---	---	---	---	---	---	---	---	---	137	---	---
---	---	---	---	---	---	185e	---	---	276	---	---
7.0	.4	---	.8	.32	---	193	72	50	293	7.6	---
---	---	---	---	---	---	165e	---	---	247	---	---
3.2	---	---	---	.12	---	140e	---	---	237	---	---
1.0	---	---	---	.25	---	85e	---	---	105	---	---
---	---	---	---	---	---	75e	---	---	83	---	---
northeast of Valley Falls (35/21–1C)											
2.0	0.1	---	---	---	---	73	24	34	84	6.8	---
1.8	---	---	---	0.19	---	70e	---	---	82	---	---
BASIN											
of Summer Lake Post Office (32/16–2NE¼)											
1,600	5.4	7.6	---	18	34	7,200	8	98	10,600	9.6	1.004
3,360	---	---	---	41	---	15,000e	---	---	20,800	---	1.011
2,720	---	---	---	36	---	12,500e	---	---	17,700	---	1.008
630	---	---	---	8.8	---	2,900e	6	---	4,860	9.5	---
840	---	---	---	11	---	3,900e	---	---	6,320	---	---
1,350	5.4	---	---	18	---	6,270	8	97	9,500	9.6	---
375	---	---	---	5.2	---	1,800e	---	---	2,990	---	---
of Summer Lake Post Office (32/16–25L)											
1,840	---	---	---	---	---	8,400e	10	---	11,900	9.7	1.005e
of Summer Lake Post Office (31/16–35NE¼)											
1,930	---	---	---	---	---	8,400e	---	97	---	---	1.005e
shore, but exact site unknown											
3,040	---	---	---	---	---	16,800e	---	98	---	---	1.015
5,350	---	---	---	---	---	27,000e	---	98	---	---	1.020e
Summer Lake Post Office (30/17–6)											
11	---	---	0.2	---	---	154	30	---	---	---	---
13	0.2	---	.1	---	0.5	161	26	74	213	8.4	---
13	---	---	---	---	---	---	24	---	223	6.5	---
14	---	---	2.6	---	---	164	24	75	---	7.7	---
14	---	---	---	---	---	---	22	---	209	8.5	---
12	.3	---	---	---	---	158	22	76	218	8.8	---

