Hydrology of Crater, East and Davis Lakes, Oregon

By KENNETH N. PHILLIPS

With a section on CHEMISTRY OF THE LAKES

By A. S. VAN DENBURGH

CONTRIBUTIONS TO THE HYDROLOGY OF THE UNITED STATES

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1859-E

Studies of water-budget balance in volcanic terranes for three lakes without surface outlets

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HYDROLOGY OF CRATER, EAST AND DAVIS LAKES, OREGON

By KENNETH N. PHILLIPS

ABSTRACT

Crater, East, and Davis Lakes are small bodies of fresh water that occupy topographically closed basins in Holocene volcanic terranes. Because the annual water supply exceeds annual evaporation, water must be lost by seepage from each lake. The seepage rates vary widely both in volume and in percentage of the total water supply. Crater Lake loses about 89 cfs (cubic feet per second), equivalent to about 72 percent of its average annual supply. East Lake loses about 2.3 cfs, or about 44 percent of its estimated supply. Davis Lake seepage varies greatly with lake level, but the average loss is about 150 cfs, more than 90 percent of its total supply. The destination of the seepage loss is not definitely known for any of the lakes.

An approximate water budget was computed for stationary level for each lake, by using estimates by the writer to supplement the hydrologic data available.

The three lake waters are dilute. Crater Lake contains about 80 ppm (parts per million) of dissolved solids—mostly silica, sodium, and bicarbonate, and lesser amounts of calcium, sulfate, and chloride. Much of the dissolved-solids content of Crater Lake—especially the sulfate and chloride—may be related to fumarole and thermal-spring activity that presumably followed the collapse of Mount Mazama. Although Crater Lake loses an estimated 7,000 tons of its 1.5-million-ton salt content each year by leakage, the chemical character of the lake did not change appreciably between 1912 and 1964. East Lake contains 200 ppm of dissolved solids, which includes major proportions of calcium, sodium, bicarbonate, and sulfate, but almost no chloride. The lake apparently receives much of its dissolved solids from subsurface thermal springs. Annual solute loss from East Lake by leakage is about 450 tons, or 3 percent of the lake's 15,000-ton estimated solute content. Davis Lake contains only 48 ppm of dissolved solids, much of which is silica and bicarbonate; chloride is almost completely absent.

Approximate physical and hydrologic data for the lakes are summarized in the following table.

Physical or hydrologic characteristic measured or estimated	Lake		
	Crater	East	Davis
Area of basin...square miles..	26.2	7.46	98
Area of lake, at high level...do....	20.5	1.47	5.9
Maximum depth...feet..	1,932	170	26
Maximum volume...thousands of acre-feet..	14,000	55	38
Altitude, high level...feet..	6,179.06	6,382.5	4,393.2
Altitude, low level...do....	6,163.2	6,366	4,376.1
Average annual precipitation...inches..	69	35	36
Average annual precipitation...acre-feet..	75,600	2,740	8,000
Average annual water supply...do....	89,600	3,890	117,000
Average annual evaporation loss...inches..	23	28	30
Average annual evaporation loss...acre-feet..	25,200	2,190	8,000
Ratio of evaporation to water supply...	0.28	0.56	0.07
Average annual seepage loss...acre-feet..	64,400	1,700	109,000
Average seepage loss...cfs..	89	2.3	150

INTRODUCTION

PURPOSE AND SCOPE

The purpose of this report is to bring together available hydrologic and chemical data on certain topographically enclosed lakes, to describe the variations within historic time of their water levels, volumes, and chemical character, and, insofar as practicable, to correlate such variations with climatic or other causal factors.

The approximate magnitudes of precipitation and runoff as sources of supply, and evaporation and leakage as means of disposition were the water-budget elements determined for each lake. Some of the quantities have been measured, some have been ascertained by correlation with published records of precipitation or runoff, some have been computed as residuals, and the others have been estimated. A large mass of water-level data was assembled, and data collection was intensified during the study.

Chemical aspects of the study included determination of the chemical character of the lakes and evaluation of the possible sources and disposition of dissolved solids.

Such basic data as precipitation and inflow can only be estimated for some of the lakes. Chemical data are scanty. This report must be viewed as an effort to ascertain preliminary hydrologic and chemical budgets for the lakes and to present what is known of their chemical quality. The conclusions reached are subject to review as more data become available.

The hydrologic aspects of the study were made by Kenneth N. Phillips, assisted by Roy B. Sanderson, district engineer, and members of his staff. Fieldwork was completed in July 1963, and the cutoff date for most hydrologic data was September 30, 1962.

The chemical phases of the study were performed by A. S. Van Denburgh.

ACKNOWLEDGMENTS

Several organizations have provided valuable information and assistance during the present study. Most of the water-level data on Crater Lake were provided by the U.S. National Park Service. The bathymetric chart for Crater Lake (fig. 3) is from a lake-bottom survey made by the U.S. Coast and Geodetic Survey. The area-volume curve and some water-level data for Davis Lake are from an unpublished engineering report by the U.S. Reclamation Service. The office of the Oregon State Engineer furnished data on Davis Lake levels and cooperated with the U.S. Geological Survey in operating stream-gaging stations to obtain data essential to this study; watermasters of that office, Aubrey Perry and James Fellows of Bend, deserve special thanks for assistance in the field.

Many individuals also were helpful in the study. The writers are especially grateful to Mr. B. W. Black, formerly chief park naturalist at Crater Lake, for assistance in the field and for criticism of a draft of the section on hydrology of Crater Lake, to Mr. S. T. Harding, consulting engineer, for results of his field observations and unpublished notes on the hydrology of Crater and Davis Lakes, to Dr. D. B. Lawrence for results of his observations on tree rings and water levels at Crater, Davis, and East Lakes, and to Mr. C. H. Nelson for the use of an unpublished thesis on the limnology of Crater Lake.

Within the Geological Survey, George T. Hirashima checked most of the hydrologic computations, and many other members of the staff contributed valuable suggestions. Walter B. Langbein and S. E. Rantz were principal reviewers of the final manuscript. Special gratitude is extended to Nyra Johnson for her dedication, patience, and understanding during the typing and assembly of this manuscript.

LOCATION AND BRIEF DESCRIPTION OF THE STUDY AREAS

The three small study areas are situated in the southwest quarter of Oregon (fig. 1). Crater Lake lies in a caldera at the summit of the Cascade Range, 65 miles north of the California-Oregon State line and 120 miles inland from the Pacific Ocean. East Lake lies 70 miles northeast, and Davis Lake 50 miles north, from Crater Lake. The three lakes are not subject to overflow, but do lose water by leakage.

The lakes lie in volcanic terranes that have been formed or significantly modified by volcanic activity in Holocene time. Crater Lake occupies the caldera of Mount Mazama, East Lake lies in the somewhat similar Newberry Crater, and Davis Lake is an impoundment on Odell Creek, formed by a Holocene permeable lava flow that dammed the creek channel. The topographic basins tributary to the lakes are small. However, because of the permeable nature of the volcanic soils and rock, some ground water may be transferred across topographic divides, and hence the contributory areas may be somewhat different from the topographic basins.

The lakes lie at moderately high altitudes, either on or adjacent to higher mountains. Crater Lake, at 6,175 feet on the crest of the Cascade Range, and East Lake, at 6,375 feet in Newberry Crater of the Paulina Mountains, are similar in altitude but somewhat different in topographic environment. Davis Lake, at 4,390 feet, lies on an extensive lava plain from which many Holocene volcanic cones rise to altitudes of more than 6,000 feet.

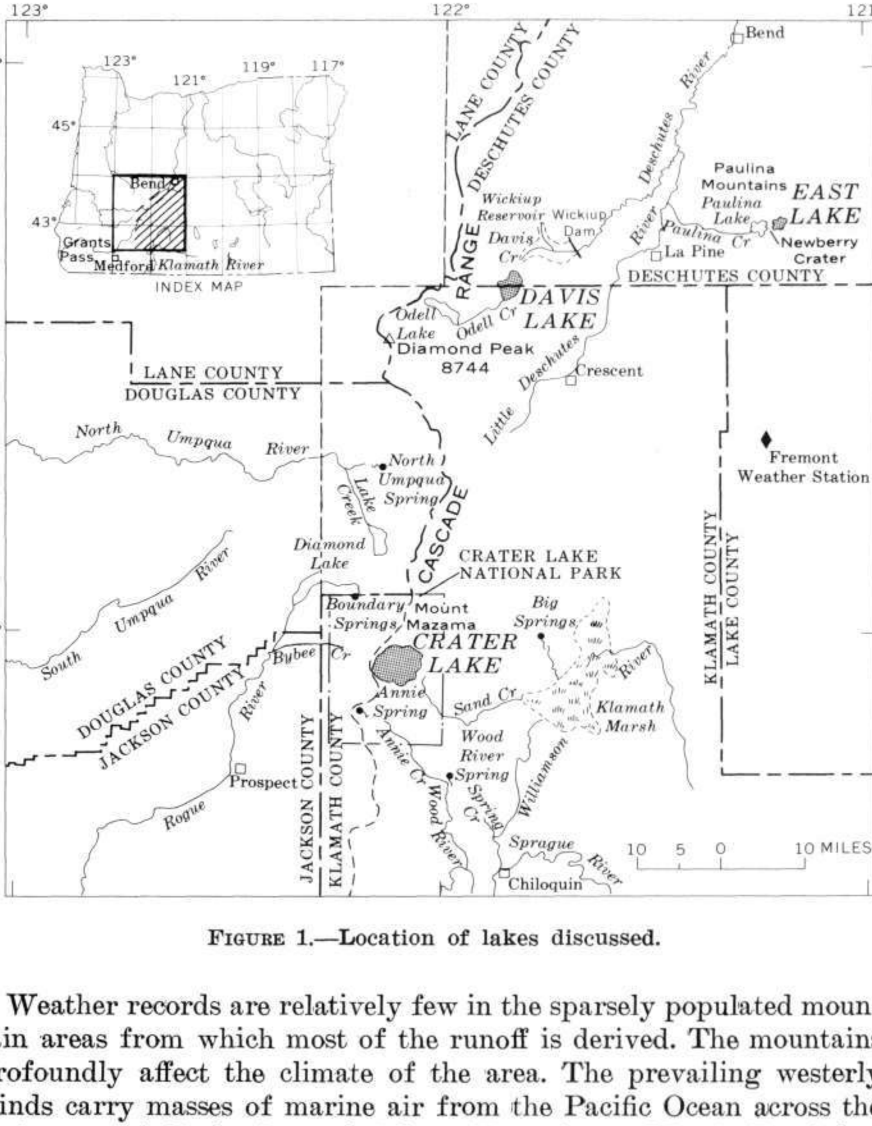

FIGURE 1.—Location of lakes discussed.

Weather records are relatively few in the sparsely populated mountain areas from which most of the runoff is derived. The mountains profoundly affect the climate of the area. The prevailing westerly winds carry masses of marine air from the Pacific Ocean across the region, especially in the period from November to March. Precipitation in that period, chiefly as snowfall, is heavy near the summits and on the windward slopes of the mountain barriers, but is considerably less at lower altitudes and on the leeward (east) side of the Cascade Range.

The average annual precipitation in the region ranges from about 70 inches along the crest of the Cascade Range to about 20 inches on the plateau about 20 miles east of the range. It may vary greatly in short distances because of changes in altitude or topographic orientation with respect to prevailing winds.

In most of the region, the period June to September is dry, with warm days and cool nights. The warmest summer weather occurs in basins at the lower altitudes (4,100 ft), but because such basins have poor air drainage, freezing occurs there in all seasons.

Small thermal springs and seeps occur near the shore of East Lake. Similar springs may enter Crater Lake below the waterline. Such springs may provide a significant part of the dissolved-solids load in each of these lakes.

The water levels of the lakes respond to variations in the annual and long-term water supply and water loss. Typically, the peak of the annual cycle occurs in the spring season, near the end of the period of greatest precipitation and runoff, and is followed by a recession during the dry, warm summer months to an annual minimum in the late summer or early autumn. In periods of greater than average precipitation and runoff, the lakes gradually rise until the combined evaporation from their increased area and leakage at the higher level offset their annual supply; in protracted periods of dryness, the water levels fall until a balance is reached.

The works of man, specifically the storage, use, and diversion of water, have not affected the lakes. Their changes in levels are indices of the balance between supply (precipitation and runoff) and loss (evaporation and seepage). All the lakes studied were at low levels in the 1930's and 1940's, after a series of dry years; all were at high levels in 1957 and 1958, after a series of wet years.

CRATER LAKE

PHYSIOGRAPHIC AND GEOLOGIC SETTING

Crater Lake (fig. 2), the deepest lake in the United States, lies in the caldera of Mount Mazama, an extinct volcano that rises on the crest of the Cascade Range in southern Oregon, 120 miles inland from the Pacific Ocean. The lake is 4½ to 6 miles in diameter and 1,932 feet deep. Its water surface is about 6,175 feet above mean sea level. The walls of the caldera descend steeply into the water, so that an observer on the rim above may see the narrow fringe of green shallow water near the shore merging within a short distance into the intense blue color of great depth. The lake has no surface outlet and no perennial inflowing streams.

Crater Lake has a surface area of 20.53 square miles (13,140 acres) at altitude 6,176 feet. The area between the encircling rim and the lake is 5.17 square miles, and Wizard Island, a volcanic cone rising 770 feet above the water surface, covers 0.47 square mile. The lake contains about 14 million acre-feet (4.2 cubic miles) of water. That volume

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FIGURE 2.—Western half of Crater Lake, view looking northward toward Mount Thielsen (right skyline). Wizard Island (center) is a volcanic cone that was formed within the caldera before the lake had attained its present height. (Oregon State Highway Dept. photograph 6639.)

represents 150 times the present average annual water supply. The water level has fluctuated about 16 feet.

A bathymetric survey in 1959 (fig. 3) disclosed a rather flat lake floor more than 1,500 feet below the water surface, from which a conical hillock (Merriam Cone) rises to within 500 feet of the surface. The lake has a depth of at least 1,920 feet over an area of 1.0 square mile.

In places, the soil cover of the steep slopes around the shores of the lake has been removed by landslides or avalanches; elsewhere, a moderately dense stand of pines, firs, and poplars covers the slopes down to the edge of the lake. When the lake is at a low stage, seedlings may be found growing below recent high-water levels, and Nelson (1961, p. 30) cited a report of the discovery in 1956 of the stump of a tree that may either have grown at altitude 6,129 feet or have been carried to that level by a local landslide. There are no confirmed reports of large trees having grown below about 6,178 feet, or of any trees below altitude 6,165 feet.

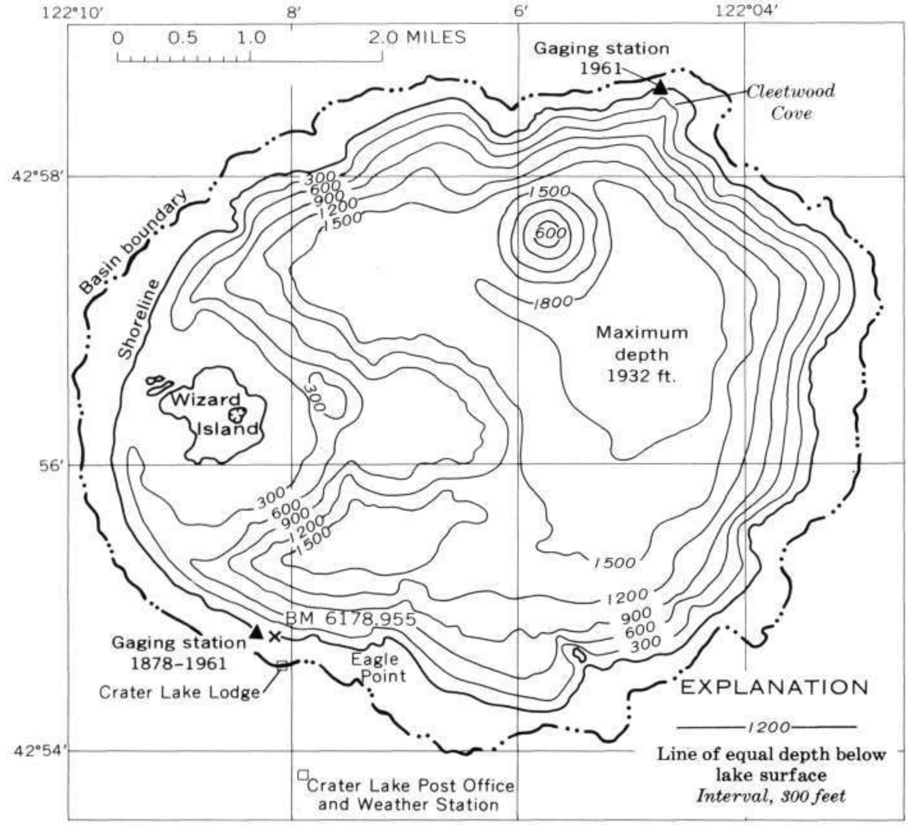

FIGURE 3.—Bathymetric chart of Crater Lake.

