Comprehensive Survey of Sedimentation in Lake Mead, 1948-49

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J. WATER BUDGET

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The water budget of Lake Mead is an account of its operation for its basic function of regulating the highly variable flow of the Colorado River for the benefit of flood control, irrigation, domestic use, and hydroelectric power generation. This regulation of the flow is brought about through storage of water in years of high runoff to supplement the flow during the years of low runoff (fig. 18).

Lake Mead in 1935 had a total controlled capacity of 31,250,000 acre-feet (to top of spillway gates in raised position), and a usable capacity of 28,027,000 acre-feet. By 1948 the usable capacity had been reduced to 27,207,000 acre-feet because of deposition of sediment. The annual inflow into the lake in the 14-year period since Hoover Dam was completed (1935–48 inclusive) averaged about 13,000,000 acre-feet. The usable capacity therefore has been equal to 215 percent, and is still nearly 210 percent of the average yearly flow through the reservoir. This storage ratio is indicative of a long detention time for river regulation and control.

Setting up the water budget of the lake requires an accounting of all items of inflow, outflow, and storage. In an ideal case, all these items would be measured independently and continuously, which would permit striking a daily balance at the close of each day's business, as is done in a financial institution. The extent to which this can be done in practice is limited because there are certain items that cannot be measured. Of the inflow items there is a significant amount of runoff into the reservoir that cannot be measured in a practical way. The outflow is measured continuously except for evaporation, for which measurement was not begun until 1952. Storage volumes in the reservoir are known from the 1935 and 1948–49 surveys, but preliminary consideration early in the history of the lake indicated a significant amount of bank storage in the sediments in the reservoir and in the sand, gravel, and rock materials underlying the reservoir. It is, therefore, inevitable that the water budget must include estimates for some items in lieu of measurement, leaving in the balance certain residuals that are indicative of net errors or items not directly accounted for. It is also impossible to obtain accurate balances for daily or even monthly periods, because of uncertainties as to time of travel of water from the points of measurement to the lake, and because of the uncertainties as to the seasonal distribution of the unmeasured inflow and of evaporation. The shortest practical period for which the budget can be set up therefore is a year. Table 9 sets up the annual budget for Lake Mead since its creation.

METHOD OF COMPUTING THE BUDGET

The water budget of table 9 is developed by (1) measuring or estimating all the accretions to Lake Mead and adding them to derive the "total inflow"; (2) similarly evaluating the depletions from the lake and deriving the "total outflow"; (3) computing the difference between inflow and outflow, and comparing that quantity with the recorded change in reservoir storage. These comparisons yield significant "residual" quantities, which may be in part due to the errors in estimations of certain items but appear to be also a measure of hidden assets or liabilities that have not been evaluated in the budget.

INFLOW

Most of the inflow to the lake is measured at the gaging station on the Colorado River near Grand Canyon, 145 river miles above Lake Mead. A gaging station is also operated on Bright Angel Creek, which enters the Colorado River below the gaging station near Grand Canyon, and another is operated on the Virgin River at Littlefield, Ariz. The sum of the flows past these three stations is shown under measured inflow (I_m).

Below the Littlefield gaging station the Virgin River traverses open desert valleys for about 40 miles to the lake and is subject to natural losses and some diversion for irrigation. No other tributaries to Lake Mead or to the Colorado River below the Grand Canyon are measured. There is thus about 25,000 square miles of tributary area from which the runoff into the lake is unmeasured. Of this area, about 10,000 square miles can be said to be desert land which yields negligible runoff. The unmeasured inflow from the remaining area is doubtless very small in comparison with the total

