Comprehensive Survey of Sedimentation in Lake Mead, 1948-49

GEOLOGICAL SURVEY PROFESSIONAL PAPER 295

Prepared in collaboration with the U.S. Department of the Interior, Bureau of Reclamation; U.S. Department of the Navy, Chief of Naval Operations, Bureau of Ships, Bureau of Ordnance, Bureau of Naval Personnel, Hydrographic Office, and Navy Electronics Laboratory; U.S. Department of Commerce, Coast and Geodetic Survey; University of California, Scripps Institution of Oceanography

M. CIRCULATION AND EVAPORATION

By E. R. Anderson, U.S. Navy Electronics Laboratory, and D. W. Pritchard, Chesapeake Bay Institute, Johns Hopkins University

Late in 1947, representatives of the Geological Survey asked the Navy Electronics Laboratory (NEL) for assistance in both equipment and personnel, on the Lake Mead Sedimentation Survey, which was then being planned. The Laboratory's contribution, in addition to furnishing equipment and consulting services, was (1) to determine the general circulation of the lake from the distribution of temperature and salinity (dissolved solids), and (2) to establish a preliminary energy budget from which an estimate of evaporation could be made.

This section of the report presents a summary of the circulation and evaporation studies, together with the major conclusions. A brief discussion of the methods and techniques employed is included, but a detailed description of the methods and techniques, complete analysis of the data with respect to circulation and evaporation, and a summary of the basic data taken on the various limnological cruises are omitted; they are published in a technical report of the Navy Electronics Laboratory (Anderson and Pritchard, 1951).

CIRCULATION

TECHNIQUES FOR DETERMINING CIRCULATION

Suitable instrumentation and techniques are not available for determining the general circulation of a body of water, such as Lake Mead, by means of direct measurements of currents. However, oceanographers for many years have utilized the distribution of various properties and their variations, for determining the movement of water in the subsurface layers of the oceans, and especially for tracing masses of sea water moving from one region to another. The waters of all the oceans acquire their original characteristics when the water is in contact with the air or subject to heating and cooling at the surface. With the passage of time the original characteristics become changed by vertical and lateral mixing. The "conservativeness,"[7] with respect to time and place, of the original temperature and salinity distribution varies, depending upon the subsequent history of the mass of water.

It was considered that some of the oceanographic techniques would be useful for determining the general circulation of a lake such as Lake Mead. In this section the following techniques, which have been employed by oceanographers, will be briefly examined regarding their utility in such an application: (a) tonguelike distributions, (b) Wüst's "core method," and (c) temperature and salinity (T–S) relations.

TONGUELIKE DISTRIBUTIONS

Without going into the dynamics of the development of ocean currents (Sverdrup and others, 1946), it may be stated that, in the northern hemisphere, the water of highest density is found on the left-hand side of a current. Thus, it is possible to interpret a tonguelike distribution in a horizontal plane as representing water movement. Considering a tongue of low temperature, and assuming that salinity is constant or its effect on density negligible, the currents will be directed along the temperature contours, not along the axis of the tongue as might be assumed if the dynamics of the system were ignored. Some modification may occur at the sea surface, where external factors may contribute toward maintaining the observed temperature distribution.

A tonguelike distribution of either temperature or salinity in a vertical section may also indicate flow. If an initial horizontal flow be assumed, then processes of vertical and horizontal mixing are important in developing the vertical tonguelike distribution. Hence the distribution is indicative of both horizontal and vertical motion.

Defant (1929) and Thorade (1931) examined analytically the relation between velocity and vertical mixing and, making certain simplifying assumptions, showed how horizontal flow and vertical mixing can produce and maintain this tonguelike distribution in a vertical plane. The tongue may curve up or down, although horizontal flow is assumed, and therefore the axis of the tongue need not coincide with

[7] As used in this report, the term "conservative" describes a property which changes relatively little from day to day.

the axis of maximum velocity. In addition, a tonguelike distribution in a vertical section may be developed by processes of horizontal and vertical mixing alone. However, in the case of relatively narrow restricted bodies of water, such as certain parts of Lake Mead, the effect of horizontal mixing would be minimized. As a result, the observed tonguelike distributions at Lake Mead are largely the result of horizontal flow and vertical mixing.

WÜST'S CORE METHOD

Wüst (1935) introduced the "Kernschicht-methode" or "core method" for studying the spreading out and mixing of water masses, a method that has been used successfully in studying the flow of deep water in the Atlantic Ocean. It does not involve any assumptions as to the character of the mixing and is especially useful in giving a qualitative picture of the spreading out of a well-defined water mass from a source region. The "core," as defined by Wüst, is that part of a layer of water within which temperature or salinity, or both, reach maximum or minimum values. For example, the water that flows out of the Mediterranean Sea has a high salinity, and the salinity maximum that is the "core" of the layer can be traced for great distances in the Atlantic Ocean. The decrease in the value of this maximum is caused by mixing processes, but the salinity is conservative for long periods of time and over great distances.

T–S RELATIONS

Helland-Hansen (1916) introduced the use of a temperature-salinity (T–S) diagram in identifying oceanic water masses and demonstrated that, for any given water mass, a plotting of temperature versus salinity resulted in a characteristic curve.

Consideration of these techniques leads to the following conclusions: In the subsurface layers of a body of water, in the absence of internal chemical effects, the salinity distribution is conservative, being modified only by mixing processes. It is possible, by observing changes in the vertical distributions, to gain knowledge of the effective circulation in a vertical plane, but great caution must be exercised regarding such details as the location of the axis of maximum velocity. The distribution of temperature can be looked upon in the same manner. However, in a lake, temperature is probably not conservative enough to be followed from one time to another because of diurnal and seasonal variations produced by the exchange of energy between the atmosphere and the lake.

In this study, the above three oceanographic techniques were utilized to establish the general features of the circulation in Lake Mead. The distribution of salinity proved sufficiently conservative to enable reasonably accurate conclusions to be drawn regarding the main features of the circulation in a vertical plane in Lake Mead.

OBSERVATIONAL PROGRAM

The objectives of this study prescribed the parameters to be measured. Data concerning the distribution of temperature and salinity in the lake and in the river water, and of temperature, humidity, and wind velocity in the air just over the lake, were required. As an aid in following the circulation, especially in relation to sedimentation, Secchi-disc readings were made. Of particular importance with regard to the circulation in the upper portion of Lake Mead are the notes made by the survey parties as to the presence or absence of the "convergence"[8] above Pierce Ferry, the intensity of this convergence if present, and notations of any other related phenomena which lent themselves to description if not quantitative measurement.

As frequently happens in a study involving a series of observational surveys, the optimum procedure was not pursued in the first few surveys. For simplicity, the observational program that was finally evolved will be discussed first, and the departures from it in any particular cruise will be mentioned where necessary.

Plate 18 shows the station locations of the observational program as finally established. At the head of the lake, the location of station 66 on any particular cruise depended upon the location of the convergence. During periods of strong convergence several stations were taken, in and very near the convergence area; they have been designated as stations 66a to 66m. Stations 67 and 68 in Lower Granite Gorge were occupied only when the stage of the lake allowed reasonably safe navigation upriver. The inset maps on plate 18 indicated the location of the stations taken near the convergence on cruises I and II.

Twelve cruises were completed during the year the program was under way, as follows:

Cruise	Cruise dates From—	To—
I	Feb. 25, 1948	Feb. 29, 1948
II	Mar. 31, 1948	Apr. 3, 1948
III	Apr. 22, 1948	Apr. 29, 1948
IV	May 25, 1948	May 31, 1948
V	June 26, 1948	June 30, 1948
VI	July 24, 1948	July 28, 1948
VII	Aug. 22, 1948	Aug. 26, 1948
VIII	Sept. 25, 1948	Sept. 29, 1948
IX	Oct. 23, 1948	Oct. 27, 1948
X	Nov. 27, 1948	Nov. 30, 1948
XI	Jan. 5, 1949	Jan. 9, 1949
XII	Feb. 11, 1949	Feb. 15, 1949

[8] A convergence can be defined as the boundary between two converging currents; in this case, at certain seasons, it is the boundary between Colorado River water and Lake Mead water (pl. 17).

In the initial cruises, all stations shown in plate 18 were not occupied, and cross sections, particularly in Boulder Basin and Virgin Basin, only approximate the lines shown on the station-location chart. The stations along the old Colorado River channel, which proved in the analysis of the data to be most important, did not shift greatly from survey to survey.

The stations occupied on each cruise and the data collected at each are appended to the NEL technical report (Anderson and Pritchard, 1951). At all stations temperature measurements were taken with a bathythermograph, except that on some cruises the uppermost station at the head of the lake was reached by foot and only surface temperature and a surface-water sample could be obtained. At about half the stations on each cruise, samples of lake water were obtained at selected depths for analysis as described below; they are called "Nansen stations" because Nansen bottles were used to collect the samples.[9] At each Nansen station from 1 to 11 samples were obtained, the number depending on depth, location, and season.

Bathythermograph[10] observations provide a continuous record of temperature versus depth. At each station a bathythermograph was lowered to the bottom and thus a complete record of the temperature of the water column from surface to bottom was obtained for each station. Surface temperature was also taken with a surface-bucket thermometer, to provide a calibration check for the bathythermograph records. Wind speed and direction, present weather, cloud types and amount, air temperature, and wet-bulb temperature were also recorded as auxiliary data to the bathythermograph record.

For all surveys subsequent to cruise III (except on cruise X, when the Secchi disc was lost during the survey), Secchi-disc[11] readings were taken at each station to obtain a measure of the turbidity of the water; a few were taken on the third cruise.

Additional data were also used extensively. Records of the daily flow and temperature of the Colorado River and the Virgin River were provided by the Geological Survey. Weather data covering the year studied were secured from the joint Weather Bureau–Bureau of Reclamation station at Boulder City, Nev. The Bureau of Reclamation also provided records of the daily volume and temperature of outflow from the lake through Hoover Dam, and of evaporation from the several evaporation pans located on the lake. The Geological Survey supplied the information on volume and capacity used in the energy-budget study.

ANALYSIS

The primary parameters used were temperature and salinity. Temperatures obtained with the bathythermograph were used in the analysis. Although the bathythermograph is a solidly built field instrument and can be expected to give good relative data, frequent checks of depth are necessary. Because the bathythermographs employed in this study were calibrated for average sea water, an initial scale correction for depth had to be made to compensate for the density difference between lake water and average sea water. This correction was taken as 2.5 feet per 100 feet of depth. The framework holding the glass slide occasionally becomes displaced slightly from the calibrated position. In order to check this possible source of error in the depth scale, comparisons were made of the bottom depth as read from the bathythermograph slide, corrected for the density difference between lake water and sea water and for the observed depth as recorded from the reading of the meter wheel. The average depth correction for each cruise was obtained from the difference between these two values.

Temperatures were read from the corrected bathythermogram for each station at the surface, at 10, 25, 50, 75, 100, 150, 200, 250, 300, and 400 feet, and at the maximum depth. These results were plotted on horizontal charts,[12] by station location, for the surface and for depths of 10, 25, 50, 100, 200, and 300 feet. The depths of integer isotherms were also obtained from the bathythermogram and plotted in vertical sections, both along the old Colorado River channel and the Virgin River channel, and across the major basins and arms of the lake. These horizontal charts and vertical sections were contoured and studied. Some of the charts and sections are presented in this report in support of the discussion.

Conductivity measurements were made on the water samples collected on each cruise, primarily by H. R. Gould, using the conductivity bridge provided by the staff of the Bureau of Reclamation at Hoover Dam.

[9] Nansen bottles are metal bottles constructed so that a series of them may be attached to a hydrographic wire. When the bottles have been lowered to the desired depths, a small weight is dropped down the wire to trip a release catch on the upper part of the upper bottle, causing it to fall over, or reverse. A second weight, or "messenger," is released from this bottle in the reversing process, and falls down the wire to trip the next bottle. In reversing, valves at each end of the bottle close, thus trapping a sample of water. By this procedure, subsurface water samples can be obtained from several depths in one lowering.

[10] A bathythermograph consists of a stylus, attached to a Bourdon tube, which records the temperature on a smoked glass slide to within 0.1°F. The slide is held in a frame attached to a pressure bellows, and hence the frame and slide move relative to the arc of the stylus as the depth changes.

[11] A Secchi disc is a white-painted horizontal metal plate, 30 cm in diameter, which is lowered into the water; the depth at which it disappears from view is a measure of the turbidity of the surface layers.

