Comprehensive Survey of Sedimentation in Lake Mead, 1948-49

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K. CHARACTER OF THE INFLOWING WATER

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SOURCES OF INFLOW

Almost all the inflow to Lake Mead comes from the Colorado River and is measured at the Grand Canyon gaging station, some 190 miles above the uppermost basin (Pierce Basin) of the lake. The discharge of the Virgin River at Littlefield, Ariz., averages less than 2 percent of the discharge measured at Grand Canyon, and as indicated by figure 19, the unmeasured inflow of other tributaries to Lake Meade is generally less than twice as great as the measured discharge of the Virgin River. Thus the water measured at the Grand Canyon gaging station probably constitues more than 95 percent of the total inflow to Lake Mead. The inflow from side canyons and tributaries below Grand Canyon, including the Virgin River, is probably not in sufficient volume to have any significant effect on the physical and chemical characteristics of the water in Lake Mead.

Records of sediment and dissolved solids as well as of river discharge have been collected at the Grand Canyon station since 1925, and records of temperature have been maintained since 1936; these serve as the basis for the study of the physical and chemical characteristics of the water flowing in the river and stored in the lake.

Records of sediment at the Grand Canyon and at other gaging stations in the Colorado River basin for the period 1925–41 have been published in two water-supply papers of the Geological Survey (Howard, 1930, p. 15–44, and 1947); all records are for the suspended loads only and there is practically no information on the amount of material carried by the Colorado River as bed load. Analytical records of the chemical character of the Colorado River water for the period 1925–41 have also been published (Howard, 1928, 1930, p. 1–14, and 1932; U.S. Geol. Survey, 1943). The records of chemical analyses, water temperatures, and suspended sediment since 1941 have been published in water-supply papers dealing with the quality of surface waters of the United States (U.S. Geol. Survey, 1943 and later.).

SEDIMENT CARRIED BY THE INFLOWING WATER

SUSPENDED LOAD IN THE COLORADO RIVER

The annual loads of suspended sediment carried past Colorado River near Grand Canyon, Ariz., during the period 1926–50 are given in table 10 (see also fig. 7). The records show that 1,990 million tons of suspended sediment passed the Grand Canyon station during the period February 1, 1935, to February 28, 1949. These dates mark respectively the beginning of storage in Lake Mead and the completion of the 1948–49 survey of the reservoir. Presumably all the sediment passing Grand Canyon in this interval was trapped in Lake Mead except for the quantity, estimated at less than 10 million tons, that passed through the dam during 1935–36 when water was discharged from the bottom of the reservoir (p. 109). However, this is not a full measure of the sedimentation in Lake Mead because the sediment carried by the Virgin River and minor tributaries is not included.

Table 10.—*Annual runoff and suspended load of Colorado River near Grand Canyon, Ariz.*

Water year	Runoff, in millions of acre-feet	Suspended sediment, in millions of tons
1926	14.4	225
1927	17.3	398
1928	15.6	172
1929	19.4	480
1930	13.4	235.4
1931	6.7	68.8
1932	16.0	261.4
1933	10.0	124.1
1934	4.7	50.1
1935	10.2	122.3
1936	12.3	157.6
1937	12.4	191.3
1938	15.6	232.4
1939	9.6	86.3
1940	7.4	75.4
1941	16.9	270.1
1942	17.3	229.6
1943	[1] 11.4	[1] 95.0
1944	13.5	97.8
1945	11.9	83.6
1946	9.1	66.0
1947	13.7	136.0
1948	13.9	144.1
1949	14.4	118.9
1950	11.2	59.8
Average, 1926–50	12.8	168
Average, 1935–48	12.5	142

[1] Estimated from records for Colorado River at Lees Ferry, Ariz.

On the basis of total sedimentation of 1,990 million tons by February 1949, the deposition in the lake has been at an average rate of 142 million tons a year. This average rate is of interest to all who would like to forecast the future of Lake Mead, but it hides some tremendous variations in sedimentation rates—daily, seasonal, and annual. Acceptance of an average figure, without consideration of these variations and the reasons for them, can result in forecasts that are basically unreliable.

Since 1926 the annual suspended load (measured at Grand Canyon) has varied from about 50 million tons in 1934, when annual runoff was less than 5 million acre-feet, to nearly 500 million tons in 1929, when annual runoff was more than 19 million acre-feet. The range in sediment load was therefore tenfold, whereas the range in discharge was only fourfold. Plotting of the annual runoff against sediment load (fig. 22) shows that the sediment load is not directly proportional to the runoff but increases more rapidly with increasing discharge. The points are widely dispersed, but they indicate that from 1941 to 1950 the sediment load was generally less at equivalent runoff than in the preceding 15 years. Daines (1949), by double-mass analysis of the records of annual runoff and suspended load at Grand Canyon, also found a fairly consistent relation from 1930 to 1941, and a different but likewise consistent relation from 1942 to 1948. The differences are not adequately explained by available hydrologic data, but it is possible that they may result at least in part from variations in distribution of precipitation and runoff in the Colorado River basin (p. 235).

The sediment concentrations and loads entering Lake Mead during the 1948–49 survey were less than the average for the period of record at Grand Canyon. On only a few occasions were there any high concentrations of sediment. The maximum daily mean sediment concentration at Grand Canyon was 2.60 percent on August 8, 1948, during a short period of increased inflow. The total load of sediment during that rise was about 7 million tons, or 75 percent of the monthly load and 5 percent of the total load for that year. At a lower concentration (not over 1.76 percent) for a longer period of time and at a higher rate of discharge in April 1948, the total load was over 30 million tons, which was about 21 percent of the annual load. The concentration of sediment and its relation to discharge for part of the period of the survey are shown graphically in figure 23.