A study of the hydrologic regimen of Crater Lake calls for a brief review of the volcanic history leading to formation of the lake. Mount Mazama is the remnant of an extinct volcano that was active during Pleistocene and Holocene time (Williams, 1957, p. 14) and was formed of alternating effusive lava flows and layers of ejecta from explosive eruptions. The volcanic cone attained an estimated height of more than 12,000 feet. During periods of quiescence, glaciers coursed down its slopes and carved U-shaped valleys and left trains of glacial till that locally were covered by material from later eruptions. Within the body of the volcano, dike-forming masses of molten lava at times forced their way upward along planes of weakness and served as feeders for effusive flows that appeared on the slopes of the volcano. Subsidiary cinder cones also developed, especially in the area north of the main volcano. Some of the explosive eruptions threw out masses of incandescent ash that flowed as glowing avalanches for many miles down the slopes of the mountain; these materials subsequently cooled and became fused. These fused deposits are now exposed as spectacular pinnacles in the canyons eroded by some streams, notably Annie Creek and Sand Creek, that flow down the slopes of Mount Mazama.

The volume of material thrown out during the late, explosive stages of the eruption has been estimated as 17 cubic miles as deposited (Williams, 1953, p. 49). Most of the material ejected was pumice and ash that now cover about 5,000 square miles to a depth of more than 6 inches. Most of the pumice was carried by the southwest wind and deposited to the east and northeast. The explosive emptying of the magma chamber finally removed the support from the upper-central part of the volcano and allowed the upper part to collapse into the empty chamber. The broad crater formed by the collapse is the spectacular caldera now occupied by Crater Lake.

The pumice explosions occurred about 6,600 years ago, as shown by carbon-14 dating of 10 specimens of carbonized wood taken from the beds of pumice (Fryxell, 1965, p. 1288).

Some volcanic activity continued after the caldera was formed; the blocky lava flows on Wizard Island, apparently formed in a subaerial environment, may be only about a thousand years old (Williams, 1953, p. 49).

All evidence indicates that Crater Lake itself is young. The lake has no well-developed beach lines in the range of observed water levels. A water body must have begun to form soon after active volcanism ceased. The floor of the crater is probably underlain by lava flows somewhat less permeable than the volcanic ejecta of the caldera walls. Given a climate like the present one, the new lake would have increased in depth rapidly until it reached a level at which its annual supply was substantially balanced by leakage and evaporation.

The oldest trees on Wizard Island are about 900 years old (Williams, 1942, p. 94), and these trees may have been among the first to have grown on the island. The climate during that time, at least, must have been generally similar to that of the present.

If we assume a climate like that of the present, a period of 500 to 1,000 years may well have been required to fill the lake to its present level. Much of the measured seepage may leave the lake 500 feet or more below the present water level. If so, the rise of the lake above that level must have been slow, but it is not possible to approximate the probable levels of seepage loss nor deduce the time of filling to the present level. The lake may have been generally at its present level, in balance with the present climate, for a similar length of time. Nelson (1961, p. 130) concluded that deposits of colloidal clay derived from volcanic ash, reworked in places by submarine landsliding, have helped to seal the bed of the lake. Such sealing may still be in progress. But continued sealing by any means during a period of stable climate should result in a slowly rising lake level and submergence of mature forest trees, of which we have as yet no confirmed evidence.

There is, however, a strong probability that the climate was not like that of the present time for about 3,000 years after the formation of the caldera. Students of post-Pleistocene climate are generally agreed that the middle third of the last 10,000 years—7,000 to 4,000 years before the present—was warm and dry in western North America. For example, Harding (1965, p. 137–140) observed stumps of trees that grew on the shore of Lake Tahoe, Calif., in a period when the lake was below the level of the root systems of the trees and below its own outlet. One stump with its base 2 feet below the basin rim had 100 countable rings in 1934. Carbon-14 dating on samples from two such stumps show ages of 4,250±200 years and 4,460±250 years. Obviously, to permit the growth of these trees a protracted warm-dry period must have occurred when inflow to Lake Tahoe did not exceed evaporation from its surface. By contrast, the present average annual inflow is more than three times the average evaporation loss (Harding, 1965, p. 136). Similar evidences of the warm-dry period have been reported in many parts of the world (Matthes, 1942, p. 208–215; Flint and Brandtner, 1961, fig. 1; Gentilli, 1961, p. 491).

Crater Lake was born in that warm-dry period. No doubt a small lake formed soon after volcanic activity in the crater ceased, but the level of the water surface must have been well below the present level until perhaps 1,000 to 4,000 years ago. The period of 2 to 5 milleniums in which the lake was low would have given ample opportunity for forest trees to grow on the crater walls well below the present lake surface. If and when the stumps of such trees can be found and dated, their altitude and age will fill a gap in our knowledge of the development of Crater Lake.

The lower slopes of Mount Mazama are drained by tributaries of the Rogue River to the west and the Klamath River to the south and east. The drainage paths for some parts of the area surrounding the basin of Crater Lake (especially on the north) are uncertain, and some ground water may interchange across topographic divides.

The pumice cover on the higher outer slopes of Mount Mazama, and much of the underlying volcanic materials, are so highly permeable that in places all precipitation infiltrates where it falls. Large areas have no stream channels or other signs of erosion by running water. Downslope from the permeable areas, and within 25 miles of Crater Lake, large springs occur in the basins of the Klamath, Rogue, and Umpqua Rivers. The less extensive areas of glacial deposits and solidified volcanic ash on Mount Mazama are relatively impermeable.

No perennial streams flow into Crater Lake, and there is no overflow. In the summer season, the melting of accumulated snow produces many rivulets that course down the steep caldera walls into the lake. The total measured flow of 63 of these streams was 10.75 cfs (cubic feet per second) in mid-July 1901 (Diller and Patton, 1902, p. 60). Presumably, these streams were not constant in flow, but varied considerably during each day with changes in the rate of snowmelt; also, some unmeasured melt water doubtless was then entering the lake as small seeps at the shore or as underground percolation.

CLIMATE

Because of its altitude and position at the crest of the Cascade Range, Crater Lake is in an area whose climate is usually cool and wet from October to May and cool and dry from June to September. Average annual precipitation exceeds 60 inches, and most of it occurs as snowfall. Air temperatures are low throughout the humid period and at night even in summer; but extremely low temperatures seldom occur at the lake or on the slopes of Mount Mazama because of frequent cloud cover and good air drainage. Relative humidity is high except for daytime hours in summer, and evaporation potential is therefore low.

From October to May, moisture-bearing airmasses frequently move up the mountain slopes from the west and southwest. Precipitation in this period is heavy, and the data available are not adequate to show whether it is uniformly distributed or not. Storms from any direction may sweep snow across the crater rim and thence into the lake. Some avalanching into the lake undoubtedly occurs at times from the steeper or less wooded slopes. These factors result in increments of water supply in the lake that may not be accurately indicated by any precipitation gage.

Records of air temperature (table 1) have been collected by the U.S. National Park Service at the sites indicated below, with some periods of incomplete record:

1. At Annie Spring (alt 6,016 ft), October 1922 to December 1925.
2. At the south rim of Crater Lake (alt 7,086 ft), November 1926 to June 1930.
3. At park headquarters (alt 6,475 ft), June 1930 to present.

The annual mean temperature is 39°F, and from October through May it averages only 32.2°F. This long period of coolness affects the temperature of the lake water and lowers the evaporation potential substantially below that of the general area.

The water of Crater Lake is cold. Below a depth of about 200 feet, the temperature approaches 39.2°F (the temperature of maximum density) at all seasons of the year (Nelson, 1961, p. 36–45). Hence, most of the lake water does not undergo the annual thermal turnovers common to shallow lakes in temperate climates. In summer, the temperature of the surface water rises to about 64°F at times.

Contrary to popular belief, ice does form at times on Crater Lake. For instance, the lake was frozen over in 1949, and at that time two men walked across the ice from the south shore to Wizard Island. Again, in January 1962, much of the lake surface was frozen.

Records of precipitation obtained at Crater Lake Weather Station, 2 miles south of the lake rim at altitude 6,475 feet, from 1930 to 1962, are summarized in tables 1 and 2. For the 32 years ending June 30, 1962, the average annual precipitation was 67.4 inches. That value appears to be a little more than the average long-term precipitation, because (1) the average annual precipitation at Grants Pass, 70 miles southwest of Crater Lake, was 30.87 inches for that 32-year period, but only 30.31 inches for the 73-year period 1889–1962, and (2) the lake level was about 8.7 feet higher in July 1962 than it was 32 years earlier—an average rise of more than 3 inches per year.

At the Crater Lake Weather Station the average long-term annual precipitation, adjusted for a constant lake level, is about 65 inches. In the wettest year ending June 30 of record, 1950–51, the observed precipitation was 93.08 inches, and the lake rose 2.5 feet; in the driest year, 1930–31, the precipitation was 33.34 inches, and the lake fell about the same amount.

The annual precipitation on the lake presumably is not the same as that reported at the weather station. The rain gage collects a sample that is almost infinitesimal as compared to the size of the lake. That sample of precipitation is subject to large and unavoidable errors, such as uneven distribution because of topographic influences and localized wind currents near trees, buildings, or even the precipitation gage itself. Also, the lake basin may at times act as a huge snow trap. For this study, therefore, the precipitation falling on the lake was compared with that observed at the weather station for storm periods in 1961–62 (see p. E15).

From 1951 to 1960, attempts were made to increase winter precipitation and summer runoff in the adjacent basins of Rogue, Umpqua, and Klamath Rivers by cloud seeding in periods thought to be favorable for that purpose. These attempts produced no statistically significant results in streamflow (Calvin and Peterson, 1960, p. 3) and probably did not change significantly the water supply of Crater Lake.

Information on evaporation loss from Crater Lake is scanty. In 1901, Diller made the only known attempt to measure evaporation (Diller and Patton, 1902, p. 58). Diller used (1) a brown floating pan, 13 by 13 inches by 6 inches deep, (2) a similar land pan, and (3) a bright land pan of the same dimensions. In a 9-day period in mid-July, observations at the floating pan showed water loss at an average rate of 0.014 foot per day (4.9 in. per month). The land pans showed considerably more loss. All his tests were of short duration, and none was made with equipment that meets present standards.

Evaporation has been measured from a 4-foot-diameter floating pan at Lake Tahoe, about 265 miles south of Crater Lake, at an altitude of 6,230 feet on the eastern slope of the Sierra Nevada. For the period May 1 to October 31, the average evaporation loss there is 25.8 inches (Blaney and Corey, 1955, table 44), and the average annual evaporation loss has been estimated at 3.07 feet (Harding, 1965, p. 20).

Evaporation has also been measured from a land pan at Odell Lake, 42 miles north of Crater Lake, at an altitude of about 4,800 feet on the eastern slope of the Cascade Range (table 11). The average evaporation loss from May 1 to October 31 is 19.3 inches, and the average for the year is estimated at 24 inches. The corresponding loss from an open water surface would be somewhat less.

The evaporation loss from Crater Lake in the period May to October is probably less than at Lake Tahoe, because Crater Lake lies 265 miles farther north and in a much more humid climate. Odell Lake is lower than Crater Lake but has comparable annual precipitation. On the basis of comparative latitude, altitude, and annual precipitation, the evaporation loss from Crater Lake is probably similar to or less than that of Odell Lake.

At Medford, 46 miles southwest of Crater Lake, evaporation has been measured for 24 years (U.S. Weather Bureau, 1962, p. 231). The Medford Weather Station is the only one that is situated on or near the path of most of the airmasses that pass over Crater Lake and has records for the entire year over a long period. The precipitation and relative humidity at Medford are lower, and the average temperature is higher, than at Crater Lake. At Medford, the average annual evaporation loss from a class A land pan at altitude 1,457 feet is 44.8 inches, of which 79 percent occurs in the period May to October. Relatively high humidity prevails at Crater Lake from November to April, so that probably not less than 80 percent of the total annual evaporation loss there occurs in the period May to October.

For this report no attempt was made to ascertain evaporation loss at Crater Lake by direct measurement of evaporation or of the factors that influence it. Rather, annual evaporation loss is considered to be the residual after the loss by seepage has been deducted from the annual water supply (see p. E20). Therefore, any error in ascertaining precipitation, inflow, or seepage introduces an error of like amount in the computed evaporation loss.

RECORDS OF LAKE LEVEL

Records of lake level are given in table 7 and are summarized in figure 4. All data are referred to a common datum by which the bench mark at the southwest shore of the lake is 6,178.955 feet above mean sea level (Marshall, 1914, p. 88). Some readings are subject to error because of waves or because of the need to use temporary reference marks, but the record, although fragmentary, is in general dependable. The highest level in many years was 6,179.06 feet in June 1958 (by later measurement to high-water mark); a slightly higher level may have occurred in 1904. The lowest level known is 6,163.2 feet, September 10, 1942.

Prior to September 1961, the occasional observations of lake level were made at several different gages at the southwest shore. On September 14, 1961, a water-stage recorder was installed at Cleetwood Cove on the northeast shore. The continuous trace of that recorder in 1961–62 was used to determine (1) the rate of seepage loss from the lake in cold periods of no precipitation and little evaporation and inflow, and (2) the increment to the lake in periods of heavy precipitation, for comparison with precipitation at the weather station. (It was necessary to ascertain the seepage rate first, because that loss continues during periods of precipitation.)

A change in the pattern of lichen growth at altitude 6,180.5 feet has been noted by many observers since 1915. The lowest living crustose lichens reach that level on the rock walls around the lake, and that level is thought to represent the highest stage ever reached by Crater Lake; the date of that high level is not known. Moreover, large living conifers along the shores of Crater Lake have their root systems within a few feet of historic high-water levels. Nelson (1961, p. 28–32) refers to the following observations made in August 1960 by D. B. Lawrence, who took cores from several of those trees and counted their annual growth rings to ascertain their age.

Altitude at base (feet)	*Tree species and significance*
6,187.4	*Abies magnifica,* living; center at A.D. 1580.
6,185.6	*Pinus monticola,* living; center at A.D. 1797.
6,182.9	*Pinus monticola,* dead; had lived at least 430 years.
6,180.5	*Rhizocarpon geographicum,* lowest living crustose lichen on stable rocks.
6,178.7	*Pinus monticola,* dead stump; tree probably died before 1900.
6,172.5	*Populus trichocarpa,* drowned about 1957; had lived 30 years.

Certainly the level of the lake has not been higher than the root system of living conifer trees within their lifetimes. From the botanical evidence, the relative youthfulness of the caldera, and the absence of defined high-level beach lines, the lichen line at 6,180.5 feet probably represents the highest level ever reached by the lake.

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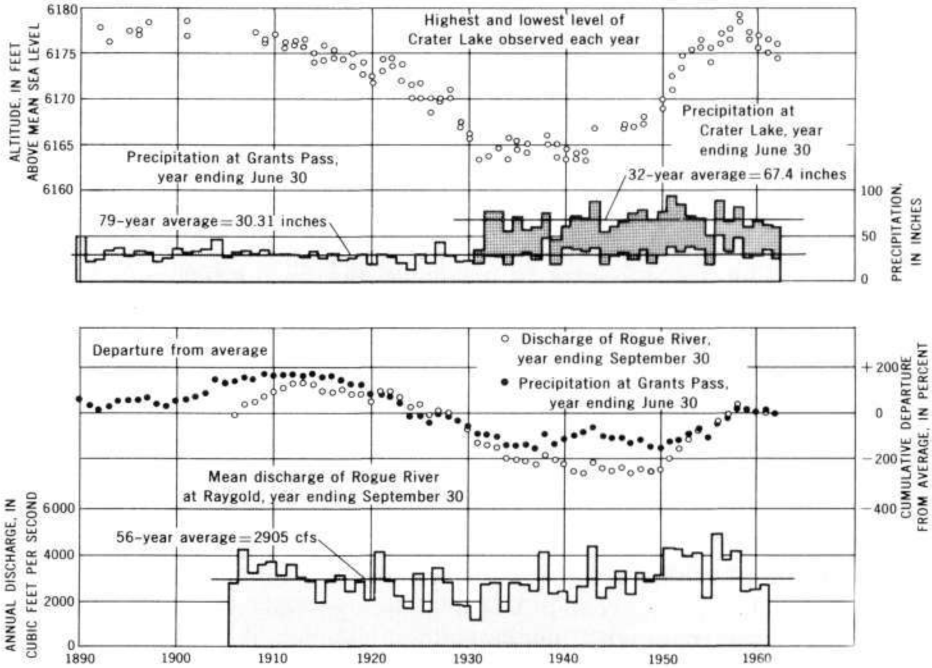

FIGURE 4.—Altitude of water surface of Crater Lake; precipitation at Grants Pass and Crater Lake; departure from average for periods of record for flow of Rogue River at Raygold and precipitation at Grants Pass; and flow of Rogue River at Raygold.