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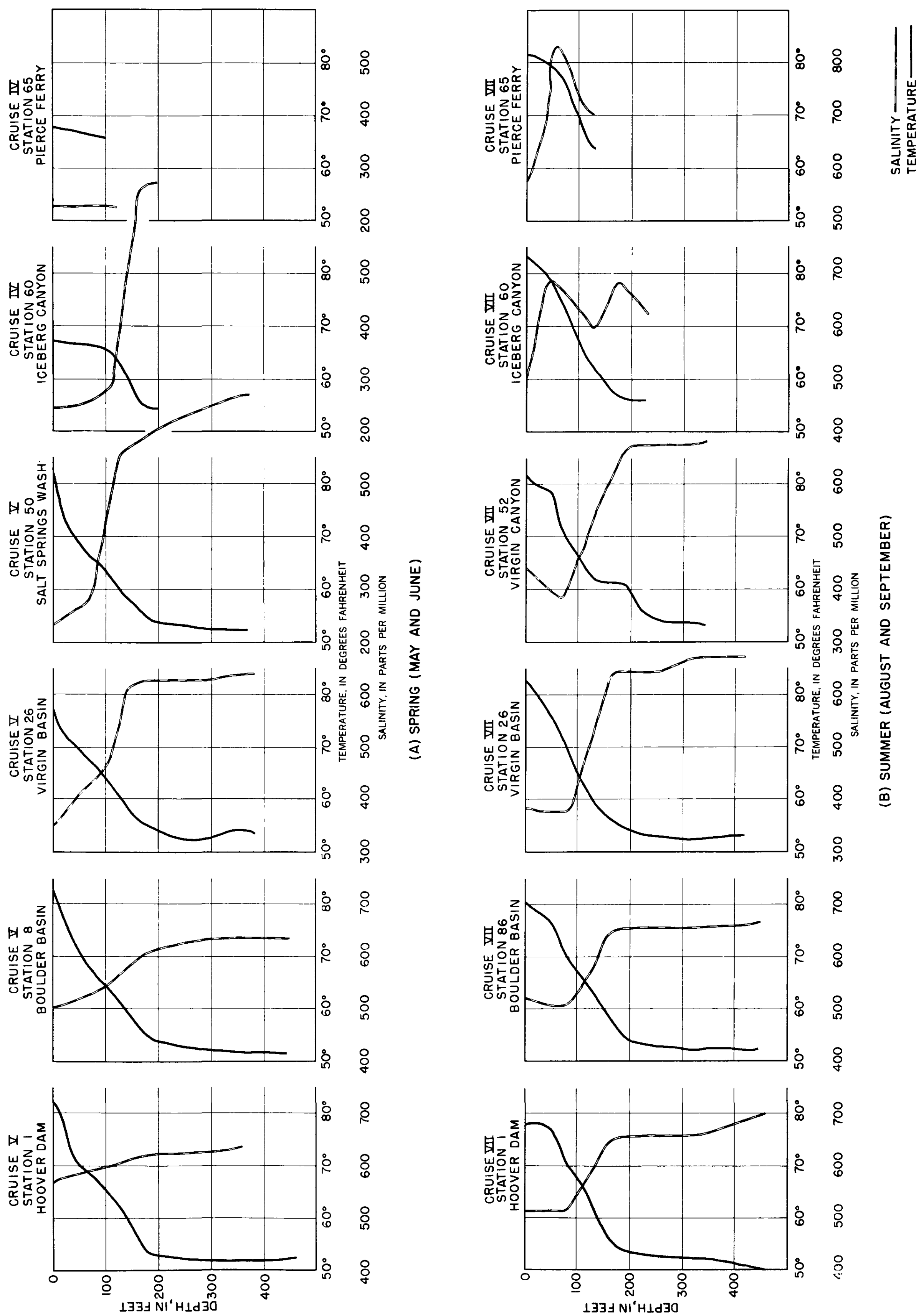

FIGURE 29.—Temperature and salinity data from selected stations on Lake Mead, spring and summer.

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For each survey a number of water samples, representative of all locations and depths, were sent to C. S. Howard, Geological Survey, Salt Lake City, Utah, for complete chemical analysis. The average ratio of salinity (total dissolved solids in parts per million) to conductivity of the samples analyzed by Howard was used to compute the salinities of all the other samples. A study of these data indicates that the error in salinity as determined by this procedure was in most cases less than 10 ppm.

The salinity was plotted against depth, for each Nansen station. A smooth curve was drawn through the points and values read from the curve at the surface and at 25, 50, 100, 200, 300, and 400 feet. The data were then used to prepare horizontal charts and vertical sections, just as for temperatures. From a study of the charts and sections it soon became evident that the longitudinal section made along the old Colorado River channel was the most important for the study of the seasonal cycle in the distribution of variables and in circulation. Most of the discussion deals with this longitudinal section.

Secchi-disc measurements were also plotted on a horizontal chart for each cruise, which was useful for determining the lateral spread of the inflowing water during the spring-flood runoff.

A *T–S* diagram was constructed for each Nansen station. For each cruise, those *T–S* diagrams that were very nearly the same were plotted on the same sheet, and the typical temperature-salinity relations for the various sections of the lake were determined. The typical relations have been plotted as "ribbons," showing the spread of observations used in constructing the typical *T–S* diagram.

Analysis of the data collected during the whole year at Lake Mead indicated a distinct and orderly cyclic progression in distribution of properties and in the implied circulation, which can be related to the seasonal changes of weather and river inflow.

On the basis of this single year's data it appears that the conditions observed in the January, February, and March cruises are characteristic of the winter season; in the May and June cruises, of the spring season; in the August and September cruises, of the summer season; and in the November and December cruises, of the fall season. The months of April, July, and October appear to be transitional between winter and spring, spring and summer, and summer and fall, respectively.

Conditions for each season are discussed on the basis of representative charts of each season. In some cases, actual observed data for a particular month are used as representative of a particular season; in other cases, distributions representing a slightly smoothed mean seasonal condition are presented. The vertical section taken along the old Colorado River channel appears to be the most important section from the standpoint of evaluation of circulation. A slightly smoothed preentation of the distribution of salinity and circulation along this section is discussed.

SPRING

The progressive nature of the changes in salinity distribution and circulation is best presented by starting with spring conditions. The inflow from the Colorado River into the lake during 1948 increased from about 22,000 cfs on April 1 to an average of 48,000 cfs during the period April 22–29, and to a peak of about 88,000 cfs in late May. Conditions characteristic of the spring season prevailed during May and June, though during June the inflow decreased slowly.

This high runoff results from spring melting, and the salinity of the inflowing water from the Colorado River is very low, having a value of approximately 220 ppm during the May cruise. Although the sediment load carried by this high flow is large, the heavier particles apparently settle out quickly upon entering the lake. The temperature of the inflowing water is nearly the same as that of the surface lake water, but its density is lower because of its very low salinity. The inflowing water, therefore, spreads rapidly downlake along the surface, overriding the residual lake water of higher salinity and density. The distribution of salinity along the old Colorado River channel in spring is indicated by one of the diagrams of figure 28. The vertical gradient in salinity in the lake above Virgin Basin is large. In Iceberg Canyon the vertical variation in salinity is from less than 260 ppm at the surface to more than 680 ppm on the bottom. Above Iceberg Canyon there is a sharp vertical increase of 300 ppm in the 50-foot layer between 80 feet and 130 feet.

The isohalines (lines of equal salinity) fan out vertically downlake. Between Virgin Canyon and Virgin Basin the vertical variation is from about 340 ppm to slightly over 660 ppm, and the layer of sharp salinity gradient is here nearly 90 feet thick, with a change of 200 ppm.

In Virgin Basin the vertical gradient has decreased still further. The 400-, 500-, and 600-ppm isohalines, which are nearly horizontal in the lake above Virgin Basin, curve upward in Virgin Basin, resulting in the largest horizontal gradient in salinity that was found along this section. In the lower end of Virgin Basin the increase from 400 ppm to 500 ppm along the surface indicates the front of the downlake spread of the lower-salinity inflow from the Colorado River.

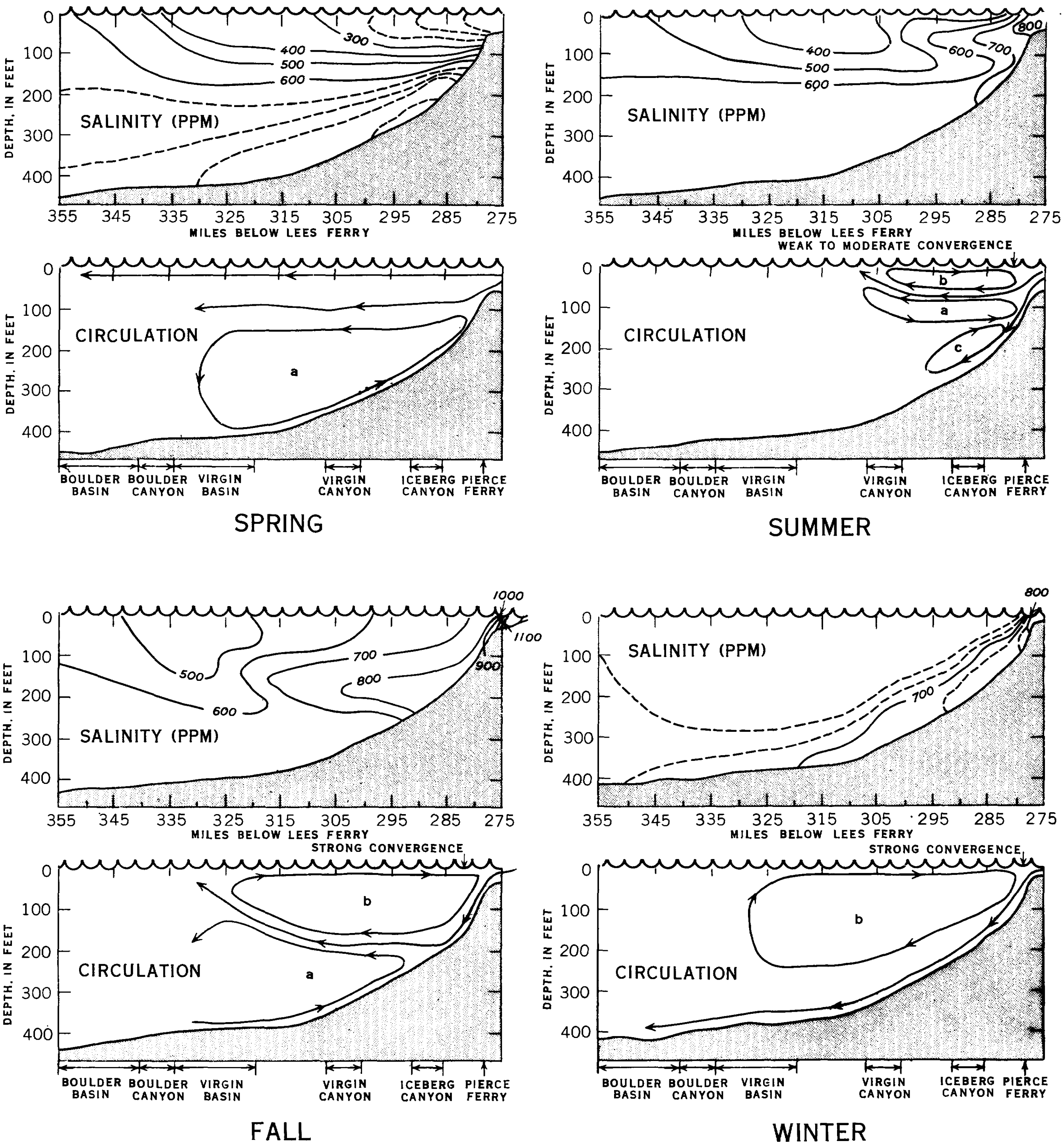

FIGURE 28.—Typical seasonal salinity distribution and circulation patterns in Lake Mead.

Characteristic of all seasons is the relatively uniform character of Boulder Basin salinity, indicating that Virgin Basin acts as a large "mixing bowl," in and above which the large seasonal variations in salinity of the inflowing waters are smoothed to nearly their mean value. Near Hoover Dam, at the lower end of Boulder Basin, the vertical salinity varies only from about 600 ppm to 640 ppm during the spring season.

Vertical curves of temperature and salinity characteristic of the spring season are plotted in figure 29*A* for stations located near Pierce Ferry, in Iceberg Canyon, Salt Springs Wash, Virgin Basin, Boulder Basin,

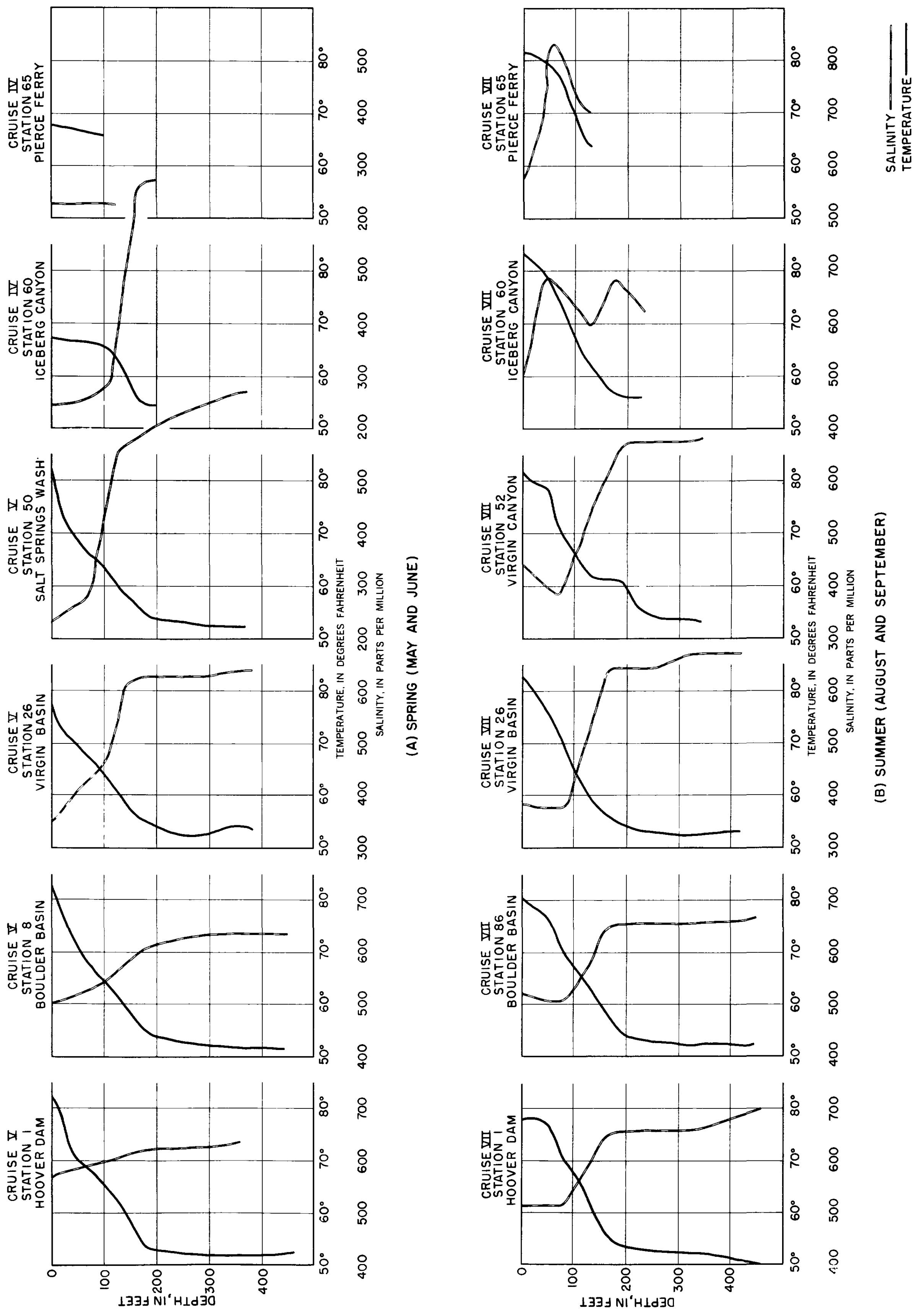

FIGURE 29.—Temperature and salinity data from selected stations on Lake Mead, spring and summer.

and in Black Canyon near Hoover Dam. These are actual observations and differ slightly from the somewhat smoothed picture presented in vertical section in figure 28.

