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

GEOLOGICAL SURVEY
AUG 22 1950

S. SEDIMENTATION IN RELATION TO RESERVOIR UTILIZATION

By H. R. Gould, U.S. Geological Survey

One of the chief problems in the operation and maintenance of the reservoir is the loss of water storage resulting from the accumulation of sediment. As shown in table 8, the sediment accumulated in 14 years has reduced the water-storage capacity of the reservoir below the permanent spillway crest (1,205.40 feet elevation) from 28,794,000 acre-feet in 1935 to 27,376,000 acre-feet in 1948, a decrease of 4.9 percent. The *usable* storage below this crest, however, diminished only 815,000 acre-feet, or about 3.2 percent, of the 1935 usable capacity. If it could be assumed that the rate of sedimentation and storage loss would continue at the same rate in the future, and that the capacity of the reservoir for storing sediment were the same as its capacity for storing water, the maximum life expectancy of Lake Mead could be calculated quite readily: about 20 times 14, or 280 years. However, neither of these assumptions is valid. Even with a uniform rate of sediment inflow, the rate of storage depletion could not be expected to remain constant, owing to the future compaction of the accumulated sediment. Also, the reservoir's water-storage capacity is considerably different from its sediment-storage capacity, because the upper surface for water must be essentially horizontal but the sediment surface can never be. It is the purpose of this section to attempt an evaluation of these factors and to forecast the pattern of sediment accumulation in Lake Mead. The problem of the "life of the reservoir," involving analysis not only of the pattern of sedimentation but its rate, and also many pertinent natural and developmental factors, is discussed in chapter T.

SEDIMENT-STORAGE CAPACITY ABOVE THE PERMANENT SPILLWAY LEVEL

It is frequently assumed that the capacity of a reservoir to store sediment is the same as its capacity to store water. Stevens (1946), for example, in estimating the life expectancy of Lake Mead assumed that the sediment-storage capacity is equal to the water-storage capacity at the permanent spillway level. This assumption would require, as pointed out by Mackin (1948), that when the delta front reaches the dam the river must transport its detrital load from the head of the reservoir to the delta front on a surface of no slope. It is obvious that such a condition could not exist and that when the reservoir is filled, the sediment surface must slope upstream from the dam. The sediment-storage capacity of the reservoir must, therefore, be greater than its water-storage capacity. For Lake Mead, the difference between the water-storage and sediment-storage capacities is equal to the volume between the level surface at the elevation of the permanent spillway crest and the sloping sediment surface that will extend upstream from the dam when the reservoir becomes filled with sediment.

In a previous discussion of the characteristics of the Colorado delta, it was shown that the topset beds over which the Colorado River flows have an average slope of about 1.25 feet per mile and that this slope has remained essentially constant since the inception of Lake Mead. The highest topset beds near Bridge Canyon are as much as 65 feet above the average lake level (about 1,170 feet elevation), and 15 feet above the highest level yet attained by the lake; but they do not, in their present stage of development, extend upstream from the eastern end of the reservoir. Whether or not the slope of the topset beds will remain the same in the future is not known, but some idea of its possible trend may be obtained from consideration of delta development in a more advanced stage at Elephant Butte Reservoir on the Rio Grande.

According to Eakin (1939), the topset beds near the head of Elephant Butte Reservior at San Marcial, N. Mex., grew about 10 feet in thickness between 1916 and 1935. Happ (1946) noted that by 1941 the aggradation of topset beds had extended at least 15 miles upstream from the head of Elephant Butte Reservoir. Furthermore, he reported a marked increase in the rate of upvalley aggradation since 1935. Between 1914 and 1935 only 15 percent of the total sediment load carried by the Rio Grande to Elephant Butte Reservoir was deposited in the topset beds upstream, but between 1936 and 1941 about 48 percent of the load was deposited in these beds. Happ predicted that in future years the topset beds would progress still farther upstream and that the percentage of the total load deposited in them would be greater than for the interval 1936 to 1941.

The net effect of this upvalley extension of the delta is to increase the gradient of the topset beds, over which the Rio Grande flows to its entrance in Elephant Butte Reservoir. This gradual steepening is in accord with Mackin's observation (1948, p. 496) that a delta in its more advanced stages of development tends to parallel the gradient of the stream channel over which it has been deposited, provided that the original stream was at grade.

The pre-Lake Mead gradient of the Colorado River in the Lower Granite Gorge averaged 7 feet per mile, but it is likely that the river was not at grade. The average gradient of the river below Yuma, Ariz., is about 1 foot per mile, and the slope of the Colorado River delta in the Gulf of California, which contains sediment comparable to that now accumulating in Lake Mead, is of the same order. The average slope of the natural channel from Hoover Dam to the Gulf of California is about 1.5 feet per mile.

Although the observations of delta growth in Elephant Butte Reservoir furnish some qualitative information of value in considering the future development of the Colorado delta in Lake Mead, essential quantitative data are lacking. However, if we assume that the slope that will be attained when Lake Mead becomes filled with sediment will be at least as great as the slope of the topset beds in 1948 (roughly 1.2 feet per mile), a conservative estimate can be made of the sediment-storage capacity above the permanent spillway level.

In figure 57 the present slope of the Colorado delta topset beds has been projected so as to extend from the permanent spillway crest at Hoover Dam to the upstream intersection of the spillway with the Colorado River channel. By operation of the spillway gates, water can be stored in the lake to a level 16 feet above the permanent crest, and in 1948 the controlled capacity above that crest was 2,450,000 acre-feet. But it is anticipated that the gates would be used for no more than temporary storage, and that the sediment surface would therefore become graded to the level of the permanent crest as an ultimate maximum. Of course, Lake Mead would no longer exist when that stage of sedimentation was reached.

On the basis of the above assumptions, the sloping surface in figure 57 delineates the upper limit of the accumulated sediment when the reservoir becomes filled. As shown by this diagram, the topset beds at the original eastern end of the reservoir (mile 235) would increase to an elevation of about 1,350 feet, or 145 feet above the permanent spillway level. The topset beds would then intersect the old Colorado River profile at mile 221.5, about 13.5 miles upstream from the original head of the reservoir and at an elevation of about 1,365 feet.

Computations of the volume between the surface at spillway level and the sloping surface of the topset beds, based on planimeter measurements of the areas enclosed by contours of the two surfaces, show that the sediment-storage capacity above the permanent spill-

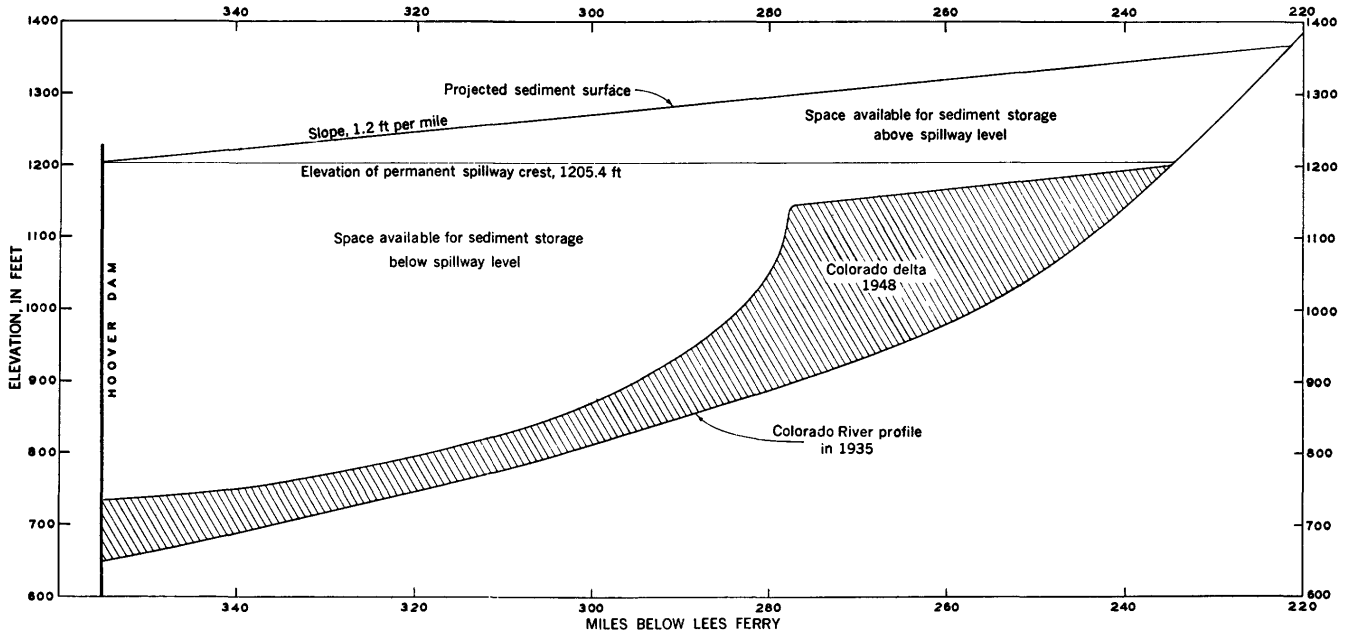

FIGURE 57.—Diagrammatic representation of the surface of the sediment that would be accumulated in Lake Mead when the lake is filled to permanent spillway level.

