Solute Balance at Abert and Summer Lakes, South-Central Oregon

GEOLOGICAL SURVEY PROFESSIONAL PAPER 502-C

Solute Balance at Abert and Summer Lakes, South-Central Oregon

By A. S. VAN DENBURGH

CLOSED-BASIN INVESTIGATIONS

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A description of the quantity and chemical character of incoming, outgoing, and stored solutes and the mechanisms of solute accumulation and depletion in a saline environment

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1975

UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

V. E. McKelvey, *Director*

Library of Congress Cataloging in Publication Data
Van Denburgh, A. S.
Solute balance at Abert and Summer Lakes, south-central Oregon.
(Closed-basin investigations)
(Geological Survey Professional Paper 502-C)
Bibliography: p.
Supt. of Docs. No.: I 19.16:502-C
1. Saline waters–Oregon–Abert Lake. 2. Saline waters–Oregon–Summer Lake.
I. Title. II. Series. III. Series: United States Geological Survey Professional Paper 502-C.
QE75.P9 No. 502-C [GB1625.07] 557.3'08s [553'.72'0979593] 75-619062

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402
Stock Number 024-001-02689-9

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By A. S. Van Denburgh

ABSTRACT

Neighboring Abert and Summer Lakes occupy the broad flat floors of deep, topographically enclosed basins in the high desert of south-central Oregon. The two saline lakes and their tributary areas provide contrasting hydrologic environments well suited to an investigation of the various aspects of solute economy. Exclusive of direct precipitation, Lake Abert receives about 90 percent (62,000 acre-ft) of its average annual water supply from the snow-fed Chewaucan River. Summer Lake, in contrast, derives about 74 percent (67,000 acre-ft per year) of its inflow from Ana Springs via Ana River. Prior to impoundment of the river and inundation of the springs, the annual contribution probably averaged about 100,000 acre-feet (83 percent of the total). The Chewaucan River at its mouth carries an average of about 120 ppm (parts per million) of dissolved solids, whereas the flow of Ana Springs contains 160 ppm.

The total solute loads contributed to Abert and Summer Lakes from all sources average about 13,000 and 24,000 tons per year, of which ground-water increments constitute approximately 25 and 95 percent. Prior to 1900 the annual increment to Summer Lake was about 26,000 tons. Constituents that dominate in the lakes (sodium plus equivalent chloride and carbonate-bicarbonate) have been contributed by inflow in the following approximate amounts during an average year: Lake Abert, 5,600 tons; Summer Lake since 1926, 14,000 tons; Summer Lake prior to 1900, 15,000 tons. The chloride:sodium ratio has been about 0.2 for each of the increments, on the basis of equivalents per million.

During the 50 years beginning in 1916, the area and maximum depth of Lake Abert have averaged almost 50 square miles and 6½ feet. The lake dried several times during the drought of the 1920's and 1930's, whereas in 1958 it covered 64 square miles and had a maximum depth of 16½ feet. By 1969 the lake contained almost 15 million tons of dissolved solids and had a chloride:sodium ratio of 0.57. The solute concentration generally is 30,000 to 60,000 ppm except at unusually high lake levels or near-dryness.

At Summer Lake prior to 1900 the average maximum depth was about 6½ feet, and the water body characteristically covered about 60 square miles. The solute load totaled approximately 5 million tons and was chemically similar to the load in Lake Abert, except that the chloride:sodium ratio was only 0.29. Since 1926 Summer Lake has dried frequently and has had an average maximum depth of only about 1½ feet and a surface area of about 40 square miles. In 1969, after containing water continuously for almost 6 years, the lake held 1.4 million tons of solutes, which included a somewhat greater proportion of chloride than prior to 1926 (chloride:sodium ratio characteristically was about 0.35). The dissolved-solids content of Summer Lake generally is between 5,000 and 50,000 ppm.

The solute tonnage in broad, shallow closed lakes with wide marginal playas fluctuates in response to long-term changes in lake area and volume. At Abert and Summer Lakes during a generally receding phase, major solute losses occur in only the final stages of recession, when much of the tonnage becomes entrapped within the peripheral playa sediments. The depletion can continue at a lesser rate with the aid of the wind during a characteristically low-level period. Much of the lost solute tonnage is recovered during or soon after a return to high level, and additional solutes accumulate if the lake remains at high level.

Fine-grained lacustrine deposits that underlie the lakes and adjacent playas harbor large solute tonnages. Beneath the lakes, interstitial brines constitute as much as 80–85 percent of the muds, by volume. Measured salinities at 2–5 feet depth are 40,000–50,000 ppm beneath Summer Lake, and they exceed 100,000 ppm beneath much of Lake Abert. The interstitial solutes are dominated by sodium among the cations and are richer in carbonate plus bicarbonate and poorer in chloride than the overlying lake waters. Characteristic chloride:sodium ratios are 0.25–0.30 for brines beneath Summer Lake and about 0.50 for those at Lake Abert.

Shallow playa sediments adjacent to the lakes contain somewhat smaller quantities of brine (50–80 percent) than the bottom sediments. At Lake Abert measured salinities also are less (80,000–100,000 ppm), whereas at Summer Lake they are greater (80,000–140,000 ppm), reflecting differences in peripheral ground-water input. The most pronounced contrast between playa and lake-bottom solutes at both lakes is in the relative abundance of anions. Deposits at the playa surface are far richer in carbonate and bicarbonate than are those in either the lake or the lake-bottom interstitial fluids. The enrichment apparently is associated with evaporation of upward-moving fluids: the first-formed salts of sodium carbonate and bicarbonate presumably tend to shield the residual chloride-enriched brine from continued evaporation and resultant crystallization. Wind removal of the powdery components of carbonate- and bicarbonate-rich salts from the playa surface causes long-term enrichment of chloride in residual brines; the relative abundance of chloride beneath the playas is far greater than in or beneath the lakes (characteristic chloride:sodium ratios beneath the playas are about 0.8 at Lake Abert and 0.5 at Summer Lake).

At Lake Abert, solute quantities in the top 5 feet of playa and lake-bottom deposits average about 550 tons per acre (the greatest amounts per acre underlie the lake), and total 25–35 million tons, of which about one-third is chloride. Comparable values at Summer Lake are about 300 tons per acre (with greatest per acre amounts beneath the eastern playa) and 15–20 million tons overall, of which only 20–25 percent is chloride.

The relation between incoming and stored solutes at the two lakes contrasts sharply. Total salts and chloride stored in Lake Abert and within the top 5 feet of bottom and playa sediments are, respectively, 8,000 and 16,000 times the average present-day income, whereas comparable values at Summer Lake are only about 1,000 and 2,000 (the higher values for chloride reflect its enrichment relative to carbonate and bicarbonate). This contrast between the two lakes contradicts the situation that would be expected because of (1) the different solute quantities that may have been retained in the two basins after the final shrinking of Pleistocene Lake Chewaucan (Summer Lake should have inherited a tonnage greater than that of neighboring Lake Abert), and (2) apparent differences in the long-term uniformity of water supply and, therefore, lake stability in the two basins (Summer Lake should have been more stable, because of the dominance of ground-water inflow). Even with allowance for possible differences in lake-basin sedimentation rates, the solute balances contrast, suggesting strongly that Summer Lake has not always had an income as abundant as it did immediately prior to man's alteration of the natural hydrologic situation. A major prehistoric increase in the amount of interbasin ground-water flow feeding Ana Springs, because of faulting, is possible, though other evidence discourages this. Alternatively, because the area-to-depth ratio at shallow levels is much greater at Summer Lake than at Lake Abert, the effects of evaporation and wind may have been magnified at the former during long prehistoric dry periods, when inflow, regardless of its source, was diminished. Large deposits of windblown sand east of Summer Lake argue in favor of extended periods of near-desiccation, with attendant depletion of stored playa salts by deflation.

INTRODUCTION

LOCATION AND GENERAL FEATURES OF THE AREA

Adjacent Abert and Summer Lakes lie in the high desert country of south-central Oregon, within the northwest limits of the Great Basin (pl. 1; fig. 1). They occupy deep, topographically enclosed basins, and lose water only by evaporation. The two saline lakes and their tributary areas cover 1,250 square miles, of which 860 square miles belongs to Lake Abert. Altitudes within the combined basin range from about 4,145 feet at Summer Lake and 4,250 feet at Lake Abert to almost 8,400 feet at one place on the western drainage divide. The lowest point of possible overflow from the combined basin probably exceeds 4,600 feet altitude. The lakes themselves are separated by a divide with a low point at about 4,385 feet.

During the late Pleistocene a large lake filled both basins to a maximum level of about 4,520 feet, covering almost 500 square miles with a volume of water that exceeded 21 cubic miles (70 million acre-ft). The fluctuations of that lake are recorded by prominent shoreline features at many places throughout the two basins.

The area surrounding the lakes is, for the most part, one of intricately faulted Tertiary volcanic flows and pyroclastic debris, mapped on a reconnaissance basis by George W. Walker (1963). Dip-slip movement along the faults has formed numerous horsts, grabens, and tilted fault blocks of spectacular proportion, such as those described by Donath (1962). Two of the most prominent structural features are Winter Ridge, a 3,000-foot scarp

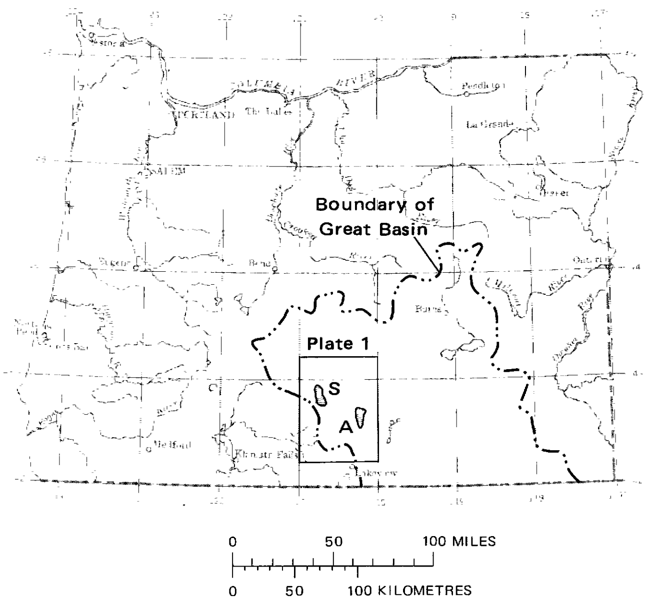


FIGURE 1.—Map of Oregon showing location of Lake Abert (A), Summer Lake (S), and the area included on plate 1.

that overlooks Summer Lake on the west (pl. 1; fig. 2), and Abert Rim, an even more abrupt escarpment that rises, at places almost vertically, to a height as much as 2,450 feet above Lake Abert within 1 mile of its eastern shore. The two lakes occupy depressions that formed during the faulting and subsequently filled with clastic and lacustrine sediments.

PURPOSE AND SCOPE OF INVESTIGATION

Because of their physical and hydrologic characteristics, Abert and Summer Lakes offer an excellent combined site for a study of various aspects of solute balance within a closed-basin environment. This investigation has furnished information on: The amounts and chemical character of incoming, outgoing, and stored solutes; the mechanisms and effectiveness of accumulation and depletion; the stability of the stored-solute resources; the manner in which these closed-lake systems react to and record changes in climate and activities of man; and the factors that may account for a contrast between solute balances at the two lakes.

A reconnaissance of the two lakes and their inflow has been made by Phillips and Van Denburgh (1971). The present study utilizes information presented in the reconnaissance report, along with new data collected since that time and previous information not included in the preliminary study.

ACKNOWLEDGMENTS

I am particularly indebted to Blair F. Jones, of the U.S. Geological Survey, who has been an invaluable source of information, advice, and great encouragement through-

FIGURE 2.—Aerial photographs of Abert and Summer Lakes. *A*, High-altitude vertical photograph of the two lakes and adjacent areas, October 24, 1972. North at top; picture width about 52 miles. Estimated lake levels: Abert, 4,258.5 feet; Summer, about 4,145 feet. (From ERTS–I satellite photograph 81093181615G000; multispectral scanner, infrared wavelength range.) *B*, Oblique view of Lake Abert, viewed to the north-northeast. In foreground, Chewaucan River meanders north to lake. Abert Rim dominates skyline east of lake. Photograph taken in August 1963; lake level 4,254.5 feet. *C*, *D*, Oblique views of Summer Lake, looking south. Marshy wildlife-management area in foreground. Broad mudflats east of lake contrast with Winter Ridge and Slide Mountain to the west and south. Photographs taken in July 1964; lake level 4,147.2 feet.

out the investigation, and to Glenn E. Tyler, retired State Watermaster, District 12, who has collected many of the critical water samples and streamflow data, and who, along with his family, has provided a hospitality that makes the high desert country of south-central Oregon so special. I am also grateful to Walter B. Langbein, Kenneth N. Phillips, Shirley L. Rettig, George I. Smith, and Alfred H. Truesdell of the U.S. Geological Survey, and Boyd Claggett of the Summer Lake State Game Management Area, who have provided valuable help during the study, as well as to Meyer Rubin of the Survey, who provided carbon-14 age determinations on four sediment samples.

LOCATION SYSTEM

The numbering system for hydrologic sites in this report indicates location on the basis of the rectangular subdivision of public lands, referenced to the Willamette base line and meridian. Each number consists of three units: the first is the township south of the base line; the second unit, separated from the first by a slant, is the range east of the meridian; the third unit, separated from the second by a dash, designates the square-mile section. The section number is followed by letters that indicate the quarter section, quarter-quarter section, and so on; the letters a, b, c, and d designate the northeast, northwest, southwest, and southeast quarters, respectively. For example, site 33/21–2cdb is in NW¼SE¼SW¼ sec. 2, T. 33 S., R. 21 E.

All locations are based on quadrangle maps of the Oregon State Highway Department (scale, about 1 inch to the mile) and U.S. Geological Survey (about 2½ inches to the mile).

HYDROLOGIC CHARACTERISTICS OF THE TWO LAKES AND THEIR BASINS

CLIMATE

Climatic conditions in the high desert country of south-central Oregon range from arid or semiarid on the valley floors to semihumid in the timbered mountain areas. Average yearly precipitation ranges from 12 inches or less in the dry northeastern parts of the two basins to more than 25 inches in the lofty, well-timbered southwestern parts. In the lowlands about 90 percent of the average annual precipitation is fairly evenly distributed throughout the 9-month period of October–June (fig. 3). From November through March most of the precipitation occurs as snowfall, whereas thundershowers are principal contributors during the remaining 7 months of the year.

Long-term records of annual precipitation at Valley Falls are shown in figure 4. The cumulative departure curve in that figure shows that rain and snowfall were characteristically less than average prior to 1940 and generally greater than average during 1940–65.

Precipitation records are also available for two other stations on the valley floors of the Abert and Summer Lake basins. These Weather Bureau data are summarized below for the short period of concurrent record, 1958–64:

Station name	Location[1]	Altitude (ft)	Average annual precipitation, 1958–64 (in.)
Valley Falls	36/21–6aba	4,320	13.8
Paisley	33/18–24dbd	4,360	11.6
Summer Lake	30/16–23acd	4,190	13.8

[1]See p. C4 for explanation of location system.

On the basis of this information and data for sites outside the two basins, the estimated lakewide average may be about 11 inches per year at both lakes. For Lake Abert, this would represent about 90 percent of the quantity at nearby Valley Falls.

Potential evaporation on the floors of the Abert and Summer Lake basins is about 40 inches per year, two-thirds of which occurs from May through September (fig. 3). The actual amount of water lost from Abert and Summer Lakes themselves is uncertain, because evaporation varies from place to place depending on differences in air temperature, relative humidity, amount of wind, and the physical, thermal, and chemical character of the water body.

Water losses from a Class-A land pan have been measured at the Summer Lake National Weather Service station during part of each year since 1961. The nearest long-term record of year-round pan evaporation is that for the Medford Experiment Station, 110 miles southwest of Summer Lake. Concurrent measurements at these two stations are available for 36 months (mostly May–Oct.) during 1961–66. The coefficient of correlation between the two sets of monthly data is a favorable 0.89. On the basis of these concurrent measurements and the year-round records at Medford, the land-pan evaporation rate at Summer Lake station for the long term is an estimated 57 inches per year. This is equivalent to about 41 inches from a freshwater body, assuming a pan coefficient of about 0.73 (Kohler and others, 1959, pl. 3). The long-term freshwater rate for the lake itself may be slightly higher because the weather station is on the cooler, western side of the basin in the shadow of Winter Ridge (pl. 1).