Other diagrams on figure 28 offer a schematic presentation of the circulation along the old Colorado River channel. The major features during spring are the flow of fresher water downlake in the surface layer, and a counterclockwise cell below 100 feet. This cellular circulation results in flow uplake along the bottom in most of the section.

The lower boundary of the surface water flowing downlake is apparently indicated in May by the very sharp salinity and temperature gradient that occurs at a depth of about 140 feet in Iceberg Canyon. From the peak inflow of 88,000 cfs moving through the cross section of Iceberg Canyon, the velocity due to this inflow was computed to be 0.42 foot per second, or about 7.0 miles per day. The velocity of the inflow can also be computed from the movement of the isohalines. Between cruise III on April 22–29, and cruise IV on May 25–31, the 500-ppm isohaline moved downlake some 34 miles from its middepth position in Iceberg Canyon to a surface position in the Virgin Canyon. This movement corresponds to an average displacement of 1.2 miles per day. During the same period, the 600-ppm isohaline moved along the surface about 40 miles downstream, appearing in Boulder Canyon on cruise IV, which indicates a displacement of 1.4 miles per day. Along the bottom between Virgin Canyon and Iceberg Canyon, however, the 600 ppm isohaline had moved uplake about 13 miles, giving an average uplake displacement of about 0.5 mile per day. In comparing these figures, it should be remembered that the salinity distribution is a result of both advective flow and mixing, and that the displacement indicated by movement of isohalines is indicative of both processes and should not be interpreted as advective flow only. The figures obtained from the movement of the isohalines are, therefore, minimum figures, and the true downstream flow is probably between 1.2 and 7.0 miles per day.

The peak runoff from the Virgin River occurred in April, a month earlier than from the Colorado River. The average inflow from the Virgin River during the last half of April was about 400 cfs, but the peak was slightly over 600 cfs. By the time of the peak inflow from the Colorado River in May, the inflow from the Virgin River had decreased to less than 100 cfs, and it was less than 200 cfs during most of the other months studied. The peak flow of the Virgin River is much less than the minimum flow from the Colorado, and the salinity distribution indicates that the conditions in Overton Arm are affected more by conditions along the old Colorado River channel than by inflow from the Virgin River. Only during May does the inflow from the Virgin River appear to affect the salinity distribution much below Overton Landing, and even then the effect does not extend down to the Lower Narrows. During May and June the low-salinity water from the Colorado River spreads along the surface into Overton Arm, affecting the salinity distribution as far north as Overton Landing. Below the Lower Narrows the salinity distribution at all depths parallels closely the conditions in Virgin Basin. Figure 30 gives the salinity distribution along the channel in Overton Arm during the spring.

The spreading of the Colorado River water up into Overton Arm is clearly shown from the horizontal plot of the Secchi-disc readings for May. The sharp demarkation between the clear lake water and the turbid river water flowing downlake on the surface occurs along a line that runs up the center of Overton Arm as far as the lower Narrows (fig. 31).

The horizontal distributions of surface salinity and temperature for the May survey are shown in figures 32 and 33. The values of temperature shown are actually for 10-foot depths, since the surface temperatures are greatly affected by diurnal processes. Note that the spread of water from the head of Virgin Basin upward into Overton Arm is shown on the horizontal salinity distribution in figure 32.

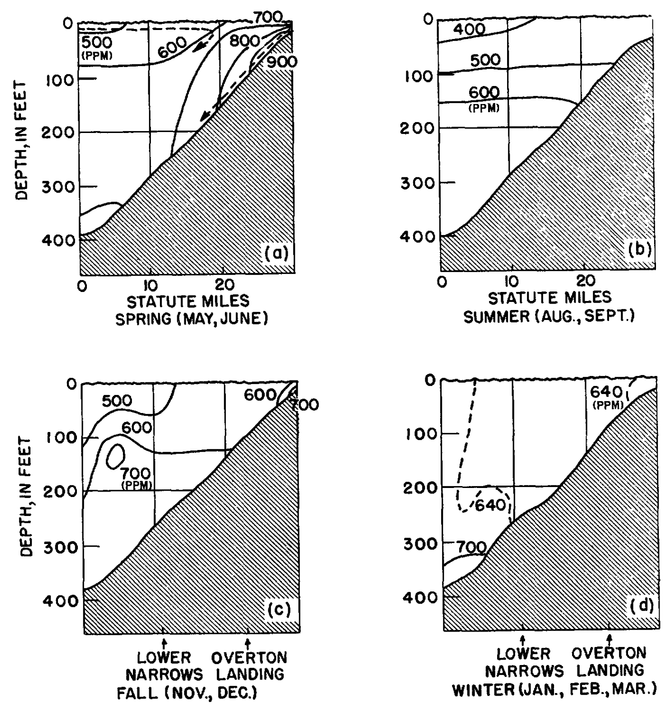

FIGURE 30.—Typical seasonal salinity distribution and indicated circulation in Overton Arm, Lake Mead.

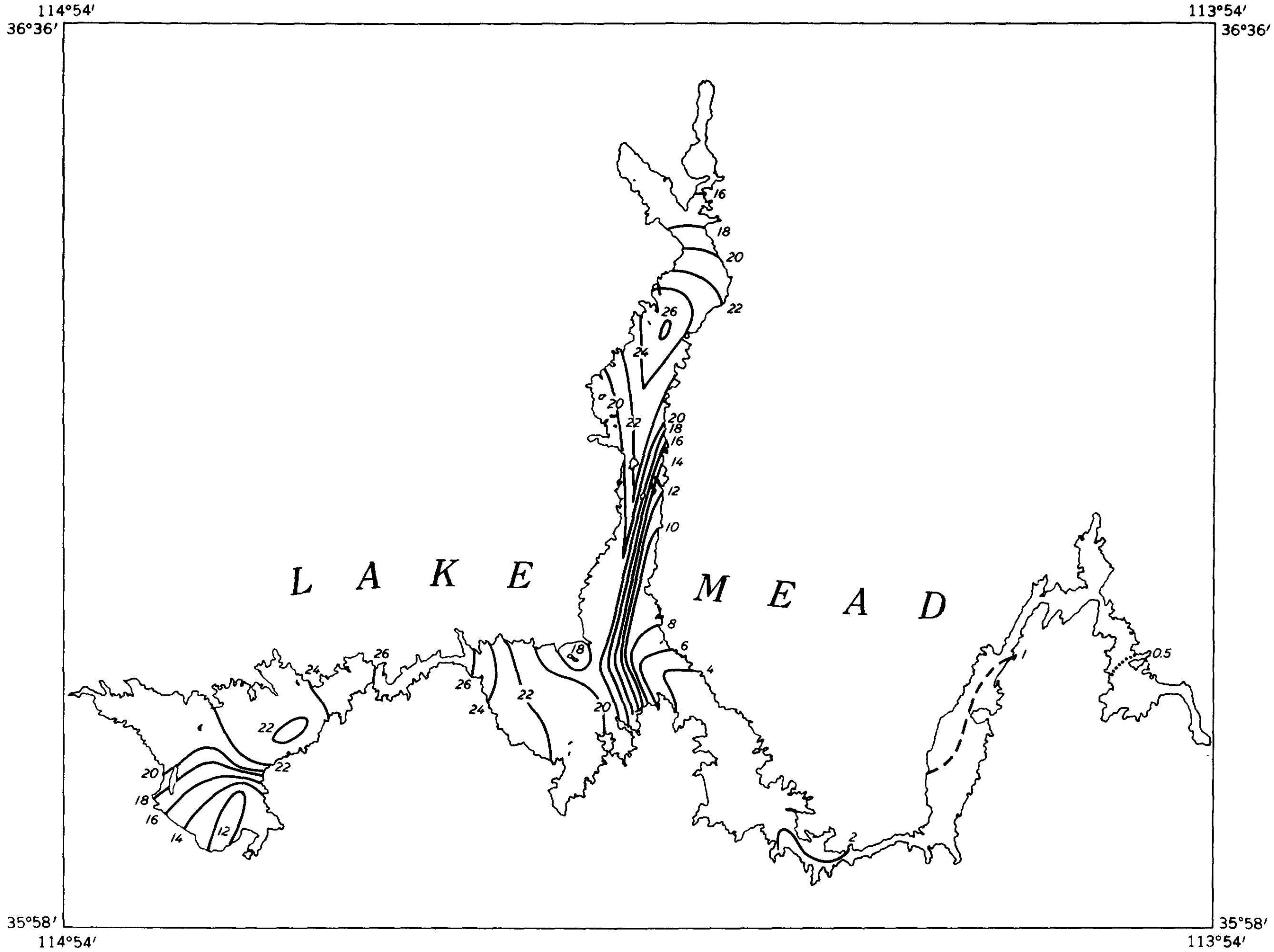

FIGURE 31.—Secchi-disc readings at Lake Mead, cruise IV, May 25–31, 1948.

SUMMER

The inflow from the Colorado River decreases rapidly after its peak in late May and early June; in 1948 it had declined to 9,500 cfs at the time of the August cruise and the extreme low for the year, about 3,000 cfs, occurred during mid-September. This decrease in volume is associated with increasing salinity. The inflowing water had a salinity of 875 ppm in August and 1,033 ppm in late September.

Inasmuch as the temperatures of the river and lake water are still nearly the same, the higher salinity results in a higher density, causing the inflowing water to sink to a depth of 80 feet beyond the edge of the delta. At this depth it spreads out over the more dilute but colder water, of still higher density, that remains from the spring inflow.

Figure 28 includes a cross section of the salinity distribution that is characteristic of summer along the old Colorado River channel. In the lake above Virgin Basin a tongue of high-salinity water extends downlake at a depth of about 80 feet, between layers of lower salinities. At 150 feet occurs a minimum-salinity layer that corresponds to the low-salinity water brought in during the high spring inflow. The high-salinity tongue extends downlake as far as the lower part of Virgin Canyon. Beyond this point the minimum-salinity layer is at the surface; there is a large region in the center of the lake with surface salinities of less than 400 ppm.

The surface water in Virgin Basin is a part of this low-salinity layer with salinities of 400 ppm or less down to about 100 feet. At a depth of 160 feet the salinity is 600 ppm; below 160 feet the salinity is very uniform but increases gradually with depth. In Boulder Basin the salinity gradients are very weak, with values of about 500 ppm at the surface and of 600 ppm to 670 ppm below 150 feet.

Vertical distributions of temperature and salinity found during this summer season are plotted in figure 29*B*, for stations located near Pierce Ferry, in Iceberg

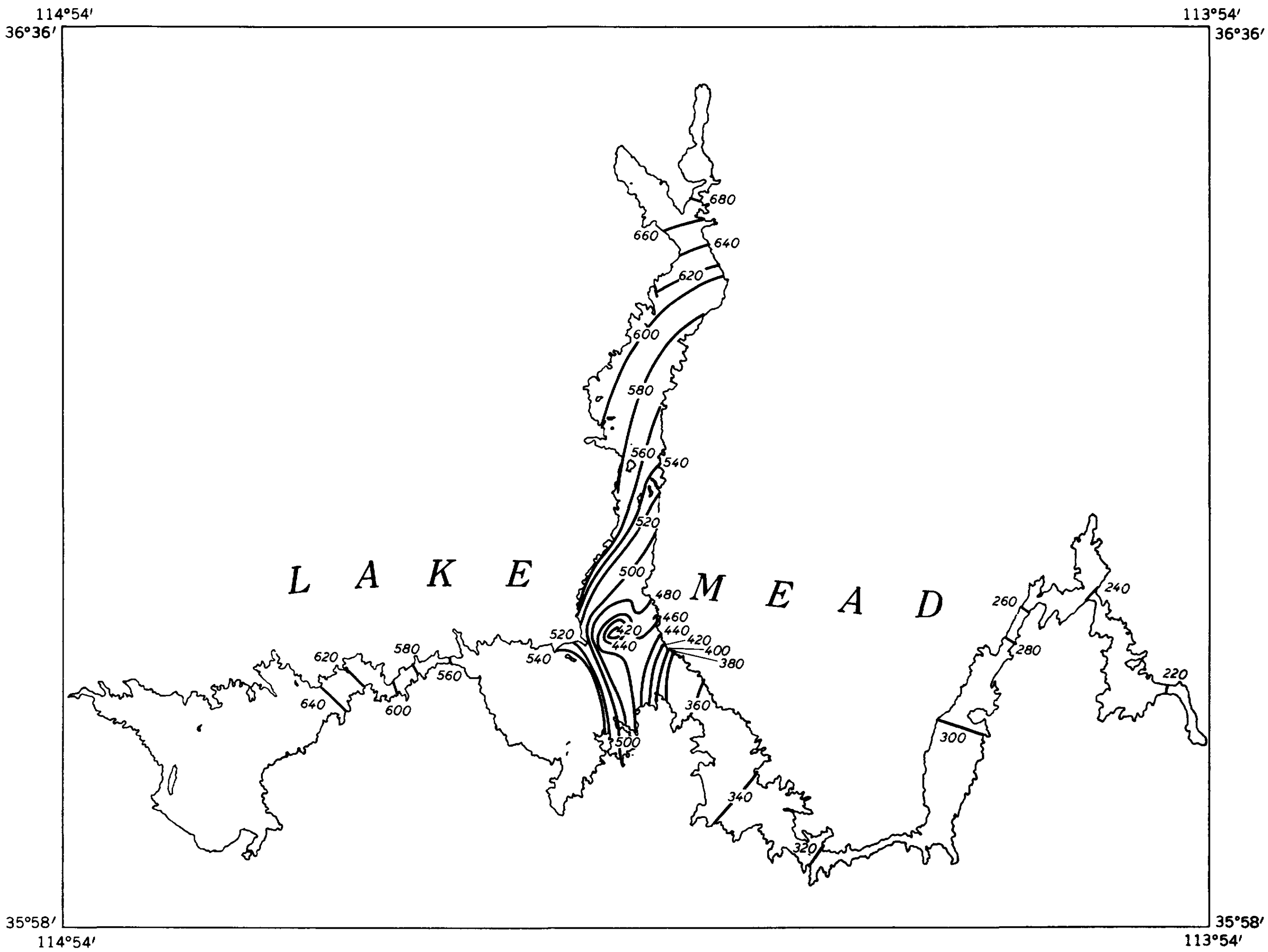

FIGURE 32.—Salinity (ppm) distribution at surface of Lake Mead, cruise IV, May 25–31, 1948.