way level is about 6 million acre-feet, almost 25 percent of the storage capacity below the permanent spillway level. The ultimate sediment-storage capacity is estimated, therefore, at 35 million acre-feet.

This estimate of sediment-storage capacity is necessarily oversimplified owing to the lack of quantitative data on the complex interrelations of factors governing stream aggradation. It has been assumed, for example, that the long, narrow arms of the reservoir will be filled to the level of the sediment in the main body of the lake, whereas it is possible that the sediment level in these regions may be considerably lower than that of the main part of the delta. Furthermore, it has been necessary to assume that Overton Arm, which extends northward from the central part of the lake, will be filled to the level of the delta surface in Virgin Basin. A considerable quantity of detrital material must be supplied to Overton Arm from the Colorado River, because the quantity of sediment transported into Lake Mead by the Virgin River alone is not sufficient to fill this part of the reservoir during the period that will be required to fill the main body of the lake. It is quite likely, however, that unless the proportion of sediment contribution from the Colorado River is reduced by upstream developments, Overton Arm may never be completely filled with sediment. Instead it may be reduced to a lake consisting chiefly of dead storage, by reason of the upbuilding of the Colorado delta along the thalweg of the Colorado River.

SEDIMENT COMPACTION

Sediment compaction has an extremely important bearing on the rate of depletion of water-storage volume and on the life expectancy of the reservoir. The sediment accumulated in Lake Mead consists of two major types of material—namely, the sand of the topset and foreset beds, and the silt and clay of the bottomset beds. The compaction of sand is probably insignificant and consequently can be neglected, but the potential compaction of silt and clay is large.

The degree to which silt and clay sediments are compacted is related primarily to the depth of their burial and to the size of their constituent particles. In order to obtain an average empirical relation between these various factors, the relations between water content and depth for all cores from the bottomset beds of both the Colorado and Virgin deltas were plotted, and a best-fit visual curve was drawn. This curve (fig. 58) shows an approximately linear relation between decrease in water content and depth of burial of the bottomset beds.

Although this curve furnishes reasonably accurate compaction data throughout a depth interval of 95 feet, it alone does not afford an adequate basis for estimating the compaction of the material at greater depths after the reservoir has become filled with sediment. However, by the use of Hedberg's porosity data (1936) for fine-grained sediments (shale), it is possible to extend the water-content curve obtained from the Lake Mead cores to considerably greater depths, as illustrated in figure 58.

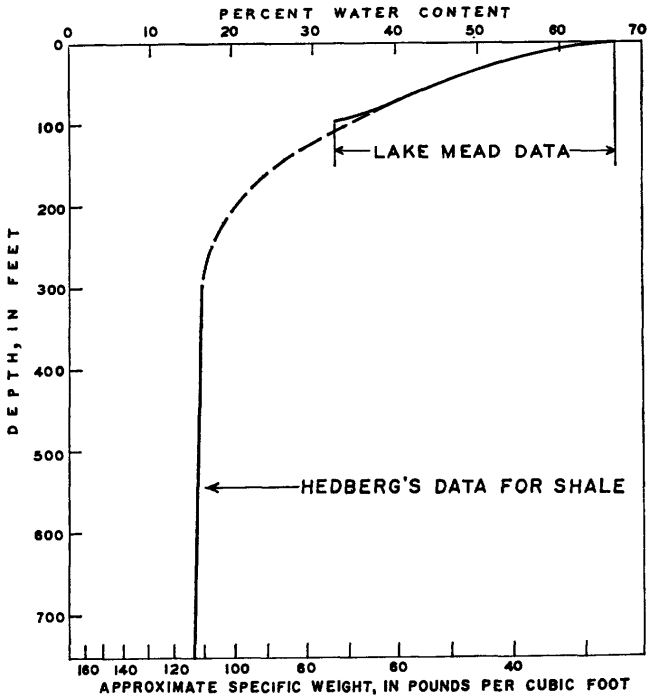

FIGURE 58.—Water content and approximate specific weight of silt and clay, plotted as a function of depth. Dashed line indicates interpolation.

In the analysis of the individual cores it was noted that the samples near the original reservoir bottom were considerably lower in water content than samples from the same sediment depth at nearby locations, but at higher levels above the original bottom. An excellent example of this relation is afforded by samples from the bottomset beds of the Colorado delta in the southern part of the Boulder Basin: One sample (No. 150) from a sediment depth of 16 feet, and only 9 feet above the original reservoir floor, had a water content of about 47 percent, whereas another sample (No. 1207) from the same sediment depth, but about 66 feet above the original reservoir bottom, had a water content of 64 percent.

A possible explanation for the low water content of the sediment near the original reservoir floor may be found by consideration of the mechanism of compaction in a very thin layer of sediment which we will assume is located midway between the top and bottom of the accumulated material. When this thin layer is subjected to increased pressure from above, such as would result from additional sediment loading, some

of the interstitial water is forced from the layer into the overlying strata, but the layer receives water that is driven from the interstices of underlying sediment. However, the inflow of water into this thin layer is less than the outflow; thus the water content of the layer under consideration is reduced. Let us now consider another increment of sediment, located at the same depth as in the example above but in contact with the original reservoir bottom. When subjected to increased loading, some of the interstitial water will be forced out of this sediment layer, as in the example above, but owing to the low compaction of the original reservoir bottom, there will be little if any squeezing out of water from below. As a result, the water content of this layer in contact with the original bottom is considerably less than that of a similar layer located at mid-depth. In their studies of cores of marine sediments, Emery and Rittenberg (1952, p. 760) concluded that because of this phenomenon, sediments overlying a buried hill would at first compact more rapidly than those in the surrounding area. The water content in the basal layers of sediment in a reservoir would also be reduced if the underlying reservoir floor were relatively impermeable, so that its saturation proceeded slowly and continued after the deposition of the first sediments, causing drainage from those basal layers.

Theoretically, the water content in the sediment at all levels would be reduced to some extent owing to the low compaction of the original reservoir floor. Only in a sediment accumulation of infinite thickness would this effect be entirely eliminated. In Lake Mead the marked reduction in water content appears to be appreciable only in about the lower 10 feet of the bottomset beds; but because of variable thickness, the water-content values in figure 58 appear to be significantly lower in the bottom 30 feet of the curve. Consequently, the values are not considered representative, and this part of the curve has been disregarded in the extrapolation of the curve to greater depths.

Returning now to the portion of the water content-depth curve based on Hedberg's data (fig. 58), one cannot be certain that his values are applicable to the silt and clay accumulated in Lake Mead. Hedberg's determinations were obtained from clay and shale strata that had been buried for a great length of time, compared to the few centuries that the earliest Lake Mead sediments will have been buried when the reservoir becomes entirely filled. Supposedly the sediments examined by Hedberg had sufficient time for the forces of compaction to reach approximate equilibrium, but we do not know whether the Lake Mead silt and clay will attain a comparable state of compaction during the life of the reservoir. Furthermore, Hedberg gives no precise information as to the size, shape, and sorting of the constituent sediment particles, and there is the possibility that the texture of the material investigated by him differs significantly from the texture of the Lake Mead silt and clay. Because of the close relation between texture and compaction, any significant difference in texture would produce a corresponding change in compaction. In applying the part of the water content-depth curve constructed from Hedberg's data to the Lake Mead sediments, therefore, it is necessary to assume that a few hundred years is sufficient for the compaction of sediments to reach a state of equilibrium with the weight of the overburden, and that the sediment investigated by Hedberg does not differ significantly in texture from the silt and clay accumulated in Lake Mead.