Evaporation at Lake Abert is less certain. During May–October 1962, K. N. Phillips and his coworkers measured a lake-surface water loss equivalent to 32.5 inches from a freshwater body (Phillips and Van Denburgh, 1971, p. B14). At the Summer Lake station during the same period, pan evaporation was 44.7 inches, which converts to an almost identical freshwater value of 32.6 inches, using the coefficient 0.73. Comparison of monthly lake and pan evaporation can be risky, owing to the effects of inflow and heat storage within the lake (Nordenson,

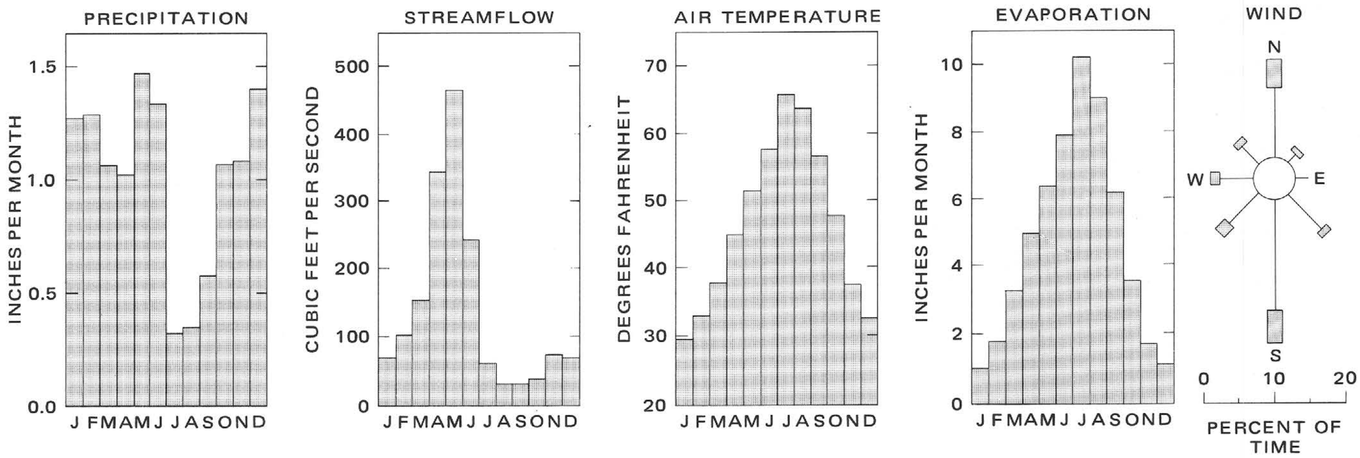


FIGURE 3.—Wind movement and representative seasonal patterns of precipitation, streamflow, air temperature, and evaporation in and adjacent to the Abert and Summer Lake basins (from records of the National Weather Service and the U.S. Geological Survey). Precipitation at Valley Falls for water years 1916–65. Streamflow for Chewaucan River near Paisley, water years 1913–21, 1925–65. Temperature at Valley Falls for calendar years 1931–60. Evaporation from Class-A land pan at Summer Lake station for water years 1961–65 (most data for May-Oct. measured; most data for Nov.-April estimated on basis of records at Medford Experiment Station, 115 miles west-southwest of Summer Lake). Average wind directions and speeds at Lakeview airport, 26 miles south of Lake Abert, based on observations during period January 1959–May 1962 (Howell, 1965). Length of each direction bar shows percentage of time that winds exceeding 3 mph (miles per hour) were from the direction indicated. Winds of 0 to 3 mph, which occurred 38 percent of the time, are not shown. Type of bar indicates wind speed: single-line bar, 4–17 mph; double-line bar, 18–35 mph.

1963, p. 279). At Lake Abert, however, the risk is minimized because inflow during 1962 was well below normal, and the lake was shallow (mean depth averaged only 5 feet during the period). Thus, the comparison suggests that the freshwater evaporation rate at Lake Abert is about 41 inches per year (slightly greater than the 40.3 inches per year estimated earlier by Phillips and Van Denburgh (1971, p. B15)). The actual rate of annual evaporation from the lake would be less than 41 inches, however, because of the effect of salinity.

INFLOW

Abert and Summer Lakes are fed by inflow of contrasting hydrologic character. The principal source of flow into Lake Abert is the Chewaucan River, whereas Summer Lake is fed principally by Ana Springs, which rise about 6 miles north of the lake (pl. 1). Both lakes are sustained partly by direct precipitation. Also, small intermittent streams drain areas adjacent to the lakes, and the discharge of peripheral springs and seeps reaches each lake.

LAKE ABERT

The Chewaucan River drains about 490 square miles, much of which is timbered and mountainous. The principal source of flow is snowmelt runoff, and most of the discharge therefore occurs during the spring and early summer. At the gaging station near Paisley (pl. 1) in an average year, 74 percent of the total annual runoff occurs during March–June (fig. 3). The station (drainage area, 275 sq mi), is about 32 river miles upstream from the mouth, but the seasonal distribution of flow into Lake Abert probably is not much different, although the average yearly volume is considerably less.

The annual flow of the Chewaucan River near Paisley has averaged 96,000 acre-feet during the period 1916–65 (maximum value was 250,000 acre-feet during the 1956 water year, minimum value was an estimated 18,000 acre-feet during the 1924 water year). The record from 1916 through 1965 is summarized in figure 4. The accompanying cumulative departure curve shows that flow was generally below normal during the period 1918–37 but was much greater than normal from 1951 to 1958. The pronounced recovery from a period of lower than average streamflow, which began in 1951, apparently lagged 11 years behind a similar recovery from generally below normal precipitation (fig. 4). The lag may reflect ground-water replenishment upstream from Paisley following the pre-1940 drought.

The average discharge of the Chewaucan River at its mouth for the period 1916–65 is an estimated 62,000 acre-feet—65 percent of the upstream value. The relation between runoff at the two sites is a refinement of that developed by Phillips (Phillips and Van Denburgh, 1971, p. B15), using an extrapolation of climatic and lake-level data obtained during the fairly well documented period 1951–65.

Agricultural activity in Chewaucan Marsh apparently has not as yet (1970) had a pronounced effect on the amount of runoff reaching Lake Abert (Phillips and Van Denburgh, 1971, p. B13). This is, at least in part, because much potential inflow was lost through natural evapotranspiration in the swampy flatlands prior to drainage of

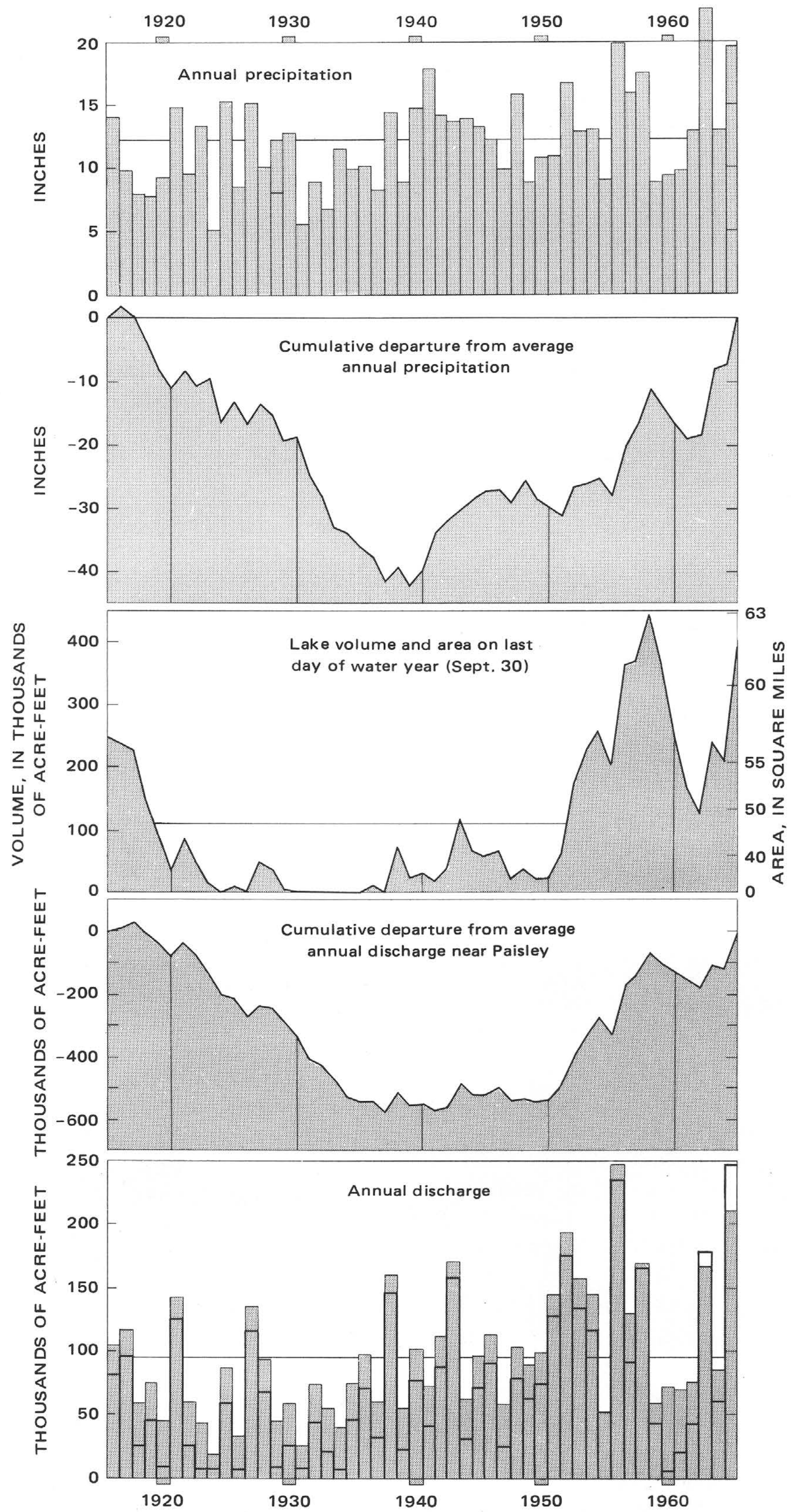


FIGURE 4.—Fluctuations in volume and surface area of Lake Abert in water years 1916–65, compared with precipitation at Valley Falls and discharge of the Chewaucan River. In bottom graph, shaded bars indicate measured annual discharge near Paisley; heavy-line bars indicate estimated total annual inflow to Lake Abert. Horizontal lines in top, middle, and bottom graphs indicate average annual precipitation (12.2 in.), lake volume on September 30 (111, 000 acre-ft), and annual discharge near Paisley (96,000 acre-ft), respectively.

the marsh for agricultural use in the early 1900's. These natural losses may have been comparable in magnitude to present losses due to irrigation.

Inflow to Lake Abert from other streams may average about 2,500 acre-feet per year, on the basis of altitude-runoff relationships developed by D. O. Moore (US. Geological Survey, oral commun., 1970) for nearby Honey and Silver Creeks (U.S. Geological Survey gaging stations 10378500 and 10390000). Data for the Chewaucan River were not used in developing the relationships because that stream's headwaters area, above Paisley, is in a much wetter altitude-runoff environment than are Lake Abert and vicinity.

The total annual discharge of all seeps and springs along the periphery of Lake Abert may be about 5,000 acre-feet, though the amount of ground-water flow actually reaching the lake may average only 2,000 to 2,500 acre-feet per year, owing to evaporation. Some of the flow doubtless is derived from recharge within the Lake Abert basin, but most of it may come from an adjacent basin or basins (Phillips and Van Denburgh, 1971, p. B13). No large submerged springs are known (none was reported in periods when the lake was dry).

In summary, then, the combined flow supplied to Lake Abert and its peripheral areas in excess of direct lake-surface precipitation probably averaged about 70,000 acre-feet per year (62,000 acre-ft from the Chewaucan River, 5,000 acre-ft from seeps and springs, and 2,500 acre-ft from ephemeral streams).

SUMMER LAKE

Ana Springs, the principal source of discharge into Summer Lake, originally provided a relatively consistent year-round supply that flowed directly to the lake via the Ana River. On the basis of an estimated average discharge of 130 to 150 ft³/s (cubic feet per second) from the several orifices, the annual contribution under natural conditions prior to 1900 amounted to about 100,000 acre-feet. A dam was completed immediately downstream from the springs in 1926, and the impounded water inundated the orifice area to a depth ranging from 16 to 46 feet (Phillips and Van Denburgh, 1971, p. B25). The resulting hydrostatic head has reduced the average discharge rate to about 92 ft³/s (or 67,000 acre-ft per year).

At present, additional springflow apparently feeds the river below the gage. Several measurements, about 2 miles downstream from the gage (listed below), suggest that the pickup in that reach averages about 10,000 acre-feet per year. Some of this increment may represent ground water that would issue from the main Ana Spring orifices under natural (pre-dam) conditions. Limited and seemingly conflicting data prior to construction of the dam (table in right column) suggest that inflow below Ana Springs may not have been much less than now, though the approximate quantities are uncertain. For the purpose of solute tonnage computations, the pre-dam increment is assumed to have been about half the present-day quantity, or 5,000 acre-feet per year.

Date	Discharge (ft³/s)		
	Near Ana Springs (30/17-6d)	Near lake (30/17-9ccd)	Increase (+) or decrease (-)
After construction of Ana Reservoir[1]			
5-16-68	27	38	+11
7-10-68	54	62	+8
11-27-68	93	114	+21
12- 5-69	94	93	-1
2-19-70	119	118	-1
3-24-70	94	106	+12
8- 6-70	34	42	+8
Before construction of reservoir[2]			
7-17-04	165	179	+14
3-28-05	148	[3]150	+2

[1]Data from Glenn E. Tyler, Watermaster (written communs., 1968-70).
[2]Data from Henshaw and Dean, 1915, p. 756-757; accuracy of near-lake measurements uncertain because of backwater (this does not apply to measurements of 1968-70 when lake was about 5 ft lower).
[3]Measured Jan. 8, 1905; assumed comparable with later upstream measurement.

The amount of flow actually reaching Summer Lake from Ana Springs and other springs tributary to the Ana River is depleted by diversions for irrigation of agricultural and waterfowl resting areas. A crude estimate of present-day net depletion due to these diversions is about 20,000 acre-feet per year (under natural conditions, only an estimated 10,000 acre-ft was lost through evapotranspiration in marshy areas north of the lake). Thus, net annual flow reaching the lake from the spring systems is now about 57,000 acre-feet—only a little more than half of the pre-1900 quantity. Furthermore, most of the present inflow occurs during the period October–April, rather than throughout the year at a nearly constant rate as it did prior to impoundment and diversion.

Many small streams, in part springfed, drain the rugged, timbered areas west and south of Summer Lake (pl. 1), and far smaller quantities of runoff occasionally reach the lake from the east during brief thundershowers. The streams may contribute about 10,000 acre-feet per year, on the basis of altitude-runoff relationships. Much of this flow is dissipated by evapotranspiration—both natural and man-caused—before reaching the lake. Under natural conditions prior to 1900, the annual depletion may have averaged only about a third of the 10,000 acre-foot total, whereas, under present-day conditions, irrigation and natural losses may dissipate about two-thirds of the total.

Springs and seeps in addition to those that feed the Ana River contribute a small amount of flow to the lake and its peripheral areas. Best known of the group is Summer Lake Hot Spring (33/17-12aac), which flowed at a rate of about 34 acre-feet per year in 1948. Many springs on the basin floor were visited in 1948-49, after a 10-year period of above-normal precipitation (fig. 4). For visited springs not contributing to the river, the combined flow was about

2,200 acre-feet per year (Trauger, 1950, p. 218–224). A reasonable estimate of total spring discharge on the basin floor, in addition to that feeding the river, may be 3,000–4,000 acre-feet per year, of which only a small part overcomes evapotranspiration and reaches the lake. Much of the springflow west and south of Summer Lake doubtless represents the reappearance of recharge from streams draining the Winter Ridge–Slide Mountain area.

At some time in the past Summer Lake received overflow from the Lake Abert basin via the channelway north of Paisley (Phillips and Van Denburgh, 1971, p. B15), but such overflow probably has not occurred since Pleistocene time.

Interbasin ground-water flow toward Summer Lake fed by percolation from the Chewaucan River north of Paisley is considered to be small. Ground-water gradients and lithologic logs for wells on the alluvial-lacustral fan north of the river indicate that the total northward flow may average only about 2,000 acre-feet per year, and well-water chemistry suggests that most of the solutes are not derived directly from the river.

Table 1 summarizes the water budget of Summer Lake for conditions before and after man's alteration of the natural hydrologic environment. The data indicate that present-day net inflow averages only about 60 percent of the quantity under natural conditions.

TABLE 1.—*Hydrologic budgets for Summer Lake before 1900 and after 1926*

[Acre-feet per year, except as indicated[1]]

No.	Item	Pre-1900	Post-1926
1.	Flow of Ana Springs	100,000	67,000
2.	Inflow to Ana River below springs	5,000	10,000
3.	Depletion of Nos. 1 and 2 by evapotranspiration before reaching Summer Lake	10,000	20,000
4.	Mountain-front streamflow west and south of lake	10,000	10,000
5.	Depletion of No. 4 by evapotranspiration before reaching Summer Lake	3,000	7,000
6.	Net inflow to Summer Lake (1 + 2 + 4 − 3 − 5, rounded)	100,000	60,000
7.	Lake area corresponding to No. 6 (acres)[2]	38,000	22,000
8.	Lake level corresponding to No. 7 (feet above mean sea level)	4,151	4,146

[1]Probable accuracy: Item 1, ± 15,000 acre-feet before 1900, ± 5,000 acre-feet after 1926; items 2, 3, and 6, ± 5,000 acre-feet; items 4 and 5, ± 3,000 acre-feet; item 7, ± 2,000 acres; item 8, pre-1900, ±1 foot, post-1926, ± ½ foot.