PARTICLE SIZES IN SUSPENDED LOAD

Size analyses of the particles of suspended sediment have been made on samples collected at Grand Canyon since 1935, and published records (Howard, 1947; U.S. Geol. Survey, 1943 and later) generally include analyses of 40 to 100 samples each year. Similar data were obtained for the samples collected at the Willow Beach and Topock stations (below Hoover Dam) while they were operated as sampling points. The methods of making the size determinations have not been uniform. For most samples, the proportions of sand-sized particles (diameter greater than 62 microns) was determined by sieve analysis, but the sieve sizes used since 1944 are different from those used in earlier years. For determination of the silt- and clay-sized particles, a dispersing procedure was used for some of the samples, but others were settled in the native water or in water having a chemical character and concentration of dissolved solids similar to those of the native water.

Laboratory tests have shown that in an undispersed sample a large percentage of the finer particles will have a much faster settling rate (that is, will act like coarser particles) than in a similar sample after dispersion. It is difficult to evaluate the analytical records based on dispersed samples, because in a reservoir the material will settle in an undispersed or partly dispersed condition. It is known that there will be some variation in the state of dispersion of the suspended material as it moves into and through the reservoir water, but the extent of this variation is not known. Since the variation applies especially to the fine particles, it is of interest to note that there was considerable difference in the nature of the material carried during the two periods in 1948 mentioned above. In the load of 7 million tons carried in August 1948, more than 60 percent of the particles were finer than 8 microns, whereas about 50 percent of the load of 30 million tons in April 1948 consisted of particles coarser than 62 microns. The determinations were made on dispersed samples but it is evident that the material carried in April consisted largely of the faster settling particles. Thus the movement into and distribution within the reservoir of the material carried during these two periods would not be the same.

Even if the size distribution of particles in individual samples could be measured accurately, the estimation of total quantities of a given size transported by the river would be subject to considerable error, because of the great variability of the sediment load from time to time and from place to place in both concentration and particle size.

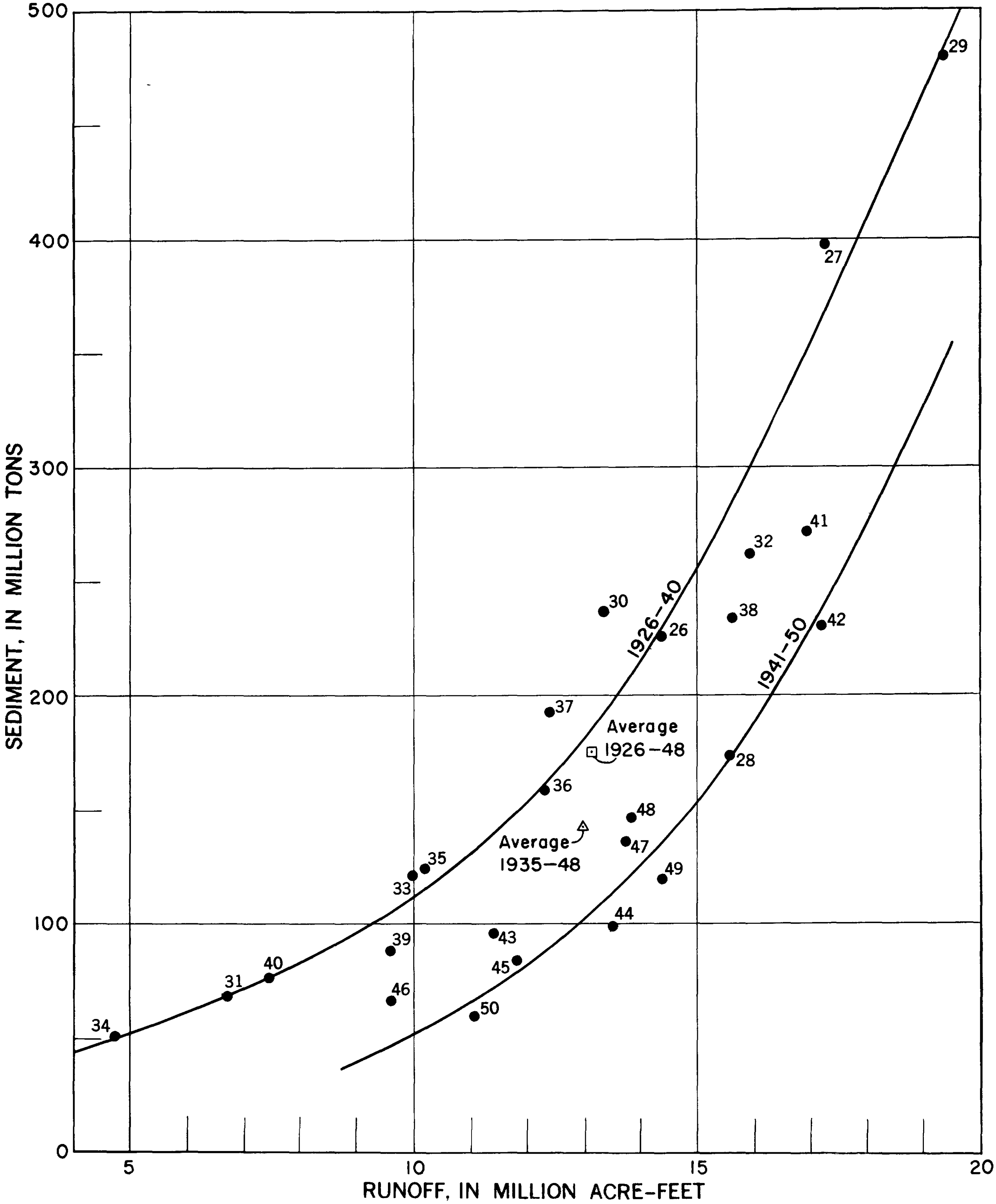

FIGURE 22.—Relation of annual runoff to sediment load at Grand Canyon.