No compaction data are available in the critical range between depths of 95 feet (the lower limit of the Lake Mead observations) and 290 feet (the shallowest observational depth reported by Hedberg). Continued observation in Lake Mead will eventually provide specific information for this zone about which very little is yet known. For the present, the interpolated part of the water content-depth curve, together with the upper few hundred feet of the curve constructed from Hedberg's data, is considered to provide reasonably reliable compaction data for deeply buried layers of silt and clay accumulated in Lake Mead when it becomes entirely filled with sediment. The accumulated sediment at the time of reservoir filling will attain a maximum thickness of about 575 feet immediately upstream from Hoover Dam.

PATTERN OF SEDIMENTATION IN THE FUTURE

The gates through which water can be discharged from the reservoir are at three levels, the highest of which is at the spillways whose permanent crests are at elevation 1,205 feet. The gates at the two lower levels are situated in the four intake towers immediately uplake from Hoover Dam. The sills of the uppermost gates are at elevation 1,045 feet, 310 feet above the 1948 sediment surface and 415 feet above the original floor of the reservoir. The sills of the lower gates are at 895 feet, 160 feet above the 1948 sediment surface and 265 feet above the original lake bottom at the intake towers. The intake towers contain the outlets through which water for generating power and for downstream users is normally discharged.

Water stored below the 895-foot level is, of course, in dead storage. When water was first impounded behind Hoover Dam, the dead-storage space measured 3,223,000 acre-feet, but by January 1949 it had been re-

duced by the accumulation of sediment to 2,620,000 acre-feet, or by 18.7 percent. When the dead-storage space becomes completely filled with sediment, it will be necessary either to discharge great quantities of sediment to downstream areas or to close the lower gates and allow them to become covered. Loss of the dead-storage space thus will mark the first critical stage of reservoir filling. Similarly, the filling of the reservoir to the levels of the upper outlet sill and permanent spillway crest will denote, respectively, the second and third critical stages. The following sections present predictions as to the amount and distribution of sediment that will have accumulated in the reservoir at each of the three critical stages; they state the methods used and the assumptions made in arriving at these predictions.

COMPLETE FILLING

On the basis of foregoing considerations it is possible to obtain a reasonable estimate of the amount of sediment that will be required for the reservoir to become completely filled; that is, the stage when the sediment accumulation would intersect the dam at the elevation of the permanent spillway crest. A total of about 2,000 million tons of sediment (dry weight) was deposited in Lake Mead during the 14-year period, 1935–48 (p. 195). This quantity is taken as a convenient unit of measurement for discussion of the future accumulation of sediment in Lake Mead. It was shown (p. 197) that the composition of this material is approximately 45 percent sand and 55 percent silt and clay; the total load of sand, therefore, is 900 million tons, and the total load of silt and clay is 1,100 million tons. There is no assurance that the Colorado River will continue to carry sediments similarly proportioned in particle size. The geologic history of the Chemehuevi formation (p. 16) shows that the river has not done so in the past, but instead has carried a considerable amount of gravel. Such changes, as recorded in geologic history, may require thousands of years; for the few centuries under discussion in the following paragraphs, it is assumed that the size distribution will be similar to that in the 2,000-million-ton sample that accumulated prior to the 1948–49 survey.

Data on the physical properties of the sediment suggest that compaction of the sand is insignificant, but that the silt and clay undergo considerable compaction as their depth of burial increases (fig. 58). It is desirable, therefore, to consider the sand and fine constituents independently.

Using a mean specific weight of 93.8 pounds per cubic foot for sand, we find that the ultimate sediment-storage capacity (35,700,000 acre-feet) was reduced 441,000 acre-feet by the first 900 million tons of sand brought into the reservoir. Since it is assumed that the sand will experience no further compaction, the sand in each 2-billion-ton unit will reduce the total sediment-storage capacity by an equivalent amount.

The rate of sediment-storage depletion resulting from the accumulation of silt and clay is not constant, but will become progressively less because of increased compaction during the filling of the reservoir. In order to obtain the rate of this sediment-storage reduction, we must first determine the total weight of sediment that will be stored in the reservoir when it becomes entirely filled. This can be accomplished by use of the sediment-compaction data shown in figure 58 and the sediment-storage capacity curve presented in figure 59.

In the following determinations, it is assumed that the pattern of sedimentation during the period 1935–48 will continue in the future—that is, the sand will be deposited in the topset and foreset beds, and the silt and clay will accumulate in the bottomset beds. When the reservoir becomes entirely filled with sediment, the sand will overlie the silt and clay. Figure 59 shows the estimate of available sediment-storage space above the permanent spillway level to be equally distributed above and below elevation 1,240 feet, the level to which the sediment compaction data in figure 58 have been referred. For example, water contents at depths of 0 feet and 200 feet in figure 58 correspond respectively to elevations of 1,240 feet and 1,040 feet in figure 59.

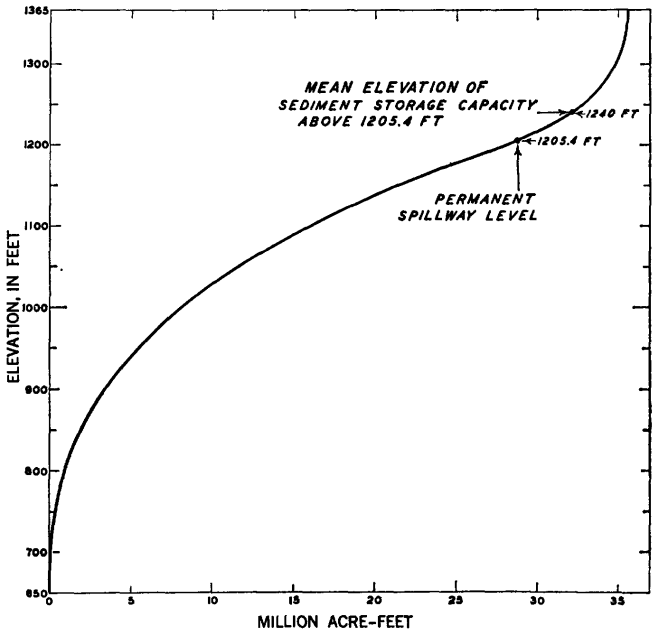

FIGURE 59.—Curve showing the estimated sediment-storage capacity of Lake Mead when the accumulated sediment reaches the elevation of the permanent spillway crest at Hoover Dam.

To obtain the weight of silt and clay accumulated in the reservoir when it becomes filled with sediment, the volumes of silt and clay in successive 50-foot increments of elevation (fig. 59) were multiplied by their average specific weights (as determined from fig. 58). Because of the assumption that the silt and clay will make up the lower part of the deposit, the computations were made from the lake bottom upward. The total weight of silt and clay (table 29) was then obtained by summation of the weights of the 50-foot increments. The results of the computations are presented in graphic form in figure 60.