TABLE 28.—*Chemical and physical character of*

Analysis No.	Collection date	Discharge (cfs) or lake level (ft)	Water temperature (°F)	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)
GOOSE LAKE											
21. Goose Lake, east shore at Oregon-											
21a	July 9, 1958	4,706.5e	----------	----------	----------	----------	160	----------	400	0	----------
21b	Jan. 30, 1959	4,706.3	----------	----------	----------	----------	----------	----------	452	24	----------
21c	Apr. 26, 1961	4,702.15	----------	58	18	5.1	358	31	628	79	62
21d	Sept. 7, 1961	4,699.98	64	74	----------	----------	666	----------	----------	----------	----------
21e	Jan. 13, 1962	4,699.81	33	66	----------	----------	592	----------	----------	----------	----------
21f	Apr. 19, 1962	4,700.56	66	50	----------	----------	411	----------	----------	----------	----------
21g	June 12, 1962	4,700.31	66	58	13	4.0	450	36	746	94	83
21h	Sept. 2, 1962	4,698.57	70	80	----------	----------	970	----------	----------	----------	----------
22. Goose Lake, west shore near Oregon-California State line											
22a	May 12, 1912	4,714e	----------	50	18	2.0	350	34	638	98	45
22b	Aug. 13, 1955	4,700e	----------	----------	15	5	450	----------	550	195	80
22c	Aug. 23, 1956	4,703.8e	----------	----------	10	5	255	----------	455	25	----------
22d	Sept. 4, 1957	----------	82	90	14	3.4	264	27	484	49	46
22e	July 9, 1958	4,706.5e	----------	----------	----------	----------	190	----------	440	50	----------
23. Goose Lake, south end near Davis Creek, California (approx.											
23a	Sept. 16, 1953	4,701e	72	68	12	4.9	469	44	704	146	76
23b	May 5, 1954	4,703e	63	64	13	4.7	292	32	566	30	51
23c	Sept. 4, 1957	----------	71	86	14	3.4	264	27	494	47	46
23d	July 9, 1958	4,706.5e	----------	----------	----------	----------	210	----------	495	55	----------
24. East Branch Thomas Creek?, 1											
24a	June 26, 1958	3e	80	46	24	4.4	141	8.4	166	0	138
25. Drews Creek, 11 miles											
25a	June 26, 1958	15e	73	29	10	5.1	7.3	2.8	76	0	1.0
26. Dry Creek, 14 miles											
26a	June 26, 1958	12e	75	36	16	2.8	8.5	4.7	86	0	2.9
27. Davis Creek, 1 mile northeast of											
27a	June 26, 1958	25	58	32	5.6	0.5	3.4	1.8	30	0	0.0
28. Willow Creek, 12 miles north of town											
28a	June 26, 1958	5e	77	42	11	5.0	7.5	3.2	78	0	1.9
29. Lassen Creek, 11 miles north of town											
29a	June 26, 1958	15e	64	35	4.0	1.7	4.0	2.1	28	0	2.9
30. Pine Creek, 1 mile southeast of											
30a	June 26, 1958	52	56	25	5.2	1.0	4.5	1.2	28	0	3.8
SILVER LAKE											
31. Silver Lake, northeast shore (28/16–31 or 32, except 28/15–22											
31a	Feb. 1912	4,308±	----------	57	42	25	[3]49	----------	319	23	9.2
31b	Jan. 29, 1959	4,307.2	37	----------	----------	----------	----------	----------	232	0	----------
31c	May 18, 1959	4,306.50	48	40	----------	----------	29	----------	268	0	----------
31d	Apr. 25, 1961	4,300.85	55	22	59	44	137	28	700	28	.4
31e	June 20, 1961	4,300.32	----------	19	16	18	234	32	354	161	1.6
32. Silver Creek, 1.5 miles southwest of											
32a	Aug. 20, 1956	23	70	32	6.4	2.1	3.7	1.1	38	0	0.3
32b	Apr. 25, 1961	11	39	----------	5.5	1.6	3.2	----------	35	0	----------

See footnotes at end of table.