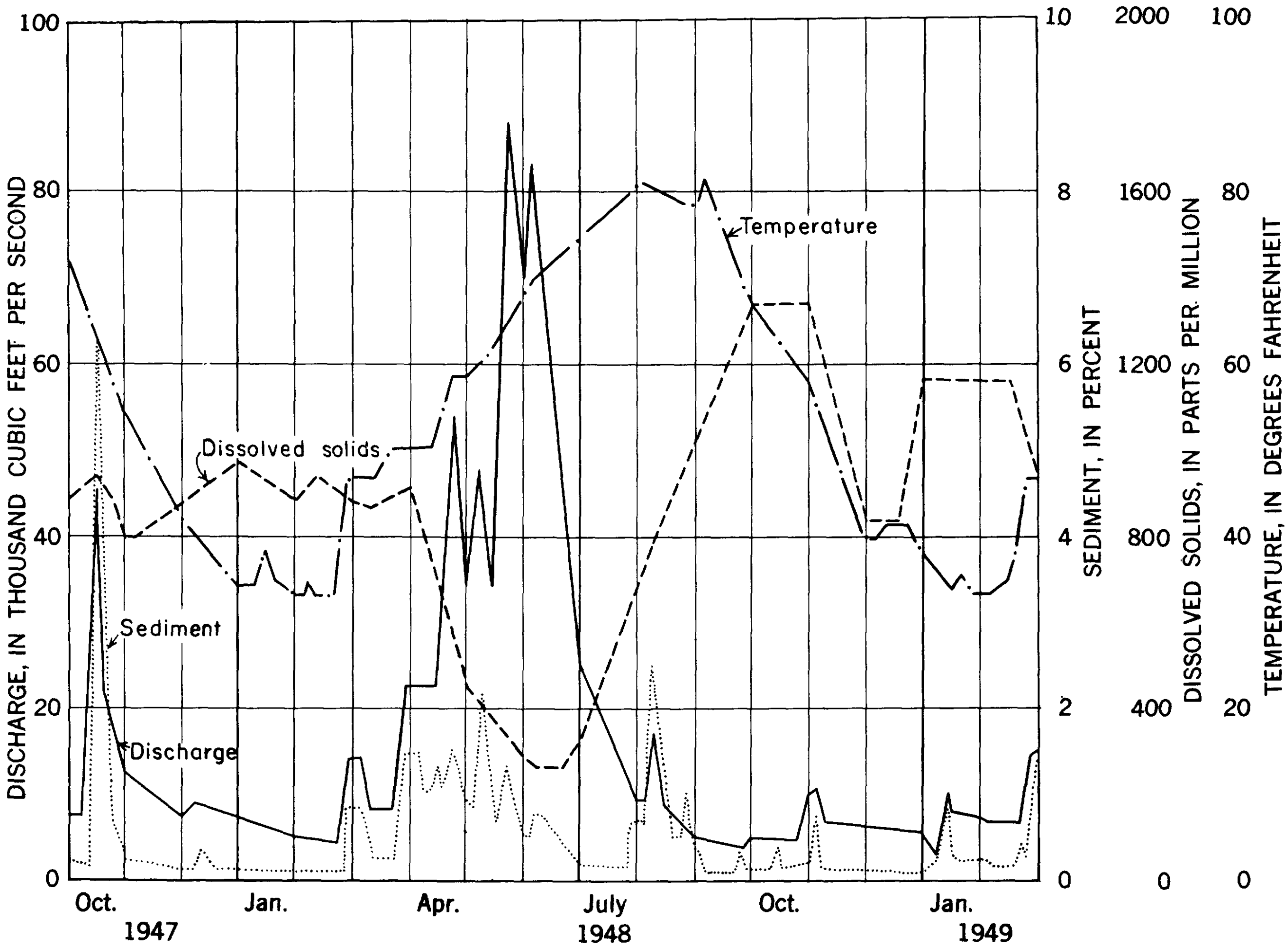

FIGURE 23.—Discharge, temperature, dissolved solids, and suspended sediment records for Colorado River at Grand Canyon, October 1947 to February 1949.

SEASONAL VARIATIONS

In winter, from November to March, the river discharge is usually near the minimum for the year, ranging from 3,000 to 10,000 cfs. Sand particles larger than 62 microns rarely compose more than 10 percent of the suspended load, and the clay fraction (smaller than 4 microns) is likely to make up half or more of the total.

The period April to July is the time of greatest volume of flow. Sand particles ordinarily constitute at least 20 percent of the sediment load, and during peak discharges the sediment load may be more than 50 percent sand and less than 10 percent clay. Even at these high discharges, however, the suspended load includes few particles larger than medium sand (500 microns in diameter).

From August to October the discharge of the river may drop to less than 5,000 cfs, or it may increase to 30,000 cfs or more for short periods because of flood runoff from cloudburst storms. Regardless of the discharge, the distribution of particles of various sizes in the suspended load is generally similar to that from November to February, with less than 20 percent larger than 62 microns.

CORRELATION OF ANALYSES OF DEPOSITED AND SUSPENDED SEDIMENT

There is some uncertainty about the proper method of correlating the reported sizes of the finer particles of suspended material with those determined from deposited samples. The difficulty of determining the sizes of particles whose diameters are less than 30 microns has been discussed (Howard, 1948). Many samples of deposited material have been dried after deposition, either in place or after collection. If the material has been dried it is necessary to disperse the samples to obtain a satisfactory sample for size analysis, especially if a large proportion is less than 30 microns in diameter. It is difficult to obtain a uniform state of particle dispersion, and for that reason complete dispersion is attempted. The particles then are in a condition which is not representative of any condition existing in nature, and the analytical results are of questionable value for correlation with results obtained from analysis of material in transport. It is true that the samples of suspended material can also be dispersed and the analytical results compared or correlated with the results obtained on the dispersed samples of deposited material. This sort of correlation has limited application, and is questionable if one wishes to compute the volume of deposit that will be occupied by a given amount of suspended load, for the sediment is transported and deposited under conditions in which the water has different chemical characteristics and dispersing properties.

Data collected during the Lake Mead survey show the particle size and weight-volume relation for materials deposited in the reservoir (p. 195). So far as particles larger than 30 microns and particularly the sand-sized ones are concerned, direct correlation should be possible with the data on suspended load in the Colorado River at Grand Canyon. However, there may be some uncertainty in the correlation of data concerning the smaller silt and clay particles, because of differences mentioned in the paragraph above.