Canyon, Virgin Canyon, Virgin Basin, Boulder Basin, and Black Canyon near Hoover Dam. These observed distributions bear out the characteristics of the salinity pattern presented in the longitudinal section in figure 28. Note the similarity between all the temperature traces in figure 29*B*. This uniformity in temperature structure is found throughout most of the lake, resulting in nearly horizontal isotherms.

The indicated circulation, based upon changes in the salinity distribution in the section along the old Colorado River channel, is also shown in figure 28. The cell designated as "a" on the graph for spring appears considerably smaller during the summer. The inflowing Colorado River water, being higher in salinity than the lake water, sinks to about 80 feet and spreads downlake at this level, thus giving rise to a new cellular circulation at the surface. This cell carries surface water uplake, causing a weak to moderate convergence to develop at the edge of the delta where the inflowing river water sinks.

There is evidence that some of the inflowing water continues to sink along the bottom past the 80-foot depth and helps to establish a clockwise circulation near the bottom above Virgin Canyon. This cell, designated on figure 28 as "c", appears only during the summer.

Between the July and August cruises the 400-ppm isohaline moved downstream some 18 miles, indicating a minimum displacement of approximately 0.6 mile per day in the region between Iceberg and Virgin Canyons. During the same period the movement of the 500 ppm isohaline gives a minimum daily displacement of 0.7 mile per day. In Iceberg Canyon during August the water flowing downlake appears to be confined to a layer about 100 feet thick, centered at about the 70-foot depth. Computing the current in this layer in Iceberg Canyon, whose width is about 1,500 feet, and average inflow is about 7,500 cfs, gives a velocity of 0.8 mile per day. Like the computations for the spring season, these figures must be conservative estimates of the actual velocity, because the salinity

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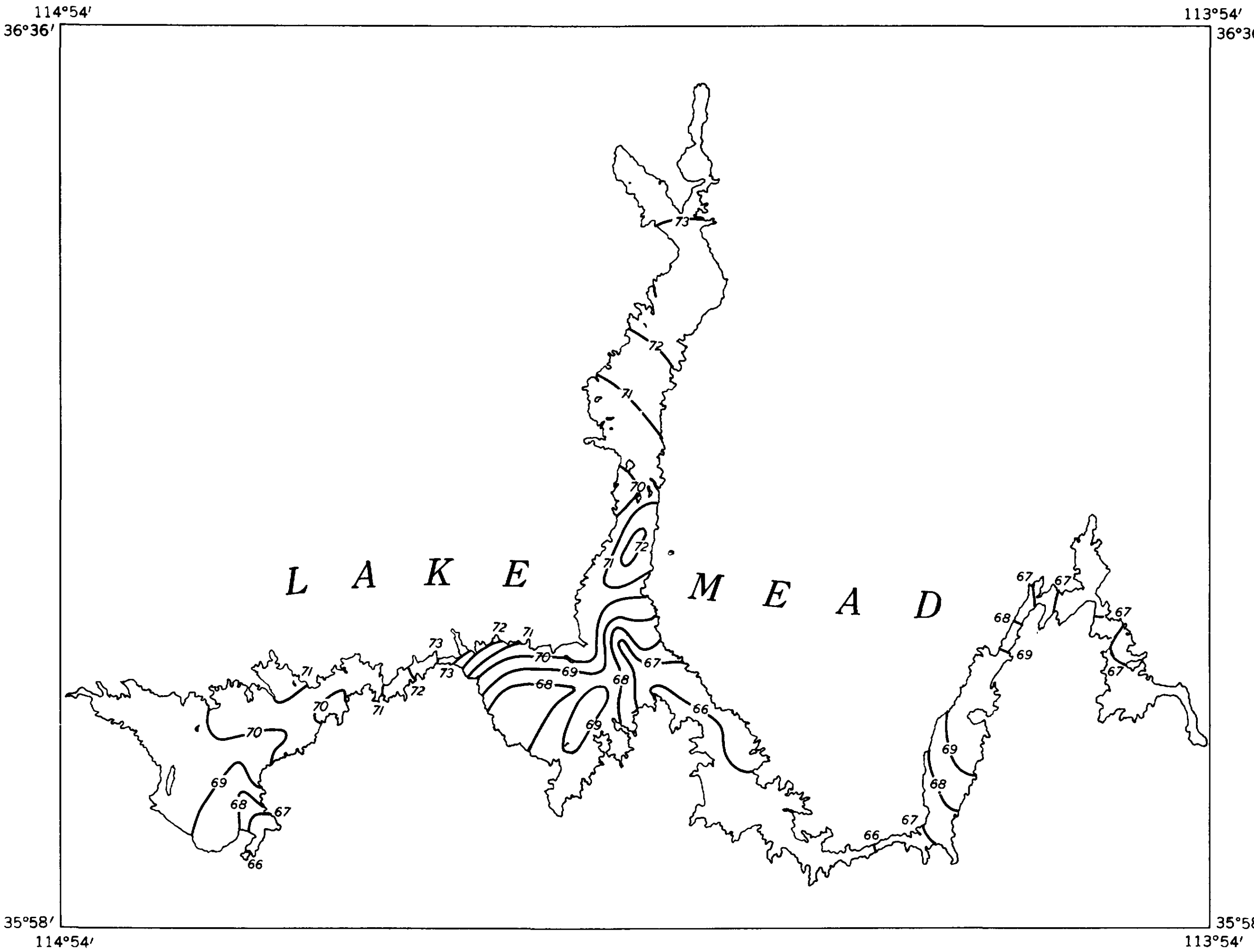

FIGURE 33.—Temperature (°F) distribution in Lake Mead at depth of 10 feet, cruise IV, May 25–31, 1948.

distribution reflects both advective and diffusive processes, and because more water is flowing downlake through Iceberg Canyon than comes in at the head of the lake, due to the effect of the cellular circulation above and below the downlake flow.

The inflow from the Virgin River into Overton Arm remains very low (about 100 cfs) during this season; in fact, from June through October. During the entire 5-month period the distribution of salinity in Overton Arm remains about the same, which reflects the spread of low-salinity water along the surface up into Overton Arm from Virgin Basin.

Figure 30 gives this salinity distribution along the channel in Overton Arm in summer. At depths less than 100 feet the salinity is less than 500 ppm; early in the season it is less than 400 ppm near the surface. The 600-ppm isohaline is found at about 150 feet during these 5 months; below this level the salinity increases slowly with depth. There is very little evidence that inflow from the Virgin River affects the salinity pattern. The dominant features in Overton Arm parallel conditions along the Colorado River channel in Virgin Basin.

The horizontal distribution of salinity and of temperature at the 10-foot depth during the August cruise are given in figures 34 and 35 respectively.

FALL

The inflow from the Colorado River remained low during the fall of 1948, averaging about 6,000 cfs during October, November, and December. The inflowing water had a fairly constant salinity of about 1,000 ppm, but its temperature steadily dropped as the season progressed, from 64°F in late October to 43°F in late November. Because of this decrease in temperature, the river water had a considerably higher density than the surface lake water.

The distribution of salinity along the old Colorado River channel in the fall is shown in figure 28. The tongue of high salinity and density, evident at about 80 feet during the summer, now extends down the face

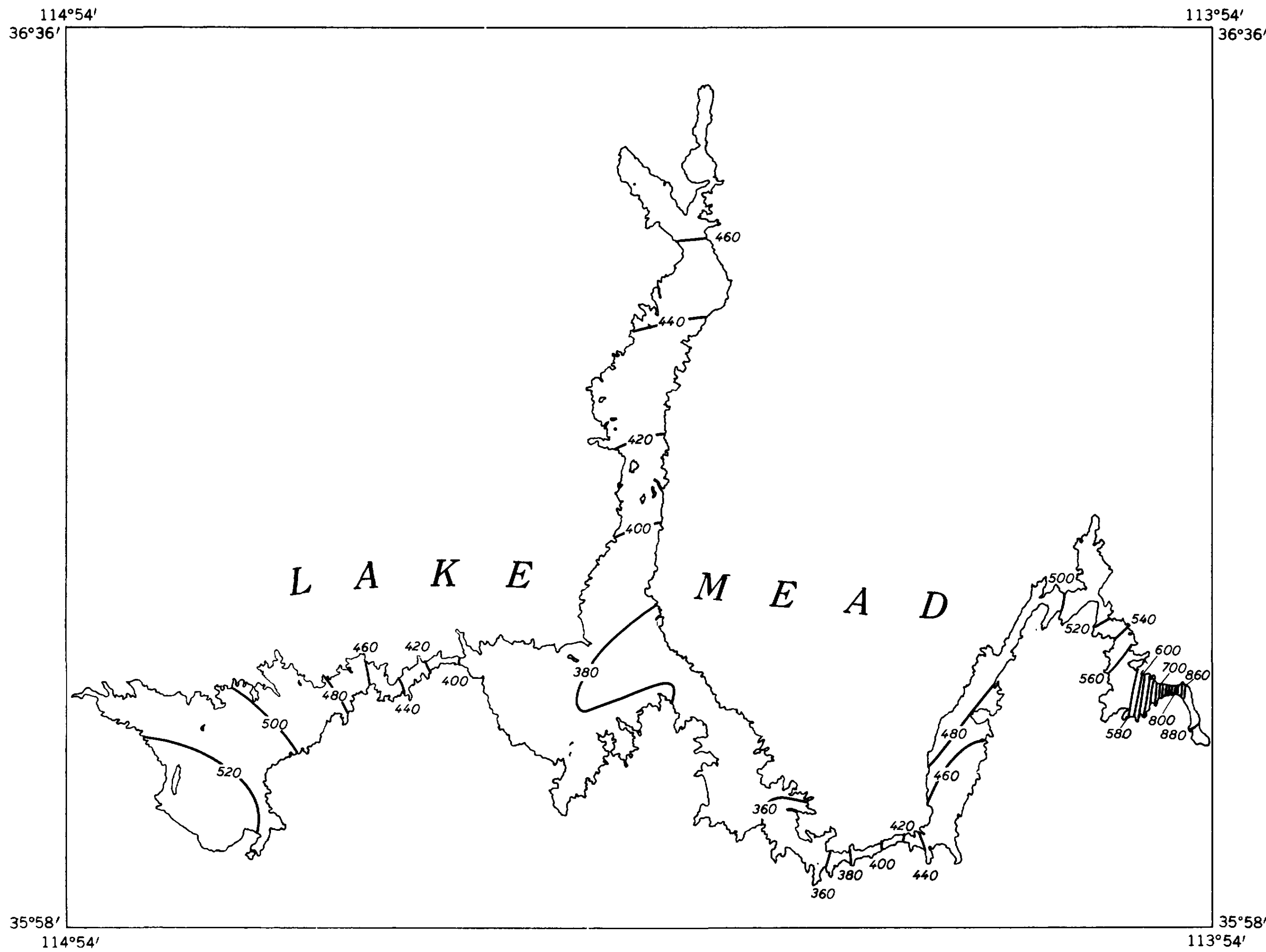

FIGURE 34.—Salinity (ppm) distribution at surface of Lake Mead, cruise VII, August 22–26, 1948.

of the delta and spreads out at about the 170-foot depth. It slopes slightly toward the surface and appears as a bulge in the 500-ppm isohaline at a depth of about 100 feet in Virgin Basin.

A very sharp salinity and temperature gradient occurs at the head of the lake; within a distance of a few hundred yards, during the November cruise, the surface values of salinity ranged from 1,070 ppm in the river to 730 ppm in the lake, and the temperature from about 43°F in the river to about 62°F in the lake. This is the area of "convergence," and it is sharply marked at the surface just below Lower Granite Gorge by a line of accumulated floating debris. Upstream from this line the surface water is flowing downriver, and downstream from it the surface lake water has a definite uplake movement. This feature was observed to be particularly strong during the period from October through March, appearing in moderate intensity in September; from June through August the convergence completely disappears.

This convergence phenomenon is always associated with flow of the river water below the lake water. Figure 28 includes the pattern of circulation deduced from the salinity distribution along the old Colorado River channel during the fall. The river water flows downward over the edge of the delta as in summer but, because of the decrease in temperature, it continues to flow down along the bottom to nearly the 200-foot depth before spreading horizontally downlake. The flow appears to slope upward as it progresses downlake, appearing near the surface in Virgin Basin. The two major cellular circulations that occur in the summer remain throughout the fall, cell "a" appearing deeper and farther downlake, and cell "b" becoming considerably larger.