lakes and their tributary streams—Continued

Chloride (Cl)	Fluoride (F)	Bromide (Br)	Nitrate (NO_3)	Orthophosphate (PO_4)	Boron (B)	Dissolved solids (calculated)	Hardness as $CaCO_3$	Percent sodium	Specific conductance (micromhos at 25° C)	pH	Density at 20° C
BASIN											
California State line (41/20–23P)											
45	----------	----------	----------	----------	----------	600e	----------	----------	860	8.5	----------
70	----------	----------	----------	----------	----------	660e	55	----------	1,010	8.8	----------
117	0.8	----------	----------	5.3	----------	1,040	66	88	1,580	9.0	----------
224	----------	----------	----------	9.2	----------	1,900e	----------	----------	2,820	----------	----------
195	----------	----------	----------	8.6	----------	1,600e	----------	----------	2,590	----------	----------
125	----------	----------	----------	----------	----------	1,100e	----------	----------	1,770	----------	----------
152	.9	1	----------	6.9	3.8	1,270	49	91	1,980	9.1	----------
335	----------	----------	----------	12	----------	2,700e	----------	----------	4,070	----------	----------
(41/19–20 or 21 in Oregon; 48N/13E–20 or 21 in California)											
100	----------	----------	1.5	1.1	----------	1,010	53	89	----------	----------	----------
160	----------	----------	----------	----------	----------	1,280e	58	90	1,990	----------	----------
85	----------	----------	----------	----------	2.3	790e	46	----------	1,190	8.5	----------
83	0.9	----------	6.8	----------	2.3	823	49	87	1,230	8.9	----------
55	----------	----------	----------	----------	----------	680e	----------	----------	1,000	8.8	----------
sites: 23a, 45N/13E–14L; 23b, 45N/13E–3; 23c and 23d, 46N/13E–34)											
162	.9	----------	1.2	----------	4.8	1,340	50	91	2,110	9.2	----------
98	.4	----------	1.9	----------	2.1	868	52	87	1,310	8.8	----------
84	.9	----------	7.8	----------	2.6	824	49	87	1,240	8.9	----------
65	----------	----------	----------	----------	----------	740e	----------	----------	1,100	8.9	----------
mile west of Lakeview (39/20–9N?)											
74	1.2	----------	1.8	----------	3.8	525	78	78	801	7.9	----------
southwest of Lakeview (40/19–18P)											
1.5	0.0	----------	0.5	----------	0.0	94	46	24	120	7.7	----------
southwest of Lakeview (41/19–7B)											
0.8	0.3	----------	0.9	----------	0.1	115	52	24	136	7.9	----------
town of Davis Creek, Calif. (45N/14E–16J)											
1.5	0.2	----------	0.0	----------	0.0	60	16	29	54	7.7	----------
of Davis Creek, Calif. (47N/14E–22Q)											
1.0	0.5	----------	0.5	----------	0.0	111	48	24	128	8.0	----------
of Davis Creek, Calif. (47N/14E–27L)											
1.0	0.4	----------	0.1	----------	0.1	65	17	30	53	7.5	----------
New Pine Creek, Calif. (48N/15E–32L)											
1.0	0.3	----------	0.2	----------	0.0	56	17	35	54	7.6	----------
BASIN											
for May 18, 1959, sample; exact site unknown for 1912 sample)											
3.3	----------	----------	0.2	----------	----------	366	208	34	----------	----------	----------
1.0	----------	----------	----------	----------	----------	300e	141	----------	361	7.9	----------
4.0	----------	----------	----------	----------	----------	370e	162	----------	427	7.5	----------
21	1.0	----------	.9	----------	----------	686	330	45	1,090	8.5	----------
40	1.4	----------	1.2	----------	----------	698	114	77	1,140	9.7	----------
Silver Lake Post Office (28/14–28SW¼)											
0.2	----------	----------	1.0	----------	----------	66	25	24	67	6.9	----------
----------	----------	----------	----------	----------	----------	----------	20	----------	56	7.6	----------

TABLE 28.—*Chemical and physical character of*

Analysis No.	Collection date	Discharge (cfs) or lake level (ft)	Water temperature (°F)	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)
HARNEY											
33. Malheur Lake, south											
33a	Mar. 8, 1912	4,091e	----------	14	27	20	117	27	439	0	37
33b	Nov. 29, 1961	4,090e	----------	26	38	12	31	4.0	177	0	51
34. Harney Lake											
34a	Mar. 10, 1912	4,086.5	----------	31	----------	----------	8,820	335	5,760	1,590	1,930
34b	Jan. 4, 1962 [6]	4,081e	----------	73	----------	----------	13,200	488	2,730	4,720	2,590
35. Donner und Blitzen River, 2.5 miles											
35a	Aug. 21, 1956	43	----------	24	8.3	3.3	9.9	1.4	63	0	----------
36. Silvies River, 6 miles northwest											
36a	Aug. 22, 1956	9.2	67	23	15	5.5	11	3.6	100	0	----------
WARNER											
37. Crump Lake, west shore about											
37a	Sept. 7, 1912	----------	----------	3.0?	13	5.6	[3] 18	----------	95	0	8.6
37b	Apr. 27, 1961	4,472.48	62	39	34	14	54	6.3	246	6	26
37c	Sept. 8, 1961	4,470.80	48	----------	----------	----------	90	----------	----------	----------	----------
37d	Apr. 19, 1962	4,474.9	60	23	----------	----------	16	----------	----------	----------	----------
38. Hart Lake, northwest shore about											
38a	Sept. 5, 1912	4,471.0	----------	19	22	9.8	[3] 49	----------	211	0	16
38b	Apr. 27, 1961	4,465.48	59	35	52	30	192	16	518	43	94
39. Bluejoint Lake, west shore about											
39a	Sept. 6, 1912	----------	----------	20	21	23	1,370	82	1,820	511	206
40. Deep Creek, 5.5 miles											
40a	Mar. 31, 1951	235	----------	----------	----------	----------	----------	----------	46	0	9.2
40b	Aug. 21, 1956	20	65	31	7.9	3.8	7.1	2.8	62	0	----------
41. Honey Creek, 0.7 mile northwest											
41a	Aug. 21, 1956	1.2	72	22	19	8.1	12	3.4	126	0	----------