Attempts have also been made to ascertain whether Crater Lake has ever been much higher than at present by searching the slopes above the lake for sponge spicules and shells of diatoms of species that now live or could have lived in the lake. Pursuing that possibility, Nelson (1961, p. 33) collected soil samples at 100-foot altitude intervals up to the crater of Wizard Island, and up to the rim of Crater Lake. Nearly every sample, even those collected from places higher than the low points in the rim, contained diatoms and sponge spicules that must have been carried by wind currents to those levels far above the lake. Their presence is certainly not evidence of former high lake levels.

WATER SUPPLY TO THE LAKE

The water supply of Crater Lake is derived from infalling precipitation, surface runoff, and ground-water inflow. Direct precipitation, chiefly in the form of snowfall, is by far the greatest contributor, because the lake itself covers most of its basin. Snowfall forms drifts on the crater walls and the snow reaches the lake either by avalanching during winter and spring storms or as summer snowmelt and deep percolation. Some precipitation that falls high on the crater slopes may be drained radially outward away from the lake. On the other hand, Williams (1942, p. 129) has suggested the possibility of slight amounts of seepage toward the lake from outside the rim and has observed that:

In general, the drainage is outward from the caldera, following the dip of the lavas and interbedded pyroclastic rocks. At several points, however, particularly where lavas rest on glacial debris, the drainage is reversed and enters the lake. Noteworthy examples may be seen on the cliffs south of Sentinel Point, on Sutton Cliff, and under the topmost flows overlooking Grotto Cove. At these and similar places, copious springs discharge down the caldera walls.

Any small contribution to the water supply of the lake that may result from a reversal of the prevailing outward drainage, as noted by Williams, probably is offset, and may be exceeded, by outward radial seepage from melting snowbanks high up on the walls of the caldera. No allowance is made herein for the possibility of such in-seepage or out-seepage above the level of the lake; rather, the topographic rim is assumed to be the hydrologic divide.

PRECIPITATION ON THE LAKE

The lake covers 20.53 square miles of the 26.17-square-mile total drainage area. The peripheral tributary area is subject to some loss of water by evapotranspiration; hence, precipitation falling directly into the lake must account for more than 78 percent of the total water supply. It is therefore desirable to measure that precipitation as accurately as possible.

The response of lake level to heavy precipitation provides a clue to the relationship of observed precipitation at the weather station to that over the lake itself. In table 3, records of heavy precipitation in 1961–62 are compared with records of lake level. In the 50 days studied (table 3), more than 60 percent of the total precipitation for the entire water year ending September 30 occurred. For these humid periods, loss by evaporation is disregarded, and outflow seepage is assumed to be steady at 89 cfs, as ascertained for periods of no precipitation in 1961–62 (p. E17). Although most of the precipitation was in the form of snow, the average inflow from the tributary area is assumed to be equivalent to 14 cfs (0.002 ft per day on the lake area), about 3 percent of the total supply for these wet periods.

For a total observed precipitation of 3.13 feet in 50 days, the lake response (adjusted for inflow and seepage) was 3.35 feet, or 7 percent more than the total precipitation observed at the weather station. The difference in periods of high wind may be due to underregistering of precipitation that fell as snow at the weather station, or to snow drifting over the rim into the lake, or to avalanching of accumulated snow into the lake during the storms. The relationship between measured precipitation and lake-level rise varied in different storms.

Annual precipitation at the weather station, summarized in table 2, has been totalized for the years ending June 30, 1931–62, to facilitate comparisons with observations of lake level, which are generally available only for the summer. The average observed annual precipitation in the 32-year period is 67.4 inches, and in the same period the average precipitation inside the lake rim is computed as 67.4×1.07, or 72 inches. This was not a normal or equilibrium period—in fact, the lake level in the summer of 1962 was about 8.7 feet higher than in 1930. Adjustment for storage in the lake during this period reduces the average long-term annual precipitation on the lake from 72 to 69 inches, and that at the weather station from 67.4 (1930–62) to about 64.8 inches.

SURFACE RUNOFF AND GROUND-WATER INFLOW

Most of the water supply for the lake comes from rain and snow falling directly into the lake. The contribution by runoff and percolation from the steep peripheral area cannot, however, be disregarded, and its amount has been estimated by considering precipitation and runoff records in Rogue River basin, over which the moisture-laden winds must pass to reach the lake. Average annual observed precipitation is about 18 inches at Medford (alt 1,300 ft), 42 inches at Prospect (alt 2,500 ft), and 67 inches at Crater Lake (alt 6,475 ft). The long-term average runoff (including ground-water contributions) of Rogue River below South Fork (alt 1,700 ft) is equal to 36 inches depth on its drainage area annually; at the river station near Prospect (alt 2,600 ft) it is 35 inches, and some large spring flows bypass the station; above Bybee Creek (alt 3,600 ft) it is 41 inches. Obviously, the annual precipitation and runoff increase with altitude. However, because of avalanching from the crater walls, the precipitation effective in producing runoff from the peripheral area is less than the computed annual average of 69 inches on the lake itself.

For this report, the average annual runoff from the peripheral area is estimated at 46 inches depth (13,840 acre-ft), including ground-water inflow.

The total water supply reaching the lake has been calculated from the area of the lake (13,140 acres) and the tributary area (3,610 acres). For 1 inch of observed precipitation at the weather station, about 1,386 acre-feet of water reaches the lake, and the average annual observed precipitation of 67.4 inches (1930–62) produces 93,400 acre-feet of water in the lake.

WATER LOSS FROM THE LAKE

Water leaves Crater Lake by seepage and evaporation only. For this report, seepage loss was first calculated, and evaporation loss was then computed as the residual needed to balance the relationship between supply, seepage, and change in lake level (table 6).

SEEPAGE LOSS

It has long been recognized that some of the water in Crater Lake is continuously being lost by seepage. In 1913, when the lake level was near 6,176 feet altitude, F. F. Henshaw estimated the seepage rate at 83 cfs (U.S. Geol. Survey, Portland, Oreg., unpub. data, July 29, 1913). Van Winkle (1914, p. 42) stated that "some of the water may find its way by percolation into Rogue River, but more of it probably goes southward, appearing as springs in the drainage basin of Klamath River." S. T. Harding (written commun., 1953), on the assumption that annual evaporation loss was 36 inches, estimated that seepage was about 58 cfs.

The trace of a continuous water-level recorder was used to ascertain the average rate of seepage loss from the lake in selected dry and cold periods in 1961–62 (table 4). That recorder was installed in Cleetwood Cove on September 14, 1961. The datum of its reference gage is the same as that of the former staff gage on the southwest shore and was ascertained by water level in periods of calm. Ordinary waves are damped out by the inlet to the water-stage recorder, and the water level can be ascertained within 0.01 foot except in rare periods of high wind.

From November 4, 1961, to April 18, 1962, there were six periods, each of 3 to 10 days' duration, in which no precipitation was recorded at Crater Lake Weather Station. Table 4 shows the fall in lake level during these periods. The evaporation rate was undoubtedly very low, because the water surface was cold and at times partly frozen. Relative humidity is generally high in such periods. Nevertheless, an average loss by evaporation of 0.002 foot per day (equivalent to 13 cfs) was assumed. Temperatures were generally low, and runoff from the peripheral tributary area of 5.64 square miles would have been minimal, but deep percolation would have continued, and an average runoff rate into the lake of 8 cfs was assumed.

The average seepage rate computed for the six short periods listed in the table was 89 cfs. That rate is applicable to a stage of 6,175.4 feet, the average level of the lake in the period November 1961 to April 1962.

SEEPAGE RATE IN RELATION TO LAKE LEVEL

It is desirable to know whether the leakage of 89 cfs computed for periods in 1961–62 is virtually constant, as would be expected if the leaks were at great depth, or whether it increases materially at higher stages, as would be expected if some of the leaks were at or near the water surface.

By utilizing the hydrologic data available, and assuming (1) the validity of the relationship of precipitation and inflow previously determined, and (2) the 23-inch annual evaporation loss (p. E20) as unvarying from year to year, seepage-loss rates ranging from 86 to 100 cfs have been calculated for low, medium, and high lake levels in seven periods of 1 to 8 years each (table 5). The calculated seepage rates have been compared graphically (fig. 5) with average lake levels in those periods.

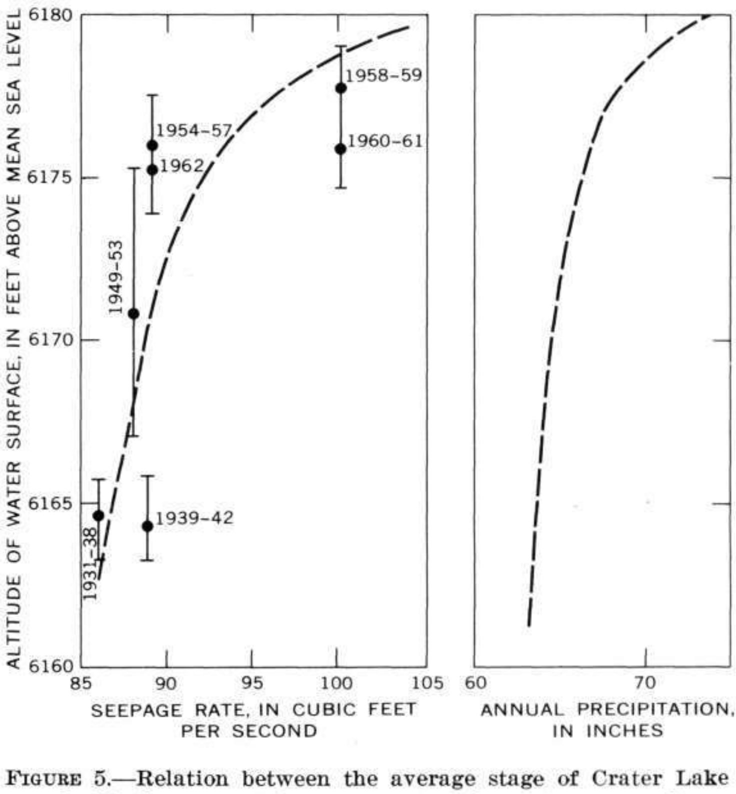

FIGURE 5.—Relation between the average stage of Crater Lake and (1) the computed seepage rates for water years shown (range of stage indicated by vertical bars) and (2) the computed annual precipitation required at the weather station to maintain a constant stage.

Figure 5 shows that the seepage rate ranges only from about 86 cfs to 101 cfs for the observed range in lake level, 6,163 to 6,179 feet. The computed points are somewhat erratic in position, and a straight-line curve possibly may better express the true relationship between stage and seepage rate. However, the curve in figure 5 is based in part on evidence that the lake has never been above 6,180.5 feet. The seepage rate probably increases rather sharply as the water level rises from 6,175 to 6,180 feet and serves as a regulator to keep the lake at levels little if any higher than those reached in recent years. This tentative conclusion is given weight by the botanical evidence (p. E13) that (1) the lake has certainly not been higher than the root system of the dead pine at 6,182.9 feet for at least 430 years, and (2) that it has probably never been higher than 6,180.5 feet. The steepness of any possible curve indicates that seepage varies little within the usual range, 6,165 to 6,175 feet, and suggests that most of the seepage occurs at some depth below the usual lake surface.

Although the increase in seepage at levels above 6,175 feet, as shown in figure 5, may be an effective control against Crater Lake ever reaching a level higher than about 6,181 feet, a recession to a level lower than any in the record could occur as a result of a long period of deficient precipitation.

Figure 5 also shows the computed annual precipitation at Crater Lake Weather Station needed to maintain the lake at various levels, assuming an annual evaporation loss of 23 inches (p. E20). For example, a uniform annual precipitation of 65 inches should cause the lake to rise or fall to 6,172 feet, at which altitude the computed losses by evaporation and seepage would balance the supply.

DESTINATION OF SEEPAGE OUTFLOW

The points where the waters of Crater Lake are lost and where they reappear are unknown. Large springs emerge at levels lower than the lake in the basins of the Rogue and Umpqua Rivers and in the tributaries of the Klamath River (Annie Creek, Wood River, and Williamson River). The total flow of these springs is many times the amount of water lost by seepage from the lake; in fact, those at the head of the Wood River, those on Spring Creek near Chiloquin, and those at the head of the North Umpqua River each yield about three times as much as the lake loses by seepage. Most of the springs have very steady flow; all are cold and clear, and the streams they feed are low in dissolved-solids content, as is the lake water.

The potential hydraulic gradient between the lake and a series of large springs in the region is steep. The difference in altitude between the level of Crater Lake and springs at the head of the Wood River is about 2,000 feet in 13 miles, and to those at the head of Spring Creek, about 2,000 feet in 20 miles. However, each of those springs generally discharges from two to four times as much as the calculated seepage loss from Crater Lake. Annie Springs, 3 miles south of the lake, and Boundary Springs, 9 miles northwest of the lake, are smaller and emerge at somewhat higher levels than the springs mentioned earlier. There is no direct evidence of hydraulic connection between the lake and any of the springs named.

The writer can only agree with Van Winkle (1914, p. 42) that some of the seepage from the lake may find its way into the Rogue River, but more probably it mingles with the underground waters that feed some of the springs in Klamath River basin.

EVAPORATION LOSS

The difference between overall water supply and seepage loss, adjusted as necessary for change in lake volume, is ascribed to evaporation. In table 6, the annual evaporation loss is computed as 23 inches, both for the complete period of precipitation records, 1930–62, and for the year ending September 30, 1962. Although for any given year or short period of years the evaporation loss may be more or less than 23 inches, for simplicity that rate is used for all computations in this report. The computed loss of 23 inches per year is in the same order of magnitude as losses based on empirical seasonal data for nearby Odell Lake, and somewhat less than that for the more remote Lake Tahoe; it is 10 inches less than the average annual lake evaporation in the area, not adjusted for altitude (Kohler and others, 1959, pl. 2).

WATER BUDGET

The water budget of Crater Lake includes income as infalling precipitation and inflow from the caldera walls and outgo as evaporation and seepage. For this study these budget items were determined in the following order: (1) Seepage loss was computed from changes in lake level during periods of no precipitation and little inflow in the period November 4, 1961, to April 18, 1962, (2) infalling precipitation was computed for periods of heavy snow or rainfall from October 10, 1961, to April 29, 1962, with adjustment for seepage and estimated peripheral runoff, and the results were compared with simultaneous records of precipitation at the weather station, (3) annual inflow (a small part of the total water supply) was estimated from runoff at gaging stations on the Rogue River, and (4) evaporation was assumed to account for the difference between total annual water supply and seepage loss, adjusted for any change in lake level.

The elements of the water budget are approximately as follows: Seepage loss ranges from about 86 cfs at a lake level of 6,163 feet to 101 cfs at a level of 6,179 feet; the long-term average loss is about 89 cfs. Infalling precipitation is about 7 percent greater than that observed at the weather station. The total water supply reaching the lake is about 1,386 acre-feet per inch of observed precipitation at the weather station. The average evaporation loss is about 23 inches per year from the lake surface. The lake level has been observed to range from a minimum of 6,163.2 feet on September 10, 1942, to a maximum of 6,179.06 feet (high-water mark of 1958).

LIMITS OF ACCURACY

The water budget was computed chiefly on the basis of hydrologic data for the water year ending September 30, 1962. Some of the factors are based in part upon personal judgment and are subject to some error even for 1962. The relationships found are subject to further error when extended to other years and other lake stages. For a single year, the relationships given may be in error as much as 10 percent, but on the average they are probably accurate within 5 percent.

Hydrologic data obtained in the year ending September 30, 1963, were used in the following table to test the overall accuracy of the water budget deduced from the data of 1962.