Figure 36 gives the vertical plots of temperature and salinity found during the fall, at stations near Pierce Ferry, in Iceberg Canyon, Virgin Canyon, Virgin Basin, and Boulder Basin, and in Black Canyon near Hoover Dam. The uniformity in the temperature

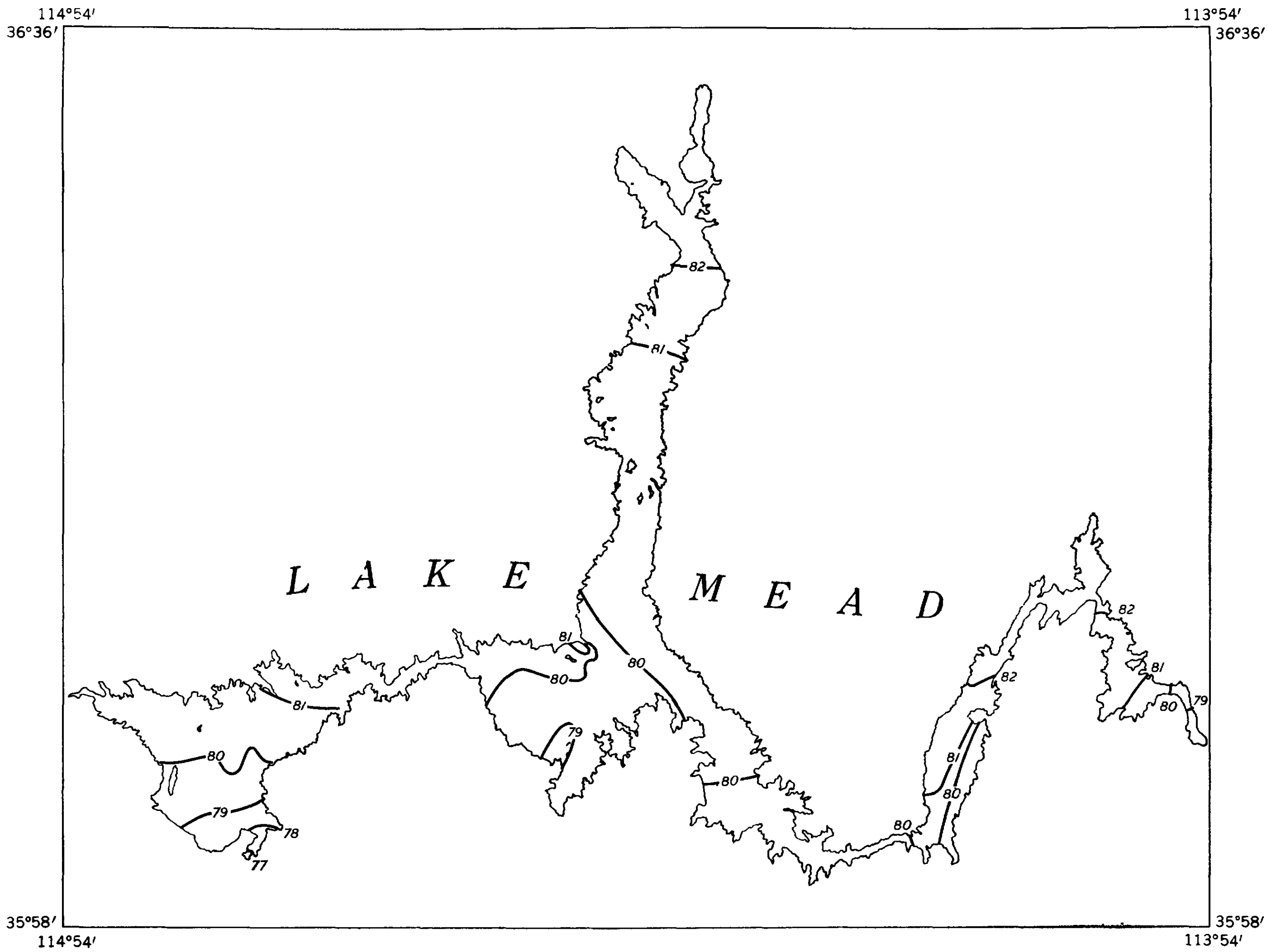

FIGURE 35.—Temperature (°F) distribution in Lake Mead at depth of 10 feet, cruise VIII, August 22–26, 1948.

structure as far uplake as Virgin Canyon is evident in these plots.

Between the October and November surveys the 700-ppm isohaline moved downlake at middepths for about 23 miles, corresponding to an average daily displacement of 0.66 mile. In Iceberg Canyon the downlake flow appears to be confined to a layer about 100 feet thick. The average inflow of 6,000 cfs would produce a flow of 0.65 mile per day in this layer in Iceberg Canyon.

The Virgin River flow increased slightly during the fall, having an average value of about 160 cfs. Evidence of relatively high-salinity flow from this river appears in the salinity distribution of Virgin Arm as far down as Overton Landing (fig. 30). At the lower end of Overton Arm the high-salinity inflow from the Colorado River probably causes the maximum of about 700 ppm at depth of 150 feet in the salinity distribution. It appears that the high-salinity water flowing down the Colorado River channel cuts northwestward across the head of Virgin Basin into Overton Arm. A low-salinity layer of less than 500 ppm remains near the surface below the Lower Narrows.

The horizontal distribution of surface salinity and 10-foot temperature for the November cruise is shown in figures 37 and 38.

WINTER

The observational program actually began in the winter, the first cruise having been made in February 1948. The last cruise was also made in February, 1 year later. The second winter was considerably colder than the first; in fact, the winter of 1948–49 was the coldest in more than 30 years, and this abnormal condition is reflected in both low temperatures and low inflows. Conditions corresponding to the first winter are discussed here with some modifications, as required by information gained from the January conditions observed in the second winter. Differences between the two February cruises are discussed at the end of this section.

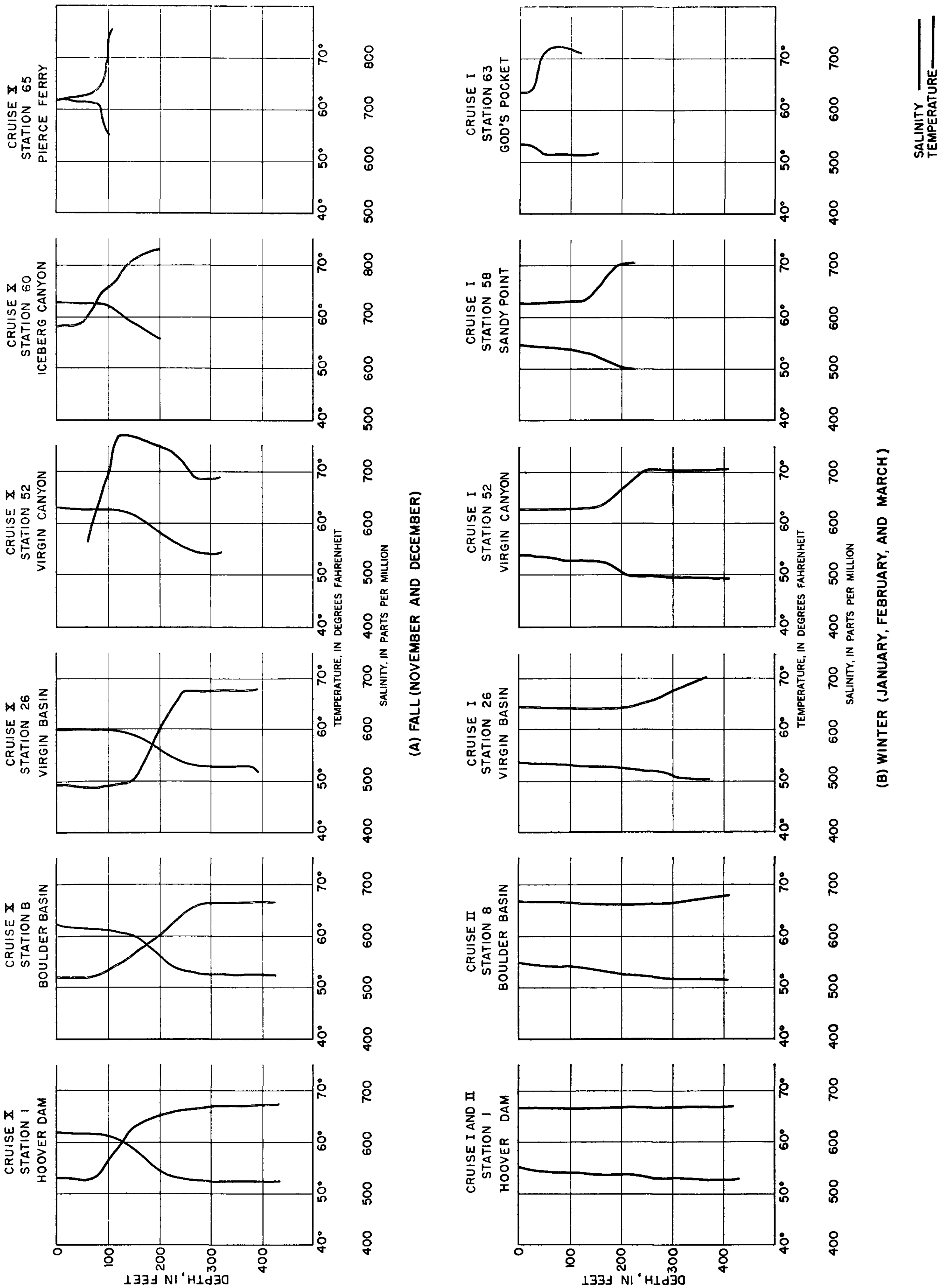

FIGURE 36.—Temperature and salinity data from selected stations on Lake Mead, fall and winter.

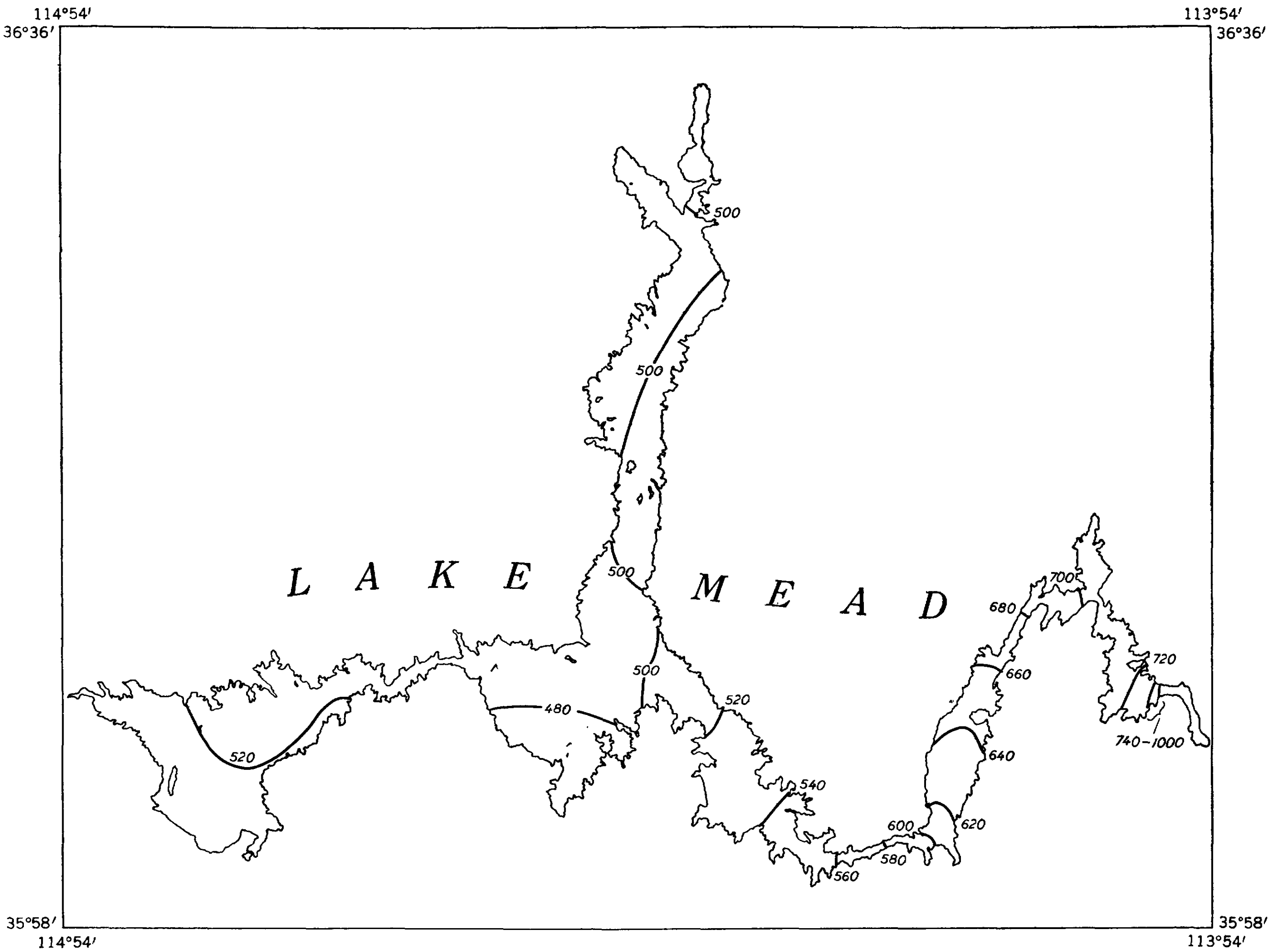

FIGURE 37.—Salinity (ppm) distribution at surface of Lake Mead, cruise X, November 27–30, 1948.

The inflowing water from the Colorado River continues to become colder, hence it sinks farther along the bottom until in midwinter the maximum salinity occurs along the very bottom and the high-salinity tongue extends into Boulder Basin. Figure 28 gives the salinity distribution along the old Colorado River channel for the first winter. Extremely uniform conditions exist throughout a large layer, extending from the surface downward for about two-thirds of the area of the section.

The circulation for this season along the Colorado River channel is also shown in figure 28. Cell "a", which dominated the spring pattern and was evident in summer and fall, has now disappeared. The river water flows down over the edge of the delta, where a marked surface convergence occurs, and spreads downlake along the bottom. Above this flow there is a cellular circulation, and the surface water moves uplake to the head and then sinks parallel to the river inflow.