The weight of sand accumulated in the reservoir when it becomes filled with sediment can be computed in the same manner as the weight of silt and clay, except that compaction need not be considered. In making these computations, the author used a mean specific weight of 93.8 pounds per cubic foot for the accumulated sand (as determined on p. 180). Because of the assumption that the sand will be confined to the upper layers of the deposit, the weight of sand in each 50-foot increment of depth was computed from the elevation of maximum sediment storage (fig. 59) downward. The total weight of sand (table 29) was then obtained by summation of the weights of the 50-foot increments. The results of these computations

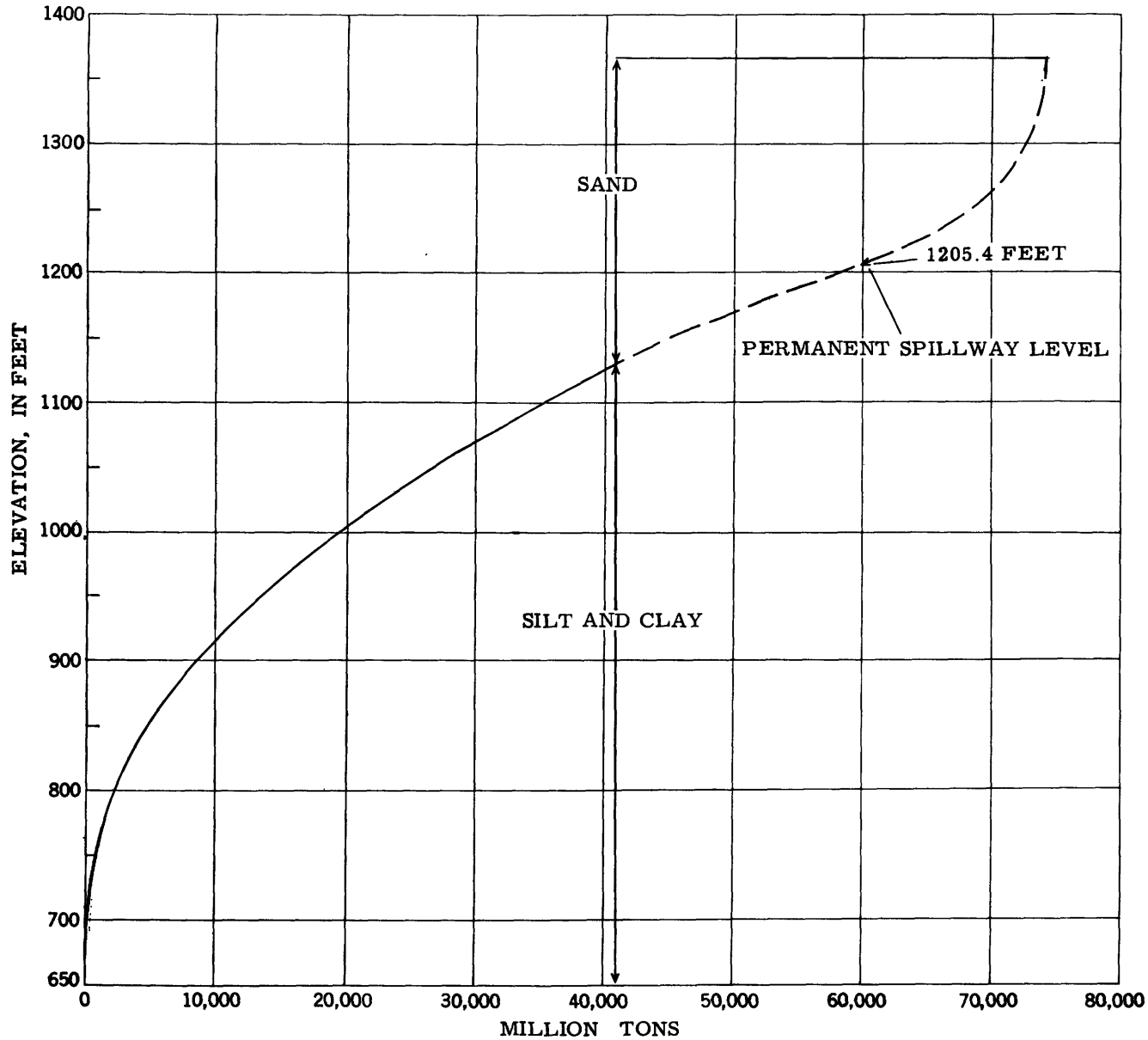

FIGURE 60.—Cumulative curve showing the estimated weight of sediment, and of coarse and fine components, when the reservoir becomes filled with sediment.

are plotted on the same graph as the silt and clay data (fig. 60).

Near the level of contact between the sand and the underlying silt and clay, the increments of elevation were reduced to 10 feet, and a graphic method was employed to obtain a better balance between the total weights of the sand and the silt and clay constituents. This procedure resulted, also, in a better estimate of the elevation of contact between the silt and clay and the overlying sand. As shown in figure 60, most of the silt and clay will presumably be stored below elevation 1,130 feet, and most of the sand will be stored above this elevation. Other quantitative results of these computations are given in table 29. Further calculations based on this table show that the average rate of reduction in total sediment-storage space during the time required to fill the reservoir is 956,000 acre-feet for each 2,000-million-ton unit. Since the sand of this volume will occupy 441,000 acre-feet (p. 219), the silt and clay when fully compacted will occupy 515,000 acre-feet.

TABLE 29.—*Estimated weight, volume, and specific weight of the sediment in Lake Mead when filled under conditions assumed*

Sediment	Weight, in millions of tons	Volume, in acre-feet	Mean specific weight, in lb per cu ft
Silt and clay	41,100	19,250,000	98.0
Sand	33,600	16,450,000	93.8
Silt, clay, and sand	74,700	35,700,000	96.1

HALFWAY POINT IN RESERVOIR FILLING

It appears that the usefulness of the reservoir will not be materially impaired until its water-storage capacity at the level of the permanent spillway crest is reduced to about 13 million acre-feet, the average annual flow into Lake Mead from 1935 to 1948. This would be slightly less than half the original water-storage capacity at that level.

Admittedly a major attribute of Lake Mead today is its capability for holdover storage; with a capacity more than twice the average inflow, it can accumulate water during years of high runoff and release it during subsequent years of low runoff, thus furnishing a relatively constant supply during wet and dry years. It might appear, then, that reduction in capacity to an amount equivalent to the average yearly inflow would be a serious impairment of its usefulness. However, under the terms of the Colorado River Compact of 1922 and the Treaty of November 1944 with the United States of Mexico, not more than 9,250,000 acre-feet of water annually is yet allocated to the Lower Basin, for which Lake Mead constitutes the prime regulating body. A capacity of 13,000,000 acre-feet, therefore, would represent an amount about 40 percent greater than the annual use in the Lower Basin, including Mexico, on the basis of present allocations. Furthermore, the usable storage in the lake at that time may be considerably greater than 13,000,000 acre-feet because of bank storage provided by alternate saturation and drainage of the delta sands as the reservoir level rises and falls (p. 99). The controlled storage in Lake Mead can also be increased substantially by raising the spillway gates at Hoover Dam.

In order to obtain an estimate of the sediment accumulation when the water-storage capacity is reduced to about 13,000,000 acre-feet, the following assumptions are made: (1) The average water level of the reservoir will be maintained at or near the elevation of the permanent spillway crest, by raising the spillway gates during months of peak inflow. (2) A proportionate amount of the total volume of sediment stored above the permanent spillway crest when the reservoir becomes filled with sediment will be deposited above spillway level each year. (3) The total weight of sediment will be made up of 45 percent sand and 55 percent silt and clay, as in 1948. (4) The mean specific weight of sand will remain the same (93.8 pounds per cubic foot) as in 1948. (5) The mean specific weight of silt and clay will increase, according to the relation shown in figure 58, from 51.8 pounds per cubic foot (the mean specific weight of silt and clay accumulated in Lake Mead from 1935 to 1948) to 98.0 pounds per cubic foot (the estimated mean specific weight of silt and clay when the reservoir becomes completely filled with sediment), and this increase will be proportional to the ratio between the sediment volume in 1948 (1,426,000 acre-feet) subtracted from the sediment volume at any future time, and the sediment volume in 1948 subtracted from the ultimate sediment volume (35,700,000 acre-feet) when the reservoir becomes entirely filled with sediment.

The volume of sediment that will be stored in the reservoir when its water-storage capacity is reduced to 13,000,000 acre-feet can be evaluated readily from assumptions 1 and 2. The volume of sediment below spillway level is equal to the difference between the original reservoir capacity below spillway level (28,794,000 acre-feet) and the space still available for water storage (13,000,000 acre-feet). The amount of sediment stored below spillway level would therefore be 15,794,000 acre-feet, or about 55 percent of the original reservoir volume below the permanent spillway level. According to assumption 2 the volume of sediment accumulated above the spillway level will be 55 percent of the total space (6,900,000 acre-feet) available for sediment storage above the spillway level, or

3,800,000 acre-feet. The total volume of sediment that will be stored in the reservoir at the time the water-storage space is reduced to 13,000,000 acre-feet is estimated therefore at 19,600,000 acre-feet.