Test of water budget for Crater Lake, year ending September 30, 1963

Water-budget item	*Equivalent volume (acre-ft)*
Precipitation and runoff for 12 months from 68.06 inches precipitation	94, 330
Seepage loss, 92.2 cfs at average level of 6,175.2 feet (from fig. 5)	66, 750
Evaporation loss, 23 inches depth on lake area	25, 180
Computed volume change (equivalent to rise in lake level of 0.18 ft in the year)	+2, 400
Actual measured rise in lake level was 0.18 foot, from 6,174.27 to 6,174.45 feet	+2, 400

On the basis of observed precipitation and estimated seepage loss and evaporation, the computed rise in lake level for the 12-month period was 0.18 foot, exactly the same as the actual recorded rise. Such a close agreement is fortuitous, because the water budget can never be known so closely. Similarly, a computation of the water budget for the year ending September 30, 1964, showed a computed decrease of 0.34 foot in water level (actual decrease, 0.58 ft). For 1965, the computed rise was 2.16 feet (actual rise, 1.83 ft). These errors for each year are less than 4 percent of the gross water supply.

The accumulation of additional hydrologic data will provide a means of refining the water budget given herein. Continuous records of lake level are needed, especially at very high and very low stages.

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EAST LAKE

PHYSIOGRAPHIC AND GEOLOGIC SETTING

East Lake is a small body of fresh water in southern Deschutes County (fig. 1). It occupies the eastern part of Newberry Crater, a volcanic caldera nearly 5 miles in diameter. The western part is occupied by the slightly larger and lower Paulina Lake. The two lakes are separated by a barrier of subsidiary volcanic cones and lava flows of Holocene age that form a ridge about 1.2 miles wide and divide the caldera near the middle along a north-south line (fig. 6).

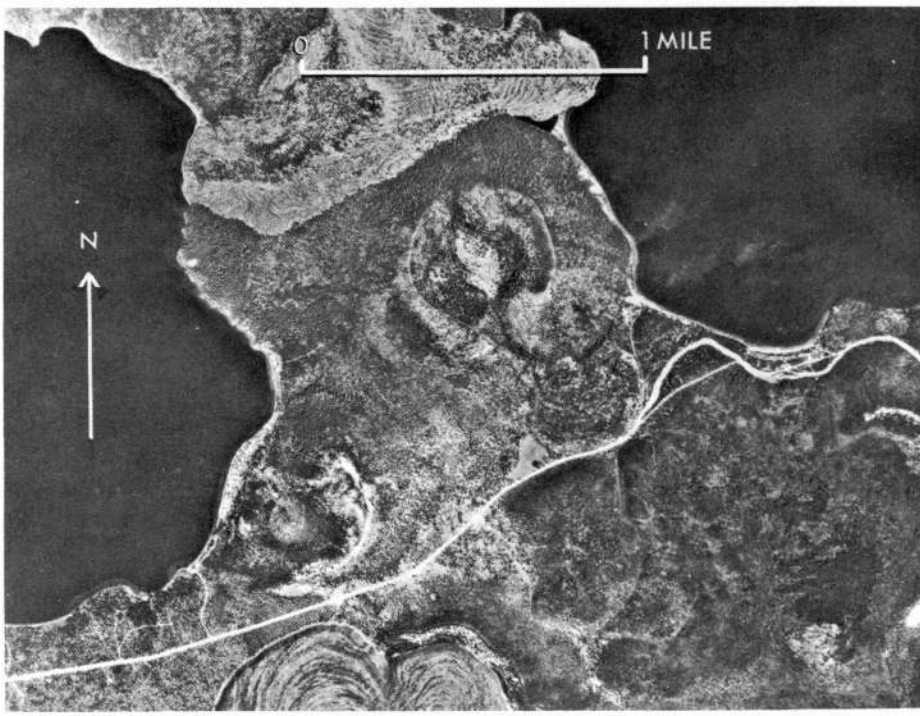

FIGURE 6.—Part of Newberry Crater; view showing cinder cones and lava flow separating East Lake (right) from Paulina Lake. Photograph by U.S. Forest Service, July 27, 1951.

The crater rim rises steeply for several hundred feet around both lakes to altitudes of 7,000 feet or more, except where Paulina Lake has breached the rim to form a perennial outlet to Deschutes River basin by way of Paulina Creek.

East Lake has a surface area of 1,030 acres at high level and 940 acres at average level. Its maximum depth is about 170 feet. The part of the caldera surrounding and topographically tributary to East Lake covers 7.46 square miles, including the lake itself. The lake has a volume at high level of about 68,000 acre-feet. The volume within the historic range of observed water level is about 15,000 acre-feet.

The hydrology of East Lake cannot be studied without also considering Paulina Lake, which is closely associated with it. Paulina Lake covers 2.10 square miles and has a maximum depth of 252 feet. The water surface ranges from 6,330 to 6,333 feet in altitude and has continuous outflow. The entire area of Newberry caldera (17.5 square miles including East Lake and its basin) is topographically tributary to Paulina Lake. East Lake basin, however, seems to be a hydraulically separate entity.

East Lake is 40 to 50 feet higher than Paulina Lake. The hydraulic gradient of 35 to 42 feet per mile from East Lake to Paulina Lake is greater than is normally observed in recent lava flows; hence it is inferred that the blocky lava flow near the north end of the separating ridge is underlain by less permeable cemented deposits. Such deposits may be seen near the southeastern shore of East Lake and along the eastern shore of Paulina Lake, and extend from levels lower than the lake surfaces to levels well above them.

Surrounding East Lake is a forest cover of a type common in high mountain areas of Oregon where precipitation is moderate. Lodgepole pine trees grow abundantly from the edge of the lake up to the caldera rim, yellow pines are scattered on the steep slopes, and some hemlocks and alders are present.

The physiographic setting of East Lake is similar to that of Crater Lake, except that East Lake occupies only 8.4 percent of Newberry caldera, whereas Crater Lake, including islands, occupies almost 80 percent of the total area of its caldera.

The geology of the region was described by Russell (1905, p. 97–110) and by Williams (1953, p. 41–52). The latter (p. 44) paints a vivid word picture of Newberry Volcano, as follows:

> Its summit, Paulina Peak, rises almost 4,000 feet above the encircling plateau. The volcano is of the shield type, and has the shape of an inverted saucer, deeply dented on top and ornamented on the sides with many small knobs. Across the base, it measures 20 miles; on its flanks are more than 150 cinder cones; and on its summit there is a caldron, 4 to 5 miles wide, hemmed in on all but one side by precipitous walls up to 1,500 feet in height. Within this huge depression lie Paulina and East lakes.

The caldera is geologically recent. Williams concludes that it was formed perhaps 20,000 to 25,000 years ago by the collapse of the cone after radial drainage had caused a recession of the molten lava within the volcano and thus removed the support for its higher slopes. Some time later, new eruptions occurred within the caldera and on the outer slopes of the volcano. Explosive activity continued at intervals almost to the present time. Indian sandals, lying below Mount Newberry pumice deposits in caves near Fort Rock, 25 miles to the southeast, were found to be 9,000 years old by carbon-14 dating, and fragments of charcoal found in the topmost pumice layer between East and Paulina Lakes were found to be only 2,050 years old (Williams, 1953, p. 51). Some of the lava flows on the outer slopes of Newberry Mountain are probably not more than a thousand years old (Williams, 1935, p. 280).

East Lake, like Crater Lake, is therefore geologically young. After the caldera was formed 20,000 to 25,000 years ago, snow and ice doubtless accumulated in it to depths of several hundred feet, and outflowing ice may have slightly scoured the outlet to Deschutes River (Russell, 1905, p. 97–104). Ash and lapilli from late phases of volcanic activity were mingled with the accumulation of ice, and as the ice melted, these fine materials formed deposits that partly sealed the bed of the lake. By the time the recent eruptions within the crater had ceased, about 2,000 years ago, the two lakes had been separated, and probably each one was then near its present level.

Paulina Lake is drained by Paulina Creek westward into Deschutes River basin. There are no records of the annual outflow. Several small springs enter the lake near the water level, and at least one is thermal. There are no surface inflow streams. Most of the water supply is derived from snowmelt that infiltrates the permeable volcanic soil cover.

East Lake has no visible outlet and no perennial surface inflow. Small mineralized thermal springs occur near and below the lake surface along the southeastern shore, and others may exist at greater depths.

CLIMATE

Newberry Volcano is surrounded by a lava plateau that has a general altitude of more than 4,000 feet and a mean annual precipitation of 10 to 20 inches. Most of that precipitation occurs as snow in the period from November to May. Temperatures are low, especially on clear winter nights in areas that have poor air drainage. Summer temperatures reach 100°F at times, but rapid radiation at night results in temperatures near freezing in every month of the year. Average annual evaporation loss from open water surfaces in the region is about 34 inches (Kohler and others, 1959, pl. 2).

East Lake lies about 2,000 feet above the general level of the plateau. There the microclimate is much more humid, the summers are somewhat cooler, and evaporation is presumably less.

No year-round records of temperature at East Lake are available. The altitude is very nearly the same as for Crater Lake, and the annual temperature cycle is no doubt very similar (table 1).

RECORDS OF LAKE LEVEL

Within the present century East Lake has fluctuated over a known range of about 16 feet, from 6,366 to 6,382.5 feet altitude. Data on its level are fragmentary (table 10). In any given calendar year, the observed fluctuation in water level has not exceeded 2 feet. The rather small annual fluctuation in stage is due to the lack of surface streams tributary to the lake, the rather close balance between annual precipitation and evaporation, and the apparently low rate of seepage loss.

The earliest known reference to the water level of East Lake was recorded by Russell (1905, p. 101), who visited the lake August 25, 1903. Russell stated:

> Like many enclosed lakes, it bears evidence of considerable fluctuations in level, the most conspicuous of which is a grove of dead spruce trees near its western shore which rise from about 3 feet of water. The trees are about 30 feet high, 10 to 12 inches in diameter, stand erect and still retain their branches. There is no indication that they were carried into the lake by a landslide, but every probability that they grew where they now stand and were killed by a rise of the lake which submerged the surface in which they were rooted.

A remarkable confirmation of Russell's observation of a high lake level in 1903 was obtained in 1959 by D. B. Lawrence, of the University of Minnesota, who observed the stump of a lodgepole pine tree that had grown on a point of land at the northeast shore of East Lake, near Cinder Hill Forest Camp, and was living until cut down in 1957 or 1958. Lawrence stated in his field notes (written commun., 1963):

> Symmetry of its central rings from time of germination about 1870 to 1904 showed that it had grown erect as a member of a dense forest there during that period. Erosion by high water apparently occurred about 1904, removing support from about half of the root system, allowing the tree to tilt strongly toward the north. The tree continued to grow, producing asymmetrical rings, wide on the lower side. The high water of 1958 seems to have reached about the same level as that which caused the erosion that resulted in tilting about 1904 or 1905.

Streamflow records show that 1904 was a year of very heavy runoff, and East Lake was no doubt slightly higher in 1904 than when Russell saw it in 1903.

The lake is known to have reached a stage of 6,382.5 feet in 1958. At that time, many trees on the sloping southwest shore were undermined at the high-water level, some of them remaining erect and others becoming tilted, much like those described by Russell and Lawrence. Along the shores of the lake, lodgepole pine trees as much as 43 years of age and as much as 13 inches in diameter were drowned in 1958. Some of the trees became established as seedlings at a level several feet below the high stage of 1958; the lowest one observed, a lodgepole pine, had its upper roots at 6,374.5 feet altitude, or 8.0 feet lower than the high level of 1958 (fig. 7).

FIGURE 7.—View eastward from southwest shore of East Lake on July 2, 1963, when water level was 4.7 feet below high level of 1958. Lodgepole pine trees in foreground were drowned when the lake rose over their root systems; former forest road in partial shade near right in view was submerged and covered with lumps of floating pumice in 1958.

The high level of 6,382.5 feet reached in 1958 has been exceeded at some time in the past. An older beach terrace occurs along the northeast shores of the lake at an altitude of 6,385.5 feet. The largest living lodgepole pine trees on that terrace were found to have germinated about 1853, 1879, and some time before 1889; hence, the terrace was apparently formed by a high stage that occurred prior to 1853.

No positive evidence was observed of lake stages higher than about 6,385.5 feet. A few large yellow pine trees are living along the steep and rocky north shore of the lake and are rooted at levels 6 to 10 feet higher than the high level of 1958. Core borings of some of these trees were taken in September 1960 by D. B. Lawrence and the writer. The growth rings of one such living tree showed that it germinated before 1850, at altitude 6,388.4 feet; another, at 6,391.2 feet, germinated before the year 1574. A large yellow pine snag at 6,389.1 feet had lived about 283 years before dying many years ago. At 6,387.2 feet, the roots of a dead yellow pine appear to have been eroded away, possibly by waves carrying floating lumps of pumice, but no beach line was found at that level. If East Lake did reach that level, it may have done so in the period 1805–25, when tree growth in eastern Oregon was unusually rapid and precipitation was probably much above average (Antevs, 1938, p. 66; Keen, 1937, figs. 7, 8). The oldest tree cored was a large yellow pine that germinated in or before the year 1439; its base was, by hand leveling, 165 feet above the water level of September 1960.

In summary, all the botanical evidence indicates that the high level of 6,382.5 feet in 1958 duplicated the high level of 1904, which was the highest since some time before 1853, when the lake level reached 6,385.5 feet.

WATER SUPPLY TO THE LAKE

The water supply of East Lake is derived from precipitation, surface runoff, and ground-water percolation. None of these elements has been measured. Most of the precipitation in the basin topographically tributary to East Lake percolates into the ground where it falls, and it may follow a path toward East Lake or one radially away from it. There is no information on the altitude or slope of local bodies of ground water.

Because Paulina Lake has a surface outlet that might also carry at least some of the outflow by seepage from East Lake, the outflow of Paulina Lake is used as a tool in estimating the total water supply of the caldera. Information on that outflow is scanty. However, the stage of the lake varies within a narrow range, and its measured outflow usually ranges between 10 and 40 cfs. A low dam and fish screen at the outlet are designed and operated to keep trout from leaving the lake rather than to control the outflow or lake level. Because of the reasonably steady outflow, a few observations provide a fair basis for estimating the order of magnitude of the average annual outflow, about 14,500 acre-feet, as shown in table 8.

PRECIPITATION ON THE LAKE

There are no year-round records of precipitation near the lake. The total snowfall is known to be considerably less than at Crater Lake, and the average annual precipitation on the lake and in the basin has been estimated for this report as 35 inches, on the basis of a comparison of records of snow accumulation at Paulina Lake, 1955–62, with records of precipitation at Bend in the same period. This is practically three times the average annual precipitation at Bend, and more than three times that at Fremont, the two nearest long-term weather stations on the plateau. This total average annual precipitation, even though estimated, is better known and more reliable than other hydrologic data for the area.

The estimated mean annual precipitation of 35 inches on the surface of the two lakes is assumed to be applicable to the entire area of the caldera, and the average annual total water supply from precipitation as direct infall to the lakes is as follows: East Lake, 2,740 acre-feet and Paulina Lake, 3,910 acre-feet. The sum for the two lakes is 6,650 acre-feet. The total average annual precipitation is 13,900 acre-feet in East Lake basin and is 18,800 acre-feet in Paulina Lake basin. The sum for the two basins is 32,700 acre-feet. In the 30-year period, January 1931 to December 1960, sometimes used to compute "normal" precipitation, East Lake rose about 7 feet, and the mean annual precipitation for that period was probably about 37 inches.

SURFACE RUNOFF AND GROUND-WATER INFLOW

As noted above, surface inflow is ephemeral and of negligible volume, and some of the ground-water flow in the caldera may not reach either lake. The maximum amounts of combined surface- and ground-water flow that could reach the lakes in an average year can be approximated by deducting the estimated annual evapotranspiration loss (12 in.) from the total precipitation (35 in.) on the tributary areas surrounding the lakes. The upper limit of the average annual runoff is 7,350 acre-feet for East Lake basin and is 9,750 acre-feet for Paulina Lake basin; the sum is 17,100 acre-feet.

Thus, the average potential supply to the two lakes is about 23,800 acre-feet per year (6,650 acre-ft from direct precipitation and 17,100 acre-ft from runoff). Evaporation of 28 inches from the surface of the two lakes annually would remove 5,300 acre-feet and would leave about 18,500 acre-feet to be expected as annual outflow.

The estimated average flow of 20 cfs at the outlet of Paulina Lake (table 8) is equivalent to a runoff of 14,500 acre-feet, or 4,000 acre-feet less than the expected volume. The estimated annual excess of precipitation over evaporation on the surface of Paulina Lake and the adjacent and topographically tributary area of 5,080 acres is 10,500 acre-feet. To obtain the estimated runoff of 14,500 acre-feet from the entire caldera, only about 4,000 acre-feet per year is needed from East Lake basin. That is only half the average annual runoff that the East Lake basin is believed to generate. Therefore, it is probable either that a large part of the water in East Lake basin never reaches Paulina Lake or that Paulina Lake basin loses some water by percolation out of the basin.