Between the February and March cruises the 720-ppm isohaline moved downlake approximately 19.5 miles along the bottom from upper Iceberg Canyon to the lower part of Virgin Canyon. During the same period the 700-ppm isohaline had moved 17.5 miles from lower Virgin Canyon to the center of Virgin Basin, and the 680-ppm isohaline had moved 11.5 miles from the upper part of Boulder Basin into Black Canyon. These three cases give displacements of 0.6 mile per day near the head of the lake, 0.5 mile per day in the midpart of the section, and 0.3 mile per day in Boulder Basin.

In Iceberg Canyon the water flowing downlake appears to have been confined to the lower 100 feet. With an inflow of 13,000 cfs, as in February 1948, the flow in this layer in Iceberg Canyon would correspond to 1.4 miles per day. The canyon, of course, is a constricted section and would give velocities greater than those occurring in other areas.

Figure 36*B* shows the temperature and salinity curves for stations located along the old Colorado River

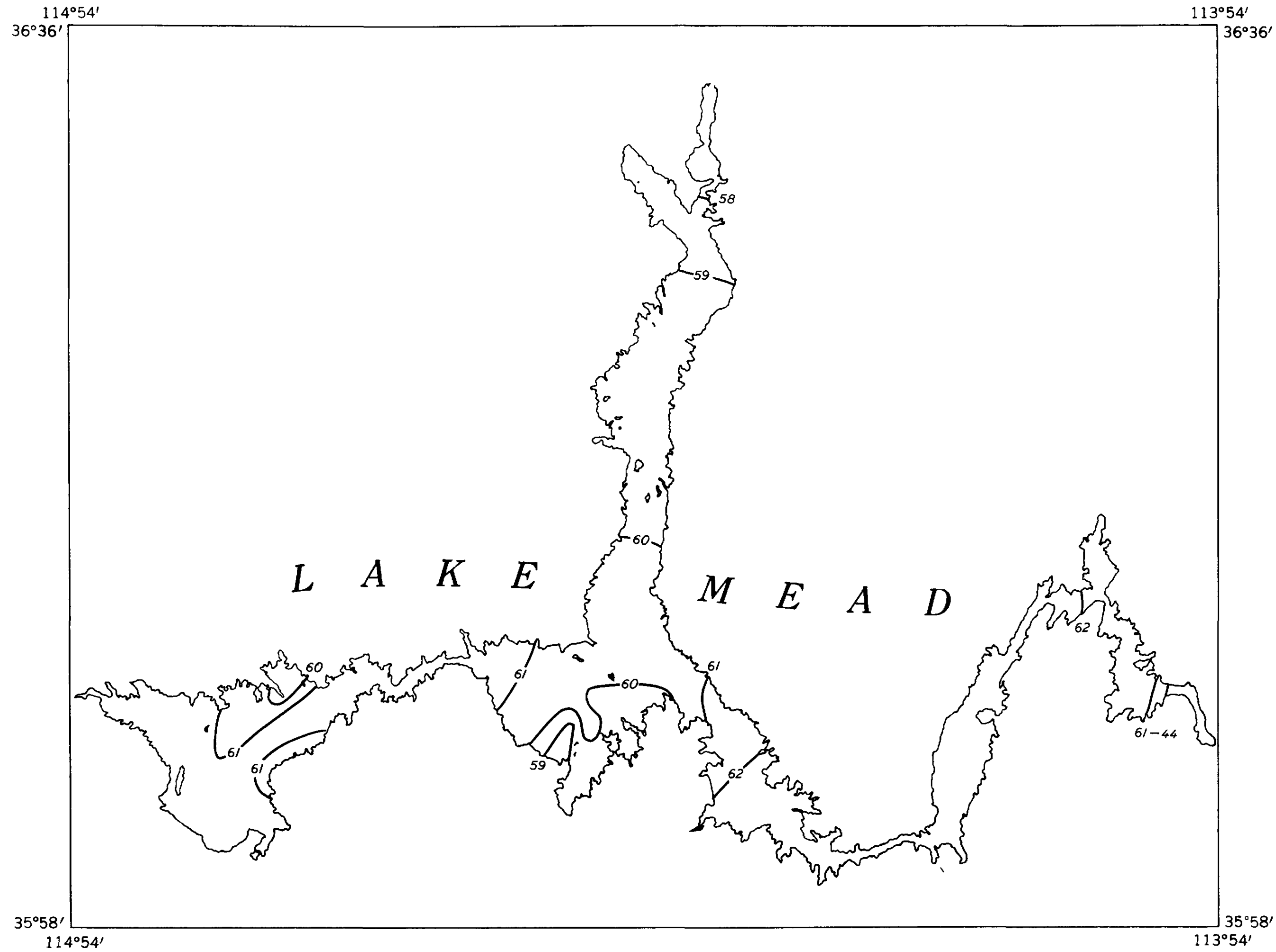

FIGURE 38.—Temperature distribution in Lake Mead at depth of 10 feet, cruise X, November 27–30, 1948.

channel. These traces show the extremely uniform conditions in both temperature and salinity that prevail over much of the section.

The uniform conditions prevailing along the Colorado River channel extend also into Overton Arm. The effect of the higher salinity flow of Colorado River water along the bottom appears at the lower end of the section along the channel in Overton Arm. The salinity distribution along this section for winter is shown in figure 30.

The horizontal distribution of surface salinity and 10-foot temperature is given in figures 39 and 40 respectively for the cruise of February 1948. The extremely uniform horizontal field is evident from these charts.

That conditions differ from year to year is evident from the differences found between cruise I in February 1948 and cruise XII in February 1949. The second winter was abnormally cold; the temperature of inflow in February 1949 was some 8°F less than in February 1948, and the temperatures in the lake were 3°F–5°F less at all levels. The inflow during cruise XII was only 4,500 cfs as compared with 13,000 cfs during cruise I.

Despite these differences the major character of the salinity pattern and the indicated circulation did not differ materially between the two winters. It is believed that the important features of the circulation for all seasons as presented above is repeated from year to year.

SUMMARY OF THE CIRCULATION PATTERNS

In winter the salinities in the lake are uniform, ranging from 600 to 700 ppm. The inflowing Colorado River water, with higher salinities, flows down over the edge of the delta and along the bottom in the old river channel, where it seems to influence bottom salinities well into Boulder Basin. A single cellular circulation exists, resulting in an uplake flow of surface waters from Virgin Basin.

The spring runoff results in high inflow from the

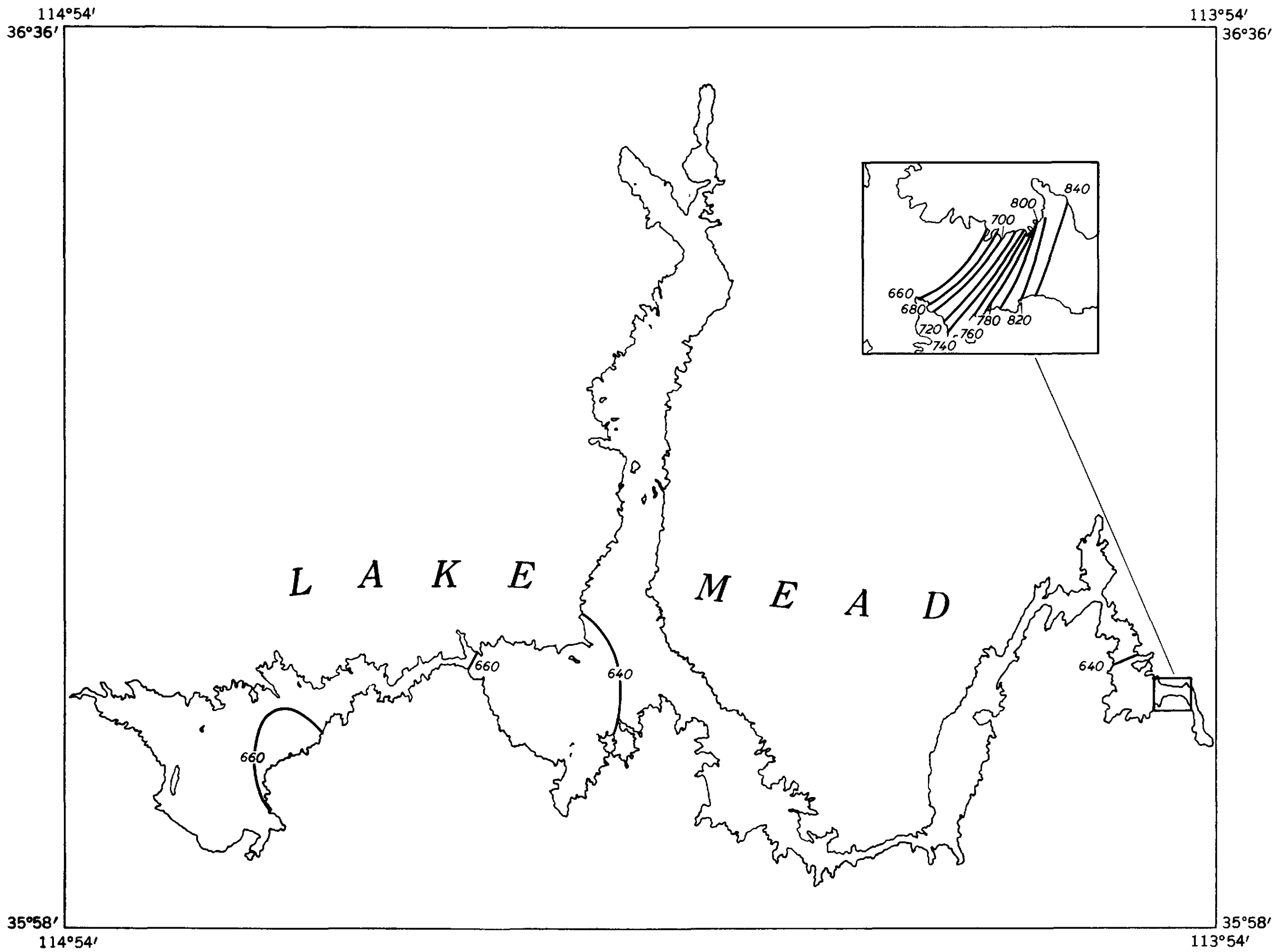

FIGURE 39.—Salinity (ppm) distribution at surface at Lake Mead, cruise I, February 25–29, 1948.

Colorado River, which, because of its low salinity of 200 to 300 ppm, flows out over the lake water, producing a layer of low salinity over most of the lake. The flow along the surface sets up a cellular circulation below the depth of 150 feet which gives rise to flow uplake along the bottom.

In summer, with decreasing inflow and increasing salinity of inflow, the downlake spread of Colorado River water occurs at about 80 feet below the surface. Above Virgin Canyon two distinct cellular circulations occur, one in the surface flow and the other below 80 feet, resulting in an uplake flow in deeper waters. There is some evidence of a third cell, which produces downlake flow along the bottom, caused by the sinking of some sediment-laden inflow water along the bottom.

In the fall the decrease in temperature of inflow from the Colorado River is associated with a further sinking of the inflowing river water. During this season there is downlake flow along the bottom until, at a depth of about 170 feet, the flow spreads horizontally downlake and then slopes slowly up toward the surface. Two large cellular circulations, one producing uplake movement of surface water and the other uplake movement of bottom water, exist above the Virgin Basin.

The seasonal cycle is completed when, with further increase in density, the inflowing waters flow all the way down the slope of the delta along the bottom. The deep cellular circulation is eliminated and the single cell of the winter season remains.

Overton Arm appears to reflect primarily the water conditions found in Virgin Basin. The influence of flow from the Virgin River is seen only in the upper few miles of the arm. Sedimentation below Lower Narrows in Overton Arm would appear from this analysis to result from the flow into Overton Arm of water of Colorado River origin. That turbid water from this source does extend into Overton Arm is evident from the Secchi-disc readings made during the May survey.