SUSPENDED LOAD FROM OTHER SOURCES

It has already been mentioned that probably more than 95 percent of the total inflow of water to Lake Mead comes from the Colorado River and is measured at the Grand Canyon gaging station. All the evidence indicates that a similarly large proportion of the sediment entering the lake also passes this station. Thus a comparison of the sediment loads measured at Grand Canyon and at Topock, Ariz. (115 miles below Hoover Dam), during the 10 years prior to 1935 indicates that the inflow of sediment from tributaries below Grand Canyon was probably only a very small part of the total load carried past the Hoover Dam site.

Beginning in 1948 the suspended load in the Virgin River has been measured at Littlefield, Ariz. The measured loads of 652,000 tons in the water year 1948, 1,310,000 tons in 1949, and 1,690,000 tons in 1950 amounted respectively to 0.45, 1.10, and 2.83 percent of the quantities measured in the Colorado River at Grand Canyon. In confirmation, the amount of sediment in the Virgin delta (in Overton Arm above the Lower Narrows, p. 157), as calculated by the volumetric survey of 1948, was about 2.4 percent of the total sediment in Lake Mead (p. 195). This sediment was evidently derived almost entirely from the Virgin River, for there is evidence that sedimentation by Muddy Creek, which also flows into Overton Arm (p. 157), is negligible in amount.

Minor tributaries or washes have doubtless contributed some sediment to Lake Mead, but the only direct evidence obtained during the 1948–49 survey is at Detrital Wash (p. 71, 171), where a cloudburst in 1939 caused erosion of several hundred acre-feet of sediment, which was doubtless carried into the reservoir. This quantity is negligible in comparison with the total sedimentation in the reservoir.

Although the sediment contribution to the lake from the part of the drainage basin below Grand Canyon was small during the years prior to 1948, it is realized that this area may receive occasional storms of high intensity, which produce short but high peaks in runoff and sediment contribution. In some months, and perhaps in some years, its contribution of sediment to the lake may rise far above the rather small average. However, these occurrences have been too rare, at least in recent years, to have a significant over-all effect upon sedimentation in the lake.

TEMPERATURE OF THE INFLOWING WATER

Records of temperature of the Colorado River at Grand Canyon may be of questionable significance as an indication of the temperature of the water entering Lake Mead, because these records are obtained at a point that is about 190 miles above the reservoir. The records are, however, the only available records of temperature of the inflowing water. The temperature and discharge of the Colorado River at Grand Canyon for the period October 1947 to February 1949 are shown in figure 23. It will be noted that the water temperature was at a minimum of less than 40°F during January and February, rose above 60°F during the spring runoff, reached a peak of about 80°F in August and September, and then decreased. The temperature of the water at Grand Canyon has followed a similar pattern of annual fluctuation since 1936, with a winter minimum ranging from 35° to 40°F., and a summer maximum of 75° to more than 80°F.

In late April the runoff consists of appreciable volumes of water with a temperature higher than that of the lake water. The concentration of suspended sediment during the spring runoff is relatively high, but the sediment consists largely of coarse particles that will be deposited at the head of the reservoir. The content of dissolved solids in the inflow during this period is decreasing, and by the end of April is usually lower than the dissolved-solids content of the lake water. As the inflow has a lower content of dissolved solids and is warmer than the lake water, it will be less dense than the water in the lake. Because of this difference in density, the inflowing water remains at the surface and floats downlake on top of the water stored in the reservoir.

DISSOLVED SOLIDS IN THE INFLOWING WATER

Most of the dissolved mineral matter in the water of Lake Mead comes from the water flowing past the Grand Canyon gaging station, for which records of quality of the water are available since 1925. Practically nothing is known about the dissolved solids in the inflow from side canyons and small tributaries; this inflow is probably more mineralized than the main stream, but in any event it is not in sufficient volume to have any significant effect on the chemical characteristics of the lake water. The principal constituents of the dissolved solids in the Colorado River water and also in the Lake Mead water are calcium and magnesium; sodium and potassium; sulfate, bicarbonate, and chloride; and silica. When the reservoir was first planned there was some concern over the possibility of the boron content of the water being sufficiently high to cause trouble when the water was used for irrigation, but the boron content of the inflow and of the release is considerably below the maximum concentration that is suitable for irrigation. Similar concern was expressed about the posibility of the fluoride content of the water being high enough to mottle the enamel of teeth when used for drinking water by growing children, but the fluoride concentration has not been high enough to cause such damage. Other constituents are present in low concentrations, but they are not significant for this discussion.

SEASONAL VARIATIONS

Water passing the Grand Canyon gaging station shows a large seasonal range in concentration of dissolved solids. As a rule, the lowest concentration is found in the spring during the flood stages resulting from melting snow, and the maximum concentration is found during the periods of low flow when the runoff consists almost entirely of ground-water inflow. The concentration of dissolved solids may also be relatively high during floods, which come after heavy rains on the arid parts of the drainage area. Analyses representing these three conditions of river stage and a weighted average for the period of the 1948–49 survey are shown as numbers 1 to 4, respectively, in table 11.

The seasonal variations in dissolved solids in the Colorado River water during the 1948–49 survey are shown in figure 23. The concentration of dissolved solids ranged from 800 to 1,000 ppm during the winter of 1947–48, decreased to a minimum of 276 ppm during June 11–20, rose to 1,380 ppm during October 11–20, and then fluctuated between 800 and 1,200 ppm during the winter of 1948–49.

The variations in concentration of dissolved solids during the period of the survey were less than have been recorded in some years since 1935. In the water year 1942, the dissolved solids reached a 10-day minimum of 225 ppm on June 11–20, and a maximum of 1,350 ppm on September 21–30. In 1940, the range in concentration was even greater: from a minimum of 334 ppm in the 10-day period June 1–10 to a maximum 1,720 ppm on September 1–10. The maximum 10-day average concentration in the period of record was 1,890 ppm on September 21–30, 1934.