However, Paulina Lake itself probably does not lose much water by seepage. If it did, the stage in a series of dry years would drop below its outlet; there is no record of such an occurrence.

WATER LOSS FROM THE LAKE

East Lake loses water by evaporation and by seepage. In this report, the annual loss by evaporation is estimated and is assumed to be the same in each year. The seepage loss is assumed to be at a rate that will balance the water budget not only in a period of average precipitation, but in wet and dry periods after adjustment for observed changes in lake volume.

SEEPAGE LOSS

The fact that East Lake water is fresh indicates that it must lose water by seepage in an amount not less than the flow of the mineralized springs that enter it. Fragmentary records of the stage of East Lake provide a clue to the general order of the rate of seepage loss. If all the precipitation in its basin reached the lake, except for the annual evapotranspiration loss of about 12 inches on the tributary area of 3,830 acres, then the estimated annual evaporation of 28 inches from the lake plus seepage loss of 10.9 cfs would be needed for balance. The seepage rate may vary with lake level, but, for a given level, it should be the same in a wet year or in a dry year. However, in a very dry year, when the total precipitation at East Lake is only about 21 inches, the evaporation would exceed the precipitation, the runoff to the lake could be no more than about 2,900 acre-feet, and leakage at a rate of 10.9 cfs would then lower the lake level at a calculated rate of 6.5 feet in 1 year. No such rapid decrease has been observed; in fact, in the year ending September 30, 1959, when the precipitation at Bend was only 53 percent of the 1931–60 normal and that at East Lake was probably not more than 21 inches, the water level dropped only 1.7 feet. The lake level was high in 1959, and the rate of seepage therefore must have been at least as much as the average long-term rate. It seems obvious that the seepage is much less than 10.9 cfs.

The assumptions and computations shown in table 9 lead to an estimate of about 2.3 cfs seepage out of East Lake. Such a rate is much more than the combined flow of the observable mineralized springs.

The estimated average annual inflow to East Lake of 1,700 acre-feet (table 9) is only 23 percent of the estimated difference (7,340 acre-ft) between the precipitation of 35 inches and evapotranspiration of 12 inches on the basin area (3,830 acres.) Therefore, the tentative conclusion must be that a large part of the basin topographically within the East Lake part of the caldera does not contribute any water to East Lake but instead drains water away from it.

The hypothesis suggested above, that East Lake basin is not all tributary to the lake, is based on sketchy hydrologic information and should receive further study when the required data have been obtained. Continuous records of lake level and precipitation are needed.

Data are not adequate to define the relation of seepage rate to lake level. It is not even certain that seepage occurs when East Lake is below the minimum known level of about 6,366 feet reached about

1941. It is probable that seepage is most rapid when the water level is high.

There is no hydrologic information to suggest where the seepage outflow reappears.

EVAPORATION LOSS

Evaporation loss has not been measured. It is perhaps somewhat more than that for Crater Lake because East Lake is in a zone of less precipitation and probably lower relative humidity. For this report the average annual evaporation is estimated as 28 inches, 6 inches less than the regional average for the 4,000-foot plateau in the general area. The annual excess of precipitation over evaporation on the two lake surfaces (7 in. in depth, or 1,330 acre-ft) is only a small part of the total annual water budget for the entire caldera.

The estimated average annual evaporation loss of 28 inches is equivalent to a loss of 2,190 acre-feet from the lake's average area of 940 acres.

WATER BUDGET

The average annual potential water supply (sum of infalling precipitation and runoff) in the entire caldera is about 23,800 acre-feet. The estimated annual evaporation loss from the lake surfaces is 5,300 acre-feet, and about 18,500 acre-feet is to be expected as runoff from the basin, if none of the water supply in the caldera is depleted by outflow as seepage. The average annual outflow from Paulina Lake is estimated at 14,500 acre-feet.

The elements comprising the average annual water budget of East Lake are about as follows:

1. Infalling precipitation, 35 inches depth (2,740 acre-ft).
2. Inflow from tributary area, 1.5 cfs (1,150 acre-ft).
3. Evaporation loss, 28 inches depth (2,190 acre-ft).
4. Outflow by seepage, 2.3 cfs (1,700 acre-ft).
5. Average annual ground-water loss from tributary area that does not reach East Lake is about 6,200 acre-feet. A part of this loss probably goes into Paulina Lake and the rest elsewhere.

LIMITS OF ACCURACY

The elements of the estimated water budget for East Lake are based to a large extent on personal judgment. The estimated average annual precipitation (35 in.) and evaporation (28 in.) are probably within 15 percent; seepage loss and runoff estimates are subject to greater possible error. The general conclusion is that the seepage rate is only a small percentage of the amount that would be needed to balance the gross water budget (precipitation plus runoff minus evaporation), if all the topographic basin were actually tributary to East Lake. Trial computations with modified values of runoff and evaporation gave results that differed only in degree and confirmed the general conclusion stated above.

DAVIS LAKE

PHYSIOGRAPHIC AND GEOLOGIC SETTING

Davis Lake is a body of fresh water in Deschutes and Klamath Counties, 19 miles west of La Pine (fig. 1). It is an impoundment on Odell Creek, formed by a blocky, permeable lava flow of Holocene age that fills the channel and valley for a distance of 2 miles (fig. 8). The lake has no surface outlet.

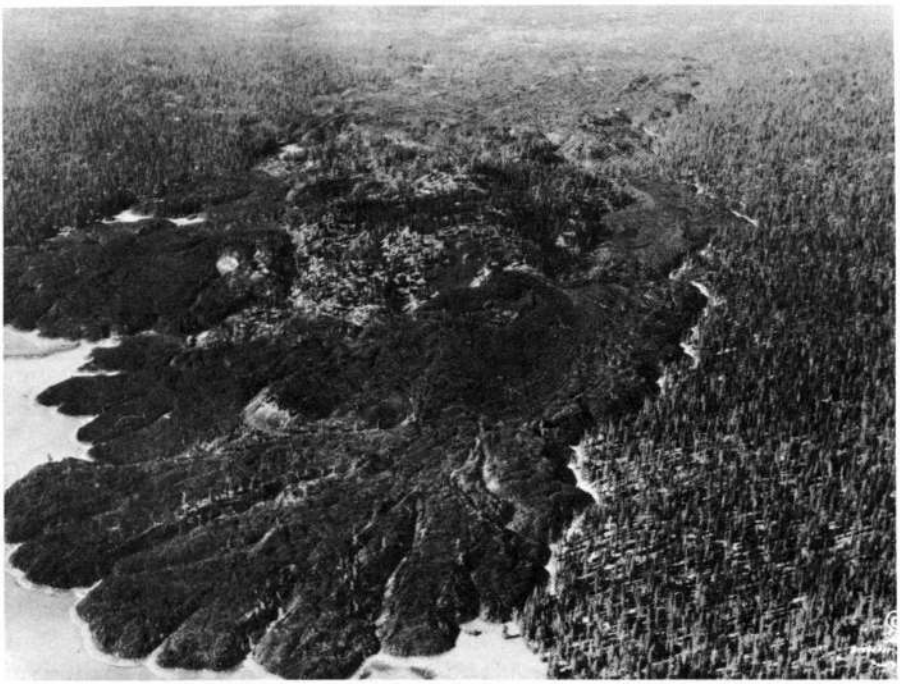

FIGURE 8.—Lava flow that impounds Davis Lake; view looking northward in summer or early autumn of 1930. A forest road (not an outlet channel) skirts the east edge of the lava. Old beach at bottom center with a solitary tree was formed by a high-lake stage prior to the year 1723. Photograph by Delano Photographics.

In 1878, Lt. T. W. Symons visited the area, and his report, quoted by Henshaw, Lewis, and McCaustland (1914, p. 15), gives the earliest known description of Davis Lake as follows:

> This lake and valley were about 12 by 6 miles in size and took us completely by surprise, as they were evidently in the course of our West Fork [Deschutes River] and were not on any map. Reaching it, we found at its southern end many

acres of rich grass and bunches of tall willows. Following around the west shore to the north end, we ascertained that there was no visible outlet. We saw the watermarks 20 feet above us on the lava bluffs of the northern and northwestern shores * * * We found the next day that these lava beds formed an impassable barrier extending unbroken for about 4 miles to the north, and at their end were again surprised to find, foaming out from underneath the giant boulders, the clear, cold river that we had seen lose itself in the lake * * *

Even then, the lake was called Davis Lake by the few people who knew of its existence. The reference by Lieutenant Symons to a 20-foot fluctuation in water level is no doubt a rough estimate (his estimated distances were about twice the actual distances), but obviously the lake was low when he saw it in 1878.

The lake was mapped in December 1934, and soundings were made by measuring from the ice surface at 4,380.8 feet. The bed of the lake at the lowest point was found to be at 4,367 feet, and the high-water line at the edge of the timber, 4,392 feet (C. C. Fisher, U.S. Bur. Reclamation, unpub. data, 1936). The area and volume of the lake for various levels, as computed from that survey, are given in figure 9.

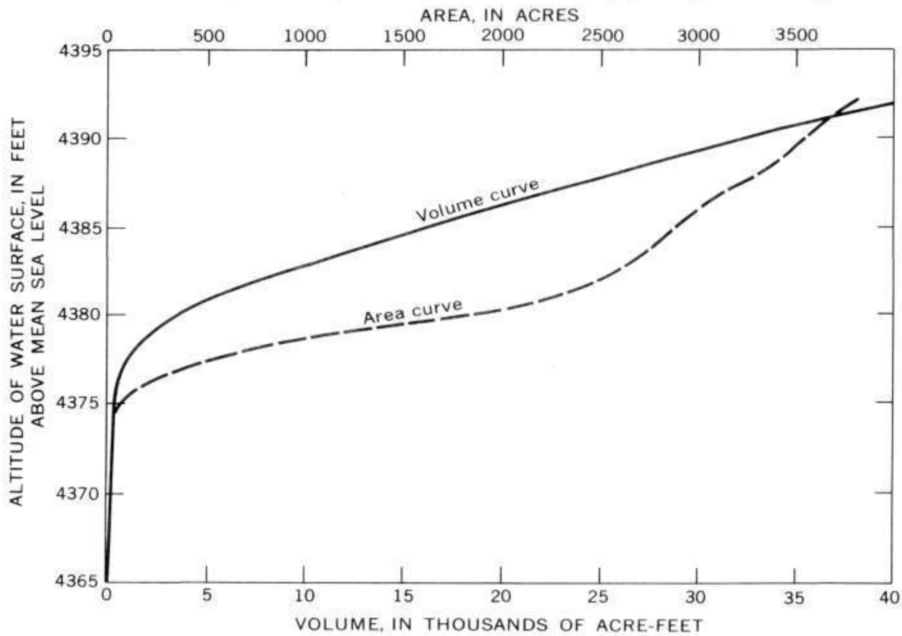

FIGURE 9.—Area and volume of Davis Lake.

The topographic basin of Davis Lake covers about 98 square miles and ranges in altitude from 4,390 feet at the lake to 8,744 feet at the summit of Diamond Peak. The lake is in volcanic terrane, which is marked by many cinder cones scattered on a lava plateau that slopes gently to the northeast. A surface deposit of highly permeable pumice overlies all but the most recent volcanic deposits and supports an almost continuous forest cover, chiefly of western yellow pine. Rainfall and melting snow readily infiltrate the highly permeable pumice cover and volcanic deposits. There is no information on the altitude and slopes of ground-water bodies, and the hydrologic boundary of the basin may not be the same as its topographic boundary.

Davis Lake occupies a channel that was slightly incised by Odell Creek into the surface of a lava plateau and was later filled downstream from the lake by a lava flow several hundred feet thick (fig. 8). The lava obstruction ponded the water and formed Davis Lake. Because Odell Creek seldom carries a significant load of sediment, the lake basin has not since been materially altered by sedimentary deposition, and the lava that forms the obstruction is not covered or sealed by sediment above the low-water level of the lake.

The lava flow is one of the youngest in the Cascade Range, and may be only about a thousand years old (Williams, 1953, p. 50–51). At places where windblown soil has collected between the blocks of lava, yellow pine trees grow, and some of them are probably at least 500 years old. The flow is not covered by the regional blanket of pumice from Mount Mazama (age, about 6,600 yr). Therefore, the basin apparently is at least 1,000 years but less than 6,600 years old. Davis Lake undoubtedly formed within a few months after the lava flow dammed the channel of Odell Creek.

Downstream from Davis Lake and the lava flow, the stream is called Davis Creek and is fed by large springs whose openings range from 4,310 to 4,360 feet in altitude. Some of the springs flow into Davis Creek channel just downstream from the lava flow, and others discharge within a mile downstream. Almost every year since Wickiup Dam was completed in 1949 at a site on the Deschutes River 10 miles northeast of Davis Lake, some of the springs have been submerged at times to a depth of about 25 feet by the water in Wickiup Reservoir. The topographic drainage area above the springs is 146 square miles, 46 percent more than that above Davis Lake.

CLIMATE

The area around Davis Lake has moderate precipitation, most of which occurs as snowfall in the period November to April. The precipitation in the headwater area is much greater than that at and downstream from the lake. For example, in 1961 the total precipitation at Odell Lake, 10 miles to the southwest, was 59.4 inches, whereas it was only 22.6 inches at Wickiup Dam, an equal distance to the northeast. The winters are cold, and snow usually lingers about the lake until

May or June. Summers are cool, and little precipitation falls from June to September.

No records of temperature exist for Davis Lake. Seasonal temperatures are probably similar to those at Odell Lake and at Wickiup Dam (table 11). Davis Lake is much nearer Wickiup Dam in altitude and presumably in seasonal temperature as well. On that assumption, the annual mean temperature at Davis Lake is estimated at 43° F.

The nearest precipitation stations are those at Odell Lake and Wickiup Dam. In the period 1950–64, the average precipitation was 61.45 inches at Odell Lake and 21.71 inches at Wickiup Dam (table 11); the long-term averages at both sites are probably a little less. The average annual precipitation at Davis Lake would almost surely be less than 40 inches and more than 30 inches; for this report, it is estimated at 36 inches.

Average evaporation from land pans at Odell Lake and Wickiup Dam for summer months is given in table 11. Annual evaporation loss from an open-water surface at Wickiup Dam is probably about 32 inches.

RECORDS OF LAKE LEVEL

Records of the lake level are fragmentary (table 12). All water levels herein are referred to U.S. Geological Survey bench mark P–9 (alt. 4,395.25 ft, datum of 1929, supp. adjustment of 1947), set in a boulder at the northwest edge of the lake.

The lake level varies in response to runoff conditions of the current water year and to a lesser extent to those of 1 or 2 immediately preceding years. The seasonal peak occurs in May or June, soon after the seasonal peak flow in Odell Creek at the station near Crescent. By early autumn the lake level is usually 2 or 3 feet below its seasonal peak. The changes of level within a single season are considerably greater than those of Crater and East Lakes.

Peak stages are of particular interest because of their implications with respect to climate and runoff over the past several centuries. The highest stage observed in recent years was 4,393.2 feet (from a floodmark) in June 1957. A floodmark at the same level was noted in 1934 during a survey of a proposed lake-outlet channel (C. C. Fisher, U.S. Bur. Reclamation, unpub. data, 1936), and it may represent a stage reached in 1904. The highest level the lake probably ever attained, 4,395.4 feet, is marked by (1) the lower limit of living crustose lichens on the lava rocks along the northern shore, and (2) the formation of a small level terrace or bar at the northeastern shore near the lava dam. A western yellow pine tree that grew on that terrace was cut in 1958, and the stump was found later to have 235 annual growth rings (Lawrence, 1961, p. 344). Older and very large yellow pine trees are living at levels less than 1 foot higher. A reasonable inference is that the high level of 4,395.4 feet was reached sometime prior to the year 1723 and has probably never been materially exceeded.

The high water of 1957 (4,393.2 ft) flooded and killed many yellow pine and lodgepole pine trees. The oldest one found, a yellow pine that grew on level ground just above the highest water level, had 185 annual growth rings at a point 15 inches above its base. The summer-growth rings were narrow for the dry years 1924, 1926, and 1955. They were very narrow for the periods 1791–97 and 1813–14, possibly because of the flooding of some of the roots by high stages of the lake. The rate of tree growth near Lakeview was much above normal in the periods 1790–94 and 1805–25 (Antevs, 1938, p. 66; Keen, 1937, fig. 7), and presumably the precipitation and runoff in those periods were also above normal. The level of Davis Lake probably was high then.