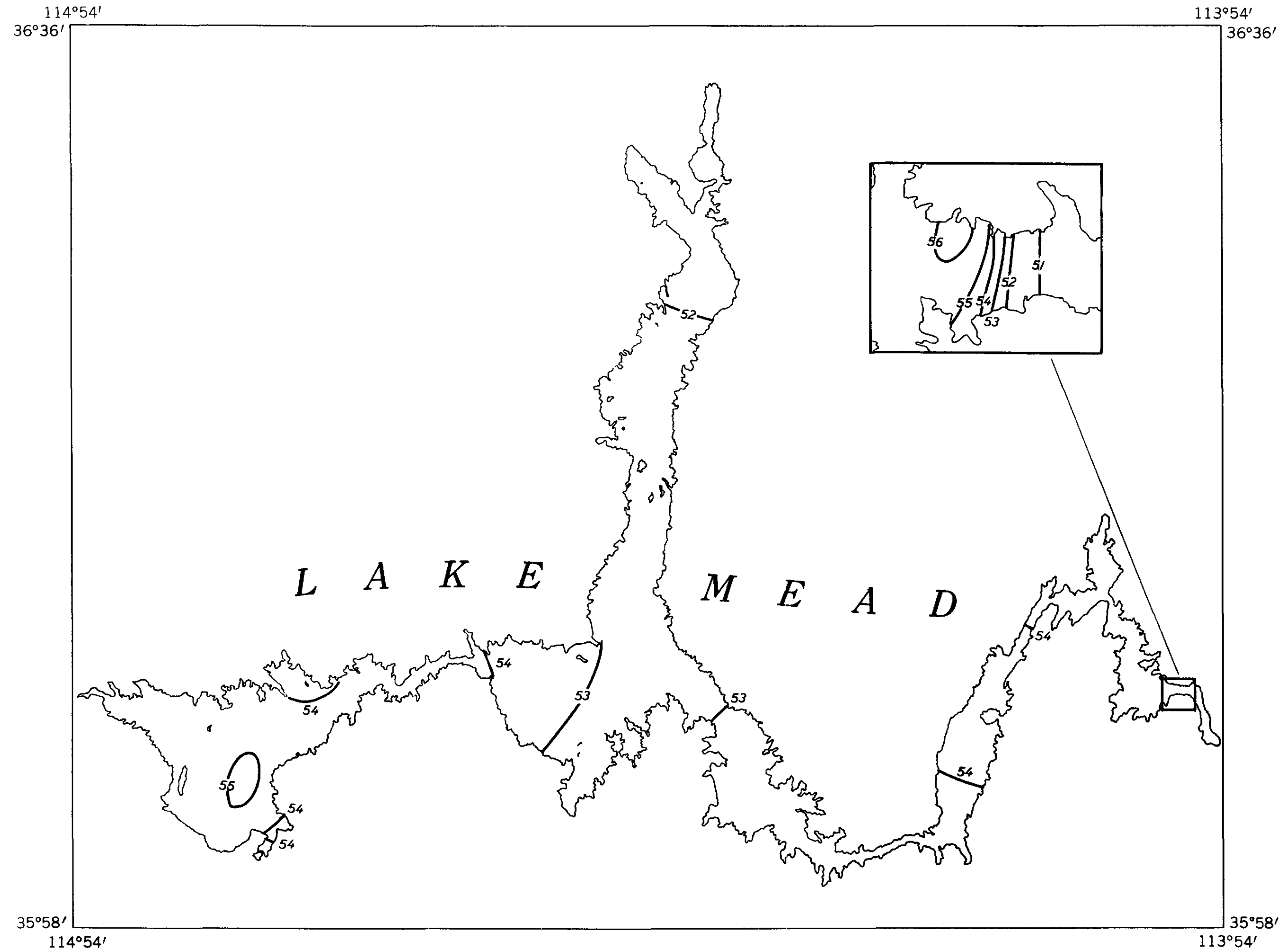

FIGURE 40.—Temperature (°F) distribution in Lake Mead at depth of 10 feet, cruise I, February 25–29, 1948.

EVAPORATION

TECHNIQUES FOR DETERMINING EVAPORATION

At present there are four methods of estimating evaporation from a body of water: (a) water budget, (b) evaporation pan, (c) mass transfer, and (d) energy budget. The nature of the observational program developed for this study made it possible to gather enough information on the pertinent parameters to establish a preliminary energy budget.

Since Schmidt (1915) first estimated evaporation from the oceans by means of the energy budget, numerous attempts have been made to apply it to the determination of evaporation from small bodies of water. For example, Ångström (1920) and Cummings (1940), respectively, computed evaporation from a lake in Sweden and from Bear Lake, Utah, using an evaporation pan together with equations based on the energy concept. These and other attempts to compute evaporation from energy concepts have been beset with difficulty in evaluating the various parameters, especially energy storage. The application of the bathythermograph (Spilhaus, 1938), an instrument that makes a vertical temperature profile at a given place, and of the echo sounder, which provides the data for obtaining accurate lake volumes, has made it possible to evaluate the energy-storage factor.

ENERGY BUDGET

The energy budget for a body of water may be written

$$Q_s - Q_r - Q_b - Q_h - Q_e + Q_v = Q_\theta \qquad (1)$$

in which Q_s is the solar radiation incident to the water surface; Q_r, the reflected solar radiation; Q_b, the net energy lost by the body of water through the exchange of long wave radiation between the atmosphere and the body of water; Q_h, the energy conducted from the body of water to the atmosphere as sensible heat; Q_e, the energy utilized by evaporation; Q_v, the net energy advected into the body of water; and Q_θ, the change in energy stored in the body of water. Q_r, Q_b, Q_h, and Q_e

have negative signs because normally they represent a loss of energy in the body of water.

This equation has been applied to the problem of obtaining a preliminary value of evaporation from Lake Mead.[13]

The energy budget equation 1 may be solved for evaporation to obtain the following

$$E=\frac{Q_s-Q_r-Q_b+Q_v-Q_\theta}{\rho L(1+R)} \qquad (2)$$

in which E is the amount of evaporation, L is the latent heat of vaporization, ρ the density of the water, and R is the Bowen ratio (Bowen, 1926) or the ratio of the energy used to conduct sensible heat to or from the water surface to that used by evaporation.

It can be shown (Anderson, 1953) that equation 2 is an approximation, inasmuch as the energy advected from the lake by the volume of evaporated water is not considered in its development. If this process is taken into consideration, slightly lower values than those given by equation 2 result. The corrective term was not applied to the computations herein reported because of uncertainties of greater magnitude that are introduced inevaluating some of the other terms.

In applying this equation to Lake Mead it is necessary to evaluate each of the terms on the right side of the equation. The terms Q_s, Q_v, Q_b, Q_e, and Q_h—the latter two being obtained through the use of the Bowen ratio—contribute directly to the energy budget, whereas Q_θ, the change in energy storage, is a balancing term and Q_r, the reflected energy, is a corrective term.

RADIATION FROM SUN AND SKY

The value Q_s was obtained by utilizing a method presented by Kennedy (1949) for computing insolation for either a day or a half-day. His method may be used when it is desired to obtain the insolation at a station that is located at the same latitude and elevation as a weather station and a pyrheliometer station where the insolation is known. Basically, the method is an extrapolation of the measured data at the pyrheliometer station to the station in question.

REFLECTED SUN AND SKY RADIATION

Part of the incoming solar radiation is lost, as far as the body of water is concerned, by reflection at the surface (Q_r). The amount lost is probably dependent upon the altitude of the sun, amount of cloudiness, turbidity of the atmosphere, and the hydrodynamic character of the water surface. The average altitude of the sun was computed for each month. Using the value for the sun's altitude and the percentage of incoming solar radiation reflected from a horizontal water surface at different altitudes of the sun in clear weather—obtained from a table prepared by Sverdrup and others (1946)—an average monthly value for reflection was obtained. Considerable controversy exists over the reflectivity of a water surface; but it was believed that the above method gave the best estimate of reflection that was possible at that time.

EFFECTIVE BACK RADIATION

The difference between the long-wave radiation emitted from the water surface and that received from the atmosphere is the effective back radiation (Q_b). It is difficult to evaluate, owing to a lack of pertinent observations. The effective back radiation is a function of the surface-water temperature, vapor pressure or relative humidity a short distance above the water surface, emissivity of the water surface, and cloudiness. The nature of the observational program made it impossible to obtain representative monthly averages of these variables, and they were therefore evaluated from Boulder City weather observations, corrected or modified as necessary by the observations taken during the monthly cruises. After obtaining the best representative values of the above variables, the effective back radiation was obtained by using empirical relationships established by Ångström (1920) and developed in graphs by Sverdrup and others (1946). This procedure may result in inaccuracies of 10 to 20 percent.

ADVECTED ENERGY

The advected energy (Q_v) is the sum of all inflows and outflows of energy. The net amount of energy advected into and out of Lake Mead has been computed on a monthly basis, largely from daily inflow and outflow information supplied by the Geological Survey and the Bureau of Reclamation. The inflow measurements were made at Grand Canyon, Ariz., for the Colorado River, and at Littlefield, Ariz., for the Virgin River, both being a considerable distance from Lake Mead. The volume of outflow, as well as its temperature, was measured at Hoover Dam.

The temperature of the inflowing Colorado River water and Virgin River water was determined from bathythermograms made near the points of inflow into the lake during the monthly cruises. Daily values of the difference of the quantity of energy flowing into and out of the lake were computed and summed to give the monthly values.

No attempt was made to evaluate seepage, bank storage, or local runoff, and any possible gain or loss of

[13] This study of the energy budget of Lake Mead and the estimate of evaporation derived therefrom represent a preliminary study made in connection with the comprehensive survey of 1948–49. The descriptions and results presented here show the stage of development of the method at that time. For a more recent and comprehensive treatment of the energy-budget method as applied to Lake Mead, see the report by Koberg (1958).

energy from these sources. Two additional sources of inaccuracy are possible in the computation of the advective term: (1) in the determination of the temperature of the inflowing and outflowing water and (2) in the use of the flow figures from the Grand Canyon station to give inflow data. The values of the temperature of inflow and outflow are believed to have a maximum error of $\pm 1.0°$F. The maximum error would result in an error in computed evaporation of less than 4 percent from July through February and about 10 percent from March through June; the latter figure would be larger primarily because of the great increase in river flow during these months. This estimate of error in the evaporation figures assumes that the error in the temperature of inflowing water was opposite in sign to the error in temperature of the outflowing water, and therefore the temperature error is cumulative. The actual error in evaporation estimates from this source may therefore be less than the above values.

The actual inflow to Lake Mead may be substantially greater or less than the flow measured at Grand Canyon, 190 miles upstream from Pierce Basin. From July through March a 10-percent error in quantity of inflow would result in an error of less than 3 percent in evaporation; but in April, May, and June the error in calculated evaporation would be 6, 14, and 15 percent, respectively.

ENERGY STORAGE

Energy storage (Q_θ) was computed from about 60 temperature profiles taken in all parts of the lake during the monthly cruises. As far as is known, this represents the first attempt to evaluate the term accurately. The energy storage was computed by layers for each temperature profile. Comparison of the various values indicates that storage is relatively constant as between one part of Lake Mead and another, and that possibly it can be evaluated from one or two profiles or at most one profile taken in each major basin.

BOWEN RATIO

The Bowen ratio (R) is the ratio of the energy conducted from the lake as sensible heat (Q_h) to the energy utilized by evaporation (Q_e). Its computation requires average monthly values of the temperature of the lake surface and the temperature and humidity of the air over the lake. Information on the lake-surface temperature was available from the monthly cruises, but information on the air temperature and humidity at the lake was quite inadequate. However, the information was available for Boulder City, in the records of the U.S. Weather Bureau. By using this information and comparing it with such data as were available at Lake Mead, an approximate Bowen ratio was determined. Inasmuch as the ratio appears only as a corrective term in the equation, the effects of errors in the ratio are small. Thus a 25 percent error in R results in a maximum error in monthly values of evaporation of only 9 percent, and an average error in the monthly calculated evaporation of 6 percent.

SUMMARY

From this discussion of the various terms in the evaporation equation, it may be concluded that the computed evaporation probably was not in error by more than 20 per cent. Figure 41 indicates the average monthly values of the various parameters in the energy budget equation as computed for Lake Mead, using the techniques outlined above.

The solar radiation (Q_s) varies as expected, the maximum radiation occurring in June and the minimum in January, while the reflected radiation (Q_r) is nearly constant from one month to the next. From April to August, energy (Q_v) is advected into the lake as a result of the high inflow from the Colorado River, and from September to March, a small amount of energy is advected from the lake. On an annual basis, more energy is brought into the lake by advection than is taken out. The effective back radiation (Q_b), which so far as the lake is concerned represents a loss of energy, is nearly constant from month to month. During the summer less than one-fourth of the total energy supplied by solar radiation and advection is dissipated by this process, but in January the back radiation is nearly equal to solar radiation. The curve for energy storage (Q_θ) follows in general the solar radiation curve, the maximum occurring in June and the minimum in November. The sum of energy used for evaporation and that used for conduction of sensible heat. (Q_e+Q_h) is the algebraic sum of the above quantities. This sum has a primary minimum in April and primary maximum in November. During November the energy utilized by these two processes is slightly greater than the energy supplied to the lake by solar radiation.

CALCULATION OF RATES OF EVAPORATION

In order to obtain the relative amounts of energy consumed by evaporative and conductive processes, the Bowen ratio (R) must be evaluated. The calculated monthly values of this quantity are as follows:

Bowen ratio for Lake Mead

1948		*1948*	
February	+0.410	October	−0.123
March	+.204	November	+.448
April	−.263	December	+.539
May	−.122	*1949*	
June	−.043		
July	−.153	January	+.412
August	−.115	February	+.309
September	−.068		

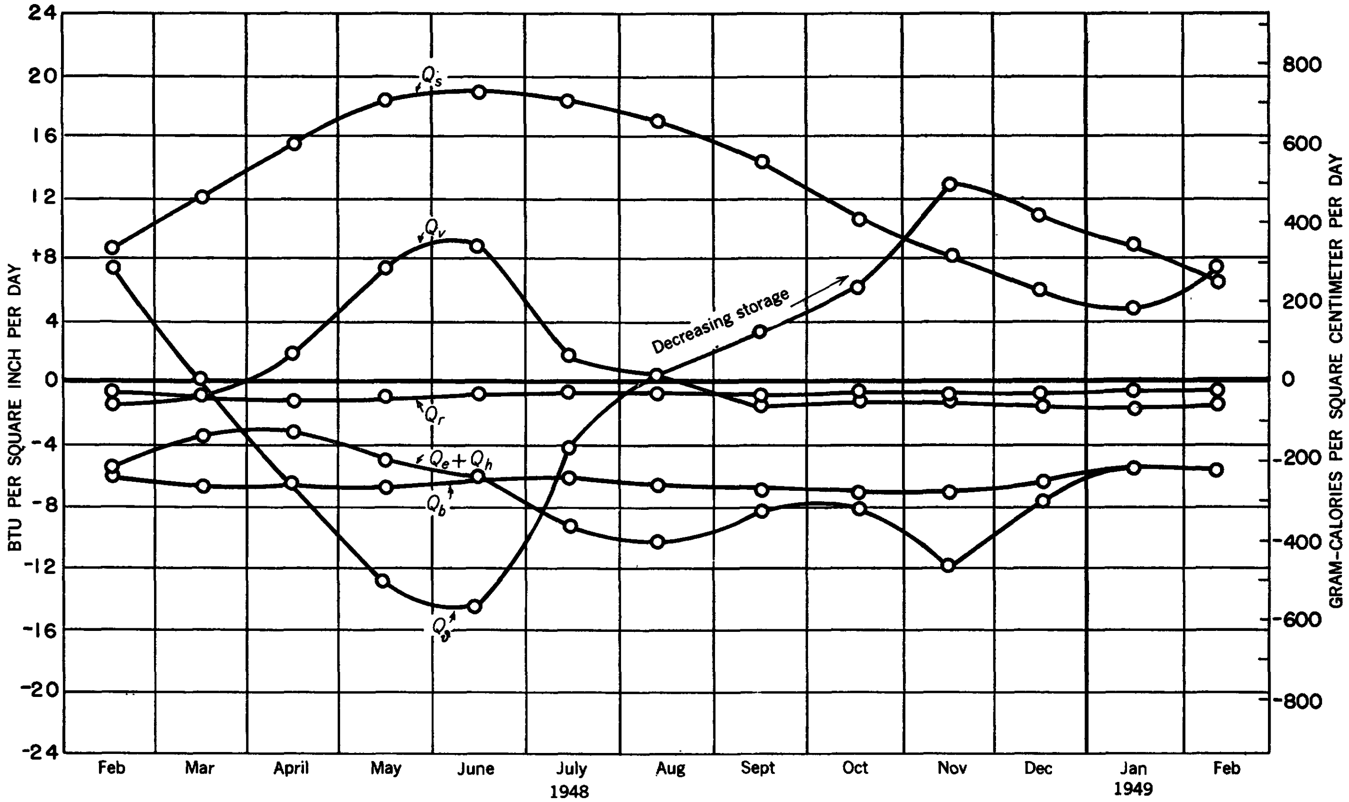

FIGURE 41.—Average monthly values of energy budget parameters as computed for Lake Mead, 1948–49.