ANNUAL VARIATIONS

The annual average concentration of dissolved solids in the Colorado River also varies widely. In the pub-

TABLE 11.—*Chemical analyses of water samples of inflow and outflow, and from various points and depths in Lake Mead, in parts per million*

Location of samples	Inflow					Pierce Basin	Virgin Canyon		Virgin Basin			Boulder Basin, intake towers				Outflow
Sample	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Silica (SiO_2) ppm	13	14	20	14	16	12	-------	-------	13	12	-------	11	12	-------	-------	12
Calcium (Ca) do	55	156	148	87	60	40	88	114	60	96	91	72	94	92	121	86
Magnesium (Mg) do	11	60	34	26	13	12	33	41	16	26	26	23	26	38	67	27
Sodium plus potassium (Na+K) do	25	222	133	90	29	20	109	119	42	93	87	60	96	94	77	95
Bicarbonate (HCO_3) do	167	261	271	216	200	117	176	372	138	164	165	121	167	176	408	167
Sulfate (SO_4) do	69	596	465	224	66	68	301	256	140	298	283	223	297	307	285	280
Chloride (Cl) do	19	188	58	71	17	17	94	96	33	73	67	52	72	88	80	71
Nitrate (NO_3) do	.7	9.9	.5	2.5	.9	1.9	2.0	5.4	2.1	2.4	-------	1.3	2.9	2.3	.7	2.3
Total do	276	1,380	992	621	301	228	714	815	374	681	644	502	682	708	832	656
Specific conductance (micromhos)	455	1,970	1,390	956	481	374	1,120	1,280	572	1,010	981	782	1,030	1,120	1,360	988

1. Inflow: June 11–20, 1948, minimum concentration of dissolved solids at Grand Canyon during period Oct. 1, 1947–Feb. 28, 1949.
2. Inflow: Oct. 11–20, 1948, maximum concentration of dissolved solids at Grand Canyon during period Oct. 1, 1947–Feb. 28, 1949.
3. Inflow: Aug. 21–31, 1947, period of summer flood at Grand Canyon, mean discharge 29,570 cfs; mean discharge for previous composite period was 18,850 cfs.
4. Inflow: Weighted average for Grand Canyon during period Oct. 1, 1947–Feb. 28, 1949.
5. Inflow: May 21–31, 1948; minimum conductance for period previous to May 28 was 455 on May 26.
6. Water at surface of lake: May 28, 1948, Pierce Basin.
7. Water near bottom of lake: Feb. 20, 1945, Virgin Canyon, depth 200 feet.
8. Water at bottom of lake: February 20, 1945, Virgin Canyon, depth 330 feet. (Sample at 325 feet had 180 ppm of HCO_3 and conductance of 1,160.)
9. Water at surface of lake :May 31, 1948, upper end of Virgin Basin, station 45.
10. Water at 320 feet depth: May 31, 1948, upper end of Virgin Basin, station 45.
11. Water at surface of lake: Feb. 29, 1948, Virgin Basin, station 27.
12. Water at surface of lake: Sept. 23, 1948, intake towers.
13. Water at bottom of lake: Sept. 23, 1948, intake towers, depth 443 feet.
14. Water at bottom of lake: July 3, 1945, intake towers, depth 442 feet.
15. Water at bottom of lake: July 3, 1945, intake towers, depth 443 feet.
16. Outflow: July 12–16, 19–20, 1948, typical release at Hoover dam.

lished records of chemical analyses (U.S. Geol. Survey, 1943 and later), weighted-average analyses for the Grand Canyon station are shown for each water year. The weighted-average analysis is computed by multiplying the discharge at the time of sampling by the quantities of the individual constituents, adding the products for all samples collected during the year, and dividing by the sum of the discharges. In the period of record the concentrations of dissolved solids have ranged from a weighted average of 491 ppm in the water year 1928 to 960 ppm in 1934.

Since Hoover Dam was completed in 1935, the weighted-average concentration of dissolved solids at Grand Canyon was greatest in 1940, the year of minimum runoff, and least in 1942, the year of greatest runoff. This weighted-average concentration has varied greatly from year to year; it decreased about 25 percent from 1940 to 1941, and increased by an even larger percentage from 1938 to 1939.

DENSITY CURRENTS

A density current has been defined by Bell (1942b) as a gravity flow of a fluid through, under, or over a fluid of approximately equal density. Apparently this flow takes place with very little mixing of the two fluids. But in Lake Mead, the water through which the density currents flow have various differences in density, which may result from differences in temperature, content of dissolved material, or suspended material, or a combination of these three factors (p. 107).

Density currents were first recognized in Lake Mead within a few months after storage began in 1935 (Grover and Howard, 1938). In most of them the difference in density has been caused to a considerable extent by fine suspended material, so that the water in the current is turbid. In some density currents, even those that are heavily laden with suspended material, an increased content of dissolved solids contributes materially to the greater density.

The water stored in the lake forms the medium in which density currents can flow; the causative factor is the inflowing water, because of its different density, which in turn is dependent upon its suspended load, dissolved solids, and temperature. Thus, the characteristics of the inflow already discussed are the characteristics which under favorable conditions produce density currents in the lake. The following paragraphs describe the investigations that have been made of density currents in Lake Mead, the record of density currents, and their correlation with characteristics of the inflowing water.

INITIAL EVIDENCE, 1935–36

The first, and still the best, evidence of density currents flowing through the entire length of Lake Mead was obtained during the first 15 months of operation of Hoover Dam. During the first year, all water released from the reservoir was discharged through tunnels at or near the base of the dam and therefore was drawn from the bottom of the reservoir. Early in 1936, some water was released through the intake towers at a level about 250 feet above the base of the dam, but discharge through one tunnel was continued until May 1. Then the gate in that tunnel was closed, and all outflow from the reservoir since that date has been through the intake towers or over the spillways.

The evidence of density currents during the period when water was discharged from the bottom of the reservoir has been described (Grover and Howard, 1938), on the basis of records obtained at the Grand Canyon gaging station and at the gaging stations on the Colorado River at Willow Beach, Ariz., and near Topock, Ariz., about 10 and 115 miles respectively below Hoover Dam.