Many young western yellow pine trees, up to 1 foot in diameter, had the ability—not shared by mature yellow pines—to survive repeated shallow flooding by Davis Lake for periods of 60 days or more in several growing seasons of the 1950's. Hence, the ages of trees of this species are not exact, dependable indices of the length of time since the lake water covered the level of the bases of the trees; consequently, the 185-year-old pine tree mentioned above may have survived in its youth (perhaps about 1813) a stage as high as the one that built the bar at altitude 4,395.4 feet.

Variations in tree-ring growth over the past 650 years indicate that climatic and lake-level variations like those of recent decades probably have occurred before in the short life of Davis Lake. Ponderosa pines have a lifespan that may exceed 750 years (Keen, 1937, p. 176). Some within 3 feet of the high lake level of 1957 are so large that they probably have lived more than 600 years. Keen (1937, p. 176, 188) established cross identification between growth rings of pine trees near Watkins Butte, north of Fort Rock, Oreg., for 650 years before 1935, and concluded that in that period there has been no general trend toward wetter or drier years, and that average growth for the period 1900–19 was identical with the average growth during the past 650 years. Keen (1937, p. 188) found that

> the present [drought period, 1917–35] is the most severe and critical that the present forests have experienced in the last 650 years. Several other periods have exceeded the present one in duration of subnormal growth, but none has approached it for severity.

On the other hand, he found (Keen, p. 186, fig. 8) that the tree growth in many periods in the last 650 years had exceeded that of any year or short term of years since 1850. From those conclusions, the low lake stages of the 1930's may inferentially recur less often than the high stages of 1904 and 1957.

WATER SUPPLY TO THE LAKE

The water of Davis Lake is derived from infalling precipitation and streamflow. Precipitation falling directly on the lake accounts for only a very small part of the total supply.

PRECIPITATION ON THE LAKE

The average annual precipitation on the lake has been estimated for this report at 36 inches. The infalling volume in a season depends not only upon the precipitation but upon the area of the lake at the time when it falls; the average volume is probably between 6,000 and 10,000 acre-feet per year, or 5 to 9 percent of the average annual water supply.

SURFACE RUNOFF AND GROUND-WATER INFLOW

Most of the water in Davis Lake comes from Odell Creek. The flow of that stream is augmented by springs and creeks that enter dowstream from the gaging station near Crescent, so that the total water supply is considerably greater than that at the station (fig. 10). The average

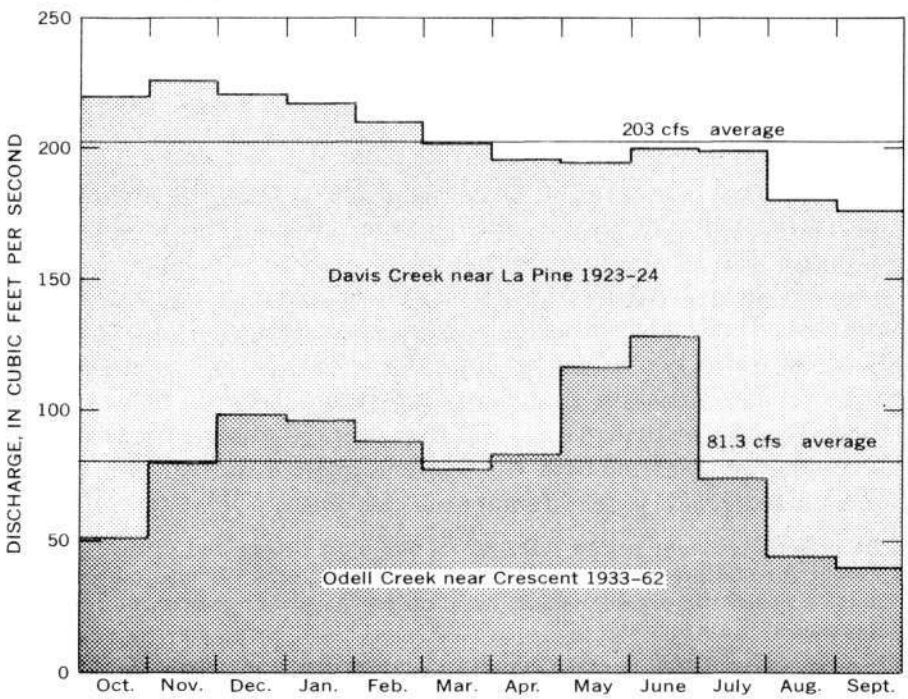

FIGURE 10.—Average monthly flows of Odell Creek near Crescent and Davis Creek near La Pine for periods of record available.

flow near Crescent (drainage area, 39 sq mi) for 29 years, 1933–62, was 81.3 cfs, and the corresponding estimated flow at Davis Lake (drainage area, 98 sq mi) is 150 cfs.

No simultaneous records of discharge are available for Odell and Davis Creeks. The records for Odell Creek, 1933–62, are about equal to the long-term average, on the basis of the longest records available at nearby unregulated spring-fed streams (Metolius, McKenzie, and Williamson Rivers). On the contrary, those for Davis Creek, 1923–24, were obtained in a year when the runoff of other spring-fed streams was below average. The average flow of Davis Creek is therefore probably more than that of 1923–24, and is estimated as 220 cfs.

WATER LOSS FROM THE LAKE

SEEPAGE LOSS

Nearly all the water that reaches Davis Lake is lost by seepage into the lava flow that dams the channel and fills the valley of Odell Creek. The seepage cannot be directly measured, but its annual volume and its rate at different lake levels can be approximated.

The volume of seepage in a year is approximately equal to the volume of inflow adjusted for change in contents of the lake. This is true because the infalling precipitation and the loss by evaporation are nearly equal and are opposite as elements of the water budget. If the average inflow is 150 cfs, as estimated above, the average seepage rate must be about the same.

SEEPAGE RATE IN RELATION TO LAKE LEVEL

The seepage rate varies with the stage of the lake, and its magnitude may be approximated, or its probable limits defined, by two different approaches.

Consider first the relationship between average lake stage and seasonal inflow with adjustment for changes in the volume of water stored in the lake. The lake level varies with annual runoff and is higher after periods of above-normal inflow. For example, in the 4 dry water years, 1940, 1941, 1942, and 1945, the average lake level was about 4,380 feet and the lake was lowered in the 4years by only a small volume, less than 1,000 acre-feet. The total runoff at the gaging station near Crescent in those 4 years was 159,000 acre-feet. The average annual seepage loss in those years, therefore, must have been about 40,000 acre-feet (55 cfs) plus the unmeasured flow of streams draining 60 square miles below the station on Odell Creek. By contrast, in the 3 wet years, 1951, 1952, and 1956, the average lake level was about 4,391 feet; its volume increased by 30,000 acre-feet; and the measured runoff at the station near Crescent was 255,000 acre-feet. The annual seepage loss at that lake level must have been about 75,000 acre-feet (104 cfs) plus the flow of the ungaged tributaries. Therefore, the seepage rate must be more than 54 cfs when the lake is near altitude 4,380 feet and more than 104 cfs when it is near altitude 4,391 feet.

The other approach is to consider the relationship between the momentary lake level and the unsubmerged flow of the group of springs feeding Davis Creek downstream from Davis Lake and its lava dam. A well-defined and nearly straight-line relationship has existed for many years between the flow of those springs and the stage of Davis Lake (fig. 11), and that fact warrants the belief that those springs derive a large part of their flow from the seepage of Davis Lake, even though efforts to trace the lake outflow to the springs have not been successful (Oregon State Game Comm., written commun., 1961). The points plotted in figure 11 cover a time period of 24 years, and the discharges for all plotted points lie within 10 percent of the discharge given by the average curve. Data are not available to plot antecedent lake levels against flows with various periods of delay for the probable time of underground travel. Both the stage of the lake and the flow of the springs no doubt respond to general runoff conditions, but the correlation shown in figure 11 seems so well defined that spring flow is believed to be a function of lake level. The lava that fills the creek channel does not seem to provide much storage to delay the passage of the water that leaks into it.

From figure 11, the spring flow is about 190 cfs for a lake level of 4,380 feet and 280 cfs for a lake level of 4,391 feet. These flows are believed to represent maximum possible rates of seepage from Davis Lake. The actual rates lie somewhere between 55 and 190 cfs for the 4,380-foot level and between 104 and 290 cfs for the 4,391-foot level. The average flow of Davis Creek is about 220 cfs. On the basis of the relative size of drainage areas, both the average inflow and the average seepage loss at Davis Lake are estimated at 150 cfs.

The relationship of lake level to spring flow shown in figure 11 has been used to estimate the stage (4,392.5 ft) corresponding to a discharge measurement of 287 cfs on Davis Creek made September 12, 1904, the highest measured flow of Davis Creek. That level exceeds any of record for the month of September.

The relationship between the water level of Davis Lake and the unsubmerged flow of all the springs feeding Davis Creek has apparently not been changed by the operation of Wickiup Reservoir. Periodic submergence of the lower springs may temporarily reduce their outflow, either by diverting a part of it to higher outlets or by inducing temporary ground-water storage. However, flow measurements of Davis Creek made after the reservoir level has been lowered below the level of the lower spring outlets agree well with those made before those springs were submerged.

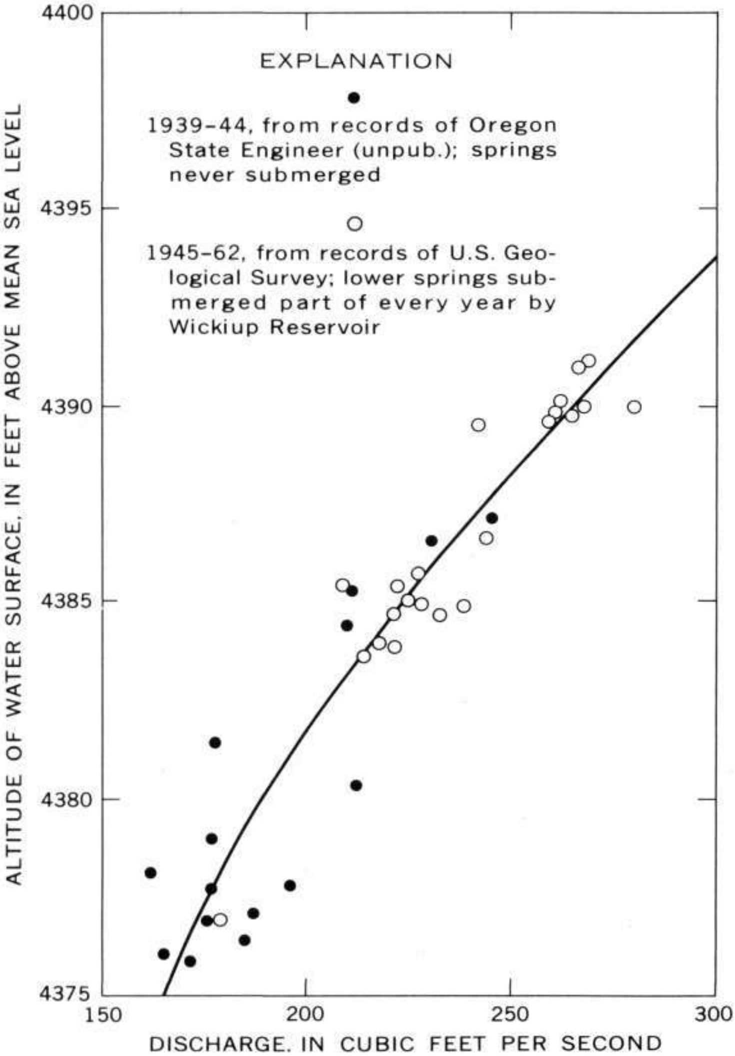

FIGURE 11.—Relation of stage of Davis Lake to simultaneous flow of Davis Creek below springs, in SE¼ sec. 5, T. 22 S., R. 8 E.

DESTINATION OF SEEPAGE OUTFLOW

As indicated above, the seepage out of Davis Lake is believed to feed some of the large springs on Davis Creek. Those springs have an average flow of about 220 cfs, of which the seepage from Davis Lake probably provides about 150 cfs.

EVAPORATION LOSS

Evaporation at Davis Lake is probably a little less than at Wickiup Dam, 10 miles to the northeast, where the average loss from a class A land pan has been measured as 34.09 inches in the period May to September (table 11). The average annual evaporation loss from the surface of Wickiup Reservoir is probably about 32 inches, and that from Davis Lake is estimated at 30 inches for this report. The volume of that loss depends upon the stage and surface area of the lake during the summer season. That area ranges from 470 acres at altitude 4,378 feet to 3,670 acres at altitude 4,391 feet. The lake area is usually greater in the summer evaporation season than in the winter precipitation season; hence, an average annual evaporation loss of 30 inches may fully offset an infalling precipitation increment of 36 inches. In any event, the average evaporation loss is less than 10 percent of the total water supply.

WATER BUDGET

The average annual water budget of Davis Lake is about as follows:
1. Infalling precipitation, 36 inches depth (8,000 acre-ft).
2. Inflow from tributary area, 150 cfs (109,000 acre-ft).
3. Evaporation loss, 30 inches depth (8,000 acre-ft).
4. Outflow by seepage, 150 cfs (109,000 acre-ft).

The observed lake level has ranged from a minimum of 4,375.9 feet on October 20, 1942, to a maximum of 4,393.2 feet (contents, about 45,000 acre-ft), high-water mark of 1957.

LIMITS OF ACCURACY

Davis Lake lies in a geographic belt where the precipitation decreases very rapidly from west to east. The average annual precipitation of 36 inches, estimated on the basis of records at nearby Odell Lake and Wickiup Dam, may be in error as much as 25 percent; it represents a small part of the total water supply reaching the lake. Average annual inflow of 150 cfs was estimated on the basis of records upstream on Odell Creek near Crescent in the period 1933–62 and gagings downstream on Davis Creek over a period of 24 years; it may be in error by 15 percent. Average annual evaporation loss of 30 inches was estimated on the basis of records in the period May to September at Wickiup Dam; it probably is accurate within about 10 percent, and over a period of years will almost exactly offset the precipitation, most of which falls in the winter period, before the lake rises to the high summer stages that present a large area for evaporation. The average seepage of 150 cfs is estimated as equal to the average inflow, and that estimate is subject to the same possible error of 15 percent.

CHEMISTRY OF THE LAKES

By A. S. Van Denburgh

Crater, East, and Davis Lakes all contain only small amounts of dissolved solids (table 13). Nonetheless, each lake is distinctively different chemically because the dilute lake waters are sensitive to the influences of even slightly differing hydrochemical environments. Thus, the character of Davis Lake is governed primarily by the constituents that are most readily drawn out of the soil and underlying rocks by very dilute natural runoff and percolation, a process that is aided by the dissolution of carbon dioxide. The resulting lake water contains only about 50 ppm (parts per million) of dissolved solids, which includes silica, bicarbonate, and very little else. Crater Lake water, with a dissolved-solids concentration of about 80 ppm, is in many respects similar chemically, but in addition it contains noticeable amounts of several hydrochemical products of its volcanic-caldera environment. Only small quantities of the telltale constituents—sodium, sulfate, and chloride—are necessary to draw attention to that environment. At East Lake, where the dissolved constituents of thermal-spring flow are the strongest and overshadowing control, the chemical character of "Davis Lake-type" water is masked almost completely. The result is a calcium sodium bicarbonate sulfate water with four times the dissolved-solids concentration of Davis Lake.

CRATER LAKE

Crater Lake is fed almost wholly by direct precipitation, and the chemical character of the lake reflects the dilute nature of that supply. The dissolved-solids concentration is about 80 ppm, made up mostly of silica, calcium, sodium, and bicarbonate (table 13). However, Crater Lake also contains significant concentrations of sulfate and chloride (about 10 ppm of each) not usually found in the surface water of humid mountainous regions.

The lake water appears to be practically uniform in chemical quality both areally and vertically. Partial analysis of 12 samples taken August 5, 1964, at three sites and at depths ranging from 1 foot to 1,900 feet showed silica concentration that ranged from 16 to 17 ppm, chloride from 9.5 to 9.8 ppm, and specific conductance from 115 to 118 micromhos at 25° C.

Crater Lake contains about 1.5 million tons of dissolved solids within its 14-million-acre-foot water body. Through 1964, the lake has been sampled only three times—in 1912, 1961, and 1964—for comprehensive chemical analysis. The results (table 13) suggest that very little net change in dissolved-solids content or chemical character occurred during the 52-year period.

Direct precipitation accounts for the greatest increment of water added to the lake, but its dissolved-solids contribution is of only secondary importance. The bulk of dissolved material now present in the lake has undoubtedly been derived from three principal sources: (1) Spring discharge and runoff from the caldera sides above the water level, (2) dissolution or mineralogic alteration of slightly soluble components of the caldera wall below the lake surface, and (3) spring flow that may issue from the lake-basin sides and bottom below the present lake level. The relative importance of these sources is uncertain. However, three of the principal constituents of the lake water—silica, calcium, and sodium—are the most mobile and common products of the low-temperature hydrochemical breakdown of most igneous rocks, including the group of volcanic rocks that form Mount Mazama.