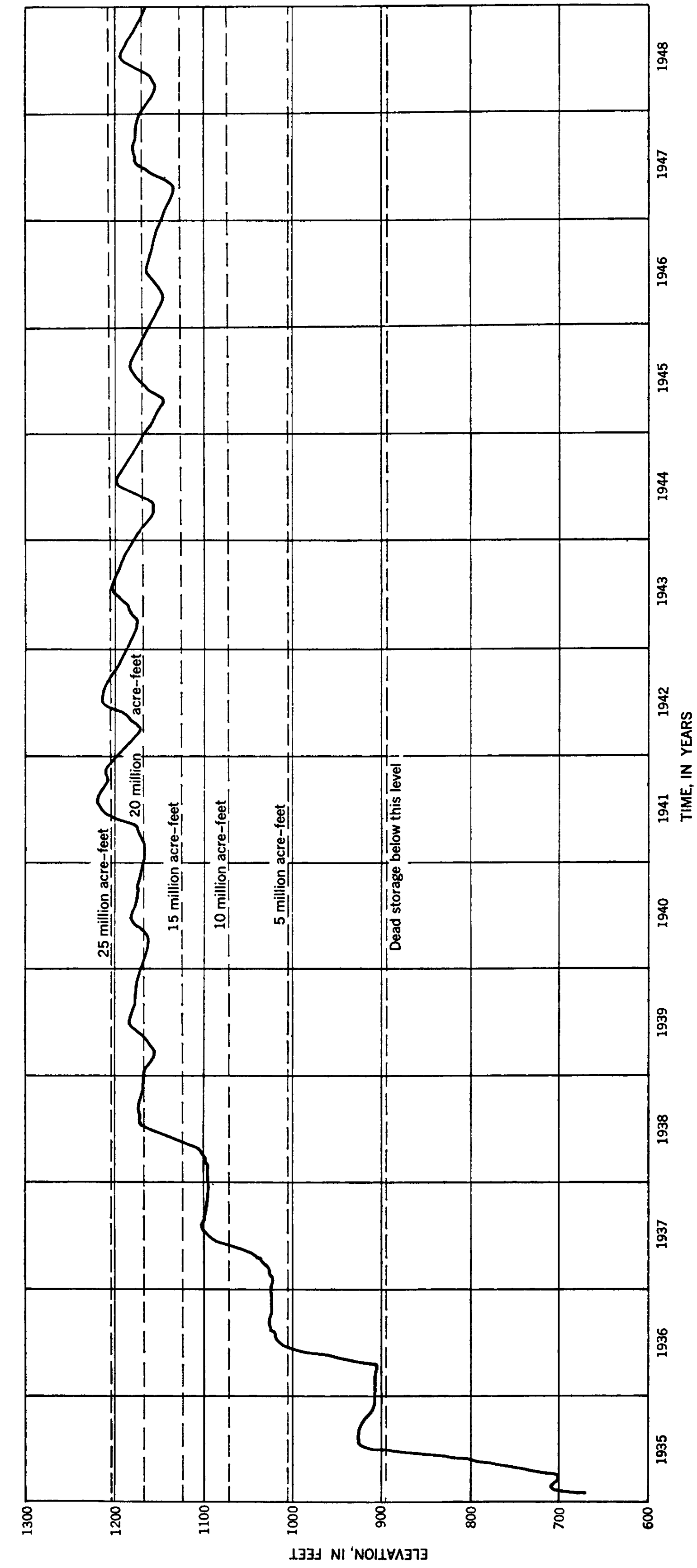

FIGURE 18.—Stage and usable storage of Lake Mead, 1935 to 1948. Slight inclination of dashed lines indicating capacity results from reduction of storage by sedimentation.

TABLE 9.—*Lake Mead water budget, 1935 to 1950*

[All quantities in thousands of acre-feet, except as indicated]