Storage in Lake Mead began on February 1, 1935, and the sediment concentration at Grand Canyon ranged from about 0.10 percent to 0.38 percent in the period January 23 to February 5. The sediment concentration at Willow Beach dropped from 0.45 percent on January 31 to 0.07 percent on February 5, chiefly because of obstruction of the flow of water, because there was not much storage in the early part of February. On the 20th, 23rd, and 24th of February the sediment concentration at Willow Beach was more than 0.15 percent, but for the remainder of the month it was less than 0.10 percent.

The first outstanding discharge of turbid water from Lake Mead occurred in March and April. On March 26 the sediment concentration at Willow Beach rose to 0.52 percent; except on the 29th, it remained more than 0.30 percent for the rest of the month but dropped to 0.07 percent on the first of April. The increase in sediment concentration at Willow Beach seemd to be directly related to an increase in sediment concentration at Grand Canyon from 0.44 percent on March 17 to 1.72 percent on March 18; this was the first apparent density current flow in Lake Mead. A similar but more turbid flow occurred in mid-April with a sediment concentration of 1.15 percent at Willow Beach, following a steady increase in sediment concentration at Grand Canyon.

In September and again in October of that year similar density currents were indicated by increases in sediment concentration at the Willow Beach station, in each case about 8 days after increases at Grand

Canyon. In these September and October flows there were also increases in the concentration of sulfate at Willow Beach following similar increases at Grand Canyon. Observations at the Topock gaging station showed increases in sediment and sulfate on the day following the increases noted at Willow Beach. The correlation of suspended load and of sulfate content at these stations above and below Lake Mead is illustrated by Grover and Howard (1938, fig. 2).

In 1936 the sediment concentration at Willow Beach increased from 0.02 percent on April 21 to 0.21 percent on April 22 and to 1.16 percent on April 23, reaching a peak of 1.44 percent on April 26. This followed and was directly related to an increase in sediment concentration at Grand Canyon from 0.22 percent on April 12 to 1.68 percent on April 18. The concentration at Grand Canyon had decreased to 1.26 percent on April 30; at Willow Beach the concentration dropped to 0.77 percent on April 30, and to 0.10 percent by May 1 and 0.01 percent by May 9. The concentration at Willow Beach has rarely been above 0.01 percent since May 1, 1936, the date on which the gates in the diversion tunnels were closed, and since which no water has been released from the bottom of the reservoir. In fact, the lowest elevation from which water can now be released from Lake Mead is at 895 feet, some 270 feet above the original bottom of the reservoir.

During the periods when turbid water was discharged from Lake Mead the reservoir was about 70 to 90 miles long and contained 4 to 5 million acre-feet of water. Apparently the turbid water flowed through the reservoir essentially unmixed. The four density currents of 1935 and 1936 carried a total suspended load estimated at 6 million tons, chiefly of clay and silt-sized particles finer than 20 microns in diameter. The absence of turbidity in the water released from the reservoir since May 1936 suggests that in the vicinity of the dam these density currents occur only near the bottom of the reservoir.

INVESTIGATIONS, 1936–49

The evidence in 1935 of density currents in Lake Mead led to a program of continuing investigation, including theoretical, laboratory, and field studies of the subject. The National Bureau of Standards made some preliminary studies of density currents and their causes, based on field data furnished by the Geological Survey and the Bureau of Reclamation. This work led to consideration of the problem by others. In particular, the Soil Conservation Service made laboratory studies at California Institute of Technology, which are reported by Bell (1942a, b).

The Bureau of Reclamation and the Geological Survey made plans for field observations of density currents in Lake Mead. The National Research Council formed its Density Currents Committee, a group that acted in an advisory capacity for studies planned for Lake Mead and for the Elephant Butte reservoir on the Rio Grande. Especially through the efforts of C. P. Vetter, a comprehensive program of sampling and observations was outlined by T. C. Mead, of the Bureau of Reclamation, and the writer in the summer of 1937. This program called for temperature observations and the collection of samples at monthly intervals at Hoover Dam, Cape Horn in Black Canyon, Boulder Canyon, and Virgin Canyon. It was hoped that sufficient warning could be given when turbid water was known to be passing Grand Canyon to permit observations to be made and samples to be collected at the upper end of the reservoir, but this was found to be impractical. The program suggested "observations to be made at locations across the lake in the wider sections to determine the outer edge of the deposited silt, reference points to be established for five locations in the lake." The five locations specified were between the Virgin River and Hemenway Wash, at the boat landing near mile 352 [5] in Boulder Basin.

This program, with some modification, was the basis for the studies carried on for several years. Monthly samples were collected from various depths at Hoover Dam and from the surface at Pierce Ferry. Occasional trips (usually two or three each year) were made to other parts of the reservoir, including Boulder Canyon, Virgin Canyon, and the Lower Narrows in Overton Arm.

Published reports of the density current investigations (National Research Council, 1949, and Bureau of Reclamation, 1949, 1953) include sounding graphs that show temperature, specific conductance, density, and specific gravity at each observation station, and also graphs summarizing the data from all stations for 18 periods during which there was evidence that density currents were flowing in the reservoir. The sounding graphs for the area near Hoover Dam are based on monthly measurements since May 1937. In other areas of the lake, notably Boulder Canyon, Virgin Canyon, and Pierce Basin, the sounding graphs are based on measurements made monthly from January 1938 to June 1940, and once or twice a year thereafter. These infrequent measurements are insufficient to indicate the duration of the reported density flows, and nothing is known about such flows in the intervals between

[5] River distances on the Colorado River are measured downstream from the Geological Survey marker opposite the mouth of the Paria River, along the pre-Lake Mead channel of the river.

measurements. The fact that several density movements are inferred during the periods of measurement is indicative that numerous other density currents may not have been recorded. H. R. Gould's graphs of daily densities at Grand Canyon (pl. 26), indicate that there are several periods in almost every year when conditions may have been favorable for development of density currents.

During the Lake Mead survey the observational and sample-collecting program was expanded; considerable emphasis was given to the collection of data in the upper end of the reservoir, particularly in the "convergence area" in the vicinity of Pierce Ferry (p. 126). Samples were collected and temperature observations made approximately once a month during the survey. The results of these observations and discussions of their significance are presented by Anderson and Pritchard (p. 125–146) and by Gould (p. 201–207).