---

[1] One of 17 samples collected at 15 sites during lake traverses on May 20, 1959. (See pl. 2.)

[2] Analysis of a composite of daily samples for the 10-day period (Van Winkle, 1914, p. 122). Composites 12a and 12b, respectively, had largest and smallest dissolved-solids contents reported for the period Aug. 11, 1911-Aug. 14, 1912.

[3] Calculated amount of sodium plus potassium, expressed as sodium. Values

lakes and their tributary streams—Continued

Chloride (Cl)	Fluoride (F)	Bromide (Br)	Nitrate (NO_3)	Orthophosphate (PO_4)	Boron (B)	Dissolved solids (calculated)	Hardness as $CaCO_3$	Percent sodium	Specific conductance (micromhos at 25° C)	pH	Density at 20° C
BASIN											
shore near wildlife refuge											
22	----------	----------	2.4	1.6	----------	484	150	58	----------	----------	----------
4.5	0.3	----------	3.3	.42	----------	258	142	31	409	7.0	----------
(exact site unknown)											
6,800	----------	----------	2.8	10	----------	22,400	28	98	----------	----------	1.021
11,700	13	47	----------	32	83	34,300	4	98	47,700	9.8	1.023
southeast of Frenchglen (32/32½–8SW¼)											
1.8	----------	----------	0.1	----------	----------	87e	34	37	111	7.9	----------
of Burns (22/30–8SW¼)											
2.2	----------	----------	0.3	----------	----------	120e	60	27	170	7.8	----------
BASIN											
6 miles north of Adel (38/24–22)											
4.2	----------	----------	1.7	----------	0.0	101	56	41	----------	----------	----------
20	0.8	----------	----------	1.0	----------	322	144	44	488	8.4	----------
30	----------	----------	----------	----------	----------	500e	----------	----------	752	----------	----------
5.0	----------	----------	----------	----------	----------	120e	----------	----------	162	----------	----------
3 miles northeast of Plush (36/24–14)											
9	----------	----------	0.8	0.8	0.0	230	96	53	----------	----------	----------
62	2.1	----------	----------	----------	----------	781	252	60	1,190	8.8	----------
25 miles north-northeast of Plush											
504	----------	----------	0.8	2.0	----------	3,630	147	92	----------	----------	----------
west of Adel (39/23–15NW¼)											
1.0	----------	----------	----------	----------	----------	----------	28	----------	79	6.9	----------
1.2	----------	----------	0.2	----------	----------	90e	35	28	105	7.1	----------
of Plush (36/24–29NE¼)											
2.2	----------	----------	0.2	----------	----------	135e	81	23	204	7.9	----------

for samples collected in 1912 from Silver, Crump, and Hart Lakes recalculated from Van Winkle's data (1914, p. 113, 117).

[4] Mean values calculated from analyses of 37 composite samples.

[5] Calculated.

[6] Lake depth at point of collection was only 2 inches, of which 1 inch was ice.