[2]Assumes average net evaporation of 2.6 feet per year before 1900 and 2.7 feet per year after 1926 (table 3).

LAKE EXTENT AND FLUCTUATION

Abert and Summer Lakes occupy broad, flat, elongate basins (pl. 1). At maximum depths of only 5 feet, the 2 water bodies cover about 44 and 57 square miles, respectively. Data relating lake volume, areal extent, and lake-surface altitude are presented for the two lakes in table 2. Data for Lake Abert are based largely on a reconnaissance survey made in 1959 and are considered to be reasonably accurate. The data for Summer Lake are approximations based on shoreline configurations from three sets of aerial photographs, information from Geological Survey 1:24,000- and 1:250,000-scale topographic maps, and personal observation. (Data from aerial photographs are as follows: 27 sq mi at 4,145.2 ft on Aug. 8, 1946; 35 sq mi at 4,145.75 ft on Sept. 9, 1953; and 49½ sq mi at 4,147.7 ft on July 23–24, 1963.)

TABLE 2.—*Area and volume of Abert and Summer Lakes*

Lake level (ft above mean sea level)	Area (sq mi)	Volume (thousands of acre-ft)
Lake Abert[1]		
4,244 ±	Dry	0.0
4,245	12.2	4.0
4,246	21.4	14.8
4,247	30.5	31.4
4,248	38.8	53.5
4,249	43.9	80.0
4,250	47.6	110
4,251	50.6	141
4,252	53.0	174
4,253	55.1	209
4,254	56.8	245
4,255	58.3	282
4,256	59.7	320
4,257	60.9	358
4,258	62.0	397
4,259	63.0	437
4,260	63.7	478
4,262	65	560
Summer Lake		
4,144.4 ±	Dry	0.0
4,145	23.5	4.5
4,146	37.5	23.9
4,147	45.5	50.4
4,148	51.0	81.0
4,149	55.2	116
4,150	58.7	152
4,152	64.0	230
4,155	70	360

[1]Data are slightly modified from those of Phillips and Van Denburgh (1971, table 4) on the basis of reevaluated bathymetry below 4,248 feet.

The long-term variations of lake level and volume reflect changing climatic conditions. The record of volume fluctuations at Lake Abert since 1915 is shown in figure 4. (Most values for the poorly documented period from 1915 to 1951 are based on lake-level estimates, using precipitation at Valley Falls and runoff in the Chewaucan River near Paisley (Phillips and Van Denburgh, 1971, p. B15). The validity of these estimates is supported by close agreement with the few recorded levels.) Comparison with curves showing cumulative departures from average precipitation and runoff in the basin illustrate how sensitive the lake is as an index of climatic and hydrologic variation. Only a few years of deficient precipitation and runoff are necessary to cause lake-basin desiccation. Once the lake is dry, an excess of local precipitation alone is not sufficient to cause lake-volume recovery, as shown during 1940–48 (fig. 4). Only after return to above-normal runoff rates does the lake respond by filling to former levels, as it did during 1951–58.

The average amount of water in Lake Abert during the present century may be less than under comparable climatic conditions in the past, owing to agricultural activity in Chewaucan Marsh. Presumably, the difference is relatively small, however (p. C5).

In contrast to conditions at Lake Abert, the extent and fluctuations of Summer Lake have been markedly altered by the activities of man. Prior to impoundment of the Ana River, Summer Lake received most of its water supply from the Ana Spring system, and the inflow occurred at a fairly constant rate. Therefore, seasonal and long-term fluctuations of lake level doubtless were much more subdued than those for Lake Abert because of the secondary importance of highly variable surface runoff. Since construction of the reservoir, however, the submergence of orifices and the seasonal diversions for irrigation have greatly reduced the amount and month-to-month consistency of flow into the lake. Present inflow averages only about 60 percent of the pre-reservoir quantity (table 1), and most of it occurs from October through April. Hence, seasonal variations in lake level are more pronounced, and the long-term average is appreciably lower than pre-reservoir values. In fact, Summer Lake has dried almost completely during the summers of many years since 1926.

The changes brought about by impoundment and diversion of the Ana River are shown more exactly by comparing hypothetical "equilibrium" lake levels under the natural and altered conditions. At "equilibrium" level the lake area is such that evaporation exactly balances the incoming water volume. Thus, the "equilibrium" lake area, in acres, equals the average annual inflow, in acre-feet, divided by average net evaporation (total evaporation less precipitation), in feet per year. Table 1 shows that Summer Lake is an average of about 5 feet shallower now than under natural conditions. (The budgets in table 1 are refined and more detailed versions of those presented by Phillips and Van Denburgh (1971, p. B26); the changes result from additional information concerning several of the budget items.)

PARAMETERS THAT CHARACTERIZE THE LAKES

Langbein (1961, p. 6, 13, 14) presented several interrelated parameters that depict the geometric and hydrologic characteristics of a closed lake and its tributary basin. These characteristics in turn strongly influence the chemical character of the lake. Among the important parameters are

1. The geometric lake-bottom shape factor, which equals the square root of the average lake-surface area, $\sqrt{A_L}$, divided by the mean lake depth, D. A high value indicates a flat saucer-shaped lake, whereas a low value indicates a deep lake.
2. The coefficient of lake-area variation, U, which indicates the variability of lake area with time, relative to the mean lake area. A high value indicates an unstable lake whose area varies greatly with time; a low value indicates a stable lake in which the variations are small relative to the mean.
3. The response time, k, which indicates how rapidly a lake reacts to changes in climate. As Langbein says (1961, p. 6): "A lake with a low value of k, near 1 year, is a playa lake. It fills and dries up in a year. It responds to the current year's rainfall and virtually not at all to that of preceding years. A lake with a high value of k, on the other hand, reacts slowly, and may be at a high level during a period of low rainfall and vice versa."
4. The long-term stability factor, P, which indicates the probability of desiccation or, at the other extreme, of freshening by overflow. Low values indicate near-desiccation or near-overflow, whereas a high value indicates greater stability.

The coefficient of lake-area variation can be calculated directly from detailed records of lake level, after converting the levels to areas. The data are applied to the general formula for a coefficient of variation $U = S_A \sqrt{A}$, where

$$S_A^2 = \frac{\Sigma(A_i^2) - \frac{(\Sigma A_i)^2}{n}}{n-1}. \quad (1)$$

In the absence of detailed lake-level data, Langbein's equation 8 (1961, p. 6) is used. The equation is

$$U = \frac{0.26n}{D} \sqrt{\frac{E(A_T/A_L)k}{2+1/k}}, \quad (2)$$

where n is the exponent in the proportionality relationship between lake area and volume, $A_L \propto V^n$; D is mean depth; E is net annual evaporation (total evaporation minus precipitation); A_T is the tributary area exclusive of the lake; A_L is lake area; and k is the response time.

The response time is defined as:

$$k = \frac{V''-V'}{E(A''-A')}, \quad (3)$$

where V'' and V' are lake volumes at a high and low stage, A'' and A' are the equivalent lake areas, and E is net annual evaporation.

The long-term stability factor, P, is defined in terms of mean lake depth, D, in feet; tributary area, A_T, in square feet; and basin volume at altitude of overflow, V_O, in cubic feet, as follows:

$$P = D\frac{V_O}{A_T} \Big/ \left(D + \frac{V_O}{A_T}\right). \qquad (4)$$

LAKE ABERT

Lake Abert invites a rather detailed analysis of characterizing parameters because of the comparatively simple hydrology and the relative abundance of data. The period of most complete record at the lake spans water years 1952–65. Unfortunately, however, the average lake level during that period was considerably higher than the average for the much longer period of record, 1916–65 (fig. 4). Nonetheless, Langbein's general parameters are evaluated for both periods. Values for several of the descriptive parameters are summarized in table 3. The geometric lake-bottom shape factors and coefficients of lake-area variation are compared with those of other closed lakes in figure 5.

TABLE 3.—*Parameters that describe the physical and hydrologic characteristics of Abert and Summer Lakes*

Parameter	Lake Abert 1952–65	Lake Abert 1916–65	Summer Lake Post-1926	Summer Lake Pre-1900
Tributary area excluding lake, in square miles (A_T)	[1]730	[1]740	350	320
At average lake level:				
Lake-surface altitude, in feet	4,254.7	4,250.5	4,146	4,151
Lake area, in square miles (A_L)[2]	58	49	38	62
Lake volume, in acre-feet	271,000	126,000	24,000	190,000
Mean lake depth, in feet (D)	7.3	4.0	1.0	4.8
At high lake level:				
Altitude, in feet	4,260	4,260	4,150	4,154
Area, in acres (A'')	41,000	41,000	38,000	44,000
Volume, in acre-feet (V'')	478,000	478,000	152,000	315,000
At low lake level:				
Altitude, in feet	4,248	4,246	4,145	4,147
Area, in acres (A')	25,000	14,000	15,000	29,000
Volume, in acre-feet (V')	54,000	15,000	4,500	50,000
Net evaporation, in feet per year (E)	2.3	2.5	2.7	2.6
Geometric lake-bottom shape factor ($\sqrt{A_L}/D$)	1.0	1.8	6.2	1.6
Exponent in area-volume equation (n)	.20	[3].32	.28	.21
Coefficient of lake-area variation (U; eq 2)	[4].085	.23	.36	.074
Response time, in years (k; eq 3)	11.5	6.9	2.4	6.8
Long-term stability factor (P; eq 4)[5]	5.6	3.5	0.99	4.6

[1]Lake Abert basin covers about 860 square miles, but effective drainage area, including lake, is only an estimated 790 square miles.

[2]Average lake area (A_L) for each period is close but not identical to area at average lake level because area-altitude curves are not linear (for example, average area of Lake Abert during 1952–65 was about 57 sq mi).

[3]Exponent is about 0.45 for lake levels below 4,248 feet and 0.20 above that level; weighted average for period is 0.32.

[4]Calculated using lake-area estimates at 2-month intervals (eq 1); agrees well with value calculated using equation 2 (0.090).

[5]Basin volume at altitude of overflow, V_O, is based on drainage divide between the two lake basins, 2.2 miles north of Paisley (alt about 4,385 ft; see pl. 1). Basin volumes at that altitude are Abert, 12×10^6 acre-feet (5.2×10^{11} cu ft); Summer, 25×10^6 acre-feet (10.9×10^{11} cu ft).

SUMMER LAKE

Summer Lake is similar to Lake Abert in that the period with most adequate data is not representative of long-term conditions. Almost all information on the lake and its inflow has been obtained since Ana River Reservoir was completed in about 1926, yet hydrologic conditions at the lake since that year have been far different than during the preceding period. Nonetheless, the lake provides an excellent site to test the applicability of Langbein's generalized parameters in a situation where about 90 percent of the inflow, exclusive of lake-surface precipitation, is provided by ground water. The calculations of several hydrologic parameters for Summer Lake use the records since 1926, as well as the largely estimated data for natural conditions prior to settlement of the area by man.

The response time and long-term stability factor for the period since 1926 are the lowest recorded in table 3; they, along with the highest recorded lake-bottom shape factor, indicate a very unstable lake, which Summer Lake is known to have been.

The low coefficient of lake-area fluctuation prior to 1900 reflects the relative seasonal and year-to-year uniformity of an unregulated inflow composed principally of ground water (Langbein, 1961, p. 15). The lake-bottom shape factor was higher than normal in combination with such a low coefficient of area variation (fig. 5). This too shows the influence of a presumably steady inflow prior to 1900. The calculated response time of only about 7 years is misleading, because equation 3 reflects only indirectly the steadying influence of ground-water increments.

SOLUTE BALANCE

Evaluation of the solute balance for any closed lake requires a knowledge of the amount and nature of solutes brought into the lake by various agencies, solutes removed from the lake and its immediate surroundings, and solutes accumulated and stored either within the lake water or as components of the lake-bottom and peripheral-playa deposits. Unfortunately, vagueness concerning the quantitative importance of various facets of a solute budget and the complexity of interrelations between those facets make anything more than a semiquantitative guess difficult even under fairly well documented present-day conditions. The task of a reliable backward extrapolation of present data over a period of several thousand years is even more formidable.

In studying the salt economy of Abert and Summer Lakes, each basin is divided into two units. The unit of principal concern includes the lake-water body, the upper few feet of saturated sedimentary deposits underlying the lake, and the near-surface parts of adjacent mudflats, which also harbor lake salts. The secondary unit comprises the remaining tributary areas and the atmosphere above. An evaluation of the salt budget, then, involves a quantitative and qualitative study of solutes entering, leaving, and remaining within the unit of principal concern. This in turn necessitates a similar study of solute movement within the secondary unit.

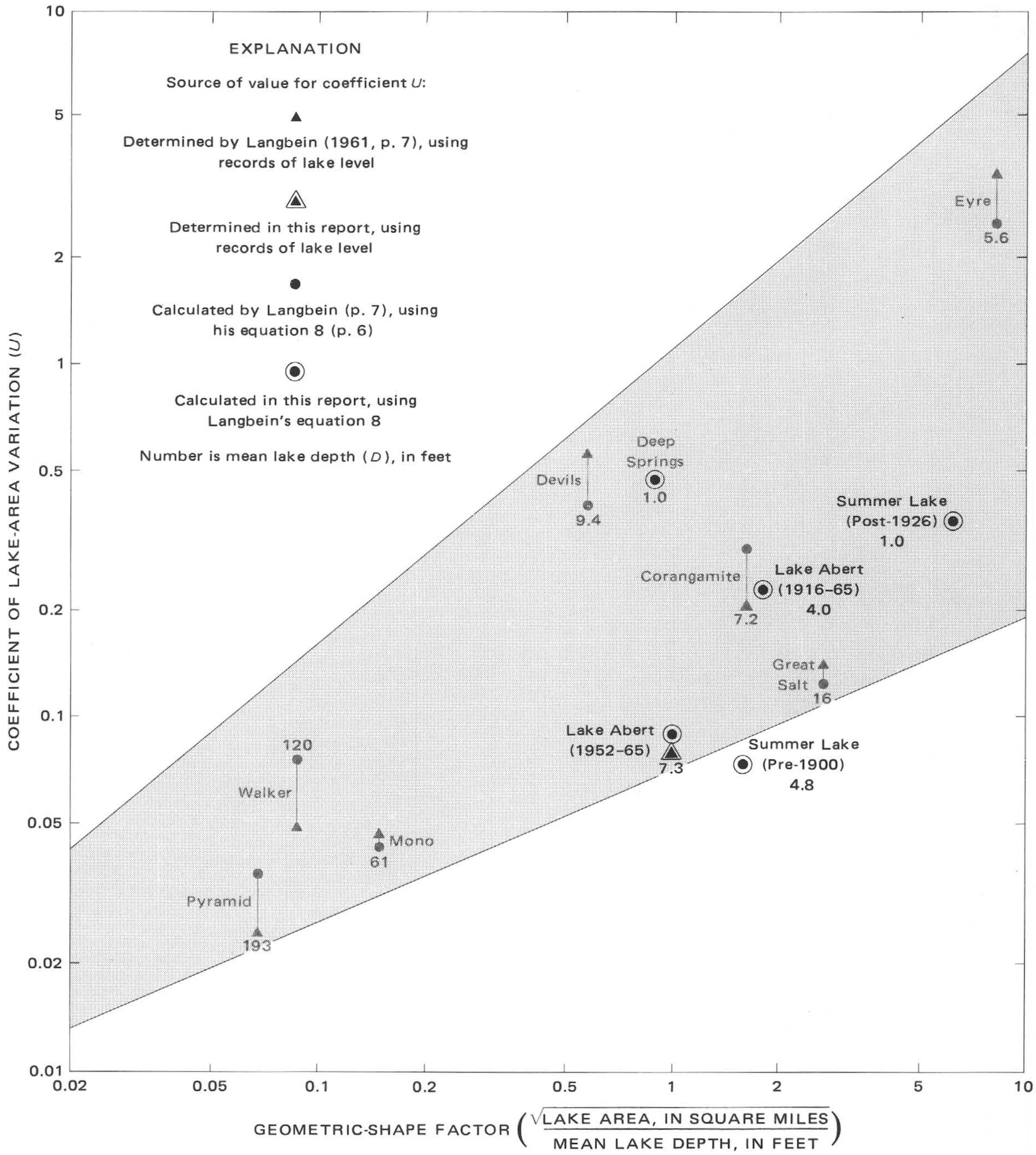


FIGURE 5.—Correlation between coefficient of area variation and geometric-shape factor for Lake Abert, Summer Lake, and several other closed lakes. Trend of increasing lake-area variation with increasing area-to-depth ratio shows that broad, shallow lakes are more susceptible to expansion and contraction because of the greater relative importance of evaporation. Stabilizing effect of ground-water inflow is shown by the low coefficient for Summer Lake prior to 1900, when springs contributed more than 90 percent of the inflow exclusive of direct lake-surface precipitation. Data for Deep Springs Lake, Calif., from Jones (1965, p. 22; coefficient U is recalculated, using information from Jones' fig. 13). Data for other lakes except Abert and Summer are from Langbein (1961, p. 7, 18); his data for Pyramid Lake have been recomputed on the basis of revised bathymetry (Harris, 1970) and the lake level as of 1970.