RECORD OF DENSITY CURRENTS

The density currents observed in 1935 and 1936 (Grover and Howard, 1938) and those reported in subsequent years (National Research Council, 1949, and Bureau of Reclamation, 1949) are listed in table 12, The antecedent characteristics are those which were observed at Grand Canyon during the reported period of the density current and the preceding week.

In every category, the periods listed cover a wide range. Density currents have been reported in each year since 1938, and in all months except January. Inflow to the lake during these periods has ranged from less than 7,000 to more than 90,000 cfs, and the temperature of the inflowing water has ranged from 34° to 81° F. During several periods the concentration of dissolved solids in the inflowing water has exceeded 1,100 ppm, but some density currents have been reported when the water had a very low concentration of dissolved matter. The peak concentration of suspended sediment at Grand Canyon has exceeded 1.2 percent in most periods, but density currents have also occurred when the inflow carried less than 0.2 percent of suspended matter. In periods during August through February, most of the suspended particles have been smaller than 20 microns in diameter; but in periods occurring in April through July the clay and fine silt has constituted only a small proportion of the total sediment in the inflowing water.

Some of these reported density currents occurred during or immediately prior to recorded increases in the amount of sediment at the face of the dam, but others are not clearly related to such increases. The accumulation of sediment at the dam is shown by monthly measurements of the position of the sediment surface between the intake towers (fig. 24). Since August 1937 the sediment surface has risen more than 15 feet in each of 8 periods; the amount of rise was more than 35 feet in the autumn of 1941, and almost as much in the autumn of 1947. Following each of these eight major rises, the elevation of the sediment surface has declined, rapidly at first and then more gradually, presumably due in large part to compaction of the accumulated sediment. Although minor fluctua-

TABLE 12.—*Reported density currents in Lake Mead, and antecedent conditions at Grand Canyon, 1935 to 1949*

Year	Reported period of density current	Rise in sediment level at Hoover Dam,[2] in feet	Antecedent characteristics at Grand Canyon [1]				
			Maximum discharge, in cfs	Temperature range, in ° F.	Maximum dissolved solids,[3] in ppm	Suspended load	
						Maximum percent	Dominantly larger (L) or smaller (S) than 20 microns
1935	Mar. 25–Apr. 1	------	8,100	------	1,010	1.72	
	Apr. 10–21	------	15,600	------	780	3.16	L
	Sept. 3–13	------	12,300	------	1,130	5.02	S
	Oct. 6–13	------	18,100	------	1,130	5.09	S
1936	Apr. 22–May 1	------	51,700	------	740	1.68	L
1938	Nov. 16–Dec. 5	0	9,300	34–45	1,050	.14	S
1939	Jan. 18–Feb. 3	[4] 4	6,800	36–39	1,110	.07	S
	Mar. 15–Apr. 5	[4 5] 8	28,500	43–57	980	2.12	L
	June 20–28	[4 5] 11	31,900	66–75	410	.32	L
1940	Apr. 30–May 5	0	23,100	60–64	660	1.25	L
	May 21–June 7	0	45,500	66–71	360	1.28	L
1941	June 2–Oct. 25	[6] 45	87,500	56–81	1,080	6.36	
1942	Apr. 21–May 1	2	68,700	53–60	420	2.15	L
1943	Aug. 24–Sept. 1	1	------		------	------	
1944	May 23–31	0	90,500	62–69	400	1.47	L
1945	Feb. 19–28	0	7,700	43–49	1,090	.42	S
1946	Mar. 18–29	2	9,500	47–54	940	.26	S
1947	Feb. 24–Mar. 4	0	9,200	44–48	1,000	.30	S
	Oct. 1–8	[6] 35	12,400	71–72	910	.90	S
1948	Apr. 19–28	0	53,600	50–58	1,070	1.76	L
1949	Mar. 21–29	[5] 2	19,200	49–53	840	1.07	

[1] As recorded during period of density current plus the preceding 7 days.
[2] Rise is above trend of preceding monthly measurements.
[3] As shown in reported 10-day averages.
[4] Observed at mile 354. uplake from coffer dam.
[5] Rise occurred more than 30 days later than reported period of density current.
[6] Rise began prior to reported period of density current.