The accumulation of sulfate and chloride in Crater Lake may not be due entirely to the normal processes of hydrochemical rock breakdown. The two constituents, and perhaps some silica and sodium as well, may have been contributed to the lake by thermal springs or fumaroles, probably located below the present lake level. Such springs and fumaroles are a common expression of hydrothermal activity at a site of volcanic eruptions.

This opinion is supported by the contrastingly small concentrations of the two constituents observed in water of Rogue River near Prospect, Oreg., about 25 miles southwest of the lake. This river drains an area adjacent to Crater Lake and underlain predominantly by volcanic rocks. Observed concentrations of sulfate and chloride were less than 2.0 ppm and usually less than 1.0 ppm in monthly samples collected during the period August 1960–September 1961.

Leakage plays an important part in the chemistry of Crater Lake. The estimated water loss (about 90 cfs) removes approximately 7,000 tons of dissolved solids from the lake each year, an amount that may be more than the quantity added annually. Thus, the lake may actually be freshening slightly over a long-term period. However, the lack of appreciable chemical change during the 52-year period 1912–64 indicates that the freshening, if it does occur, is a slow process.

EAST LAKE

Although the geologic environments of East and Crater Lakes are quite similar—each occupies a volcanic caldera of Holocene age—their chemical characters are dissimilar. East Lake contains about 200 ppm of dissolved solids, more than twice the amount in Crater Lake. The principal cations are calcium, sodium, and magnesium, which are present in almost equal amounts, based on equivalents per million. Bicarbonate and sulfate are by far the most abundant anions, whereas the concentration of chloride is remarkably small (about 0.2 ppm; table 13).

Perhaps the most important source of dissolved solids in the East Lake basin is the discharge of hot springs situated in one known shallow area of the lake basin below the present water level; similar springs may occur in deeper parts of the lake as well. The analysis of a lake-water sample collected in the area of spring activity at the southeastern shore shows that the major constituents contributed by the springs probably are silica, bicarbonate, and sulfate; the identity of the principal cation(s) is uncertain. The springs also emit gaseous hydrogen sulfide, and almost certainly carbon dioxide as well.

Additional less important sources of dissolved solids are: Hydrochemical alteration and decomposition of the lakebed below the present lake level, percolation and surface runoff into the 1.5-square-mile lake from the surrounding 6.0-square-mile drainage basin, and precipitation falling directly into the lake. Hydrochemical action of the lake water may be accelerated in areas of hot-spring activity by an abundance of carbon dioxide. The carbon dioxide tends to inhibit the increase in pH normally associated with the decomposition or alteration of some common minerals, such as alkaline-earth carbonates, feldspars, micas, and certain clay minerals. As the pH of a solution that surrounds the altering mineral increases in the range from pH 7 to 10, the tendency to be altered (or, in the case of minerals such as calcite, to be dissolved) decreases. Thus, the presence of gaseous carbon dioxide aids the decomposition processes because dissolution of the gas and subsequent dissociation of the carbonic acid initially formed provides hydrogen ions that depress the pH.

The relatively dilute character of the lake water, in spite of the dissolved-solids contribution from hot springs, supports the hydrologic evidence (p. E29) that some of the water and its dissolved material are leaving the lake rather than accumulating. Because there is no indication that the lake has ever overflowed into adjacent Paulina Lake, subsurface leakage is the only means of water loss with concurrent dissolved-solids removal. If, as suggested on page E29, leakage from the lake is about 2.3 cfs, the annual loss of dissolved solids would be about 450 tons, or 3 percent of the lake's estimated 15,000-ton dissolved-solids load. The magnitude of annual dissolved-solids depletion in East Lake is by itself ample evidence that lakes in leaky basins remain dilute, even if the leakage is slight.

A logical path for the leakage would be westward from East Lake (alt about 6,380 ft) to adjacent Paulina Lake (alt about 6,330 ft).

However, the almost ninefold difference in magnitude between the outflow from Paulina Lake (about 20 cfs) and the estimated leakage from East Lake (about 2.3 cfs) prevents the detection of leakage to Paulina Lake from chemical criteria alone, despite the marked differences in chemical character (table 13).

DAVIS LAKE

Davis Lake is fed by snowmelt runoff, direct precipitation, and spring flow, all presumably very dilute. The dilute nature of this inflow is mirrored by the chemical character of the lake. The dissolved-solids concentration is only about 50 ppm, and the principal constituents are silica, calcium, sodium, and bicarbonate (table 13). These constituents are common to most dilute ground and surface water of mountainous regions where annual precipitation rates are high and evaporation rates are low.

The small dissolved-solids content of Davis Lake supports the hydraulic evidence that subsurface leakage is an important means of water loss. The average seepage of 150 cfs from Davis Lake and its dissolved-solids concentration of 48 ppm indicate an average annual loss of about 7,000 tons. The similarity between the dissolved-solids concentration of Davis Lake (as indicated by a specific conductance of 57 micromhos) and that of a spring (58 micromhos) 1.8 miles north-northeast of the lake and about 50 feet lower, suggests significant leakage by way of this spring and several others, which have combined discharge of 160 to 280 cfs.

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HYDROLOGIC AND CHEMICAL DATA

TABLE 1.—*Monthly and annual temperature and precipitation at Crater Lake* [1]

Month	Temperature (°F) Means: Daily maximum	Daily minimum	Average	Extremes: Highest of record °F	Highest of record Year	Lowest of record °F	Lowest of record Year	Precipitation (inches): Average	Maximum daily
January	34.6	17.4	26.0	58	1931	−14	1949 [2]	10.85	3.83
February	34.7	18.1	26.4	66	1954	−18	1933	8.68	3.49
March	37.7	19.3	28.5	67	1934 [2]	−6	1956	8.22	2.31
April	44.7	23.8	34.3	71	1927	0	1955	4.34	4.19
May	51.8	29.0	40.4	80	1931	5	1930	3.31	1.88
June	59.8	35.2	47.5	90	1924	11	1952	2.54	2.02
July	70.4	42.2	56.3	91	1924	18	1935	.63	1.54
August	70.3	41.6	56.0	89	1933	16	1925	.56	1.10
September	62.6	36.9	49.8	86	1955 [2]	18	1933 [2]	2.05	2.64
October	52.1	31.1	41.6	80	1958	10	1935 [2]	6.42	3.17
November	41.7	24.5	33.1	75	1931	−7	1955	7.95	2.63
December	35.0	20.1	27.6	62	1956	−18	1924	11.69	5.06
Year	49.6	28.3	39.0	91	1924	−18	1933 [2]	67.24	5.06

[1] Average and extreme temperatures and precipitation are based on 27 years of complete records in the period 1924–61. Data furnished by U.S. Weather Bureau from station at park headquarters, 2 miles south of Crater Lake rim.
[2] Also in other years.

TABLE 2.—*Precipitation, in inches, at Crater Lake Weather Station for years ending June 30, 1931–62* [1]

Year	*Precipitation*	*Year*	*Precipitation*	*Year*	*Precipitation*
1931	33.34	1942	68.24	1953	71.21
1932	75.21	1943	87.01	1954	68.82
1933	75.65	1944	53.65	1955	50.92
1934	54.24	1945	59.77	1956	87.68
1935	71.33	1946	66.64	1957	65.26
1936	55.30	1947	74.58	1958	81.14
1937	58.92	1948	78.55	1959	58.66
1938	74.41	1949	66.93	1960	64.68
1939	45.16	1950	77.07	1961	64.70
1940	59.96	1951	93.08	1962	58.12
1941	71.51	1952	84.60		
				Average	67.4

[1] Records for August 1930 observed at south rim of Crater Lake, altitude 7,086 feet; records for July, September, and October 1930 estimated for this report. From November 1930 through 1962, precipitation station has been at altitude 6,475 feet. Records for most months, November 1942 to June 1946, were estimated by U.S. Weather Bureau using correlation techniques.

TABLE 3.—*Rise in level of Crater Lake in selected periods of heavy precipitation, 1961–62*

Number of days	Last day, ending 8 a.m.	Precipitation [1] (feet)	Rise in lake level (feet)		
			Observed	Adjustment [2]	Adjusted
4	10–13–61	0.23	0.20	0.04	0.24
3	10–28–61	.29	.27	.03	.30
7	11–26–61	.61	.63	.08	.71
5	12–21–61	.44	.56	.06	.62
3	1–20–62	.17	.10	.03	.13
5	2–10–62	.20	.17	.06	.23
5	2–17–62	.21	.17	.06	.23
5	3–4–62	.26	.22	.06	.28
3	3–11–62	.19	.10	.03	.13
7	3–27–62	.30	.20	.08	.28
3	4–29–62	.23	.17	.03	.20
Total (50)		3.13			[3] 3.35

[1] From records of U.S. Weather Bureau.
[2] Adjustment applied to change in lake stage to compensate for tributary inflow estimated at 14 cfs (equivalent to 0.002 ft depth per day on lake surface) and outflow by seepage at 89 cfs (equivalent to 0.0134 ft per day on the lake surface).
[3] Ratio of total adjusted changes in lake level to total precipitation is 1.07.

TABLE 4.—*Fall in level of Crater Lake in selected periods of no precipitation, 1961–62*

Number of days	Last day ending 8 a.m.	Average altitude (feet)	Fall in lake level (feet)	
			Observed	Adjusted for evaporation [1]
5	11–9–61	6,174.81	0.08	0.070
5	11–17–61	6,174.82	.10	.090
10	2–5–62	6,175.33	.13	.110
7	4–3–62	6,175.91	.10	.086
5	4–14–62	6,175.76	.06	.050
3	4–18–62	6,175.71	.03	.024
Sum (35)				.430
Average		6,175.4		.0123

[1] Evaporation rate of 0.002 foot per day assumed.

TABLE 5.—*Computed seepage rates for Crater Lake* [1]

Period		Average values				
Number of years	Last year, ending Sept. 30	Precipitation (in. per yr)	Runoff (acre-ft per yr)	Volume change (acre-ft per yr)	Computed seepage rate (cfs)	Lake level (feet)
8	1938	62. 25	86, 280	−1, 310	86	6, 164. 6
4	1942	60. 74	84, 180	−5, 260	89	6, 164. 3
5	1953	78. 35	108, 590	+19, 970	88	6, 170. 9
4	1957	68. 68	95, 190	+5, 910	89	6, 176. 0
2	1959	70. 75	98, 060	+660	100	6, 177. 8
2	1961	62. 50	86, 620	−10, 840	100	6, 176. 0
1	1962	60. 17	83, 400	−6, 310	89	6, 175. 4

[1] Precipitation is that observed at Crater Lake Weather Station. Runoff includes precipitation and is computed as 1,386 acre-feet per inch of precipitation. Volume change is computed from observed change in stage and constant lake area of 13,140 acres. Annual evaporation loss is assumed constant as 23 inches (25,180 acre-ft) per year. Lake level is partly estimated because of lack of data in winter and spring periods.

TABLE 6.—*Computation of annual evaporation loss from Crater Lake*

	Acre-feet
Period 1930–62:	
1. Average annual water supply (computed for average annual observed precipitation of 67.4 in.)	93, 400
2. Average annual storage increment	−3, 560
3. Average annual seepage loss, at rate of 89 cfs	−64, 430
4. Computed average annual evaporation loss (equivalent to depth of 1.93 ft, or 23 in., on lake area of 13,140 acres)	25, 400
Period October 1, 1961, to September 30, 1962:	
1. Water supply (computed for 60.2 in. observed precipitation)	83, 440
2. Storage loss (fall of 0.47 ft)	+6, 180
3. Seepage loss at rate of 89 cfs	−64, 430
4. Computed evaporation loss (equivalent to depth of 1.92 ft, or 23 in. on lake area)	25, 200

TABLE 7.—*Altitude of water surface in Crater Lake, 1878–1963*

Date	Altitude (feet [1])
1878	
-------------	[2] 75
1892	
Sept. 10	[3] 77.8
1893	
Sept. 26	[3] 76.2
1895	
Sept. 25	[4] 77.5
1896	
Aug. 22	77.7
Aug. 30	77.6
Sept. 4, 5	77.5
Sept. 13	77.2
Sept. 23	77.1
1897	
Aug. 1	78.4
1901	
July 1	78.6
July 20	78.3
Aug. 1	78.1
Aug. 16	77.8
Sept. 1	77.6
Sept. 15	76.9
Oct. 12	77.1
1907	
July 20	[5] 76.3
1908	
July 28	77.3
Oct. 8	[5] 75.9
1909	
Aug. 14	76.5
Sept. 7	76.3
1910	
Aug. 16	77.1
1911	
Aug. 21	76.2
Sept. 21	75.6
1912	
July 10	76.3
Aug. 1	76.1
Aug. 12	76.0
Aug. 26	76.0
Sept. 17	75.9
1913	
July 19	76.6
Aug. 3	76.5
Aug. 9	76.32
Sept. 1	76.00
Sept. 6	75.98
Sept. 11	75.88
Sept. 16	75.78
Sept. 21	75.72
1914	
July 12	75.0
July 20	74.9
July 31	74.7
Aug. 10	74.5
Aug. 20	74.3
Aug. 30	74.2
Sept. 5	74.1
Sept. 13	74.0
Sept. 30	74.3
1915	
June 13	75.78
June 20	75.66
June 30	75.50
July 10	75.32
July 20	75.16
July 31	74.98
Aug. 10	74.82
Aug. 20	74.66
Aug. 31	74.50
Sept. 10	74.44
Sept. 18	74.22
1916	
July 22	75.4
Aug. 2	75.3
Aug. 13	75.2
Aug. 20	75.1
Aug. 26	75.0
Sept. 12	74.82
Sept. 30	74.5
1917	
Sept. 13	74.3
Sept. 17	74.2
1918	
July 14	75.0
July 30	74.0
Aug. 23	73.5
Sept. 7	73.5
1919	
July 5	73.9
July 11	73.9
Sept. 20	72.8
Sept. 25	72.7
1920	
July 6	72.4
Aug. 14	71.7
1921	
Aug. 2	74.3
Aug. 20	73.7
Sept. 16	72.9
1922	
July 21	74.4
July 26	74.2
Aug. 20	73.7
Sept. 10	73.5
1923	
July 1	73.7
July 21	73.5
July 24	73.4
Aug. 7	73.2
Aug. 26	72.8
Sept. 11	72.7
Sept. 24	71.8
1924	
June 2	71.5
July 2	71.4
Aug. 2	70.6
Sept. 2	70.1
1925	
July 1	71.7
Aug. 1	71.1
Sept. 1	70.2
1925	
Sept. 22	70.0
1926	
May 22	70.0
July 22	69.5
Aug. 22	68.9
Sept. 15	68.3
1927	
July 22	70.0
Aug. 22	69.7
1928	
July 1	70.9
Aug. 6	70.4
Sept. 1	70.0
1929	
Sept. 8	67.4
Dec. 5	66.91
1930	
July (?)	66.21
Aug. (?)	65.61
Sept. 20	65.66
1931	
Sept. 18	63.26
Oct. 12	63.31
1932	
Sept. 13	63.71
1933	
Sept. 12	64.5
Oct. 17	64.6
1934	
Apr. 26	65.76
June 15	65.4
July 10	65.2
Aug. 13	64.6
Aug. 20	64.39
Oct. (?)	63.41
1935	
June 27	65.36
July 1	65.21
July 11	64.88
July 24	64.86
Aug. 10	64.63
Aug. 19	64.48
Aug. 30	64.35
Sept. 2	64.30
1936	
June 10	65.1
Sept. 17	63.93
1938	
July 2	65.92
Sept. 15	64.92
1939	
June 9	64.9
July 10	64.9
July 16	64.98
July 27	64.78
Aug. 7	64.5
Aug. 15	64.4
Aug. 26	64.3
Sept. 1	64.1
Sept. 6	63.9

See footnotes at end of table.