Water year	Mean surface area, in thousands of acres	Inflow				Outflow				Inflow minus outflow		Reservoir storage			Residual $I-O-\Delta S$
		Measured I_m	Unmeasured I_u	Precipitation on lake I_o	Total inflow I	Evaporation (estimated) O_e	Measured O_m		Total outflow O	Annual $I-O$	Cumulative	Stage at end of water year, in feet above sea level, powerhouse datum	Reservoir content at end of water year [1]	Net change ΔS	
							Hoover Dam	Pumping							
1935	21	10, 417	266	6	10, 689	150	5, 556	1	5, 707	+4, 982	4, 982	920. 75	4, 140	+4, 140	+842
1936	49	12, 476	174	16	12, 666	350	6, 282	1	6, 633	+6, 033	11, 015	1, 024. 6	9, 621	+5, 481	+552
1937	82	12, 692	468	37	13, 197	585	5, 826	1	6, 412	+6, 785	17, 800	1, 097. 65	15, 639	+6, 018	+767
1938	111	15, 953	573	31	16, 557	790	6, 168	1	6, 959	+9, 598	27, 398	1, 173. 8	24, 272	+8, 633	+965
1939	131	9, 799	238	79	10, 116	930	8, 473	1	9, 404	+712	28, 110	1, 178. 95	24, 956	+684	+28
1940	131	7, 641	290	48	7, 979	930	7, 694	1	8, 625	−646	27, 464	1, 174. 4	24, 351	−605	−41
1941	141	17, 404	900	119	18, 423	940	11, 730	1	12, 671	+5, 752	33, 216	1, 209. 85	29, 357	+5, 006	+746
1942	144	17, 504	400	43	17, 947	1, 045	17, 880	3	18, 928	−981	32, 235	1, 205. 0	28, 637	−720	−261
1943	141	11, 642	301	49	11, 992	982	12, 515	16	13, 513	−1, 521	30, 714	1, 195. 70	27, 277	−1, 360	−161
1944	135	13, 739	314	45	14, 098	990	14, 465	17	15, 472	−1, 374	29, 340	1, 187. 10	26, 067	−1, 210	−164
1945	130	12, 063	268	64	12, 395	870	12, 947	9	13, 826	−1, 431	27, 909	1, 177. 95	24, 827	−1, 240	−191
1946	124	9, 233	147	24	9, 404	845	11, 295	7	12, 147	−2, 743	25, 166	1, 157. 65	22, 217	−2, 615	−133
1947	123	13, 950	338	32	14, 320	825	10, 666	8	11, 499	+2, 821	27, 987	1, 178. 02	24, 832	+2, 615	+206
1948	132	14, 006	133	37	14, 176	985	12, 755	7	13, 747	+429	28, 416	1, 180. 82	25, 209	+377	+52
1949	126	14, 547	241	62	14, 850	875	13, 200	7	14, 082	+768	29, 184	1, 186. 86	26, 035	+826	−58
1950	128	11, 228	163	23	11, 414	925	12, 940	7	13, 872	−2, 458	26, 726	1, 168. 77	23, 617	−2, 418	−40

[1] Original capacity table, used without correction for datum difference (see Surface Water Supply of the United States, Part 9, Colorado River Basin, for the years 1940–49). This introduces no significant error as the differences in yearly content are used here, and the difference in datum is indistinguishable on fig. 21.

inflow, but it must be taken into account in preparing a budget for the reservoir. The actual amount is unknown, but it doubtless varies from year to year; and provided the record of the Virgin River can be used as a satisfactory index, it can be used to estimate the unmeasured inflow according to the formula: I_u (unmeasured inflow) $=aI_v+b$, in which I_v is the measured inflow of the Virgin River. The evaluation of the constants a and b is explained in the section on "statistical analyses." The estimates determined in this way are given as unmeasured inflow (I_u).

The precipitation on the lake is computed from the rainfall recorded at three locations about the lake, multiplied by the mean surface area during each year. Allowance was made for the higher rainfall during months when the surface area of the lake is least, but the resulting estimates of precipitation are subject nevertheless to large error because rainfall over the lake is highly variable. Precipitation is a very small item in the budget, and great accuracy, although desirable, is not essential.

OUTFLOW

The water released through Hoover Dam constitutes practically all the outflow from Lake Mead; it is adequately measured at the gaging station 1 mile below the dam, originally built by the Bureau of Reclamation and now operated by the Geological Survey in cooperation with the Bureau. The quantities are given in table 9. The quantities diverted by pumping from the lake for use at Henderson and Boulder City are also shown.

There is some depletion of storage by evaporation from the surface of the lake and by transpiration from the small areas of vegetation in some spots around the lake shore. To the extent that the rate of evaporation is a constant, the estimated annual evaporation may be evaluated by multiplying the mean surface area of the reservoir (with due allowance for the higher rate of evaporation in summer) by the annual rate of evaporation. The annual rate of evaporation has been estimated by the methods explained in the section "Statistical analyses," and the volumes of evaporation are the results of these computations.

RESERVOIR STORAGE

The stage of Lake Mead at the end of each water year and the corresponding contents according to the original capacity table are listed under "Reservoir storage." These volumes include water plus sediment, which is proper inasmuch as the inflow includes the volume of sediment particles of the suspended load.

STATISTICAL ANALYSES

Algebraically the water budget may be set up as follows:

$$I_m+I_u+I_p-\Delta S=O_e+O_m$$

in which I_m is the measured surface inflow, I_u is the unmeasured inflow, I_p is the precipitation on the lake surface, ΔS is the increase in storage, O_e is the evaporation, and O_m is the measured surface outflow.