Two general categories of solutes exist within each basin. One category comprises solutes that are mobile (that is, tend to remain in solution) in a saline high-pH environment; it includes constituents dissolved in the lakes, as well as those dissolved or dissolvable adjacent to and beneath the lakes. At the other extreme are solutes that are mobile in dilute inflow (table 6) but which do not accumulate in solution within an alkaline, saline lake and, therefore, do not play a role in the long-term solute economy of the lakes and their peripheries. These "immobile" solutes yield important organic and inorganic components of the lacustrine deposits beneath and adjacent to the lakes (Jones and Van Denburgh, 1966, p. 443–444).

The major immobile constituents are silica, calcium, and magnesium, whereas the mobile solutes are dominated by sodium, chloride, and carbonate-bicarbonate. Potassium and sulfate lie somewhere between the two extremes; they are depleted in the lakes, but not to the same drastic extent as silica or the alkaline earths.

In computing the balance between incoming, outgoing, and stored solutes, the mobile constituents are by far the most important and are easiest to deal with quantitatively. However, they are subject to recycling within and between the two major units of the basin, and their various increments are therefore difficult to separate into new and recycled portions.

INCOMING AND OUTGOING SOLUTES

LAKE ABERT

Among the several parameters of solute balance at Lake Abert, the contributions of surface flow are the best known quantitatively and qualitatively. (At Summer Lake, in contrast, the character of surface inflow exclusive of spring-fed Ana River is uncertain, but that flow contributes only a small percentage of the total incoming solute load.)

Chewaucan River is the largest tributary to Lake Abert. It drains about 57 percent of the basin and probably supplies almost 90 percent of the surface inflow. The chemical character of the river near its mouth is highly variable seasonally. The measured dissolved-solids content has ranged from about 70 to 260 ppm[1] (parts per million) during the sampling period (April 1961 to September 1965). As shown in figure 6, peak values generally occur sometime during the winter or spring, whereas the smallest concentrations are characteristic of flow during late fall and early winter. Seasonal fluctuations of solute content are related in part to irrigation activity in Chewaucan Marsh (pl. 1). The largest concentrations of dissolved solids seem to coincide with periods when irrigation return flow from the marsh provides most of the stream water, whereas the dilute runoff represents flow passing directly through the marsh without diversion for irrigation.

[1]In calculated dissolved-solids concentrations, which are used almost exclusively in this report, bicarbonate values are conventionally multiplied by 0.492 to make the overall results comparable with those of dissolved-solids residue determinations. This convention is based on the fact that during the residue procedure, half of the bicarbonate is generally lost as CO_2 (carbon dioxide), and the other half is converted to carbonate (Hem, 1970, p. 218, 220). Under natural conditions, however, evaporation of a brine that is rich in sodium and bicarbonate generally produces a residue that contains appreciable amounts of bicarbonate as well as carbonate (Bradley and Eugster, 1969, p. 36–58). Thus, not as much CO_2 is lost, and the quantity of natural residue is therefore greater than that determined either analytically or by standard computation. Water of hydration in the naturally occurring evaporite deposits makes the difference even greater. Nonetheless, all computations of solute concentration and tonnage in this report are based on the 0.492 convention for consistency of results.

Estimates of average monthly discharge for the Chewaucan River at its mouth during water years 1961–65 are shown in figure 6. The values are derived by relating estimated amounts of lake-surface precipitation and evaporation to changes in the volume of Lake Abert; the net increment is then ascribed to inflow, most of which is provided by the Chewaucan River. Dissolved-solids tonnages and concentrations based on the data in figure 6 are summarized below:

Water years	Inflow (acre-ft per yr)	Dissolved solids	
		Tons per year	Parts per million[1]
1961	12,000	2,700	165
1962	34,000	5,600	120
1963	170,000	28,000	120
1964	55,000	10,000	135
1965	230,000	36,000	115
1961–65	100,000	16,000	120
1916–65	62,000	10,000	120

[1]Rounded to nearest 5 ppm.

Silica, sodium, calcium, and bicarbonate are the principal dissolved constituents of the river, regardless of total dissolved-solids content. However, figure 7 shows that the relative abundances of sodium and chloride increase with respect to the other major constituents with increasing dissolved-solids content. At the average dissolved-solids content of 120 ppm, sodium and chloride comprise about 37 and 7 percent of the cations and anions, respectively, on the basis of equivalents per million (hereafter abbreviated "epm-percent"). Comparable percentages for Lake Abert, in contrast, are 98 and 56. Two representative chemical analyses of the Chewaucan River near Valley Falls are presented in table 4 (analyses 2 and 3). They show the chemical character at low and high dissolved-solids content (79 and 193 ppm).

Silica, the only abundant undissociated (nonionic) component of the streamflow, is generally present to the extent of about 30 ppm, regardless of dissolved-solids content; hence, it constitutes about 30 percent of the total salts at 100 ppm, but only 12 percent at 250 ppm. (Actually, most dissolved silicon is present as undissociated monomeric silicic acid (H_4SiO_4) under normal hydrochemical conditions. By convention, however, the constituent is reported as silica (SiO_2).)

The present-day chemical character of the stream water changes appreciably as it passes through the Chewaucan Marsh. Table 5 shows estimated solute tonnages gained and lost within the marsh during the 1961 water year (about 20 percent of normal discharge at the river mouth), the 1965 water year (370 percent of normal discharge), and during a hypothetical average year. The data show that in dry years, such as 1961, incoming solutes—especially silica—are stranded in the marsh. Contrastingly, in years of greater than average runoff (such as 1965), more salts are

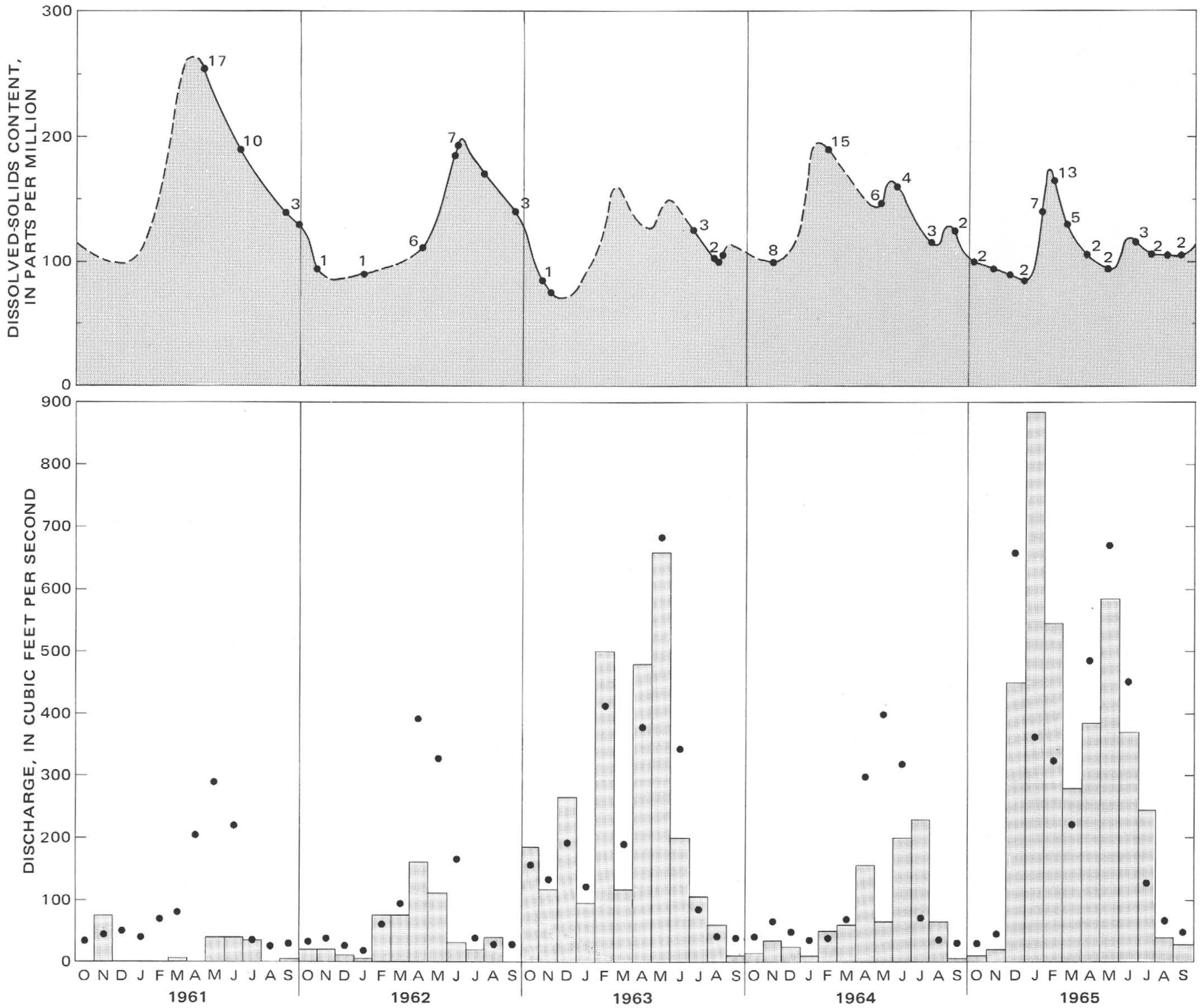


FIGURE 6.—Estimated discharge and dissolved-solids content of Chewaucan River near Valley Falls, water years 1961–65. Numbers above dissolved-solids curve indicate chloride concentration, in parts per million. Dots in discharge graph indicate monthly average streamflow of Chewaucan River measured near Paisley.

carried out of the marsh than are brought in (the silica increase is very small, however). In an average year, about a third of the silica is lost, but other components undergo moderate to substantial enrichment; as a result, the total incoming and outgoing tonnages are about the same. A significant point with regard to the possible solute contribution of agricultural activity is that about 90 percent of the chloride delivered to Lake Abert by the Chewaucan River is accrued within the marsh. Part of the increment doubtless was a component of (1) windblown alkali dust and (2) salts that were stranded during the contraction of pluvial Lake Chewaucan. However, an undetermined amount of chloride—perhaps as much as 5 percent or more of the total load—has been introduced by man in the form of salt licks for the large cattle herd that grazes in the marsh each year. Thus, much of the chloride in the river at its mouth has been recycled, and other increments are attributable to the activities of man. As a result, the net amount of incoming chloride that is naturally "new" to the lake cannot be determined quantitatively. Similar statements apply to the other major constituents of Lake Abert as well.

Table 6 summarizes the total solute contribution to Lake Abert by the Chewaucan River, including the constituents that dominate in the lake (sodium plus equivalent chloride and carbonate-bicarbonate; see footnote 3 in table 6). The net effect of agricultural activity in the marsh on the chemical character of the river at its mouth, relative

TABLE 4.—*Chemical analyses of representative surface and ground waters in the Abert and Summer Lake basins*

[Analytical results are in parts per million, except pH]

Analysis No.	Source	Location[1]	Collection date	Discharge or lake level[2]	Water temperature (°F)	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Dissolved solids (calc.)[3]	pH (laboratory)
				Lake Abert basin												
1.	Lake Abert	34/21-24dca	Jan. 12, 1962	4,251.81	33	144	1.4	0.6	22,000	752	5,930	9,460	990	19,300	[4]55,900	9.6
2.	Chewaucan River at mouth.	35/21-21cdb	May 15, 1969	800e	58	32	6.0	2.4	8.3	2.3	52	0	.4	1.8	79	7.6
3.	.......do	35/21-21cdb	June 12, 1962	30e	69	26	20	5.3	36	5.5	162	0	12	7.0	193	7.6
4.	Seep N. of Lake Abert	32/21-35bac	Aug. 12, 1963	<0.0002e	59	41	7.0	3.0	102	13	216	4	26	40	346	8.4
5.	Spring SW. of Lake Abert.	35/21-21bba	June 9, 1962	.33e	66	65	9.5	7.5	290	14	282	0	47	295	867	8.1
				Summer Lake basin												
6.	Summer Lake	32/16-2abd	Apr. 25, 1961	4,146.32	68	110	2.5	.3	2,830	115	1,880	1,230	348	1,600	7,200	9.6
7.	Ana River	30/17-6dd	Apr. 25, 1961	92	58	36	5.0	2.3	39	3.6	91	9	5.8	12	158	8.8

[1]See p. C4 for description of location system.

[2]Discharge in cubic feet per second (ft^3/s); estimated values indicated by "e." Lake level in feet above mean sea level.

[3]Includes bicarbonate multiplied by 0.492. (See text footnote, p. C12.)

[4]Includes minor constituents not shown in tabulation. Density 1.045 g/cm^3 at 20°C.

TABLE 5.—*Changes in dissolved-solids tonnage during passage of Chewaucan River through Chewaucan Marsh in water years 1961 and 1965 and in an average year*[1]

[All solute quantities are given in tons]

	1961 water year			1965 water year			Average year[2]		
	Upstream from marsh	Downstream from marsh	Percentage lost or gained	Upstream from marsh	Downstream from marsh	Percentage lost or gained	Upstream from marsh	Downstream from marsh	Percentage lost or gained
Discharge..........(acre-ft)	68,000	12,000	-82	212,000	230,000	+9	96,000	62,000	-35
Percentage of average annual discharge	71	19	.....	210	370	....	100	100	....
Total dissolved solids (rounded)	6,000	2,700	-55	19,000	36,000	+47	8,500	10,000	+15
Silica	2,800	490	-82	8,600	9,500	+9	3,900	2,500	-36
Calcium plus magnesium	740	360	-51	2,300	5,000	+54	1,000	1,500	+33
Sodium	440	440	0	1,400	4,400	+68	610	1,400	+57
Chloride	20	120	+83	60	790	+92	30	250	+88
Other components	2,000	1,300	-35	6,500	16,500	+61	2,900	4,600	+37

[1]Stations upstream and downstream from the marsh are near Paisley and Valley Falls, respectively (pl. 1).

[2]Based on runoff data measured or estimated for the period 1916-65, and chemical-quality data collected during the period 1959-65.

TABLE 6.—*Solute contributions to Abert and Summer Lakes and their peripheral areas by streams, springs, and seeps*

[All values rounded to two significant figures or less]

Source	Acre-feet per year	Silica (SiO_2)		Calcium (Ca) plus magnesium (Mg)		Sodium (Na)		Chloride (Cl)		Other constituents[1] [2]		Total (rounded)		Sodium plus equivalent chloride and bicarbonate[2] [3]	
		ppm	Tons per year	ppm	Tons per year	ppm	Tons per year	ppm	Tons per year	ppm	Tons per year	ppm	Tons per year	ppm	Tons per year
Lake Abert															
Chewaucan River	62,000	30	2,500	17	1,500	16	1,400	3	250	54	4,600	120	10,000	38	3,200
Peripheral streams	2,500	20	70	10	30	15	50	2	7	35	120	80	270	35	120
Peripheral springs and seeps	5,000	45	310	10	70	140	950	85	580	170	1,200	450	3,100	340	2,300
Total	70,000		2,900		1,600		2,400		840		5,900		13,000		5,600
Summer Lake															
Ana Springs:															
(pre-1900)	100,000	37	5,000	8	1,100	39	5,300	13	1,800	63	8,600	160	22,000	92	13,000
(post-1926)	67,000	37	3,400	8	700	39	3,600	13	1,200	63	5,700	160	15,000	92	8,400
Peripheral springs and seeps:															
(pre-1900)	8,000	40	440	10	110	60	650	15	160	90	980	220	2,400	140	1,500
(post-1926)	13,000	40	700	10	200	130	2,300	30	500	190	3,500	400	7,100	300	5,300
Peripheral streams	10,000	25	340	15	200	20	270	2	30	60	820	120	1,600	50	680
Pre-1900 total	120,000		5,800		1,400		6,200		2,000		10,000		26,000		15,000
Post-1926 total	90,000		4,400		1,100		6,200		1,700		10,000		24,000		14,000

[1]Mostly bicarbonate.

[2]Bicarbonate is multiplied by 0.492. (See text footnote, p. C12.)

[3]Dominant solutes in Abert and Summer Lakes. Concentrations include all sodium and chloride, plus an amount of bicarbonate equivalent to the "residual" sodium (that is, sodium in excess of chloride).