With this estimate of sediment volume the mean specific weight of the silt and clay accumulation may be determined as outlined in assumption 5. According to figure 58, the mean specific weight of the silt and clay (51.8 pounds per cubic foot) that accumulated in Lake Mead from 1935 to 1948 is the same as the specific weight of a layer of silt and clay buried to a depth of 50 feet. Similarly, the estimated mean specific weight (98.0 pounds per cubic foot) of the silt and clay accumulation when the reservoir becomes filled with sediment is the same as the specific weight of a layer covered by 200 feet of overburden. The mean specific weight increases not only with depth of burial, but also with the volume of sediment. According to assumption 5, the increase in the mean specific weight of silt and clay resulting from increased depth of burial will be proportional to the increase in sediment volume. For example, when the mean specific weight of the silt and clay becomes the same as the specific weight (79.0 pounds per cubic foot) of a layer at a depth of 125 feet (midway between the 50-foot and the 200-foot layers, fig. 58), the volume of accumulated sediment will increase by half of the difference between the volume of sediment that accumulated from 1935 to 1948 (1,426,000 acre-feet) and the ultimate sediment volume (35,700,000 acre-feet), or by 17,137,000 acre-feet.

The 19,600,000 acre-feet of sediment that will be stored in the reservoir when its water-storage capacity is reduced to 13,000,000 acre-feet represents an increase of 18,174,000 acre-feet over the volume of sediment accumulated from 1935 to 1948. Using the method outlined above, it is estimated that the silt and clay accumulated in the reservoir at the halfway point will have a mean specific weight of 80.0 pounds per cubic foot.

From assumptions (3) and (4) above, the total weight of the sediment accumulated in the reservoir when its water-storage capacity is reduced to 13,000,000 acre-feet can be computed by the following equations:

$$0.45W_t = 21.78S_s\,(V_t - V_f) \qquad (1)$$

$$0.55W_t = 21.78S_fV_f \qquad (2)$$

where W_t is the total weight of the accumulated sediment in tons, S_s is the mean specific weight of the sand fraction, V_t is the total volume of the accumulated sediment in acre-feet, V_f is the volume of the silt and clay fraction in acre-feet, and S_f is the mean specific weight of the silt and clay fraction. The numerical factor 21.78 is used for converting pounds to tons and cubic feet to acre-feet; the numerical values 0.45 and 0.55 are proportions of the total weight of sediment made up by the sand fraction and the silt and clay fraction, respectively.

Solving equation 2 for V_f in terms of W_t and substituting this value in equation 1, we find that W_t, the total weight of sediment accumulated in the reservoir when the water-storage capacity is reduced to 13,000,000 acre-feet, is 36,600 million tons. Further computations show that the sand fraction will have a volume of 8,100,000 acre-feet and a weight of 16.5 billion tons. The silt and clay fraction will occupy a volume of 11,500,000 acre-feet and weigh 20,100 million tons. The mean specific weight of the total accumulation will be 85.7 pounds per cubic foot.

Of the 8,100,000 acre-feet of sand, 3,800,000 acre-feet will be deposited above the altitude of the permanent spillway crest. The 4,300,000 acre-feet of sand to be deposited below spillway level would be enough to fill all the original water-storage space below that level in Lower Granite Gorge, Pierce Basin, Grand Bay, Iceberg Canyon, Gregg Basin, and the upper 3 miles of Virgin Canyon. Even without any accumulation of bottomset beds in these areas, the top of the delta front at the halfway point in filling of the reservoir must advance at least to mile 306, about 28 miles downlake from its position in Pierce Basin in 1948.

Assuming that the topset beds maintain an average slope of about 1.2 feet per mile as at present, the 1948 delta surface in Lower Granite Gorge and Pierce Basin would be buried under about 69 feet of additional material, of which 35 feet would result from increasing the average water level in the reservoir from 1,170 feet to 1,205 feet, and the remainder (34 feet) would be accounted for by upbuilding of the topset beds at a rate of 1.2 feet for each mile of advance of the delta front. The highest delta deposits at that time would be 8 miles upstream from Bridge Canyon rapids (which will then be covered by sediment) at altitudes as high as 1,300 feet, or about 95 feet above the altitude of the permanent spillway crest. These deposits are included in the 3,800,000 acre-feet of accumulation above the spillway level.

The silt and clay fraction, as estimated above, will amount to 11,500,000 acre-feet, and it will accumulate in the bottomset beds. If this material were to form a level surface in the lowest parts of the reservoir west of the delta front at mile 306, it would rise to an altitude of 1,070 feet, or 25 feet above the altitude of the sill of the upper outlet gates. However, in order for turbidity currents to transport the detrital load to the lowest parts of the reservoir, the bottomset beds must

have a downlake slope. To obtain a reasonable estimate of this slope, let us consider the declivity of the subaqueous delta surface in 1948 and the space available for sediment storage in the lowest parts of the reservoir west of the top of the delta front (mile 306) at the halfway point. As pointed out on page 164 there is a marked reduction in declivity of the 1948 delta surface, beginning in the vicinity of Virgin Canyon and extending to Hoover Dam, and it was shown that this decreased slope is related to a progressive thickening of the bottomset beds toward Hoover Dam. Both the decreased slope and the delta thickening are ascribed to the basining effect of the dam (p. 205).

An analysis of volume capacities (tables 5–7, p. 91–93) shows that this basining effect at the halfway point must extend approximately the same distance uplake from the dam as it did in 1948, and that the slope of this part of the delta cannot be greater than the average slope (1.2 feet per mile) of the bottomset beds in Boulder Basin in 1948, which is the best available example of the basining effect. Calculations based on volume capacities and an assumed slope of 1.2 feet per mile show that the bottomset beds at the halfway point would extend to mile 308, where they would have an altitude of 1,100 feet. Assuming that the delta front maintains its 1948 slope of about 55 feet per mile, the surface of the bottomset beds would grade into the foreset beds at about the same position as in 1948; that is, 105 feet below the altitude of the top of the delta front and 2 miles downlake. The bottomset beds at the dam would then rise to an altitude of 1,044 feet, only 1 foot below the sill of the upper outlet gates. The available capacity below this assumed slope of 1.2 feet per mile is just sufficient to store the 11,500,000 acre-feet of silt and clay accumulated in the reservoir at the halfway point.

If a slope greater than 1.2 feet per mile is assumed in these calculations, the capacity will not be sufficient to store the 11,500,000 acre-feet of silt and clay. For example, the capacity below a surface with a slope of 1.8 feet per mile extending from an altitude of 1,100 feet at the face of the delta front and intersecting the dam at an altitude of 1,010 feet is only 10,000,000 acre-feet of the 11,500,000 acre-feet required. Likewise, the capacity below a surface with a subaqueous slope of 5.8 feet per mile, which is slightly greater than the average subaqueous slope of the delta in 1948, is only 10,000,000 acre-feet. The inadequacy of the reservoir for storing the 11,500,000 acre-feet of silt and clay below these higher gradients is explained by the irregular distribution of available storage space west of mile 306. At the halfway point, the upper 25 percent of the subaqueous profile where the sediments are thickest will be confined to the narrow Virgin Canyon–Temple Bar area (miles 306–317), which cannot possibly store a corresponding percentage of the 11,500,000 acre-feet of silt and clay to be deposited west of the delta front. This quantity will invade considerable portions of Virgin Basin and Boulder Basin where greater storage capacity is available. The assignment of sufficient quantities of sediment to these areas requires a slope not greater than 1.2 feet per mile.

For many years the accumulation of bottomset beds will continue in the portion of the reservoir east of Virgin Canyon, in the area over which the delta front will have advanced when the reservoir is half filled with sediment. Some of the space in these upper areas will thus be preempted by bottomset beds, so that the topset beds and foreset beds must advance farther downlake than would be estimated on the basis of basin capacities alone. Assuming that 20 percent, or 860,000 acre-feet, of the capacity below spillway level in the upper basins will be occupied by bottomset beds, the top of the delta front would have to advance over the underlying bottomset beds to mile 317 at the eastern end of Virgin Basin. Using a slope of 1.2 feet per mile for the profile west of the delta front at this point, and a volume of 10,740,000 acre-feet of bottomset beds to the west, we find that the bottomset beds would intersect the intake towers at an altitude of 1,025 feet, or about 20 feet below the upper outlet sills.