TABLE 29.—*Trace-element content of samples from Abert, Summer, and Goose Lakes and from the Chewaucan River*

[Spectrographic analyses by U.S. Geol. Survey, Sacramento, Calif. Results reported in parts per billion. Symbols: >, more than amount indicated; <, less than amount indicated; ≧, about equal to but slightly more than amount indicated; ≦, about equal to but slightly less than amount indicated]

	Lake Abert			Chewaucan River	Summer Lake	Goose Lake
Analysis No.[1]	1f	1i	8a	14l	16f	21g
Collection date in 1962	Jan. 12	June 12	Sept. 17	June 12	June 12	June 12
Appearance when collected	Turbid; light tan.	Clear	Clear	Slightly turbid; light amber.	Very turbid; light tan.	Turbid; tan.
Time lapse until filtration [2]	2.0	1.1	0.8	1.2	1.2	1.4
Aluminum (Al)	270	76	77	8.6	168	11
Beryllium (Be)	<1.0	<1.9	<1.9	<.57	<2.0	<.57
Bismuth (Bi)	<.48	<1.0	<.9	<.29	<1.0	<.29
Cadmium (Cd)	<2.4	<4.8	<4.7	<1.4	<5.0	<1.4
Chromium (Cr)	<2.4	<4.8	<4.7	<1.4	<5.0	<1.4
Cobalt (Co)	<2.4	<4.8	8.3	1.5	19	<1.4
Copper (Cu)	<2.4	<4.8	<4.7	<1.4	<5.0	<1.4
Gallium (Ga)	<9.6	<19	<19	<5.7	<20	<5.7
Germanium (Ge)	<.48	<1.0	<.9	<.29	<1.0	<.29
Iron (Fe)	>96	90	84	64	15	5.1
Lead (Pb)	<2.4	<4.8	23	<1.4	<5.0	<1.4
Manganese (Mn)	≧2.4	≦4.8	<4.7	<1.4	<5.0	<1.4
Molybdenum (Mo)	>48	13	31	.4	44	6.3
Nickel (Ni)	≧.48	17	17	2.8	1.9	1.7
Titanium (Ti)	<1.0	≦1.9	<1.9	<.57	<2.0	<.57
Vanadium (V)	>48	77	≧47	5.7	1.6	14
Zinc (Zn)	<19	<19	<19	<5.7	<20	<5.7

[1] Number of the companion major-constituent analysis in table 28.

[2] Time, in days, between sample collection and filtration through 0.45-micron pore-size pads. Sample from Summer Lake remained opalescent even after filtration; others were clear.

TABLE 30.—*Chemical and physical*

[All analyses by U.S. Geological Survey. Results reported in parts per million, except as indicated. Estimated values throughout

Site No. (on pl. 1)	Location [1]	Collection date	Discharge [2] (gpm)	Water temperature (° F)	Silica (SiO₂)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)
									Lake Abert
101	32/21-26D	June 9, 1962	700e	68	34	----------	----------	----------	----------
102a	33/22-16F	May 20, 1959	----------	66	46	----------	----------	159	----------
102b	33/22-16F	June 9, 1962	200e	66	46	4.5	2.5	160	7.6
103	33/22-20A	June 9, 1962	200e	71	33	----------	----------	----------	----------
104	34/21-6J	June 9, 1962	3e	68	51	8.0	6.9	270	16
105	35/21-1C	June 12, 1962	1.5e	56	34	23	9.3	23	3.5
106	35/21-21D	June 9, 1962	150e	66	65	9.5	7.5	290	14
									Summer Lake
107	30/17-5A	Oct. 17, 1955	500e	60	37	3.2	1.9	43	3.6
108	33/17-12A	Oct. 8, 1948	21	116	96	1.4	.4	399c	6.8
									Goose Lake
109	39/20-27B	June 23, 1948	49	157	66	15	0.4	152c	2.2
110	39/20-27L	May 22, 1948	50	185	140	8.5	1.4	268c	8.8
									Warner
111	38/24-27N	Sept. 16, 1948	5	104	125	18	2.0	175c	8.7

[1] Spring locations are designated according to the rectangular system of land division. (See p. B53.)