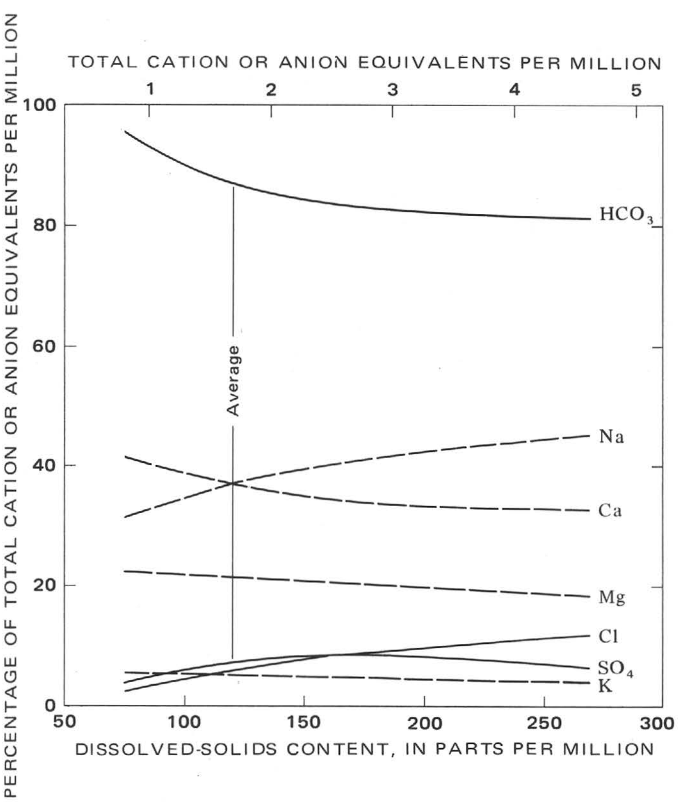


FIGURE 7.—Changes in the relative amounts of major ions in Chewaucan River near Valley Falls with increasing dissolved-solids content. Solid lines for anions; dashed lines for cations. Chemical symbols as follows: HCO_3, bicarbonate; Na, sodium; Ca, calcium; Mg, magnesium; Cl, chloride; SO_4, sulfate; K, potassium.

to natural conditions prior to settlement of the area, is unknown. The overall differences are assumed to be slight, however, and the estimates in table 6 probably characterize the river's contribution before as well as after man's development of the marsh, even though the estimates are based on postdevelopment data.

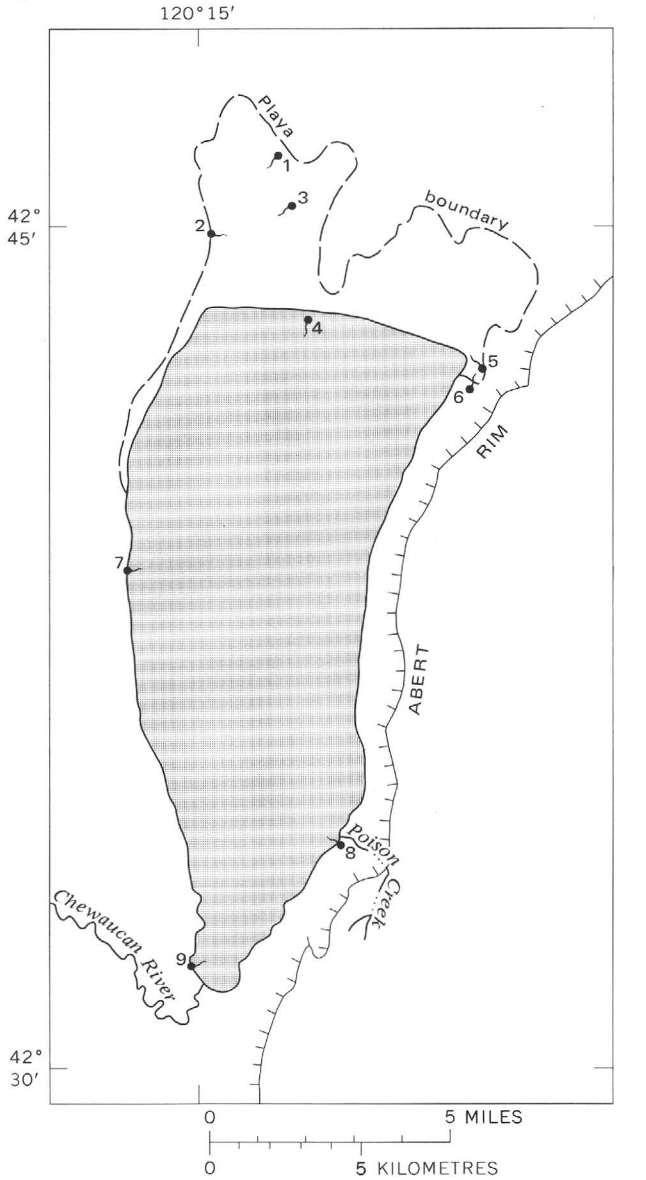
The amounts and chemical character of solutes contributed by small streams adjacent to Lake Abert are uncertain. Poison Creek, the only near-perennial stream aside from the Chewaucan River, carries the runoff from a 3-square-mile basin on Abert Rim. During periods of low flow, the stream characteristically contains about 75 ppm of dissolved solids. Overland flow and runoff in normally dry stream channels occasionally reaches Lake Abert from the arid peripheral areas to the north and west following summer thunderstorms and other heavy rains. Although the quantities of such flow can be appreciable during short periods of time, the contribution, in terms of average annual water volume, is small. Likewise, the solute contribution is small, and much of it represents increments derived from peripheral springflow that evaporated before reaching the lake, along with recycled salts, such as (1) components of windblown alkali dust, (2) salts isolated from the pluvial lake during contraction, and (3) dissolved constituents of lake water previously blown out upon the flat northern playa and isolated above present lake levels. Excluding the solutes of peripheral springflow (which are accounted for below), the average dissolved-solids content of all inflow from small streams adjacent to the lake is assumed to be about 80 ppm. The estimated solute contribution is listed in table 6.

Ground-water contributions outside the Chewaucan River drainage are limited to seeps and springs adjacent to the lake. The chemical character of this flow is wide in range, as shown by the dissolved-solids values and chloride:sodium ratios in figure 8. (See representative analyses 4 and 5 in table 4; samples were collected from sites 3 and 9, fig. 8.) The figure also shows that, with one exception, the greatest solute content is characteristic of flow emerging closest to the lake. (The exception is seepage at site 8, which represents emergent underflow from the alluvial fan of Poison Creek and is fed in part by dilute percolating surface water.)

Although the peripheral ground-water flow actually reaching the lake may be only 2,000 to 2,500 acre-feet per year (p. C7), the total estimated spring and seep discharge, about 5,000 acre-feet per year, must be considered as a source of solutes. Table 6 summarizes the estimated solute contribution to the lake by peripheral ground water.

The net contribution of air-transported solutes at Lake Abert is the most difficult of the several elements of salt gain and loss to evaluate properly. The two media of transport are atmospheric moisture (ultimately precipitation) and windblown dust. Whereas precipitation is a salt contributor only, the transport of dust both contributes salts to and removes salts from the basin. The impression gained from observations at Summer Lake is that large salt tonnages are carried from the playa surface, especially during periods of low lake level. (For example, see Phillips and Van Denburgh, 1971, fig. 23.) Alkali dust clouds have been observed moving east from Summer Lake toward Lake Abert (R. W. Childreth, U.S. Geological Survey, oral commun., 1963) and moving both south and north from Summer Lake to areas outside its basin (Boyd Claggett, Oregon State Department of Game, oral commun., 1966). The actual quantities of salts entering and leaving the two basins, however, may be less impressive in magnitude than the billowing dust clouds are in appearance. Regardless of magnitude, though, the net result almost certainly is a loss of salts from the two tributary basins.

The chemical character of the dissolvable alkali dust from the peripheral salt flats has not been determined directly. However, it can be inferred on the basis of the character of efflorescent top salts that coat the dry playa surfaces at times. Dissolvable parts of the surface deposits adjacent to Abert and Summer Lakes are chiefly sodium carbonate and bicarbonate, as shown in figure 9. In fact,



Site	Location	Collection date	Dissolved-solids content (ppm)[1]	Chloride : sodium ratio[2]
1	32/21-26bbc	6- 9-62	285e	0.21e
2	-33dcb	9-28-68	355	.36
3	-35bac	8-12-63	346	.25
4	33/21-11dbb	8-14-63	550e	.29
5	33/22-16bdc	6- 9-62	475	.42
6	-20aab	6- 9-62	580e	.44e
7	34/21-6da	6- 9-62	800	.62
8	35/21-1bac	7-26-64	156	.87
9	-21bba	6- 9-62	867	.66

[1]"e" indicates estimated value. Includes bicarbonate multiplied by 0.492. (See text footnote, p. C12.)

[2]Based on equivalents per million; "e" indicates estimated value. Ratio for lake, 0.57.

FIGURE 8.—Source and chemical character of sampled spring and seep flow peripheral to Lake Abert.

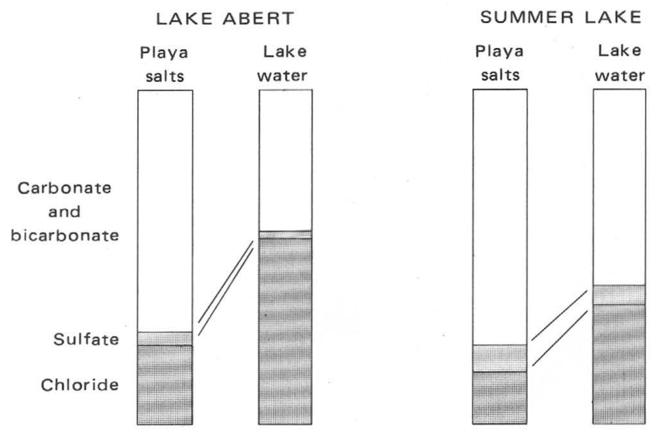


FIGURE 9.—Relative abundance of major anions in playa-surface salts adjacent to Abert and Summer Lakes, compared with the chemical character of the lake waters themselves. Relative abundances are based on equivalents per million (each bar represents 100 percent of the major anions). Playa data are averages for the following samples. Lake Abert: locations 33/22-9ccc (Sept. 4, 1944); 33/22-9db (May 20, 1959); 33/22-9cc (Sept. 17, 1962); 33/22-7ba (July 23, 1964); 33/21-9acd (Sept. 27, 1968); and 33/21-10bcc (Sept. 28, 1968). Summer Lake: locations 32/16-14, 32/17-26, 32/17-3 (all Aug. 30, 1944), 31/17-10bab (Sept. 30, 1968); and 32/16-2aad (Oct. 1, 1968). Analytical results for samples collected in 1944 are from Allison and Mason (1947, p. 3, 7). Sampling-site locations and other information were obtained from Ralph S. Mason (Oregon Department of Geology and Mineral Industries, oral commun., 1964).

the carbon species make up a far greater percentage of total salts in the surface deposits than in the adjacent lake water. Consequently, the net outgoing load of airborne salts may be removing carbonate-bicarbonate from the playa surface in preference to chloride.

The quantitative role of precipitation as a contributor of solutes is uncertain. In qualitative terms, however, the role is two-fold—incoming moisture brings soluble salts from outside the basins, and it also flushes local salts from the atmosphere above the basins. Therefore, the solute contributions of rain and snow are in part new to the basins and in part recycled, although the relative importance of the two increments is unknown.

Records of precipitation chemistry are meager. The five available analyses, for samples collected at or near the Valley Falls weather station, are tabulated on page C18. Considering the semiarid closed-lake environment, the samples are distinctive in their dilute character and near absence of sodium or chloride, and they support Gambell's contention (1962, p. 94) that "excluding the immediate coastal areas, marine aerosols appear to constitute a small portion of the soluble material brought down in precipitation over the United States." Regardless, the tonnage of solutes contributed directly to Lake Abert by lake-surface precipitation is insignificant in comparison with increments from other sources.

[Results in parts per million, except as noted]

Date[1]	[2]1-12-62	5-1-64	6-9-64	7-30-64 to 8-1-64	11-12-64 to 12-11-64
Precipitation amount (inches of water)	0.06	0.15	1.10	0.59	0.61
Type of precipitation	Snow	Rain	Rain	Rain	Rain and snow
Sodium (Na)	1.2	3.8	0.8	1.1	1.2
Bicarbonate[3] (HCO_3)	3	10	10	13	21
Sulfate (SO_4)	.0	5.6	.0	2.0	3.0
Chloride (Cl)	1.0	.5	.0	.0	.0
Specific conductance (micromhos per cm at 25°C)	9	35	23	37	52
Estimated dissolved solids	5	20	15	20	30

[1]All except first sample were collected at weather station and stored in closed polyethylene or glass bottles as long as 1–2 months before analysis.
[2]Collected at east shore at Lake Abert, 10 miles northeast of Valley Falls. May have been inadvertently contaminated by lake water during collection and melting.
[3]Samples contained no detectable carbonate when analyzed.

SUMMER LAKE

Among the natural sources of inflow to Summer Lake, the most plentiful contribution of solutes is provided by Ana Springs, via the Ana River. The spring flow contains about 160 ppm of dissolved solids—mostly silica, sodium, and bicarbonate (analysis 7, table 4). Sodium and chloride make up 76 and 15 epm-percent of the cations and anions, respectively, in the spring discharge, compared with 97 and 36 epm-percent in the lake.

Despite present-day depletion of the spring flow downstream from Ana Reservoir, the discharge at the reservoir should be considered in calculations of solute income because it gives a true indication of the solute contribution of the springs. Table 6 lists the present-day contribution, as well as that estimated for the more nearly natural conditions prior to 1900.

Additional natural ground-water flow in the Summer Lake basin includes springs tributary to the Ana River below the stream gage, seeps along the west and south shores, springs northeast of the lake, and Summer Lake Hot Spring to the southeast. Only the nearby seep and spring flows actually reach the lake, but all other ground-water sources contribute solutes that can be transported to the lake in surface runoff or dissolved when the lake is high. On the basis of scanty data regarding the chemical character of peripheral spring flow, the following estimates are made:

	Average dissolved solids (ppm)
Spring inflow to Ana River below gage:	
Pre-1900 (5,000 acre-ft per yr)	200
Post-1926 (10,000 acre-ft per yr)	450
Other peripheral springs and seeps (3,000 acre-ft per yr)	250

Combining these data, along with estimates for specific chemical constituents, the total solute contribution of peripheral springs and seeps is listed in table 6.

Water wells provide an additional source of solutes within the Summer Lake basin. However, their contribution has been restricted to the last few decades and probably has not had more than a slight effect on the chemical character of the lake.

The percentage of total salts that has been recycled rather than newly introduced to the lake is unknown. Some of the increment emerging as springflow immediately adjacent to the western lakeshore may be derived from salts associated with the lake and its periphery; likewise, at least a small part of the salts in other locally derived ground-water discharge must originally have been a component of windblown alkali dust that was dissolved by percolating runoff. However, the Ana Springs system, which dominates the inflow to Summer Lake, is thought to be fed by ground water that originates outside the basin (Phillips and Van Denburgh, 1971, p. B39), and most of its solute contribution could therefore be considered new to the lake rather than recycled.

The solute contribution of small peripheral streams is as uncertain at Summer Lake as at Lake Abert. The dissolved-solids content of drainage from the Winter Ridge–Slide Mountain area may be 100–140 ppm during near-low-flow conditions, on the basis of scanty data. Wet-season flow from that area doubtless is more dilute, but the occasional thundershower runoff from flat salty areas east of the lake may be more concentrated. For lack of definitive information, the average solute content of all peripheral streamflow (exclusive of Ana River) upstream from the influence of agriculture is assumed to be on the order of 120 ppm. Table 6 summarizes the contribution of specific solutes.

The contribution and depletion of solutes by atmospheric means is discussed on pages C16–C17.

In about 1916 commercial salt recovery by solar evaporation began after about 1,000 acres at the southeast end of Summer Lake had been dyked off (Allison and Mason, 1947, p. 1). The short-lived operation made a small profit but ceased when the salt-processing mill burned (Boyd Claggett, Summer Lake State Game Management Area, oral commun., 1966). According to R. S. Mason (Oregon Department of Geology and Mineral Industries, written commun., 1971), the total tonnage of salts removed was small.

SUMMARY OF SOLUTE GAIN AND LOSS

The estimates of total solutes delivered to Abert and Summer Lakes and their immediate peripheries by streams, springs, and seeps during an average year are summarized in table 6. These sources contribute about 13,000 tons to Lake Abert in an average year, but less than half of that amount (about 6,000 tons) consists of constituents that dominate in the lake (sodium plus equivalent chloride and carbonate-bicarbonate). Most of the remainder includes such components as silica, calcium, and magnesium that are permanently removed from the solute cycle by organic processes and inorganic reactions.

Solutes contributed to Summer Lake have averaged about 25,000 tons per year, both before 1900 and since 1926. Sodium plus equivalent chloride and carbonate-bicarbonate total almost 60 percent of that quantity (about 15,000 tons). Thus, the annual contribution of these constituents to Summer Lake is about 2½ times the contribution to Lake Abert. The overall chloride:sodium ratio for inflow to both lakes has been about 0.2.

In addition to surface- and ground-water increments, salts also are contributed to the lakes and their peripheral playas as components of precipitation and windblown dust. However, the tonnages added in this manner are small compared with those delivered by surface and ground water, and most of the contribution probably represents recycled salts.

The only effective means of solute removal from the lakes and their peripheries is wind transport of powdery alkali dust from the dry playa surfaces. The quantity of salt removed by this means is unknown, but it presumably exceeds the amount brought in as a component of precipitation and dust.