In summary, it is predicted that the filling of Lake Mead will have reached the halfway point when the sediment accumulation becomes slightly more than 18 times as great as the amount brought into the lake between 1935 and 1948. At that time the topset, foreset, and underlying bottomset beds will fill all the reservoir east of Virgin Basin and extend into that basin. The bottomset beds at the dam will reach almost to the level of the upper outlet gates. The water-storage capacity (not including ground-water storage) will be about 13,000,000 acre-feet below the permanent spillway crest, comprising about 4,500,000 acre-feet in Boulder Basin, 500,000 acre-feet in Boulder Canyon, 5,000,000 acre-feet in Virgin Basin and 3,000,000 acre-feet in Overton Arm. The total water storage can be increased to about 14,900,000 acre-feet by raising the spillway gates.

FILLING TO SILLS OF LOWER OUTLET GATES AT HOOVER DAM

The general procedure outlined in the preceding pages is used to estimate the amount of sediment required for filling the reservoir to the altitude (895 feet) of the lower outlet sills at Hoover Dam. In this estimate it is assumed that the lower 46 miles (extending downlake from mile 308 at the mouth of Virgin

Canyon) of the delta profile will exhibit some basining effect and that this part of the profile will have a slope of 1.2 feet per mile. With the lower end of this sloping plane intersecting the dam at the level of the lower outlet sills, the upper end will rise to an altitude of 950 feet at mile 308. Uplake from this position it is assumed that the subaqueous profile will have the same slope as the upper part of the 1948 subaqueous profile relative to the position of the delta front. It is assumed, also, that the average slope of the subaerial part of the delta (topset beds) east of the delta front will remain at 1.2 feet per mile as in 1948, and that the average water level in the reservoir will be maintained about at the elevation of the permanent spillway crest.

Based on these assumptions, the delta front at this stage of reservoir filling will have progressed to the mouth of Iceberg Canyon at mile 290, about 12 miles downlake from its position in Pierce Basin in 1948. The sediment accumulated in the reservoir at this stage will have a total volume of 8,400,000 acre-feet which will comprise 3,000,000 acre-feet of sand and 5,400,000 acre-feet of silt and clay.

The sand fraction will be deposited, of course, as foreset beds at the delta front and as topset beds farther east. Of the total volume of sand, 1,400,000 acre-feet will be deposited below altitude 1,205 feet, and 1,600,000 acre-feet will be deposited above this altitude. Assuming that the topset beds will maintain their present slope of 1.2 feet per mile, the 1948 delta surface in Pierce Basin and Lower Granite Gorge would be buried by about 49 feet of additional material, of which 35 feet would result from increasing the average operating level of the reservoir from 1,170 to 1,205 feet, and the remainder (14 feet) would result from upbuilding of the topset beds at a rate of 1.2 feet for each mile of advance of the delta front. The topset beds at this stage would extend about 6 miles upstream from Bridge Canyon rapids and they would rise to a maximum altitude of 1,280 feet, or 75 feet above the altitude of the permanent spillway crest.

Of the 5,400,000 acre-feet of silt and clay, about 500,000 acre-feet will underlie the accumulation of sand east of the delta front. This part of the silt and clay fraction comprises the bottomset beds in the area over which the delta front will have progressed at this stage in reservoir filling. The remaining 4,900,000 acre-feet of silt and clay will make up the bottomset beds extending from the foot of the delta front to Hoover Dam.

At a mean specific weight of 93.8 pounds per cubic foot, the sand will have a total weight of 6,100 million tons. Further calculations, based on the method outlined on pages 221–223, show that the silt and clay will have a mean specific weight of 62.6 pounds per cubic foot and a total weight of 7,400 million tons. The entire accumulation will have a mean specific weight of 73.6 pounds per cubic foot and a total weight of 13,500 million tons.

In summary, the sediment level at the dam will have reached the elevation of the lower outlet sills when the total accumulation becomes about 7 times as great as the amount brought into the lake from 1935 to 1948. At that time the reservoir east of Gregg Basin will be completely filled with sediment, but abundant storage space will still be available in the western part of the reservoir. The water-storage capacity below the permanent spillway crest will be about 22,000,000 acre-feet, comprising 6,300,000 acre-feet in Boulder Basin, 800,000 acre-feet in Boulder Canyon, 8,000,000 acre-feet in Virgin Basin, 3,300,000 acre-feet in Overton Arm, 2,000,000 acre-feet in the Temple Bar area, 300,000 acre-feet in Virgin Canyon, and 1,300,000 acre-feet in Gregg Basin. By raising the spillway gates, the total storage can be increased to about 24,100,000 acre-feet.

As pointed out on page 221, these predictions are based on certain assumptions, of which an important one depends on reservoir operations. It is assumed that the average operating level will be at spillway level, and on that assumption it is predicted that about 20 per cent of the total sediment load will be deposited above the level of the permanent spillway crest. Lower average operating levels will reduce the proportion of sediment deposited at high levels, extend the delta front downlake, reduce the area available for deposition of silt and clay, and result in a more rapid rise of the sediment level at the dam.

TERMINAL SLOPE AND RESIDUAL STORAGE

In the foregoing discussion of the various stages of reservoir filling, it has been assumed that all the sediment transported into Lake Mead will be deposited in the lake and that none will be discharged through the outlet gates or spillway tunnels of Hoover Dam. If the outlet gates are used for discharging sediment through the dam, however, it is likely that the reservoir will never become entirely filled with sediment but will eventually reach a terminal stage when all the sediment transported into the lake will be discharged through the outlet gates and spillway tunnels of Hoover Dam. Inasmuch as the intake towers are only a few hundred feet from the dam, the sediment surface at the terminal stage will intersect the dam at about the elevation of the upper sills (1,045 feet). At this stage the reservoir will be almost completely filled with

sediment. There will remain, however, a very small space still available for water storage. This space is referred to in this paper as "residual storage," and the slope of the sediment surface underlying the residual storage space is referred to as the "terminal slope."

As estimated on the preceding page, the sediment surface at the dam will rise to the level of the lower outlet sills when the accumulation becomes about 7 times as great as in 1948. Even before this time, however, turbidity currents carrying an appreciable quantity of suspended sediment may be expected to override intermittently the sills of the lower gates. Use of these gates may then be abandoned, in order to avoid passing great quantities of suspended sediment into the small reservoirs (Lake Mohave and Havasu Lake) downstream from Hoover Dam, unless some method is developed for passing sediment through them also.

If the use of the lower gates is abandoned at that time, the upper gates will still be capable of discharging clear water until they, too, begin to be engulfed in sediment. According to the estimate on page 223, this stage will be reached when the reservoir becomes about half filled with sediment, or when the total accumulation becomes about 18 times as great as in 1948. At that time the delta front will be near the eastern end of Virgin Basin, about 37 miles uplake from the dam, and the sediment surface at the dam will be only a few feet below the sills of the upper gates. Probably some sediment will have to be passed through the upper gates before this stage is reached, but the following considerations indicate that the quantity will be small. As noted on page 203, the suspended sediment entering the lake during most of the year travels downlake along the bottom of the reservoir. In consequence, the upper water strata are generally clear and uncontaminated by suspended sediment. However, when the Colorado River is in flood (usually from late April to early July), the turbid water spreads out over the lake surface and travels for a considerable distance downlake. In May 1948 turbid surface flow was observed as far west as the center of Virgin Basin, about 48 miles from the river entrance. Thus we may expect that some suspended sediment will be discharged during late spring and early summer through the upper outlet gates prior to the time the sediment level reaches the gate sills, because the distance between the dam and the Colorado River entrance will probably be much less than 48 miles.