[2] 449 gpm equals 1 cfs.

character of sampled spring waters

table are indicated by "e" following the value. Calculated sodium and sulfate concentrations are indicated by "c" following the value]

Bicarbonate [3] (HCO₃)	Carbonate [3] (CO₃)	Sulfate (SO₄)	Chloride (Cl)	Fluoride (F)	Nitrate (NO₃)	Orthophosphate (PO₄)	Boron (B)	Dissolved solids (calculated)[3]	Hardness as CaCO₃	Percent sodium	Specific conductance (micromhos at 25° C)	pH [3]
basin												
198	8	---------	29	---------	---------	---------	---------	285e	44	---------	483	8.5
216	12	---------	104	---------	---------	---------	---------	---------	22	---------	781	8.6
224	8	32	104	0.7	---------	0.21	---------	475	22	92	777	8.5
256	16	---------	141	---------	---------	---------	---------	580e	17	---------	973	8.7
298	0	40	260	.6	---------	.14	---------	800	48	90	1,360	8.1
69	0	24	50	.0	---------	.15	---------	201	96	33	345	7.0
282	0	47	295	.3	---------	.13	---------	867	54	80	1,450	8.1
basin												
109	3	9c	6	---------	0.2	---------	---------	162	16	82	206	8.4
374	30	111	285	2.2	.1	---------	1.0	1,120e	5	98e	1,760	8.5
basin												
84	0	152	99	3.1	0.2	---------	7.0	531	39	89	813	7.7
208	0	223	146	6.9	.3	---------	9.9	905	27	89	1,320	7.3
basin												
[4] 130	---------	116	150	1.9	1.5	---------	7.3	662e	53	86e	935	8.7

---

[3] See headnote in table 28.

[4] Carbonate plus bicarbonate, expressed as bicarbonate.

TABLE 31.—*Chemical and physical*

[All analyses made by U.S. Geological Survey. Well data largely from Trauger (1950, table 1). Results reported in parts

Site No. (on pl. 1)	Location [1]	Depth (ft)	Water-bearing material	Collection date	Water temperature (° F)	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)
Lake Abert									
112	33/18-24L	114	Gravel	Oct. 7, 1948	----------	54	14	3.2	21c
113	33/18-24(?)P	165	----------	Apr. 4, 1961	----------	44	5.0	2.9	69
114	36/21-6B	80	Sand, black	Jan. 12, 1962	----------	58	22	13	31
Summer Lake									
115	30/16-1F	339	Sand, fine, red	Oct. 15, 1955	69	35	12	1.4	49
116	30/16-1R	209	Lava above red and black cinders	Oct. 15, 1955	67	40	5.6	1.4	58
117	30/16-12A	248	Lava	Oct. 15, 1955	60	42	3.2	1.9	82
118	30/16-12J	375	Lava, red, pumiceous	Oct. 15, 1955	66	39	3.6	.7	98
119	30/17-7F	414	Lava, red, spongy, with pumice	Oct. 15, 1955	66	38	2.8	2.6	68
120	33/18-15B	134	----------	Oct. 10, 1948	92	106	16	4.7	194c
Goose Lake									
121	38/19-24B	343	Gravel, sand	July 2, 1948	54	44	18	1.8	7.3c
122	38/19-36A	205	Gravel	July 2, 1948	53	46	10	4.2	13c
123	38/20-33Q	400	----------	June 30, 1948	182	95	12	2.6	209c
124	39/19-15H	90	Gravel, fine	Aug. 2, 1948	54	62	20	4.7	7.7c
125	39/20-4C	38	----------	June 30, 1948	212	145	15	4.4	236c
126	39/20-16A	365	Gravel, medium to fine	July 10, 1948	79	77	1.1	.8	45c
127	39/20-29L	210	Sand (?)	July 13, 1948	----------	64	4.7	4.6	40c
128	40/19-5D	100	Gravel	Aug. 2, 1948	----------	57	48	9.2	47c
129	40/19-22M	3,000	do	Nov. 2, 1950	66	64	5.0	12	546
130	41/20-13Q	17	----------	June 25, 1948	65	52	8.2	3.1	183c
Silver Lake									
131	27/14-35M	61	Sand	Feb. 18, 1950	50	51	17	17	20
132	28/14-21Q	240	Cinders and clay, red	Dec. 12, 1958	----------	43	14	7.7	10
133	28/14-22L	34	Gravel, sand	Feb. 18, 1950	48	53	13	9.8	13
Warner									
134	33/26-20L	600	Sand, black	Aug. 13, 1948	----------	67	42	46	402c
135	36/24-17J	128	Volcanic breccia(?)	Feb. 13, 1950	----------	45	13	8.7	21
136	39/24-34L	156	----------	Aug. 9, 1948	50	65	5.9	5.5	46