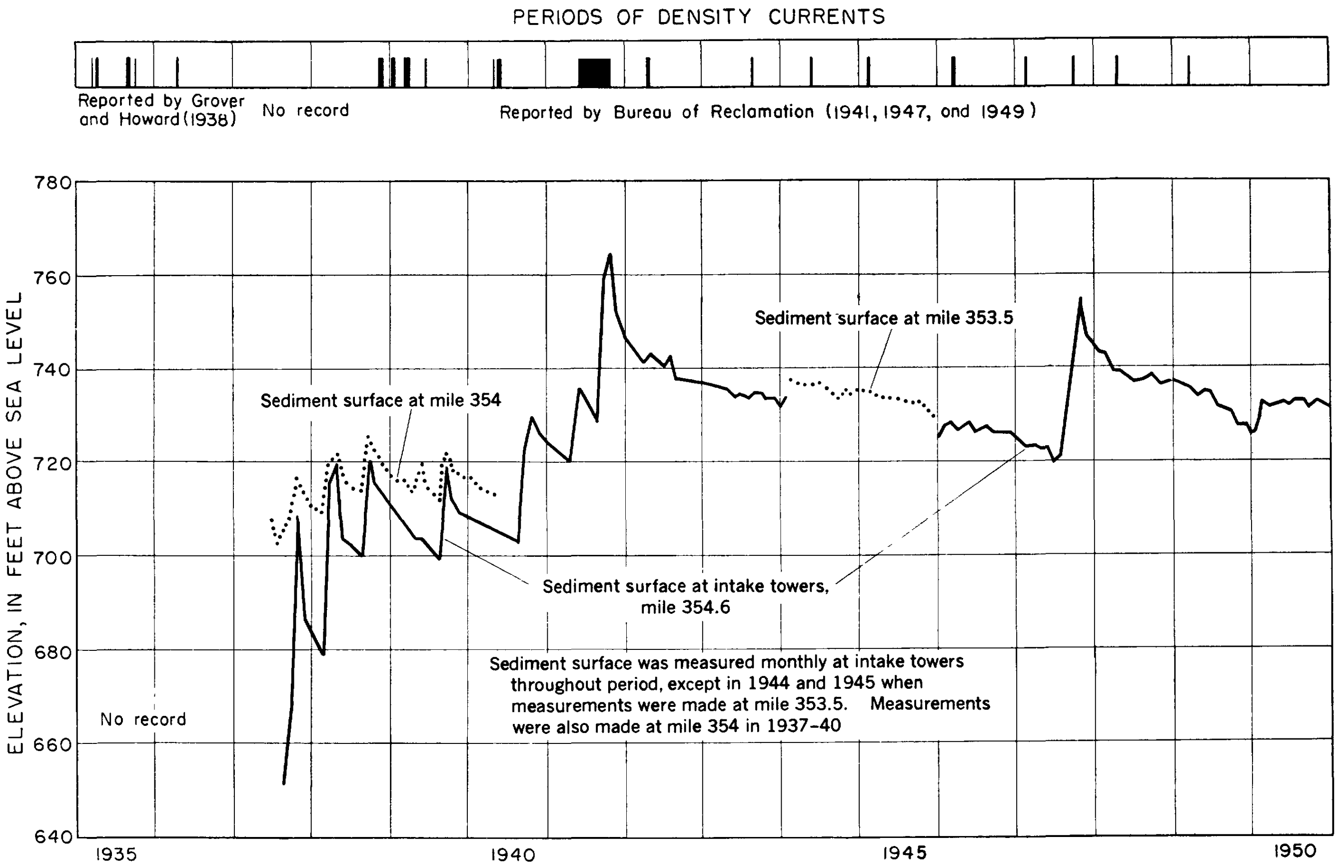

FIGURE 24.—Periods of reported density currents and elevation of sediment surface at Hoover Dam, 1935 to 1950.

tions in the graph may result from the difficulty of determining precisely the actual sediment level, several small rises or interruptions in the general downward trend may indicate minor accretions of sediment at the dam. It is possible also that there is some redistribution of sediment in Boulder Basin subsequent to the periods of the density currents.

The difficulty of correlating the periods of reported density currents with the changes in level of the sediment surface at the dam is evident from inspection of figure 24. No reservoir observations were made during the three prominent rises of sediment level in 1937 and 1938. Several density currents are reported in the reservoir during the years 1938 to 1940, but the sediment level at the dam showed no increase for these particular periods. Density currents were reported during the major rises of 1941 and 1947, but in each instance the field observations were made subsequent to the beginning of rise in sediment level. The sediment surface declined generally from 1942 to early 1947, and during 1948 and 1949.

The period of the Lake Mead survey was a relatively poor time to observe density currents in action. Only one density current, on April 19–28, 1948, is recorded during the period, and that one was unlike many of the earlier currents in that the greatest velocity of movement through Boulder Canyon was in the shallower water. The progressive downward trend in the position of the sediment surface indicates no accretions of sediment at the dam. It is possible that no major density currents traversed the entire length of the lake during the survey, and it thus appears that the combined effects of suspended and dissolved load and temperature of the inflowing water (as depicted on fig. 23) were not such as would cause extensive density currents. However, in the discussion of the chemical characteristics of the lake water (p. 115) evidence is given which indicates a density movement along the surface of the lake during the spring of 1948.

Following the completion of the survey, the records at the intake towers show an increase in concentration of dissolved solids in deep waters between February and April 1949. The sediment surface at the intake towers rose slightly during May of that year, giving further evidence of the movement of a density current into and through the lake at this time. The calculated increases in density were from 2 to more than 6 percent and, though small, appear to have been the effects of appreciable density flows along the bottom of the lake.

In the early days of construction, a cofferdam was built 700 feet upstream from the face of Hoover Dam; its crest was at elevation 720 feet. The cofferdam was inundated by April 1935, but until 1940 it acted as a barrier to sediment moving toward the face of the dam along the bottom of the reservoir. The relative rates of sediment accumulation above and below the cofferdam since August 1937 are shown by comparison of the position of the sediment surface at the intake towers with that measured about half a mile upstream from the cofferdam, at mile 354 (fig. 24). During October 1937 the sediment level at the intake towers rose 42 feet; above the cofferdam it rose only 9 feet during that month, but it rose to within 3 feet of the top of the cofferdam, and it is apparent that large quantities of sediment surmounted that barrier and came to rest below it. The movement of sediment over barriers is described by Bell (1942). Three times during 1938 and 1939 the sediment level at mile 354 rose above the 720-foot elevation, and each time the sediment surface at the intake towers rose to the level of the top of the cofferdam. Since October 1940 the cofferdam has been no barrier, because the sediment level at the intake towers has been higher than 720 feet.

The rapid rise of the top of the sediment layer between the intake towers (100 feet in the first 3 years of reservoir operation) was considered by some to indicate that within a very few years the sediment level would reach 895 feet, the lowest elevation from which water can be released through the intake towers. The additional rise of 40 feet in the single year 1941 doubtless caused further alarm. However, the subsequent records indicate a gradual but progressive lowering of the sediment surface, with the result that by July 1947 it was down to the level of the top of the cofferdam, and 45 feet lower than the highest sediment level measured in 1941. Another major influx of sediment, recorded at the intake towers in the latter part of 1947, has had a similar history. Throughout 1950 the sediment surface was more than 20 feet lower than its recorded position in October 1947.

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Water year	*Water-Supply Paper*	*Year published*	*Pages*
1941---	942	1943	56–68
1942---	950	1944	39–64
1943---	970	1945	80–125, 159–167
1944---	1022	1947	176–245
1945---	1030	1949	265–323
1946---	1050	1950	419–477
1947---	1102	1952	569–637
1948---	1133	1952	286–361