Measurements during the high spring inflow of 1948 show that the average suspended-sediment concentration in the upper lake layers at a distance more than 20 miles from the river entrance was only about 0.008 percent. Using this value for the suspended-sediment concentration and assuming that the water discharged through the upper outlet gates will average 30,000 cfs during a 3-month period of high spring inflow, a total of 580,000 tons of sediment will be discharged annually through the upper gates. This is only 0.4 percent of the average annual weight of sediment accumulated in Lake Mead from 1935 to 1948. It may be concluded, therefore, that the sediment discharged through the upper outlet gates will initially be in small quantities and limited to the period of spring floods. However, as the sediment surface approaches the upper gates, some of the turbidity currents flowing along the bottom of the reservoir will overtop them, which will result in the passage of progressively larger quantities of sediment through the dam.

When that happens, consideration and evaluation of a number of factors will be required by those responsible for operation of Lake Mead and the control of the Colorado River. The passage of large amounts of sediment through the dam will destroy the usefulness of downstream reservoirs, unless some provision is made for passing sediment through them. On the other hand, if the upper outlet gates are abandoned and the reservoir is allowed to become entirely filled with sediment, all the sediment carried into the lake will ultimately be discharged downstream through the spillway tunnels. This, of course, will also result in the filling of downstream reservoirs, but at a somewhat later date.

Still another factor must be considered. If the upper outlet gates are permanently closed to avoid discharging large quantities of sediment downstream, the power output of Hoover Dam will cease. On the other hand, if the upper outlet gates are used for discharging sediment, Hoover Dam can continue indefinitely a large proportion of its average annual output of electrical energy.

The question as to whether the dam could pass large quantities of sediment requires consideration of a number of factors, the most important of which appear to be the following: (1) The maximum water-discharge capacity of the upper outlet gates when the lake surface is at an elevation of 1,205.4 feet; (2) the maximum sediment particle size that can be physically passed by the powerplant turbines; and (3) the abrasive effects of sedimentary debris on the powerplant turbines and appurtenant structures. These factors are evaluated as follows by C. P. Vetter and J. W. Stanley:

> The maximum discharge which could be passed through the upper outlet gates by power units now operating or under

installation and outlet needle valves, with a forebay level of 1,205.4 feet, is approximately as follows:

	Cubic feet per second
Through power units	33,500
Through 12 lower tunnel needle valves	41,200
Through 11 canyon wall needle valves	41,800
Total	116,500

In view of the outlet capacity listed above, it is apparent that all the flood inflow, except during short peaks of extreme floods, could physically be passed without use of the spillways.

The present sediment inflow to Lake Mead could be passed through the powerplant turbines, although some increase in turbine wear would result and more frequent repairs would be necessary. Gravel, of course, would cause excessive wear, but particles of the size now entering the lake could be passed, if necessary.

On the basis of this competent appraisal there seems to be no question that most of the sediment and water delivered to Lake Mead could be passed through the upper outlet gates by the powerplant turbines and outlet needle valves. Only during short peaks of extreme floods would use of the spillways be required.

If sediment is intentionally and regularly passed through the upper outlet gates, it is of interest to speculate briefly on the possible course of sedimentation as the reservoir passes into its terminal stage, the stage when all the sediment transported into Lake Mead will be discharged through Hoover Dam. The coarser particles, principally sand, will presumably continue to accumulate in the topset and foreset beds, and part of the silt and clay will accumulate in the upper reaches of the bottomset beds. In this way the delta front will continue its advance down the lake, but at a diminishing rate owing to the passage of progressively larger quantities of sediment through the upper outlet gates. The amount of sediment discharged through the upper outlet gates must necessarily increase because of the reduced distance between the river entrance and the dam, and because of the growth downlake of the steeper parts of the delta profile. The slope of the lower, flatter part of the delta profile—produced chiefly by the basining effect of Hoover Dam—will increase, approaching the slope of a delta built into a lake of "infinite extent." These factors will result, of course, in a steeper average slope of the subaqueous delta surface, which will increase the velocity and sediment-transporting power of turbidity currents moving along the bottom of the reservoir. In other words, the sediment that formerly accumulated on the lower and flatter part of the delta will be discharged through the upper outlet gates.

As the steeper parts of the delta grow toward the dam, the average slope of the subaqueous delta surface will become progressively greater. Eventually, an average slope will be attained that is great enough to provide a sufficient velocity for the transportation through the upper outlet gates of all the sediment delivered to Lake Mead. This slope is referred to as the "terminal slope."

Owing to the lack of quantitative data and to an incomplete understanding of the interrelations of factors governing transportation of sediment through reservoirs, it is possible to predict the nature of the terminal slope only in a very general way. It seems reasonable to assume that the terminal slope will not be less than 55 feet per mile, which was the average slope of the Colorado delta front in 1948 (measured along the axis of the valley traversing the foreset beds). That slope in 1948 was apparently in equilibrium with the bottom velocities then prevailing in its vicinity. As the reservoir nears its terminal stage, however, the velocity at the bottom may be expected to increase appreciably. Part of this increase will result from the limited capacity of the reservoir at its terminal stage, which, during times of flood at least, will require a considerable increase in the discharge of water through the upper outlet gates. A further increase in the bottom velocity may be expected in the narrow constriction of Black Canyon upstream from Hoover Dam. Presumably, this increase in velocity will provide a terminal slope somewhat steeper than that of the Colorado delta front in 1948, but there is no reasonable basis for estimating with any precision the amount of steepening to be expected. Consequently, it is assumed that the terminal slope will be the same as the average declivity (55 feet per mile) of the delta front in 1948.

If the lake is maintained at the level of the permanent spillway crest (elevation 1,205.4 feet), the terminal slope will intersect the upper outlet sills at the intake towers when the Colorado River entrance is only about 3 miles uplake from Hoover Dam. Because it is assumed that all the sediment entering the reservoir in its terminal stage will be discharged through the dam, a small space, referred to as "residual storage," will still be permanently available for water storage. In order to obtain an estimate of the residual storage capacity, a terminal slope of 55 feet per mile was assumed as a basis for constructing a hypothetical topographic map of the reservoir floor at its terminal stage (fig. 61). A contour interval of 10 feet was used, the areas enclosed by the contours were measured by planimeter, and the volumes between adjacent contour surfaces were computed. According to these computations, the reservoir at its terminal stage will have a residual storage capacity of 64,700 acre-feet, or only 0.22 percent of the initial storage capacity (28,794,000