Ground water in some parts of the Abert and Summer Lake basins may be subject to interbasin movement similar to that suggested for certain topographically enclosed basins in Nevada (for example, Eakin, 1966; Van Denburgh and Glancy, 1970, p. 13). In fact, most of the discharge of Ana Springs may originate in adjacent areas to the north, rather than in areas topographically tributary to Summer Lake. However, no salts are thought to be removed from the lakes by such mechanisms, because of the presence of peripheral springs at Abert and Summer Lakes and because of the low altitude of the two basin floors (they are the lowest within at least 50 miles).

STORED SOLUTES

Most of the annual increment of mobile solutes brought to each lake and its periphery by streams and ground water remains and accumulates within the lake and its immediate surroundings. The incoming solutes are stored in three environments—as dissolved constituents of the lake water itself, as interstitial components of the peripheral and lake-bottom sediments, and, part of the time, as thin salt deposits atop the peripheral playas. The first environment is easy to evaluate both quantitatively and qualitatively because the shallow lakes remain almost homogeneous except during periods of abundant inflow. In contrast, the peripheral and lake-bottom salts are not homogeneous, either areally or vertically, and an accurate evaluation of them is much more difficult.

SOLUTES DISSOLVED IN THE LAKES

Although both lakes are chemically similar, Lake Abert has by far the largest tonnage of dissolved solids. As of 1969 the lake contained almost 15 million tons of solutes, consisting mostly of sodium, carbonate, bicarbonate, and chloride. In fact, those four constituents account for more than 96 percent of the total tonnage (table 4, analysis 1). Potassium and sulfate are of secondary importance; they make up an additional 3 percent of the salts. Several minor constituents, including silica, bromide, orthophosphate, and boron, are present in appreciable parts-per-million amounts, though together they make up less than 1 percent of the total tonnage (Phillips and Van Denburgh, 1971, p. B17). The most noticeable chemical characteristic of Abert and Summer Lakes is the near absence of calcium and magnesium. The two alkaline-earth ions are among the major constituents of most inflow, yet their combined concentrations in the lakes are less than 10 ppm. The dearth is ascribed to mineral reactions—most of the calcium apparently is tied up organically and inorganically as $CaCO_3$, whereas magnesium is largely incorporated within the silicate fraction of lake-bottom sediments (Jones and Van Denburgh, 1966, p. 446).

The relative percentages of major constituents in the lake have not exhibited an appreciable net change since 1912 (fig. 10), on the basis of a comparison of recent analyses with one reported by Van Winkle (1914, p. 119).

The measured dissolved-solids content of Lake Abert has ranged from 18,700 to 95,000 ppm. Concentrations were much greater at near-dryness, but the low value probably represents almost the minimum overall concentration attained within the last century, and it occurred at the time of maximum observed lake extent, in mid-1958 (fig. 4). The broad shallow lake remains nearly homogenous throughout, except during periods of appreciable inflow, because of continual mixing by the wind.

The solute tonnage in Lake Abert has varied considerably during the 20th century, as indicated by the few reliable concurrent measurements or close estimates of dis-

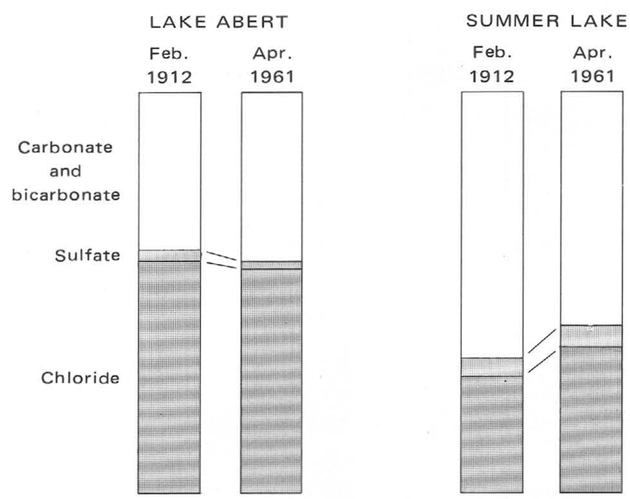


FIGURE 10.—Relative abundance of major anions in Abert and Summer Lakes in 1912 and 1961, on the basis of equivalents per million (each bar represents 100 percent of the major anions).

solved-solids content and lake level listed in table 7. (The tonnage for February 1912 is only approximate, because the estimated lake level is based on a measurement on October 4, 1915; the altitude for 1915 has been extrapolated to 1912 using estimated inflow and net evaporation during the intervening 3.6-year period. Furthermore, the 1912 sample was collected near the south end of the lake and may not have represented a lakewide average because of dilution by stream or seep inflow; this would make the 14-million-ton value too low.)

TABLE 7.—*Dissolved-solids concentrations and tonnages in Lake Abert at various times since 1911*

Date	Lake-surface altitude (ft above 4,200 ft)	Dissolved solids	
		Parts per million[1]	Millions of tons[2]
1912, Feb.[3]	56.5	29,600	14±
1939, July 21	48.2	95,000	8.2
1952, Aug.	52.7	35,000	9.7
1955, Aug. 12	52.8	40,400	11.5
1958, July 9	60.5	18,700	12.8
1959, May 20	58.9	21,700	13.0
1961, Sept. 7	52.04	55,400	13.8
1962, Sept. 17	50.70	71,000	13.5
1963, Aug. 7	54.45	37,500	13.6
1964, July 23	53.94	40,000	13.7
1966, Aug. 4	56.2	31,400	14.4
1969, June 17	55.46	35,400	14.8

[1]Includes bicarbonate multiplied by 0.492. (See text footnote, p. C12.)
[2]Tonnage = parts per million × density × volume, in acre-ft × 0.001360. Densities, in grams per millilitre at 20°C, are 1.025; 1.077; 1.027; 1.032; 1.014; 1.014; 1.044; 1.058; 1.026; 1.035; 1.026; and 1.029.
[3]Lake level is estimated and may be inaccurate by 1 foot or more; thus, the tonnage may also be inaccurate, by 2 million tons or more.

The chemical character of Summer Lake is similar in general to that of Lake Abert (table 4). However, chloride is considerably less abundant relative to carbonate-bicarbonate and sulfate in Summer Lake (fig. 10).

The distribution of major negative ions in Summer Lake underwent a significant net change between 1912 and the 1960's—the amounts of chloride and sulfate increased relative to carbonate-bicarbonate, as shown in figure 10.

The dissolved-solids content of Summer Lake, in tons and in parts per million, varies even more than that of Lake Abert on a seasonal and long-term basis. Measured dissolved-solids contents have ranged from 1,800 to 81,800 ppm. Tonnage estimates for Summer Lake are based on relations similar to those for Lake Abert but are less accurate because of a less certain area-volume relation and a greater tendency for uneven distribution of solutes within the lake during some of each year. The most reliable approximate tonnages are listed in table 8.

Langbein (1961, p. 9–10) described the general pattern of variations in the dissolved-solute content of closed lakes. The amount of salts in solution at any particular moment depends on the lake-level history prior to that time and on the level at that moment compared with the levels at dryness and at an unusually high stage. In this regard, a close relation exists between solutes in the lake and those stranded on flat peripheral playas, where such playas exist. At an unusually high lake level, most of the adjacent mudflats are inundated, and almost all of available salts are in solution. Hence, the dissolved-solids concentration within the lake may be relatively small, but the tonnage is large. In contrast, at near-dryness, the tonnage is small, but the concentration is large; at such a time most of the solutes are stored within the peripheral and lake-bottom sediments or are precipitated on the lake bottom.

TABLE 8.—*Dissolved-solids concentrations, tonnages, and chloride: sodium ratios in Summer Lake at various times since 1911*

Date	Lake-surface altitude (ft above 4,100 ft)	Dissolved solids[1]		Chloride-sodium ratio[4]
		Parts per million[2]	Millions of tons[3]	
1912, Feb.[5]	51.5	16,800	5±	0.29
1944, Sept. 1	46.2	27,000	1.0	.32
1952, Aug.	46.8	8,400	.5	....
1959, Jan. 30	48.2	8,400	1.0	.37
1961, June 21	45.86	15,000	.43	.37
1962, June 12	46.43	6,270	.30	.36
1963, Aug. 20	47.23	6,300	.49	.36
1964, July 21	47.15	9,200	.69	.35
1965, Sept. 9	48.5	7,200	.96	.35
1966, Aug. 6	47.42	12,500	1.08	.34
1967, Sept. 12	46.92	18,600	1.24	.35
1968, July 27	45.9	45,400	1.4	.33
1969, Sept. 6	45.26	51,500	.63	.33

[1]Samples collected during the period October–April may indicate tonnages lower than the lakewide average because of nonuniform dilution by inflow.
[2]Includes bicarbonate multiplied by 0.492. (See text footnote, p. C12.)
[3]Tonnage = parts per million × density × volume, in acre-ft × 0.001360. Densities, in grams per millilitre at 20°C, are 1912 sample, 1.015; 1944, 1.020; 1952, 1.005; 1959, 1.005; 1961, 1.011; 1964, 1.009; 1966, 1.010; 1967, 1.014; 1968, 1.042; and 1969, 1.049.
[4]Based on equivalents per million. Trend of net decreasing chloride:sodium ratio during 1959–69 is apparent rather than real, as indicated by additional data not listed in this table.
[5]Lake level is estimated on the basis of a measurement made Nov. 10, 1912 (4,151.3 ft) and, therefore, could be inaccurate by as much as 1 foot. Tonnage could likewise be inaccurate.

Several of the general trends in solute content discussed by Langbein (1961) can be evaluated using observations at Abert and Summer Lakes. For example, Langbein (1961, p. 9) postulated a net loss of salts from solution throughout a period of generally receding lake stage (segment A–B of Langbein's schematic fig. 8, which is shown in fig. 14 of the present report). Data for Lake Abert during 1958–62 suggest that such a trend may exist but not at high to medium lake levels. In June 1958 the lake reached the highest stage of modern times (16½ ft maximum depth). During the 4 subsequent dry years ending in September 1962, the level receded almost 10 feet, and the volume decreased from about 500,000 to about 120,000 acre-feet (fig. 11). Although solute concentrations during the 51-month interval increased from 18,000 to almost 80,000 ppm, the changes in tonnage were slight (table 7). In fact, the tonnage apparently increased from 12.8 million to 13.8 million between 1958 and 1961, even though the lake level

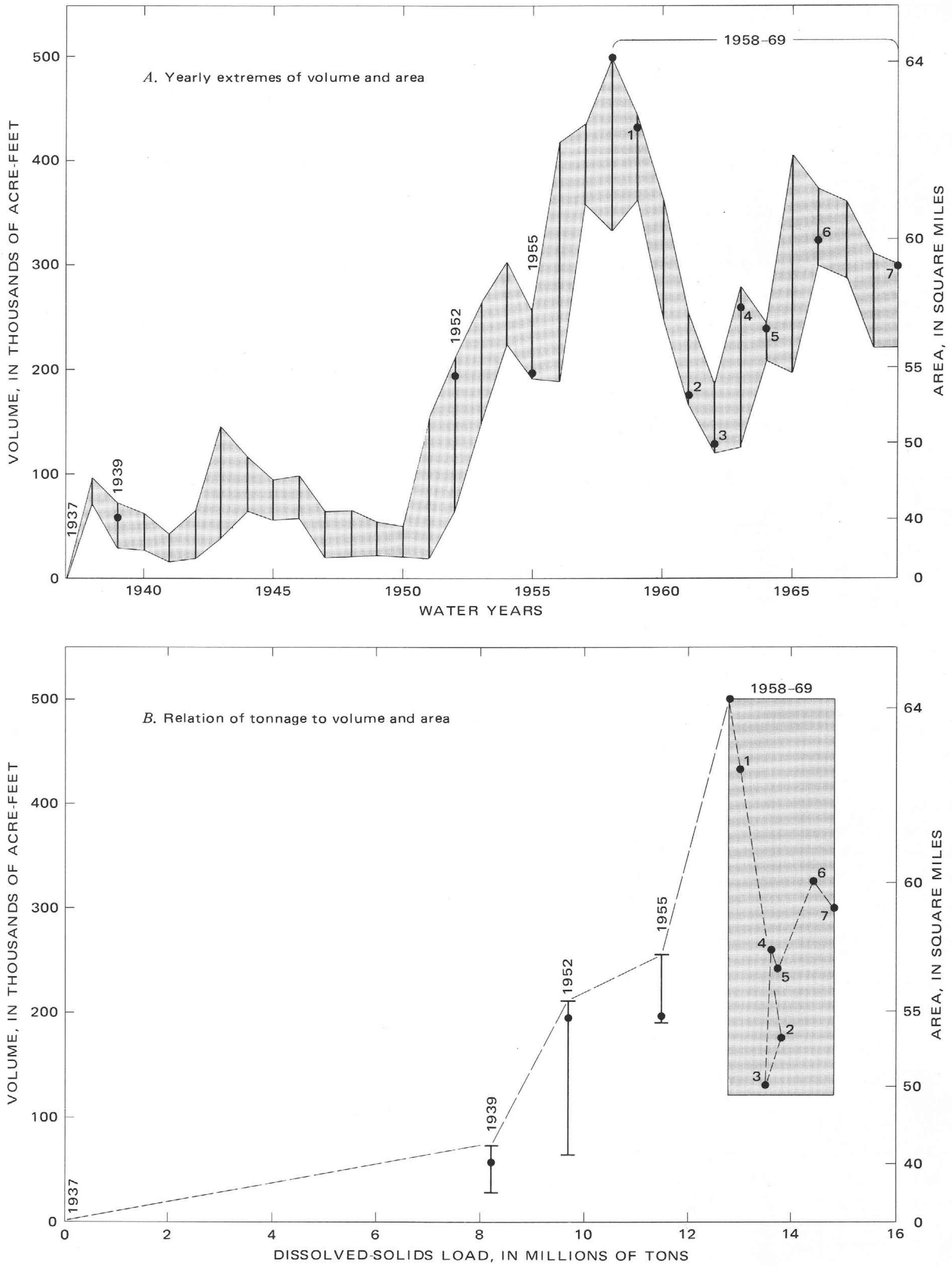


FIGURE 11.—Relation of dissolved-solids tonnage to fluctuations of volume and surface area of Lake Abert, 1937–69. Dots indicate chemical analyses used to compute tonnage (table 7). Yearly extremes of volume and area prior to 1951 estimated by K. N. Phillips (U.S. Geological Survey, written commun., 1964).

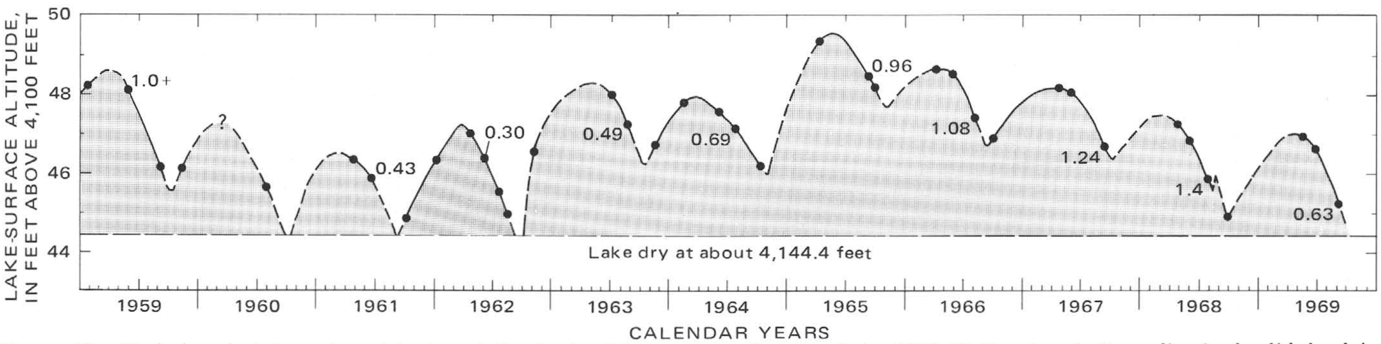


FIGURE 12.—Variations in lake-surface altitude and dissolved-solids tonnage at Summer Lake, 1959–69. Numbers indicate dissolved-solids load, in millions of tons.

declined 8½ feet. Only during the final year of recession, in 1962, did a net depletion apparently occur, and even that loss was a mere 2 percent of the total tonnage (which may well be within the limits of error of the computations themselves). At Summer Lake, the period 1965–68 was one of generally receding lake level, yet the solute tonnage increased, rather than decreased, each year (fig. 12, table 8). The diminished tonnage in 1969 indicates that depletion occurs only at near-dryness (below about 4,146 ft).

On the basis of observations at Abert and Summer Lakes, a major loss of dissolved solids during the reduction in volume of a broad, shallow closed lake occurs for two reasons only—precipitation of evaporite salts and isolation of brine from the main body. In closed lakes, regardless of their chemical composition, no major loss of salts through mineral precipitation can occur in the dissolved-solids range from less than 10,000 ppm to about 100,000 ppm. When the increasing solute content reaches 10,000 ppm, virtually all the calcium carbonate or calcium sulfate or both have already been depleted, and no additional solubility limits are exceeded below about 100,000 ppm. Actually, depending on chemical character, the range can be even greater. At Lake Abert, for example, the "no precipitation" range may be from about 1,000 ppm to about 200,000 ppm or more, because of the low sulfate and high carbonate concentrations. Under present conditions (1970) precipitation of sodium carbonate and bicarbonate minerals, followed by sodium chloride, would not begin at Lake Abert until the volume had decreased to 35,000 acre-feet or less, which is equivalent to a lake stage about 3 feet lower than that attained in September 1962. In summary, mineral precipitation as a mechanism of dissolved-solids depletion is applicable only under certain well-defined hydrochemical conditions.