TABLE 7.—*Altitude of water surface in Crater Lake, 1878–1963*—Continued

Date	*Altitude (feet* [1]*)*
1939	
Oct. 12	63.65
1940	
June 19	64.5
July 2	64.3
July 15	64.2
July 21	64.1
Aug. 2	63.9
Aug. 14	63.7
Aug. 30	63.4
Sept. 2	63.3
1941	
July 1	64.0
July 10	63.9
July 28	63.8
Aug. 13	63.7
Aug. 29	63.3
Sept. 4	63.5
1942	
July 3	64.2
July 13	64.0
July 20	63.9
Aug. 10	63.7
Aug. 17	63.6
Aug. 25	63.5
Sept. 10	63.2
1943	
-------------	[6] 66.73
1946	
-------------	[6] 67.1
Aug. 16	66.7
1947	
-------------	[6] 66.8
1948	
June 26	67.9
Aug. 1	67.7
Sept. 5	67.2
1950	
June 15	69.8
July 15	69.7
Aug. 13	69.3
Aug. 22	69.3
Sept. 11	68.9
1951	
June 29	72.3
Sept. 11	70.9
1952	
July 13	74.56
Aug. 19	74.31
Sept. 22	73.31
Oct. 3	73.24
1953	
Aug. 11	75.3
1954	
Aug. 4	76.5
Aug. 11	76.32
Sept. 23	75.83
Oct. 9	75.53
1955	
July 10	75.03
July 22	74.92
July 29	74.83
Aug. 25	74.39
Sept. 1	74.25
Sept. 23	74.05
Oct. 4	73.87
Oct. 26	73.91
1956	
July 6	77.15
July 25	77.07
Aug. 6	76.89
Aug. 21	76.67
Sept. 10	76.5
Sept. 21	76.17
Oct. 18	75.91
Oct. 28	76.09
1957	
July 3	77.58
Aug. 2	77.13
Aug. 16	76.85
Sept. 5	76.51
Sept. 10	76.39
Sept. 30	76.31
1958	
-------------	[6] 79.06
July 15	78.85
July 31	78.73
Aug. 15	78.45
1959	
Aug. 3	77.21
Aug. 12	77.00
Aug. 22	76.81
Oct. 2	76.37
1960	
July 8	76.77
July 15	76.65
July 27	76.47
Aug. 11	76.23
Sept. 9	75.67
Sept. 23	75.42
1961	
May 24	76.4
July 10	76.2
July 20	76.1
Sept. 7	75.22
Sept. 17	75.05
Sept. 30	74.75
1961	
Oct. 9	74.60
Oct. 31	74.83
Nov. 15	74.70
Nov. 30	75.26
Dec. 15	75.07
Dec. 31	75.50
1962	
Jan. 15	75.44
Jan. 31	75.31
Feb. 15	75.52
Feb. 28	75.48
Mar. 15	75.70
Mar. 31	75.78
Apr. 15	75.72
Apr. 30	75.79
May 3	75.84
May 15	75.82
May 31	75.71
June 15	75.61
June 30	75.48
July 15	75.26
July 31	75.07
Aug. 15	74.99
Aug. 31	74.66
Sept. 15	74.39
Sept. 30	74.27
Oct. 6	74.20
Oct. 15	74.94
Oct. 31	74.74
Nov. 15	74.84
Nov. 30	75.05
Dec. 15	75.35
Dec. 31	75.09
1963	
Jan. 15	74.85
Jan. 31	75.00
Feb. 15	75.34
Feb. 28	75.48
Mar. 15	75.29
Mar. 31	75.50
Apr. 15	75.76
Apr. 30	75.71
May 7	75.88
May 15	75.81
May 31	75.75
June 15	75.67
June 30	75.60
July 15	75.46
July 31	75.20
Aug. 15	75.05
Aug. 31	74.75
Sept. 15	74.62
Sept. 30	74.45

TABLE 7.—*Altitude of water surface in Crater Lake, 1878–1963*—Continued

[1] Altitude is excess above 6,100 feet. Most observations were made and furnished by U.S. National Park Service. Continuous records of stage are available from September 14, 1961, to September 30, 1963, and beyond. Some readings made in periods 1913–17, 1926–28, 1935, 1940–42, and 1954–63 are not included in the listing.
[2] Water surface reported nearly 6 feet below watermark (assumed to be same watermark later found to be at 6,180.5 ft).
[3] Based on lowest part of painted name on rock wall near boat landing; water surface may have been lower but not higher.
[4] From newspaper report (S. T. Harding, written commun., 1959).
[5] Uncertain; based on memory of observer in 1913.
[6] Seasonal high watermark.

TABLE 8.—*Estimated outflow from Paulina Lake* [1]

Month	*Average flow (cfs)*	*Month*	*Average flow (cfs)*
October	10	May	35
November	15	June	25
December	15	July	20
January	20	August	15
February	20	September	10
March	25		
April	30	The year	20

[1] Above estimates are based on observations of flow given below:

Date	*Description of measurement*	*Flow (cfs)*
Aug. 23, 1903	Measured over wooden weir	13.0
May 23, 1930	Measured with current meter, drouth year	23.4
Spring 1958	Peak flow from watermark, computation of flow over weir plus an estimate.	70
Sept. 16, 1958	Field estimate of flow	10
May 18, 1959	do	23
June 20, 1961	do	30
May 28, 1962	do	40

TABLE 9.—*Estimate of rate of leakage from East Lake*

Average annual values	Long-term rate	Period of water years ending September 30: 1931–60	1942–58	1959–61
Precipitation at Fremont ... inches	[1] 10.0	[2] 10.4	[2] 11.67	[2] 8.27
Precipitation at Bend ... do	[1] 11.4	[2] 11.9	[2] 13.06	[2] 8.30
Precipitation at East Lake ... do	[1] 35	[3] 37	[4] 41	[4] 26
Evaporation at East Lake ... do	[5] 28	[5] 28	[5] 28	[5] 28
Average lake area ... acres	940	910	950	1,000
Change in level of East Lake ... feet	0	[6] +.23	[6] +.94	[6] −1.3
Change in volume ... acre-feet	0	[7] +210	[7] +890	[7] −1,300
Infalling precipitation ... do	[7] +2,740	[7] +2,800	[7] +3,250	[7] +2,170
Runoff to lake ... do	[8] +1,150	[8] +1,250	[8] +1,450	[8] +700
Total water supply ... do	+3,890	+4,050	+4,700	+2,870
Loss by evaporation ... do	[7] −2,190	[7] −2,120	[7] −2,210	[7] −2,330
Loss by seepage, assumed constant ... do	−1,700	−1,700	−1,700	−1,700
Residual ... do	0	+20	−100	+140

[1] Estimated, about 5 percent less than in period 1931–60, when lake was rising.
[2] From records of U.S. Weather Bureau, estimated for some months.
[3] Estimated on basis of precipitation at Bend and snow-water content at Paulina Lake, 1955–62.
[4] Estimated on basis of records at Fremont and Bend.
[5] Estimated from regional value adjusted for altitude.
[6] Computed from occasional observations of stage.
[7] Computed from average lake area on basis of unpublished surveys of Oregon Game Commission.
[8] Estimated as 50×(precipitation less 12 inches allowance for evapotranspiration).

TABLE 10.—*Altitude of water surface in East Lake*

Date	Altitude [1] (feet)	Basis
([2])	6,385.5	Beach terrace, minimum age based on age of living pine tree cored by D. B. Lawrence.
1903		
Aug. 25	6,380	I. C. Russell noted lake level high; here estimated as 2.5 ft lower than peak of 1904.
1904		
Peak	6,382.5	Deduced from field notes of D. B. Lawrence, 1960, as equal to peak of 1958.
1927		
Aug. 3	6,374.87	Leveling by U.S. Forest Service.
1931		
	6,371	Survey for Newberry Crater sheet of topographic atlas.
1932		
June 9	6,369	Photograph by Howel Williams (1935, pl. 29); lake depth at camera site, 8.9 ft on July 2, 1963.
([3])	6,366	Statement of resort operator; about 16 ft below level of 1958.
1951		
July 27	6,374	Estimated from aerial photographs taken by U.S. Forest Service.
1958		
Peak	6,382.5	From high-water mark.
Sept. 16	6,381.66	By leveling.
1959		
May 18	6,381.74	Do.
Oct. 26	6,379.90	Do.
Nov. 10	6,379.80	Do.
1960		
July 27	6,379.81	Do.
Sept. 10	6,379.12	Depth 1.80 ft over reference mark.
1961		
June 20	6,379.40	Depth 2.08 ft over reference mark.
Sept. 6	6,378.1	By leveling.
Oct. 26	6,377.57	Depth 0.25 ft over reference mark.
1962		
May 28	6,378.50	Depth 1.18 ft over reference mark.
Nov. 12	6,377.09	By leveling, following heavy October rains.
1963		
Peak	6,378.3	Watermark observed July 2, 1963.
July 2	6,377.8	By leveling.

[1] Altitude based on datum of 1929, supplementary adjustment of 1947, by which the altitude of benchmark F8-1931, in boulder 250 ft southeast of southwest corner of lake, is 6,382.68 ft.
[2] Before 1853.
[3] Low level, probably in 1941 or 1942.

TABLE 11.—*Monthly and annual average temperature, precipitation, and evaporation at Odell Lake [1] and Wickiup Dam, [2] near Davis Lake*

Month	Temperature [3] (°F)		Precipitation [3] (inches)		Evaporation (inches)	
	Odell Lake	Wickiup Dam	Odell Lake	Wickiup Dam	Odell Lake	Wickiup Dam
January	26.6	27.5	9.50	3.62		
February	30.0	29.5	6.87	2.52		
March	30.8	33.6	7.70	1.89		
April	36.9	41.3	3.94	.97		
May	43.2	48.1	3.25	1.52	[4] 3.35	[5] 5.77
June	50.2	55.3	2.36	1.25	[5] 4.05	[5] 6.80
July	58.0	62.2	.49	.25	[5] 5.54	[5] 9.03
August	56.1	60.0	.87	.52	[5] 3.72	[5] 7.35
September	51.4	54.2	2.03	.63	[5] 1.93	[5] 5.14
October	42.9	45.4	5.39	1.97	[5] .70	
November	34.0	35.7	8.33	2.73		
December	29.6	30.8	10.72	3.84		
Year	40.8	43.6	61.45	21.71	[6] 24	[6] 45

[1] Weather station altitude, 4,795 ft.
[2] Weather station altitude, 4,358 ft.
[3] From records of U.S. Weather Bureau for the period January 1950 to December 1964, not adjusted to long-term average.
[4] Average of land-pan values for May 1951–63.
[5] Normal evaporation from land pans (records of U.S. Weather Bureau).
[6] Estimated for this report.

TABLE 12.—*Altitude, in feet, of water surface in Davis Lake*

Date	Altitude [1]
Before 1728	[2] 95.4
1878	
	[3] Lake low
1904	
Sept. 12	[4] 92.5
1930	
	[5] 89
	[6] 80
1934	
Aug. 14	[6] 81.2
Dec.	[6] 80.8
1939	
Oct. 17	77.7
Nov. 28	77.8
1940	
May 2	84.4
June 7	84.1
July 27	80.3
Sept. 24	77.0
Oct. 3	77.1
Nov. 13	77.7
1941	
	[7] 79.3
May 14	79.0
July 18	78.2
Sept. 26	76.1
Nov. 28	78.3
1942	
Apr. 21	81.4
June 11	82.4
July 23	81.3
Sept. 15	76.9
Oct. 20	[8] 75.9
1943	
May 19	87.3
July 15	88.6
Sept. 2	87.0
Nov. 17	86.6
1944	
Apr. 18	85.3
May 22	84.8
Oct. 23	76.4
1945	
May 7	82.7
June 4	83.6
June 18	83.5
July 18	81.3
Aug. 29	78.2
Nov. 1	76.9
1946	
May 29	85.6
June 17	86.1
June 24	86.2
July 1	86.2
1946	
July 20	85.9
Sept. 8	85.9
Oct. 29	83.9
1947	
Apr. 30	85.6
May 21	85.9
July 12	85.1
Aug. 20	84.5
Sept. 9	83.2
Oct. 6	82.4
Dec. 4	83.9
1948	
May 26	85.2
June 29	87.3
July 9	87.4
July 17	87.3
Aug. 13	86.2
Aug. 20	85.9
Sept. 17	85.0
Oct. 11	84.8
1949	
May 22	87.8
Sept. 12	85.7
Oct. 14	84.7
1950	
May 12	87.4

See footnotes at end of table.

TABLE 12.—*Altitude, in feet, of water surface in Davis Lake*—Continued

Date	Altitude [1]	Date	Altitude [1]	Date	Altitude [1]
1950		*1955*		*1960*	
May 29	87.7	May 12	87.7	May 9	86.3
July 17	89.4	June 11	87.7	June 30	87.0
Sept. 25	87.2	June 23	88.0	July 14	87.0
1951		July 1	88.1	July 29	85.3
May 31	92.7	July 18	87.8	Aug. 9	85.3
June 27	92.3	Aug. 2	87.2	Aug. 13	84.7
July 31	91.2	Aug. 22	86.4	Sept. 1	85.4
Sept. 12	90.0	Aug. 30	85.7	Sept. 14	84.0
Oct. 10	89.8	Sept. 23	85.2	Nov. 4	83.0
Oct. 30	89.8	Oct. 28	84.9	*1961*	
1952		*1956*		Jan. 18	85.3
May 9	91.2	June 20	92.6	Apr. 10	86.6
June 2	92.4	July 18	92.7	April 14	87.7
July 10	92.6	Sept. 26	91.3	May 11	86.7
Aug. 3	92.0	*1957*		June 20	87.1
Aug. 22	91.4	May 9	92.9	June 30	86.9
Sept. 24	90.6	June 13	93.0	July 31	85.4
Nov. 4	89.5	Peak	93.2	Aug. 31	84.1
1953		July 9	92.4	Sept. 11	83.8
May 19	90.3	Nov. 8	88.0	Sept. 27	83.2
June 1	90.7	*1958*		Oct. 26	83.6
Aug. 5	90.3	June 19	91.7	Oct. 31	83.5
Sept. 10	89.4	Peak	92.1	Nov. 4	83.7
Oct. 28	88.1	July 20	91.5	*1962*	
1954		Nov. 7	89.4	May 16	87.2
Apr. 23	91.4	*1959*		June 28	87.1
June 25	92.1	Apr. 9	90.0	July 31	86.6
July 24	91.6	Aug. 21	86.9	Aug. 30	85.3
Dec. 2	88.4	Sept. 13	86.0	Sept. 19	84.7
		Nov. 14	86.5	Sept. 30	84.5
				Oct. 29	85.2
				Oct. 31	85.2

[1] Above 4,300 feet.
[2] Beach and lichen line interpreted as extreme high level.
[3] "Twenty feet" below high mark; see p. E32.
[4] Estimated on basis of a downstream gaging.
[5] Apparently intended as a recent high water level; taken from Maiden Peak sheet of topographic atlas edition of 1934.
[6] C. C. Fisher, U.S. Bur. Reclamation, unpub. data, 1936.
[7] Peak stage, May or June.
[8] Minimum of record.

TABLE 13.—*Chemical and physical character of the lakes*

[Results in parts per million, except specific conductance and pH. Analyses by U.S. Geol. Survey]

Source	Collection date	Lake level (ft above mean sea level)	Water temperature (°F)	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3) [1]	Carbonate (CO_3) [1]	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids (calc) [2]	Hardness as $CaCO_3$	Specific conductance (micromhos at 25° C)	pH [1]
Crater Lake, about 1 mile from shore [3]	Aug. 27, 1912	6,176.0	------	18	7.1	2.8	11	2.2	34	0	11	11	------	0.4	80	29	------	------
Crater Lake, north shore at Cleetwood Landing	Sept. 6, 1961	6,175.25	61	18	7.0	2.6	11	1.7	37	0	10	10	0.2	.1	79	28	117	7.6
Crater Lake, 4.3 miles north 47° E. of lodge, 1 foot below surface	Aug. 5, 1964	6,174.89	57	16	7.0	2.5	11	1.6	35	0	10	9.5	.1	.0	75	28	117	7.4
East Lake, east shore at resort launch ramp	Sept. 11, 1960	6,379.12	------	13	26	10	23	3.7	125	0	59	.2	.1	.0	197	108	323	8.1
Do	Sept. 6, 1961	6,378.1	62	15	------	------	23	------	------	------	58	.2	------	------	------	107	316	------
Paulina Lake, west shore at outlet	Sept. 10, 1960	------	------	46	26	39	47	5.2	352	23	3.8	2.8	.6	.0	366	226	566	8.8
Davis Lake, north shore	Oct. 26, 1961	4,483.58	46	19	4.0	1.2	5.1	1.4	34	0	.2	.0	------	------	48	15	57	6.9

[1] All determinations were made in laboratory rather than at sampling sites. Carbonate: bicarbonate ratios and pH values can change appreciably during period between sample collection and analysis.

[2] Values represent summation of concentrations of all constituents determined in a comprehensive analysis (bicarbonate is recalculated as carbonate using the factor 0.492).

[3] Analysis by Van Winkle (1914, p. 43).

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