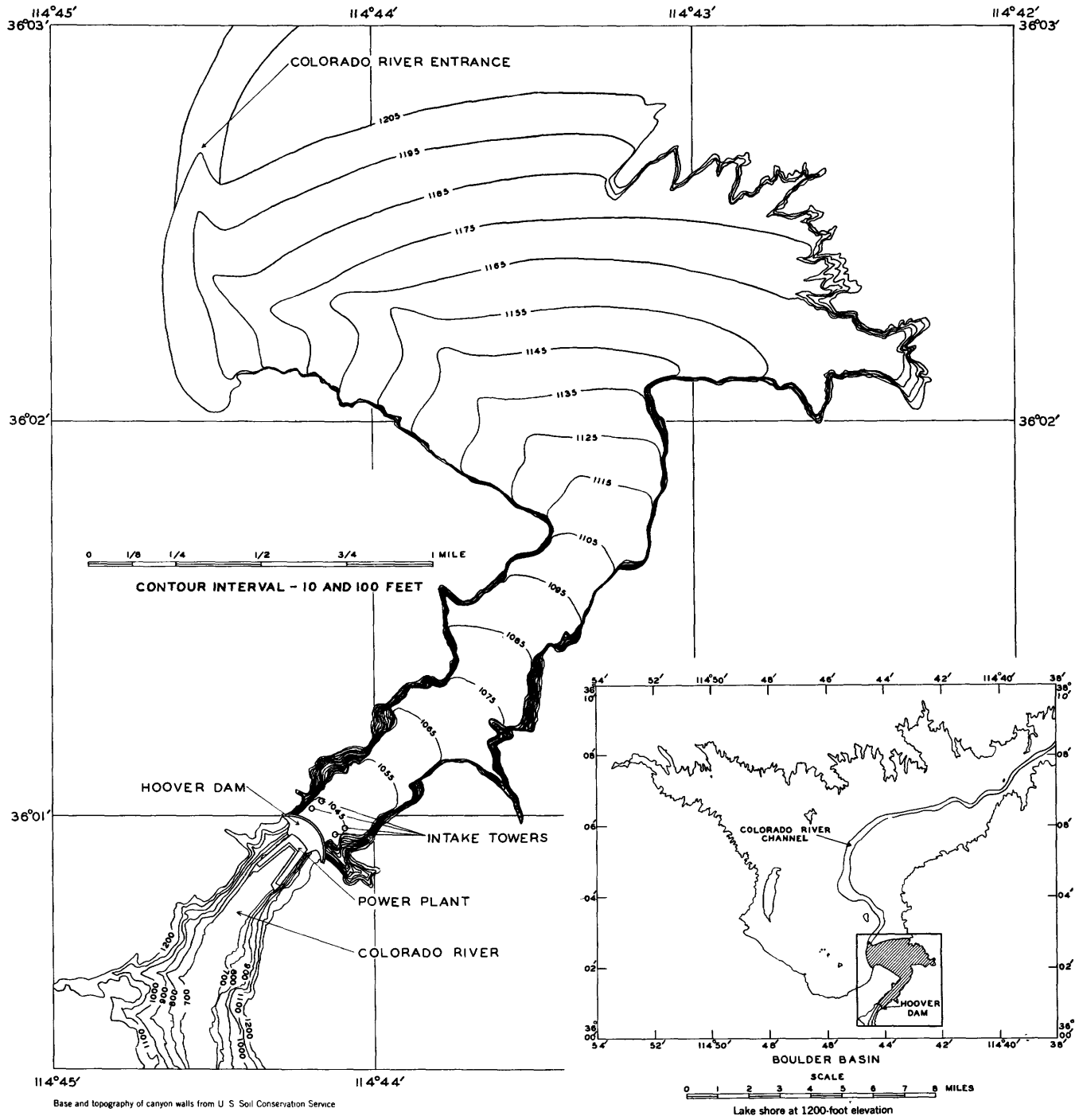

FIGURE 61.—Hypothetical bottom topography of Lake Mead at its terminal stage. The relation of the lake at its terminal stage to Boulder Basin appears in the inset.

acre-feet) of Lake Mead at the elevation of the permanent spillway crest (1,205.4 feet). Expressed in other terms, the reservoir in its terminal stage will hold only 0.48 percent of the average annual inflow to Lake Mead during the 14-year period 1935–48.

Under the conditions assumed, during December, January, and February, when the flow into the lake generally averages less than 7,000 cfs (U.S. Geological Survey, 1954, p. 551–573) the reservoir will be capable of storing the equivalent of 6 days of inflow. In May and June, however, when the flow averages about 50,000 cfs, the holdover storage will be reduced to the quantity of water flowing into the reservoir in only 16 hours. During this period and especially at times of

peak discharge, when the flow sometimes exceeds 100,000 cfs, the spillway gates may be raised to provide some regulation of the river flow. At the terminal stage these gates can increase the water-storage capacity by about 280,000 acre-feet, which can be used for a small measure of flood control, but will be entirely inadequate for seasonal regulation for downstream users.

AMOUNT OF EROSION REQUIRED FOR FILLING LAKE MEAD

The quantitative measurements of the sediment accumulated in Lake Mead provide a basis for estimating with considerable accuracy the average rate of erosion from the tributary drainage basin during the 14-year period 1935–48. Most of the weathering products are carried from their source areas in the detrital load of the Colorado River and its tributaries; since the closure of Hoover Dam in 1935 this material has accumulated in Lake Mead. The 2,000 million tons deposited in Lake Mead from 1935 to 1948 is therefore a measure of the total amount of stream-transported detritus removed from the tributary drainage basin during this period.

According to C. S. Howard (p. 121), 140 million tons of dissolved solids was carried in the Colorado River as it passed through Grand Canyon from February 1935 to September 1948, and the total dissolved load brought into Lake Mead during the 14-year period 1935–48 was probably of the order of 148,000,000 tons. The total weight of material carried from the tributary drainage basin in solution and as stream-transported detritus during this interval is therefore estimated at about 2,150 million tons. No data are available on the amount of material removed by wind action, but the sediment transported in this fashion is probably negligible compared to the amount of material removed by other agencies.

Using the above value for the total weight of material removed and a value of 2.67 for the specific gravity of the mineral particles, we can obtain a reasonable estimate of the average rate of erosion from the basin from 1935 to 1948.

The rate of erosion can be expressed in terms of either soil or unweathered rock. According to Lutz and Chandler (1946), the mean porosity of average soils is about 50 percent. Assuming this to be the average soil porosity in the Colorado River basin, calculations indicate that a layer of soil having an average thickness of 0.133 inch has been removed from the 168,000 square miles of the tributary drainage basin during the 14-year interval. If this rate of erosion were to continue in the future, a layer of soil having an average thickness of 1 foot would be removed every 1,260 years.

The average porosity of all types of unweathered rock in the basin is very difficult to estimate from available data. Average shale has a porosity of about 13 percent (Pettijohn, 1949), but the unconsolidated and semiconsolidated sediments, which are widely distributed in the basin, probably have porosities ranging to more than 35 percent. Even crystalline rocks have an appreciable porosity due to joints and other fractures. Solution cavities in limestones, and gas vesicles in basalt and other lava flows, give a considerable porosity to rocks of these types. For this estimate an arbitrary assignment of 15 percent for the mean porosity of unweathered rock in the Upper Colorado River Basin is probably not unreasonable. Expressed in terms of unweathered rock having an estimated porosity of 15 percent, we find that the tributary drainage basin has been reduced in elevation by an average of about 0.078 inch from 1935 to 1948. At this rate, the average lowering of the basin by erosion would be about 1 foot every 2,150 years.

The 75,000 million tons of sediment required to fill the reservoir completely would represent the erosion products from a soil layer averaging 4.9 inches in thickness over the entire tributary basin. However, we may be sure that the rate of erosion will be far from uniform over the basin. Judging by the history of the past century, we may expect that between now and the date when the reservoir is full of sediment, the erosion in some parts of the basin will be negligible and in others will be measurable in tens of feet.

The records of suspended sediment in streams indicate these inequalities in sediment production and therefore in the rates of erosion in various part of the basin (p. 26). The network of sediment-gaging stations is enough to indicate that the drainage basin tributary to Lake Mead could be divided approximately into halves, consisting of (1) headwater areas in Colorado, Wyoming, and northern Utah, which commonly contribute more than three-fourths of the water but less than one-fourth of the sediment to Lake Mead; and (2) arid areas in New Mexico, Nevada, Arizona, and southern Utah, which produce less than one-fourth of the water but most of the sediment carried into the lake. Assuming a similar contrast in sediment production in the future, the filling of Lake Mead would be accompanied by erosion averaging nearly 8 inches in the arid areas but only slightly more than 2 inches in the headwater half of the drainage basin.

REFERENCES CITED

Eakin, H. M., 1939, Silting of reservoirs, revised by Brown, C. B.: U.S. Dept. Agriculture Tech. Bull. 524, p. 90–99.

Emery, K. O., and Rittenberg, S. C., 1952, Early diagenesis of California basin sediments in relation to origin of oil: Am. Assoc. Petroleum Geologists Bull. v., 36, p. 735–804.

Happ, S. C., 1946, *Discussion of* Stevens, J. C., Future of Lake Mead and Elephant Butte Reservoir: Am. Soc. Civil Engineers Trans., v. 111, p. 1298.

Hedberg, H. D., 1936, Gravitational compaction of clays and shales: Am. Jour. Sci., ser. 5, v. 31, p. 241–287.

Mackin, J. H., 1948, Concept of the graded river: Geol. Soc. America Bull., v. 59, p. 496–498.

Stevens, J. C., 1946, Future of Lake Mead and Elephant Butte Reservoir: Am. Soc. Civil Engineers Trans., v. 111, p. 1242–1254.

U.S. Geol. Survey, 1954, Compilation of records of surface waters of the United States through September 1950; part 9—Colorado River basin: U.S. Geol. Survey Water-Supply Paper 1313, 733 p.

496918 O—60——16