Of these quantities I_u is unknown, and the bank storage component of ΔS is also unknown. These factors can be resolved provided they can be related to known variables. There is a strong possibility that the unmeasured inflow can be related to the record of the Virgin River at Littlefield, Ariz.; and total storage can be expressed as a constant times the measured change in reservoir contents, it being assumed, subject to test, that the bank storage is proportional to the annual changes in reservoir storage.

In lieu of formal least-square analysis, these relations were defined by a graphical method of converging approximations. In other words, preliminary assumptions were introduced for the unmeasured inflow, and net storage changes were then computed and related to the storage changes in the reservoir basin as given by the capacity table. This result indicated, for example, that total storage change is about 12 percent greater than that given by the capacity table. Using this result, calculations were made of the unmeasured inflow, which was then graphically related to the flow of the Virgin River. The points defined a satisfactory relation, quite different from the initial assumption. Now using these graphs, the process was repeated, which yielded results not very different from those obtained during the second approximation. The process was therefore not repeated. The results are given in figure 19.

The efficacy of the method used depends on the mutual independence of the factors used—Virgin River runoff and storage change—and the range through which these factors vary. The independence is not as great as might be desired. Greater variations in the record prior to the filling of the reservoir would have been invaluable for evaluating the unmeasured inflow. The flow of the Virgin River is roughly correlated with changes in storage, because large increments in reservoir storage tend to occur in wet years when flow of the Virgin River is high, and vice versa. Nevertheless there is enough independence to make the derived relations useful.

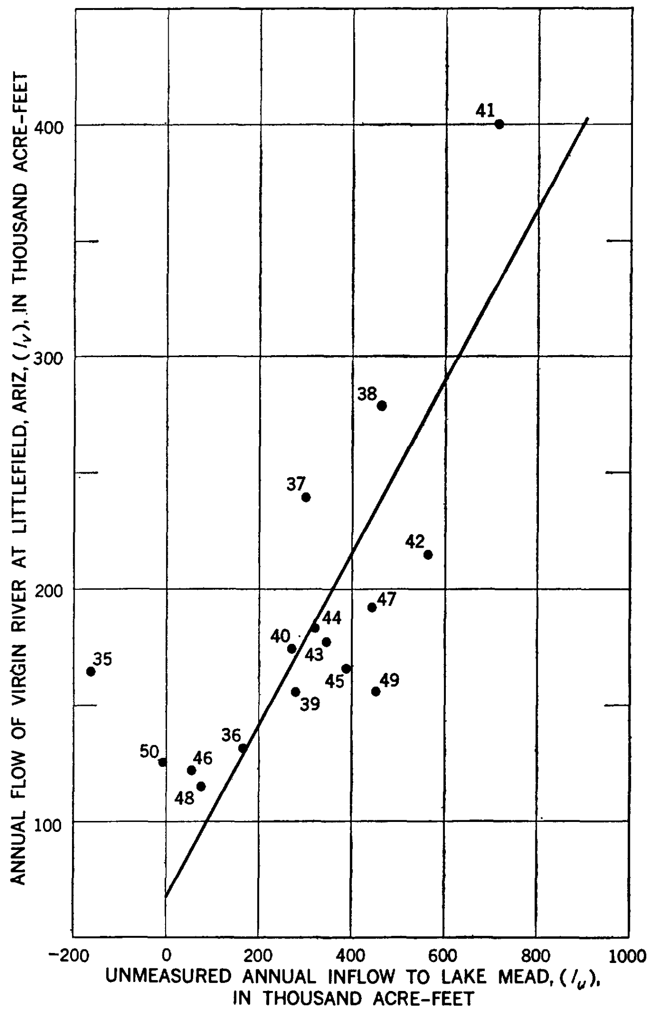

FIGURE 19.—Relation between unmeasured inflow to Lake Mead and runoff of Virgin River at Littlefield, Ariz.

EVAPORATION

Evaporation is an important item in the water budget of Lake Mead. Estimates of annual water loss made from several different assumptions have ranged from as much as 100 to as little as 64 inches. The inadequacy of these estimates had long been recognized, and the plans for the 1948–49 survey envisaged the collection of data that might provide a basis for comparison with the records of pan evaporation that had been collected at Lake Mead since 1935. As described on page 141, a reconnaissance energy budget was derived, which afforded a means of calculating evaporation during the period of the survey. But analysis of the possible errors introduced in estimating some important items of the energy budget led the authors of that reconnaissance to conclude that their estimates may be in substantial error.