Langbein (1961, p. 9) suggested that during a period of low lake level, the dissolved-solute tonnage may undergo a significant net increase, as shown by segment B–C of his schematic figure 8. However, such a net increase would not be expected in broad, shallow water bodies that dry every few years, because of solute depletion during the periods of low level. Under these conditions, some aspects of the solute cycle resemble those of an intermittent playa lake (Langbein, 1961, figs. 9*B*, *C*). At Summer Lake, for example, the solute tonnage was about 400,000 in June 1961, after a short period of dryness or near-dryness during the previous fall. The following summer, after a second brief dryness or near-dryness, the lake contained an even smaller load, about 300,000 tons, despite a seasonal lake-level maximum almost 1 foot higher than that of the previous year (fig. 12). Not until the lake had attained an even higher level following a third desiccation in September 1962 did the solute tonnage finally exceed that of 1961.

Wind can play an important role in the depletion of dissolved salts. When a broad shallow lake covers only part of its flat playa, wind can blow the residual water body out over peripheral mudflats. This mechanism, which has been observed at Summer Lake, isolates some of the brine as much as several feet above the lake level under calm conditions. Such action increases the amount of evaporation by increasing the temperature and surface area of lake water exposed to the atmosphere, and it also leaves the residual lake body depleted in solutes.

During a protracted period of desiccation and near-desiccation, wind also can cause a permanent removal of solutes from the basin floor (p. C16). Such a mechanism may have been an important factor in the major depletion that occurred at Goose Lake, 30 miles south of Lake Abert, in the drought-stricken 1930's (Phillips and Van Denburgh, 1971, p. B34). Similarly, Summer Lake contained 5 million or more tons of solutes in 1912, before man's activities began diminishing the quantity of inflow, yet the dissolved load is not known to have exceeded about 2 million tons since the onset of frequent desiccation following 1926. Even if the lake were to rise again to, and remain at, the high pre-1926 levels, the amount of salt regained from the lake-bottom sediments alone probably would fall short of the 5 million tons estimated for 1912 because of net depletion during the years since 1926. The effect of the salt-recovery operations between 1915 and

1920 (p. C18) on the total quantity of solutes dissolved in the lake is considered to be negligible because the tonnage removed apparently was small.

Langbein (1961, p. 9) suggested that during the third part of his long-term cycle, the dissolved-solute load should increase as the lake stage rises from a low to a high level over a period of years (limb C–D in his fig. 8). This phenomenon is illustrated clearly at Lake Abert (fig. 11). The figure shows that the lake rose about 12 feet and accumulated about 5 million tons of dissolved solids between July 1939 and July 1958. Only about 125,000 tons of lake constituents were contributed by inflow during that period. Thus, much of the salt increment was derived from the newly reinundated mudflats and doubtless represented solutes isolated from the lake during the 15-year period of desiccation or near-desiccation prior to 1938 (fig. 4). The principal mechanism of reaccumulation may be upward diffusion of solutes from the interstitial brines of lake-bottom sediment, as described by Lerman and Jones (1971).

Records at Summer Lake also show effective solute recovery during a rising stage (fig. 13). In the 6-year interval following desiccation or near-desiccation in the fall of 1962, the lake gained more than 1 million tons of solutes, of which less than 10 percent was contributed by Ana River and peripheral streams to the west and south. The greatest gains were in 1963 and 1965, the 2 years of net lake-level rise. However, the extraction of lake-bed salts continued at a relatively constant annual rate, even during the years of net falling level (fig. 13*B*).

The final stage in Langbein's schematic salt cycle (1961, p. 9), "a stable high-level phase of a lake during which annual input of salts exceeds the losses * * *," can only be inferred at Abert and Summer Lakes, on the basis of a continual inflow of solutes, as well as the slow accrual of salts from the lake bottom and immediate periphery. Even the short period of generally moderate levels at Lake Abert during 1964–69 produced a net solute enrichment (fig. 11*B*).

The sequence of changes in dissolved-solute tonnage at shallow Abert and Summer Lakes that would accompany the idealized long-term fluctuation of lake volume used by Langbein (1961, fig. 8) can be compared with the salt cycle he proposed. Given Langbein's pattern of lake-volume changes (top curve in fig. 14), the variations in dissolved-solids load observed or postulated at Abert and Summer Lakes are depicted in cycle 2 of figure 14. For comparison, the hypothetical pattern of variations suggested by Langbein (1961, p. 9) for closed lakes in general is shown as cycle 1. The greatest contrasts between the two cycles occur in segments A–B and B–C. Data in the present report indicate that a major loss of solutes occurs in certain lakes during only the final stages of a receding phase, and that the losses can continue during the subsequent period of low level. Much of the loss is temporary, however, and salts are recovered during a return to high lake level (segment C–D in cycles 1 and 2). Additional salts are gained during any extended period of characteristically high stage (segment D–A in cycles 1 and 2), and completion of an ideal long-term cycle can even produce a net solute increase, as shown by segment A–A′ in cycle 2.

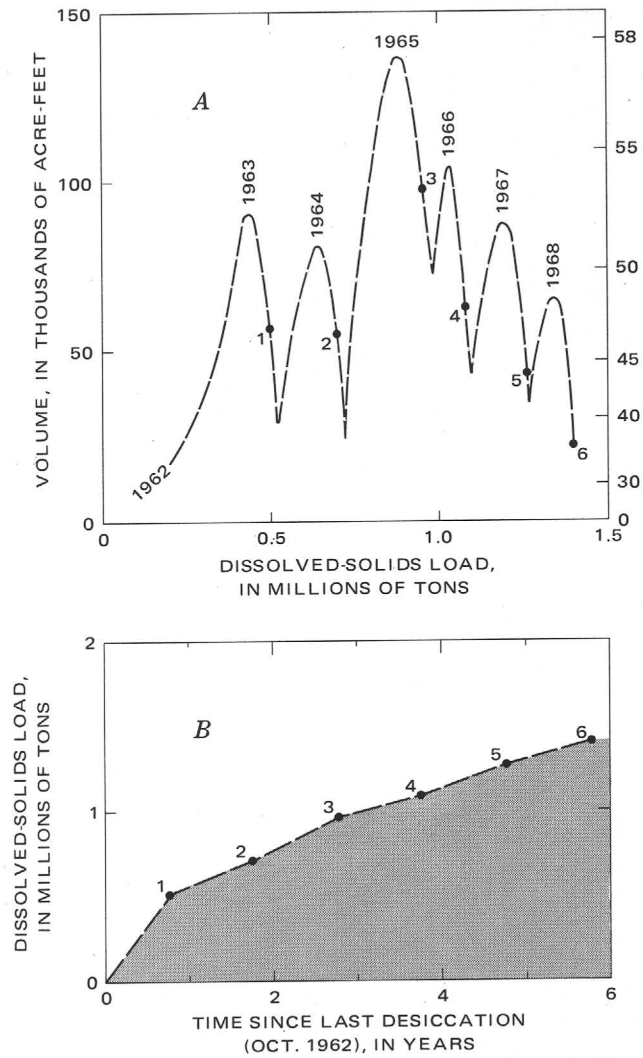


FIGURE 13.—Relation of increasing dissolved-solids tonnage in Summer Lake during 1963–68 to (*A*) fluctuations of lake volume and surface area, and (*B*) time since last prior desiccation (Oct. 1962). Calculated tonnages numbered 1–6 are from table 8 (values for Aug. 20, 1963, through July 27, 1968).

The complete sequence depicted in cycle 2 (fig. 14) applies only to shallow closed lakes that occupy expansive flat playas, such as those on the floor of the Abert and Summer Lake basins. Water bodies in deeper, more nearly bowl shaped basins, such as Pyramid and Walker Lakes in Nevada (Langbein, 1961, p. 18), would have a different, more stable volume-tonnage cycle, given the same relative magnitude of long-term volume fluctuation. Likewise, in

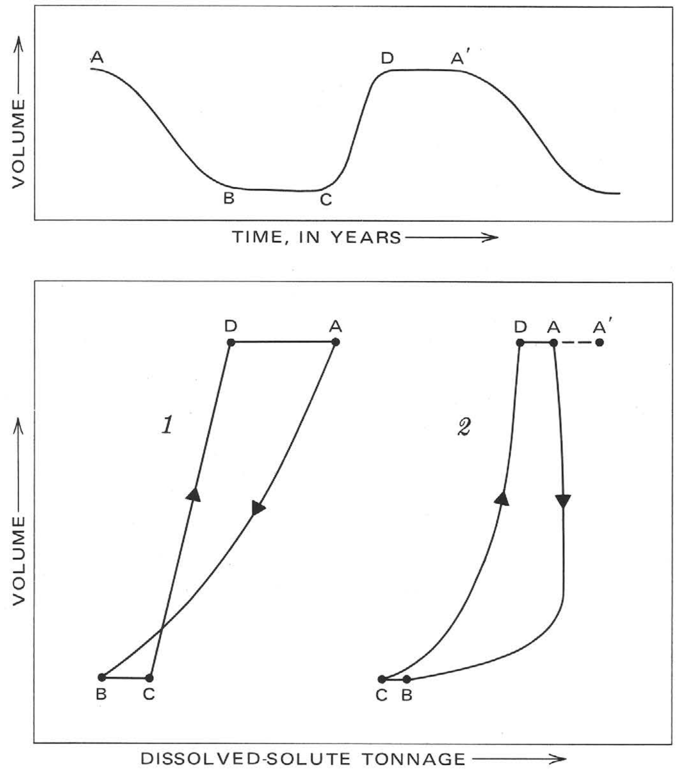


FIGURE 14.—Hypothetical long-term cycles of dissolved-solute tonnage and lake volume for a closed lake, based on Langbein's idealized sequence of lake-volume fluctuations (top graph; 1961, fig. 8). Cycle 1 in bottom graph is Langbein's schematic pattern of solute fluctuation; cycle 2 is the pattern observed or hypothesized for Abert and Summer Lakes.

a basin where irregular lake-bottom features result in depressions and embayments that become isolated from the main water body at lower levels, the volume-tonnage cycle would be different from those at smooth-sided Abert and Summer Lakes.

Lake chemistry also influences the pattern of dissolved-solute fluctuation. For example, if a slightly saline lake at high level contains appreciable amounts of calcium and sulfate relative to sodium and carbonate-bicarbonate, the solute-tonnage variation during lake contraction will not resemble the upper part of segment A–B in cycle 2 (fig. 14) because of solute loss through precipitation of gypsum.

LAKE-BOTTOM AND PERIPHERAL SOLUTES

No sharp physical or chemical boundary exists between peripheral and lake-bottom solutes at Abert and Summer Lakes, because the areal extents of the two lakes are by no means stable. The two environments—one exposed to the atmosphere and the other covered by lake water—merge and could perhaps be considered as a single unit. However, the modes of occurrence and chemical character of the solutes, as well as the processes that affect them, are different in each environment.

LAKE ABERT

The lake and its broad northern playa are underlain by fine-grained sedimentary deposits that store large solute tonnages. Several short lake-bottom cores have been analyzed in detail. Representative results for one of the cores (table 9) indicate that the quantity of interstitial

TABLE 9.—*Analytical data for sediment and interstitial brine at representative lake-bottom and playa sampling sites shown on plate 1*

[Based on information from B. F. Jones, U.S. Geological Survey, written communs., 1966–71]

Depth interval (feet)	Brine content (percent of volume)	Dissolved-solids content of brine (thousands of parts per million)	Chloride : sodium ratio[1]	Dissolved-solids content of mud (tons per acre-foot)
Lake Abert, bottom sediments, site 17				
0.0–0.85	87	62	0.55	80
0.85–1.7	83	94	.50	110
1.7–2.4	[2]85	125	.51	160
Lake Abert, playa sediments, site 23				
0.0–0.003 (crust)	....	....	0.50	[2]300
0.003–0.1	47	173	.65	140
0.6–1.2	44	149	.61	100
1.2–1.7	53	143	.62	110
1.7–2.2	37	131	.67	70
2.2–2.8	56	125	.70	110
2.8–3.3	56	115	.72	100
3.3–3.8	76	102	.75	110
5.2–5.8	80	93	.76	110
5.8–6.3	80	95	.77	110
6.3–6.9	78	92	.78	100
Summer Lake, bottom sediments, site 5				
0.5–1.0	73	43	0.34	46
1.0–1.5	69	37	.29	38
1.5–2.0	73	38	.27	38
2.0–2.5	72	40	.26	46
2.5–3.0	75	35	.30	42
3.0–3.5	74	33	.26	36
3.5–4.0	78	32	.28	36
4.0–4.5	83	33	.28	40
4.5–5.0	77	36	.28	42
5.0–5.5	78	39	.29	42
5.5–6.0	77	34	.30	40
6.0–6.5	82	34	.30	40
6.5–7.5	82	30	.30	34
Summer Lake, playa sediments, site 3				
0.0–0.1	....	....	0.26	....
0.1–0.45	47	185	.47	140
0.45–0.8	51	163	.54	130
0.8–1.2	79	156	.54	190
1.2–2.1	66	156	.56	160
2.1–3.1	61	139	.55	130
3.2–3.5	70	137	.56	140

[1]Based on equivalents per million.
[2]Estimated.

brine is large (more than 80 percent of the sediment-brine total, by volume), and that brine salinity increases with depth. In fact, about 2 feet below lake bottom, the concentration is more than twice the long-term average salinity of the overlying lake. Other data (pl. 1) show similar characteristics. (Information in table 9 and on pl. 1 is based on analytical data provided by B. F. Jones (U.S. Geological Survey, written communs., 1966–71); chemical analyses by S. L. Rettig, U.S. Geological Survey. Shrock and Hunzicker (1935, p. 14–17), Allison and Mason (1947, p. 1–7), and Stott (1952, p. 41–47) also have evaluated the chemical and physical characteristics of lake-bottom and peripheral deposits at the two lakes, but their information unfortunately cannot be used in appraising the stored-solute quantities because no data are available on the brine content of the sediments they sampled.)

Chemically, the brines resemble the overlying lake water, except that they are somewhat enriched in carbonate plus bicarbonate, relative to chloride (table 10). The enrichment may be due at least in part to the production of dissolved carbon species during anaerobic decay of organic material within the lake-bottom sediments (Jones and Van Denburgh, 1966, p. 444; Jones and others, 1969, p. 260).

On the playa north of Lake Abert, the environment and distribution of solutes are considerably different. The fine-grained sedimentary deposits there are generally exposed to the atmosphere, rather than sealed off by overlying lake water, and entirely different chemical and physical processes operate. Immediately following inundation or "washing" of the playa surface by windblown lake water or rain, the remaining salts lie within the fine-grained deposits. During subsequent evaporation, some of the near-surface brine moves upward, producing an efflorescent salt accumulation on the playa surface that has both powdery and crusty components. Chemically, the surface salts are dominated by carbonate plus bicarbonate relative to the other anions (fig. 9). (As in the lake water, sodium is by far the most plentiful cation; it is accompanied by only a small amount of potassium, and negligible calcium or magnesium.) The dominance of sodium carbonate and bicarbonate may result from differing solubilities. Bradley and Eugster (1969, p. 46–57) show that sodium carbonate and bicarbonate minerals precipitate much sooner than sodium chloride during evaporative concentration of brines such as the interstitial fluids at Lake Abert. The crustier components of the first-crystallized efflorescent salts may subsequently shield the underlying chloride-enriched (carbonate-bicarbonate-depleted) residual brine from appreciable evaporation. This situation is shown by the chemical character of efflorescences and shallow interstitial fluids at location 5, Summer Lake (p. C26).

In contrast to the paucity of chloride in efflorescent deposits, brines at 3- to 5-foot depth beneath the playa at Lake Abert are even richer in chloride than the lake itself and far richer than the lake-bottom brines. Table 9, which lists data for a representative site on the northern playa, shows this contrast, on the basis of chloride-to-sodium ratios. Plate 1 and table 10 also show the contrast. The apparent chloride enrichment may be due in large part to a net depletion of salts rich in sodium carbonate and bicarbonate, owing to wind transport of powdery playa-surface efflorescences (p. C17). In fact, such a mechanism may help explain why the relative amount of chloride is far greater in, beneath, and adjacent to Lake Abert than in most waters feeding the lake, even with allowance for depletion of "immobile" solutes.

Brine salinity at 3- to 5-foot depth on the northern playa is greater than that of the lake, but less than that of the lake-bottom interstitial fluids. Brine quantities are characteristically less also.