Positive values of the Bowen ratio indicate that heat is being conducted away from the lake—that is, the air is colder than the water; negative values indicate the opposite effect. Inspection of the data shows that heat is conducted to the lake from April to October and away from the lake from November to March. By using these monthly average values of the Bowen ratio, the sum of energy utilized by evaporation and that utilized by conduction, shown in figure 41 as (Q_e+Q_h), can be broken down into its component parts. The results are graphically presented in figure 42. Evaporative processes use a minimum amount of energy in March and a maximum amount in August.

Table 15 shows the monthly values of the amounts

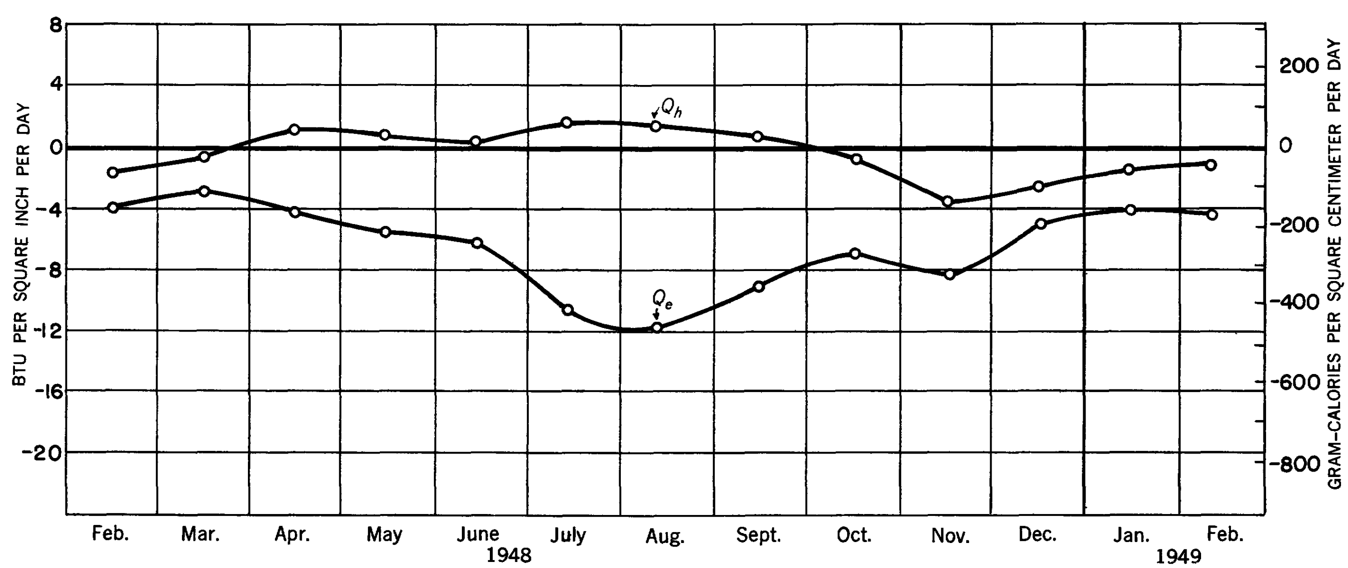

FIGURE 42.—Average monthly values of Q_e and Q_h.

TABLE 15.—*Preliminary energy budget for Lake Mead*

[All units are 10^{14} Btu. The convention regarding signs is the same as used in equation 1, p. 141]

	1948											1949	
	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.
Parameter:													
Q_s	1.90	2.76	3.45	4.34	4.68	4.83	4.43	3.58	2.71	1.95	1.45	1.18	1.48
Q_r	.16	.22	.23	.25	.20	.18	.19	.19	.20	.20	.20	.13	.13
Q_b	1.34	1.54	1.47	1.64	1.57	1.62	1.69	1.72	1.75	1.69	1.56	1.35	1.22
Q_v	−.29	−.20	.42	1.83	2.21	.50	.13	−.33	−.29	−.28	−.38	−.42	−.29
Q_θ	−1.06	−.03	1.48	3.09	3.62	1.11	−.05	−.79	−1.57	−3.08	−2.58	−2.09	−1.36
Q_h	.34	.14	−.25	−.17	−.07	−.44	−.36	−.15	.22	.89	.66	.40	.28
Q_e	.83	.69	.95	1.36	1.57	2.86	3.08	2.27	1.82	1.98	1.23	.97	.92

TABLE 16.—*Monthly evaporation as determined from energy budget*

	1948											1949	
	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.
Evaporation..........inches..	2.88	2.44	3.35	4.60	4.96	8.81	9.64	7.17	5.96	6.48	4.13	3.15	3.35
Do..........centimeters..	7.3	6.2	8.5	11.7	12.6	22.4	24.5	18.2	14.9	16.5	10.5	8.0	8.5

of energy utilized or supplied by the various processes entering into the energy budget for Lake Mead. The values given are totals for the month in British thermal units. An inspection of the table reveals that tremendous quantities of energy are represented in the various parameters. The energy utilized by evaporation in August is approximately three-fourths of that which was made available to the lake by solar radiation; in March it is about one-fourth of that which was supplied by solar radiation.

The volume of monthly evaporation, in centimeters and inches, as computed for the 13 months of this investigation is shown in table 16. The greatest evaporation occurred in August, when approximately 9.6 inches of water was evaporated, and the minimum was 2.4 inches in March. In February 1948 the evaporation was about one-half inch less than in February 1949, indicating that year-to-year variations occur. The computed total evaporation was 67.1 inches (169.8 centimeters) for the 13 months covered by the investigation; by averaging the February evaporation, the annual rate of evaporation was about 64 inches. The monthly average of 5.2 inches (13.1 centimeters) may be compared with a monthly average of 3.3 inches (8.4 centimeters) for the oceans of the world.

In table 17 the computed monthly volume of evaporation is compared with the monthly volumes of Lake Mead and the monthly outflow of the lake. The percentage of the volume of lake that is evaporated is at a maximum in August, when its value is 0.4 percent, and at a minimum in March, when it is 0.1 percent. The estimates indicate that during August a quantity of water equal to 11 percent of the outflow is evaporated. Over the 13-month period, an average of 0.24 percent of the average monthly volume of the lake, and 5.2 percent of the average monthly outflow was utilized by evaporative processes.

TABLE 17.—*Comparison of evaporation with other pertinent factors*

	Volume of lake, in acre-feet	Volume of outflow, in acre-feet	Volume of evaporation, in acre-feet	Percent of lake volume evaporated	Percent of outflow volume evaporated
1948					
February	21,400,000	1,138,000	29,100	0.136	2.56
March	20,750,000	1,150,000	24,000	.116	2.09
April	20,690,000	1,202,000	33,000	.160	2.75
May	21,890,000	1,142,000	42,100	.192	3.68
June	24,250,000	1,076,000	55,100	.227	5.12
July	25,320,000	1,156,000	100,500	.396	8.68
August	24,780,000	967,000	107,700	.434	11.13
September	24,250,000	981,000	79,100	.326	8.06
October	23,590,000	903,000	64,700	.274	7.16
November	22,790,000	1,009,000	69,100	.303	6.85
December	22,260,000	1,127,000	42,900	.193	3.82
1949					
January	21,460,000	1,214,000	31,800	.148	2.62
February	20,690,000	1,218,000	32,800	.159	2.69

Annual evaporation:
Year beginning February 1, 1948: 679,000 acre-feet
Year beginning March 1, 1948: 683,000 acre-feet

COMPARISON WITH RATES OF PAN EVAPORATION

Previous estimates of evaporation have been obtained by utilizing evaporation pans located on the shores of the lake and others floating in the body of water. It is recognized that pan measurements are an index of the lake's evaporation, but the nature of the correction to be applied is poorly understood. As a result, the general practice is to apply some arbitrary index correction to the pan-evaporation data to obtain a lake-evaporation estimate. Figure 43 represents a comparison of the evaporation as computed by this study with evaporation as measured at a land pan at Boulder City,

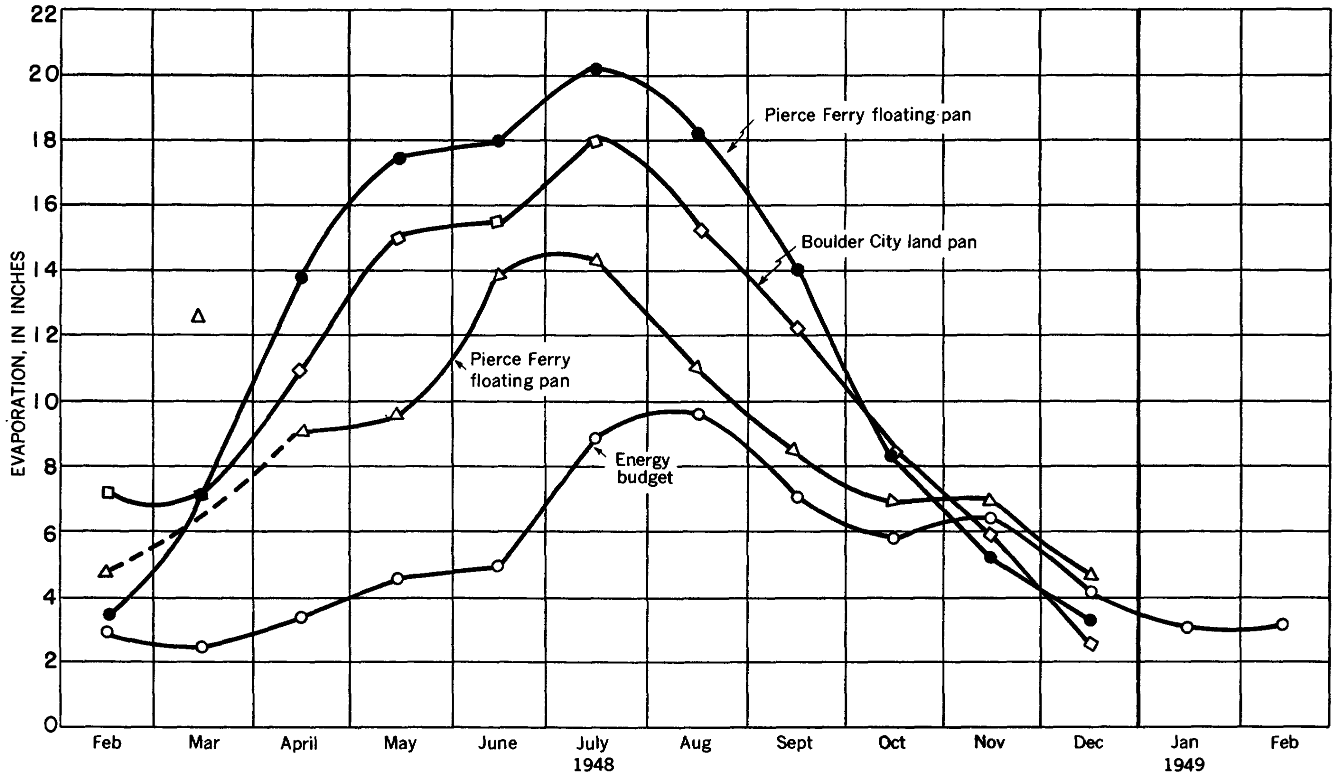

FIGURE 43.—Comparison of evaporation as computed from energy budget with pan evaporation.

Nev., and a land pan and a floating pan located at Pierce Ferry. It is evident from the figure that during most of the year all the evaporation pans give values considerably higher than those computed from the energy budget. The maximum evaporation from the pans occurred during July, but the maximum value computed from the energy budget occurred during August. This was probably caused primarily by the seasonal temperature lag of the lake. The curves show a marked seasonal variation in the ratio between evaporation as measured by land pans and as computed by the energy budget. The evaporation from the Pierce Ferry land pan during the months of high evaporation was nearly double that obtained by the energy budget, but during the months of October, November, and December the pans and the energy budget were in close agreement. The primary cause of these variations is again the seasonal temperature lag of the water body as compared to the air, which would result in both the lake and the pans having similar temperature structures during the fall, and the closer agreement of computed values. It is interesting to note the similarity in shape of the energy-budget evaporation curve and that for the floating pan located at Pierce Ferry. (Only one point, that for March, shows major disagreement. Since the disparity is so large, the pan evaporation for this month was assumed to be in error.) The pan obtained its maximum temperature in July and the lake in August; thus the evaporation maximum was displaced by a time interval of 1 month.

Finally, it may be concluded that the index correction for the pans varies from month to month, having a maximum value for the summer and a minimum for the fall and early winter transition season. It seems almost certain that the use of a constant pan index will lead to erroneous monthly results.

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