[1] Well locations are designated according to the rectangular system of land division.

[2] See headnote in table 28.

[3] Also includes 0.42 ppm of orthophosphate (PO_4).

character of sampled well waters

per million, except as indicated. Calculated sodium and sulfate concentrations are indicated by "c" following the value]

Potassium (K)	Bicarbonate [2] (HCO_3)	Carbonate [2] (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids [2] (calculated)	Hardness as $CaCO_3$	Percent sodium	Specific conductance (micromhos at 25° C)	pH [2]
basin												
8.8	96	0	15	7.0	0.3	1.3	0.03	172	48	44	202	8.0
6.4	215	0	.4	1.5	.7	.2	---------	237	24	82	326	7.8
7.4	199	0	8.0	10	.2	---------	.51	[3] 249	110	36	354	7.2
basin												
6.0	41	19	19c	44	---------	1.2	---------	208	36	71	310	9.2
4.8	114	3	20c	22	---------	.2	---------	212	20	83	277	8.4
9.1	180	2	34c	24	---------	.0	---------	288	16	87	384	8.4
5.8	228	3	11c	19	---------	.2	---------	293	12	92	433	8.5
4.8	157	4	17c	12	---------	.1	---------	227	18	86	299	8.6
13	132	0	227	104	1.9	2.0	0.8	734	60	85	1,050	7.7
basin [4]												
4.4	80	0	4.3	1.5	0.0	0.1	0.1	120	52	22	140	8.2
5.4	90	0	3.7	1.8	.0	.2	.1	128	42	37	144	7.8
5.8	72	0	259	119	4.7	.1	6.7	749	40	90	1,100	8.1
5.1	[5] 104	---------	4.5	1.5	.1	.2	.01	157	69	18	176	8.8
6.6	107	0	289	132	4.6	.2	7.6	893	56	89	1,240	7.9
2.0	121	0	1.4	3.2	.6	.3	.52	192	6	92	196	8.2
3.0	138	0	1.0	2.8	1.0	.9	.02	190	31	72	234	8.2
15	[5] 200	---------	12	16	.4	98	.01	401	158	37	553	8.7
36	1,520	0	1.1	39	.4	1.5	6.6	1,460	62	92	2,150	7.9
6.0	338	0	47	80	2.4	.5	4.4	553	33	91	874	7.7
basin												
5.6	184	0	1.0	1.0	0.2	3.2	0.01	207	112	27	285	7.5
2.8	107	0	4.4	1.5	.1	.5	---------	137	66	24	177	8.2
4.8	94	0	9.0	8.0	.2	8.8	.00	166	73	27	210	7.4
basin												
24	748	0	226	246	0.5	1.2	3.5	1,420	294	73	2,190	-----------
7.0	122	0	8.5	5.0	.2	1.9	.01	170	68	37	225	8.1
5.6	156	0	.7	10	.8	.3	.04	217	37	69	266	-----------

[4] For additional published analyses of well waters in California, refer to California Department of Water Resources (1965, p. 157; 1966, table 44).

[5] Carbonate plus bicarbonate, expressed as bicarbonate.

INDEX

[Italic page numbers indicate major references]

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