Carbon-14 dates for sediment from the depth interval 4.0–5.0 feet at site 16 (pl. 1) suggest that the top 5 feet of sediment there has been deposited during about the last 5,000 years but that the carbonate and bicarbonate components of the interstitial brine are somewhat younger. The average age of leached sediment from the interval is 4,530±250 years (U.S. Geological Survey Radiocarbon

TABLE 10.—*Relative abundance of major ions in representative samples of lake water and interstitial brine from lake-bottom and peripheral-playa sediments*

Source	Relative abundance, as a percentage of total cations and anions, on basis of equivalents per million				
	Sodium (Na)	Potassium (K)	Carbonate plus bicarbonate (CO_3+HCO_3)	Sulfate (SO_4)	Chloride (Cl)
Lake Abert	98	2	42	2	56
Lake-bottom interstitial brine	97	3	52	3	45
Playa interstitial brine	97	3	20	4	76
Summer Lake	98	2	61	6	33
Lake-bottom interstitial brine	97	3	61	11	28
Playa interstitial brine	98	2	37	8	55

Laboratory No. W-2196), whereas that of the sediment plus brine is 3,830±250 years (No. W-1594). These interpretations require that old detrital carbonate minerals constitute only a small percentage of the total carbonate, which may be a reasonable assumption on the basis of grain size and mineralogy (B. F. Jones, oral commun., 1971).

Measured and estimated solute tonnages stored within the top 5 feet of lake-bottom and peripheral sediments at Lake Abert are shown on plate 1. Tonnages (as well as characteristic brine salinities) are generally greatest within the deposits underlying the deepest parts of the lake, presumably owing largely to entrapment of more concentrated residual fluids during periods of low lake level. Beneath both the playa and lake, the greatest tonnages are farthest away from areas of ground-water and surface-water inflow. The average quantity in the top 5 feet of sediment is about 550 tons per acre. On the basis of data on plate 1, the total quantity of solutes in the top 5 feet of sediment (total area, about 80 sq mi) is an estimated 25-35 million tons, of which about a third (8-12 million tons) is chloride.

Sediments beneath the northeast playa of Lake Abert have been sampled to depths of 15 and 30 feet near the west and east margins, respectively. The data suggest that solute content diminishes with depth:

Approximate location	Depth (ft)	Dry-weight percentage of water-soluble salts
33 22-9c[1]	Top crust	39
	0-3	6-8
	3-19	2-5
	21-30	1
33 21-1d±[2]	0.0-0.5	14
	1.2	9
	1.9-9.5	3-5
	12.5	3
	14	5
	15	2

[1]Data from R. S. Mason (Oregon Dept. of Geology and Mineral Industries, written commun., 1964). Brine encountered at 11 ft; water level rose to 0.5 ft.
[2]Data from Stott (1952, p. 45). Brine (about 28,000 ppm) encountered at 10 ft.

Unfortunately, both sites are near areas of emerging ground water, and therefore may represent fresher than average conditions. The solute situation at depths greater than 5 feet in the central parts of the playa is unknown.

The total thickness of lacustrine deposits beneath and adjacent to Lake Abert may be great in places; eastward extrapolation of land-surface slopes west of the lake indicates that the sediments may be more than 1,000 feet thick near the east shore. The chemical character of the deep interstitial fluids is not known.

SUMMER LAKE

Lacustrine deposits beneath and adjacent to Summer Lake also harbor large solute tonnages. Two sites that normally are inundated by the lake were examined in September 1968, when the lake was almost dry. Results for one of the locations, near the west shore (site 5, pl. 1), are listed in table 9. The data show that brine content is similar to that beneath Lake Abert (values range from 69 to 83 percent, by volume), but the salinity at depth is considerably less (30,000-40,000 ppm at 1-7½ feet, versus 90,000-130,000 ppm at Lake Abert). Data from the other site (near the east shore; site 8) indicate greater salinities at depth (50,000-60,000 ppm at ½-4 feet), but the values are still less than those measured at Lake Abert. Beneath Summer Lake, just as at Lake Abert, the brines contain proportionally more carbonate plus bicarbonate, and less chloride, than the lake water itself (table 10).

On the broad playa east of Summer Lake, solute characteristics and processes are analogous to those north of Lake Abert. Data for site 3 (pl. 1) are listed in table 9. The effect of playa processes is best shown by the solute characteristics at location 5 (pl. 1) in September 1968. The site, normally covered by lake water, was sampled soon after being exposed to the atmosphere (the shoreline was only 100-200 ft away), yet capillary forces had already affected the uppermost sediments, producing a playalike solute resemblance. The thin top crust was rich in carbonate and bicarbonate, whereas brines in the interval from 0.05 to 0.3 feet were chloride rich, relative to the lake water and the deeper interstitial fluids:

Interval (feet)	*Ratio of carbonate plus bicarbonate to chloride (on basis of equivalents per million)*
0.00-0.01	11
0.01-0.05	2.1
0.05-0.3	1.2
0.5-1.0	1.8
1.0-5.0	2.5-2.6
Lake (average during previous several years)	1.7-1.8

The quick response of newly exposed lake-bottom sediments to physical and chemical processes characteristic of a playa environment can be deduced on the basis of chemical changes in Summer Lake during the later stages of contraction (below about 4,146 ft). As the lake shrinks, wind can temporarily blow the water body out over recently exposed bottom sediments, dissolving the newly formed carbonate-bicarbonate-rich efflorescences. The result is enrichment of the residual lake water in carbonate and bicarbonate relative to chloride. The enrichment is only short-term, though, because when the lake begins to fill again later in the year, winds apparently are able to mix the lake water with the uppermost part of newly reinundated bottom sediments. The result is a blending of carbonate-bicarbonate-enriched lake water and chloride-enriched interstitial fluids, which produces a brine with the chemical characteristics of a "normal" lake water. This is shown by the following data for 1968-69:

Date	Lake level	Ratio of carbonate plus bicarbonate to chloride in Summer Lake (on basis of equivalents per million)
4-22-68	Near seasonal maximum	1.9
7-27-68	Receding	2.0
8-13-68	do	2.2
9-11-68	Receding, nearly dry	2.3
9-30-68	Beginning to rise following near-dryness	2.0
6-21-69	Near seasonal maximum	1.6

Wind transport of powdery, efflorescent playa salts as an effective mechanism of chloride enrichment is particularly evident at Summer Lake. During at least the last few centuries before impoundment and diversion of flow from Ana Springs, the lake doubtless dried rarely, if ever, owing to its relatively consistent and abundant inflow (p. C7). Since 1926, however, the lake has dried or nearly dried frequently, and the average lake area has been far smaller (about 40 sq mi versus 55–65 sq mi previously). This, in turn, has increased the effectiveness of wind in isolating residual brine on the peripheral playa and removing powdery salts from the playa surface. Because these salts are enriched in carbonate and bicarbonate relative to chloride (fig. 9), the effect of frequent desiccation has been a net depletion of carbon species and a resultant enrichment of chloride in the lake (p. C20; fig. 10). At Lake Abert, the periods of dryness or near-dryness during the 1920's and 1930's (fig. 4) apparently were too few in number and too short in duration to permit similar net compositional changes.

Solute tonnage measurements and estimates for the top 5 feet of sediments at five sites beneath and adjacent to Summer Lake are shown on plate 1. Contrary to conditions at Lake Abert, the greatest quantities apparently underlie the eastern playa rather than the lake. This situation may reflect (1) the absence of large quantities of westward-moving ground water that presumably would tend to flush the sediments east of Summer Lake, and (2) the characteristic diluteness of the lake water prior to impoundment and diversion of the prolific outflow of Ana Springs.

Solute quantities beneath the lake and playa average about 300 tons per acre in the top 5 feet of sediment, compared with about 550 tons per acre at Lake Abert. The total quantity for 95 square miles may be 15–20 million tons, of which about 4 million tons (23 percent) is chloride. At only two sites has the solute content of the lacustrine sediments been evaluated to depths much greater than 5 feet. The data indicate diminished quantities below 6 feet at a site west of the lake near the south end, and variable quantities to a depth of 24 feet southeast of the lake. (See table in right column.)

As at Lake Abert, the lacustrine sediments beneath Summer Lake are thick. A seismic-refraction profile northeast of the lake (Donath, 1962, p. 5) and the log of a water well to the southeast (location 33/17-14bb; Trauger, 1950, p. 256) indicate that the thickness exceeds 1,000 feet. However, the solute content of these deposits is unknown.

Approximate location	Depth (ft)	Dry-weight percentage of water-soluble salts
32 16–13 or 24[1]	Top crust	67
	0–6	2–4
	6–30½	1
32 17–34 or 35±[2]	0–6	3–4
	9–21	5–6
	24	3

[1]Data from R. S. Mason (Oregon Dept. of Geology and Mineral Industries, written commun., 1964). Considerable water encountered during augering.
[2]Data from Stott (1952, p. 41). Stott indicates that location is 32 17–32, but sections 34 or 35 seem much more likely than section 32 on basis of his verbal description: "Samples taken from playa at south end of Summer Lake, northwest of old dyke." Some seepage into hole at about 9 feet.

SUMMARY OF STORED SOLUTES

Lake Abert contained about 15 million tons of solutes in 1969. The top 5 feet of lake-bottom and marginal sediments contain 25–35 million tons. Thus, the total solute accumulation in the water and shallow sediment is 40–50 million tons. Chloride may make up about 30 percent (12–15 million tons) of this total, whereas it makes up only about 15 percent of the mobile solutes (that is, sodium plus equivalent chloride and carbonate-bicarbonate) dissolved in the inflow. The contrast reflects long-term enrichment of chloride at the lake relative to carbonate and bicarbonate. This is probably due in large part to the playa-surface processes described above.

The quantity of salts dissolved in Summer Lake is variable but may average only about 1 million tons. Stored solutes within the top 5 feet of lake-bottom and playa sediments amount to 15–20 million tons. Chloride contributes about 23 percent of the total (approximately 4 million tons), whereas it makes up only about 12 percent of the incoming mobile-solute total. As at Lake Abert, the difference points to chloride enrichment.

CONTRASTING SOLUTE BALANCES AT THE TWO LAKES

The relation between estimated incoming and stored solutes at the two lakes differs. The total quantity of sodium plus equivalent chloride and carbonate-bicarbonate stored in Lake Abert and in the upper 5 feet of lake-bottom and adjacent playa sediments is almost 8,000 times the average annual increment of these constituents. In contrast, the same mobile solutes in Summer Lake and the top 5 feet of its sediments total only about 1,000 times the average annual increment.

Comparisons based in part on estimates of stored solutes in the top 5 feet of lake-bottom and peripheral playa deposits may be misleading, however, because sedimentation rates at the two lakes probably have been different.

Direct age-dating evidence is not available, but the two drainage basins contrast geologically. Area surrounding Lake Abert is dominated by resistant volcanic flows, whereas Summer Lake is bordered to the west and south by far less resistant tuffaceous volcanic rocks (and the landslide debris therefrom) and to the east by a broad area of unconsolidated sediments (Walker, 1963). Although flood flows of the Chewaucan River would increase sedimentation rates in Lake Abert, this source of sediment is considered to be less important than the sediment in runoff from heavy rains adjacent to the lakes. Thus, a comparison of interstitial solute quantities stored per "time unit" of accumulated sediment at the two lakes may give more representative results than the comparison base on "depth units" of sediment, despite the possible influences of vertical diffusion (p. C23) or deflation (p. C28).

Nonetheless, the quantity of stored solutes at Summer Lake prior to 1900 was inconsistent with rates of solute accumulation. The anomaly is shown clearly by calculating the hypothetical lake salinity, using parameters listed in table 3. Langbein (1961, p. 13–14) developed an equation to determine the theoretical salinity (C) of a closed lake. More recently, he reevaluated the information published in 1961, and formulated a more sophisticated least-squares regression that gives a favorable correlation coefficient of 0.92 for his data (written commun., 1964). The regression is

$$C = 45{,}000 \frac{E^{1.2}\overline{A}_L^{1.14} \; 10^{0.0182P}}{A_L D \, \overline{D}^{0.05} A_T^{\;0.155}}. \qquad (5)$$

Terms are defined in table 3. Overbarred parameters are long-term historical averages, whereas other parameters apply to the shorter periods of specific concern.

For Lake Abert during the high-level period 1952–65, equation 5 and data in table 3 give a hypothetical dissolved-solids content of 34,000 ppm—encouragingly close to the estimated actual average of 35,000 to 40,000 ppm, based on known lake levels and solute tonnages. For 1916–65 the hypothetical salinity is 75,000 ppm, which compares reasonably well with the actual time-weighted mean concentration, an estimated 50,000 to 70,000 ppm. Thus, the agreement between theoretical and actual concentrations of dissolved solutes in stream-fed Lake Abert is reasonably close even when applied to two periods of contrasting climatic conditions.

At spring-fed Summer Lake for the high-level period prior to 1900, calculations based on equation 5 indicate a salinity of about 80,000 ppm. This is equivalent to a solute load of about 21 million tons, more than 4 times the actual amount thought to have been stored in the lake during that period. Even with inclusion of the 520 square-mile Silver Lake drainage (which is thought to feed Ana Springs), the calculated salinity and load are about 70,000 ppm and 19 million tons, again much greater than actual quantities. This disparity contrasts sharply with the agreement between theoretical and actual values for Lake Abert.

Other lines of evidence, which assume long-term conditions similar to those of about 1900, also suggest that Summer Lake should have contained more dissolved salts than it actually did. Immediately following the final shrinking of huge Lake Chewaucan at the close of Pleistocene time (p. C2), the Summer Lake basin contained more water and, therefore, a greater salt tonnage than the Lake Abert basin. Assuming that the combined lake at its peak level contained 100 ppm (10 million tons) of present-day lake constituents and that it did not leak appreciably during subsequent recession, Summer Lake would have received almost 7 million tons of the high-level load, whereas Lake Abert would have received only about 3 million tons.

This paradox in the geohydrologic behavior of the two basins is heightened by recorded differences in the uniformity of water supply to the two lakes. The year-to-year pattern of surface-water flow into a lake is dependent on short-term climatic fluctuations, which can be extreme. On the other hand, in basins where ground water is the principal source of inflow, the effect of climatic variation is subdued, and only long-term trends of wetness or dryness have much influence on lake-level fluctuations. For example, at Summer Lake, where more than 90 percent of the inflow was provided by ground water, the coefficient of lake-area variation was a very stable 0.07 prior to 1900 (table 3). In contrast, at Lake Abert, where ground water contributes less than 10 percent of the inflow, the coefficient has been a far less stable 0.23. Thus, if a comparable balance between ground water and surface water had existed at the two lakes throughout the last 10,000 years, Summer Lake would have accumulated a much greater solute tonnage than Lake Abert because at Summer Lake the initial quantity would have been greater, the average annual increment of constituents that dominate in the lakes would have been larger, and the mechanisms of solute depletion (which are most effective during periods of low lake level) would have been less active.

Two factors—prehistoric dry periods and differences in lake-bottom flatness—may help explain the apparent discrepancy between solute balances at Abert and Summer Lakes.

The ground-water reservoir feeding Summer Lake probably has not provided a flow adequate to maintain a large stable lake throughout the post-Pleistocene. In fact, extensive sand dunes northeast of Summer Lake strongly suggest that the lake was small enough at some time before 1900 to permit appreciable deflation of the playa sediments and their entrapped salts.

The change in hydrologic regimen may have been triggered by tectonic activity that produced or increased the carrying capacity of fault-zone conduits which now allow movement of ground water from the north toward Summer Lake. Donath (1962, p. 8) indicated that although major faulting in the Summer Lake area must have preceded the late Pliocene, faulting on a smaller scale probably continued into the Holocene epoch (less than 10,000 years ago). Other evidence, however, discourages the possibility of major Holocene faulting as an influence: The highest known Pleistocene shorelines in the Summer Lake and Silver Lake basins are at about the same altitude (4,520 ft; Phillips and Van Denburgh, 1971, p. B12, B37), suggesting that an effective subsurface hydraulic connection may have existed even prior to the Holocene (the two lakes are not thought to have had a surface connection).

Another factor that more certainly contributed to quantitative changes in the ground-water system tributary to Summer Lake was the climatic fluctuation that followed the extremely wet periods late in the Pleistocene. The very dry conditions that Morrison and Frye (1965, fig. 2) inferred to have been characteristic of the Great Basin in Nevada and Utah between about 7,000 and 4,000 years ago doubtless would have extended into south-central Oregon. If true, inflow to Summer Lake during this period probably was much less than it was immediately prior to 1900. As a result, the lake may have dried even more frequently than it does now. Thus, the annual solute income would have been less, and solute depletion by wind would have been greater. The same dry conditions would also have affected Lake Abert, but the influence would not have been as great as at Summer Lake because of differences in lake-bottom flatness. The effectiveness of evaporation and wind as a solute-depletion mechanism increases with increasing basin flatness, and at shallow lake levels (less than about 3 feet maximum depth) a given volume of water at Summer Lake covers 125 percent to more than 175 percent as much area as it would at Lake Abert.

In summary, then, prehistoric dry periods, aided by differences in lake-bottom flatness, may have combined with dissimilar rates of sediment income to cause the present-day contrast in the relation between incoming and stored solute quantities at Abert and Summer Lakes.

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☆U.S. GOVERNMENT PRINTING OFFICE: 1975—677-313/62