Recognizing the important need for accurate information, intensive research into the problem of evaporation from reservoirs was undertaken in 1950 and 1951 at Lake Hefner, in Oklahoma, a reservoir that was well suited to the proof and test of new methods of measuring evaporation loss (U.S. Geol. Survey, 1954 a and b). After these tests, investigations were begun in March 1952 for the purpose of determining evaporation from Lake Mead as accurately as possible, applying the methods tested at Lake Hefner, specifically adapted to fit conditions at Lake Mead. The Geological Survey, Bureau of Reclamation, and Weather Bureau collaborated in that investigation, the results of which have been published (U.S. Geol. Survey, 1956). The total evaporation determined for the 1953 water year was 875,000 acre-feet, or 85.5 inches over the average area of the lake during that year. The investigations also provided a means for making estimates of annual evaporation from the lake during previous years, and for keeping monthly records of evaporation in the future, within limits such that annual figures will not be more than 10 percent in error.

TRANSPIRATION

The change in ecologic conditions brought about by the formation of Lake Mead has sustained the introduction of a new species of vegetation into the desert wasteland that became its shores. The saltcedar, *Tamarix gallica*, is a lusty water-loving exotic that has been able to displace native species rapidly wherever water is accessible, notably along streams and canals, and in areas of shallow water table. Around Lake Mead it is seen at various places below the high-water line established in 1941: in coves and bays of shoaling water, on some islands far from shore, along the beaches in Las Vegas Wash and Overton Arm, and along both sides of Lower Granite Gorge where it contrasts with the creosote bush (*Covillea tridentata*) and other xerophytes above the high-water line.

No studies were made during the 1948–49 survey to determine the areal extent of the saltcedar growth around the reservoir, or the quantity of water that might be consumed by it. Research in southern Arizona (Gatewood and others, 1950; Robinson, 1958) indicates that the saltcedar is an extravagant water user and, acre for acre, may transpire more water than is evaporated from a free water surface. Thus, if the area covered by saltcedars is sufficiently large, there could be significant losses from the reservoir in addition to the quantities evaporated from the reservoir surface.

Fluctuations in the level of the reservoir are somewhat discouraging to all types of vegetation, but saltcedar fares better than most. Plants on islands in Las Vegas Bay flourish even when the reservoir level has dropped 60 feet below them (pl. 29), and it seems that they are able to follow the water down with their roots. On a rising stage, a saltcedar plant can be drowned if it is completely submerged for an extended period, but in 1952 some plants in Las Vegas Wash survived a period of several weeks in water as much as 5 feet deep, while only the topmost branches reached above the lake level.

From these casual observations, it may be concluded that the zone in which saltcedar can become established ranges from the high-water line at 1,221 feet elevation down perhaps to the average operating level at 1,170 feet. The area of reservoir bed between these elevations is more than 30,000 acres. Reconnaissance trips on the lake, however, indicate that only a small proportion of this area is actually covered by saltcedar. The rock walls below the high-water line are almost invariably barren, and they appear to predominate around the shore. If as much as 10 percent of this 30,000 acres is occupied by saltcedar—and this is probably a very liberal estimate—the annual loss by transpiration would be of the order of 20,000 acre-feet, which is less than 3 percent of the evaporation from the free water surface and well within the limit of error of the evaporation calculations.

PRECIPITATION

Rain gages maintained by the Office of River Control in conjunction with its evaporating pans show marked variations in precipitation in various parts of the Lake Mead region. Random variations in monthly totals, particularly during the summer, doubtless reflect the intense but local cloudburst storms that are common in the region.

The variations in annual precipitation from one locality to another give some indication of the geographic distribution of rainfall. The precipitation recorded at Pierce Ferry, at the base of the Grand Wash Cliffs, may be two to four times as great as that at stations around Boulder Basin of Lake Mead. Between 1936 and 1949 the average annual precipitation at Pierce Ferry was 6.8 inches, compared with 3.7 to 3.8 inches at gages near the western end of the lake. It is not known whether the rate of precipitation increases sharply near the base of the Colorado Plateaus, or whether there is a progressive increase eastward from Boulder Basin.

The values shown in table 9 are based on three available records around the lake. It is not known to what extent the 3-station average represents the actual precipitation upon the lake, but, as already pointed out, these quantities are in any event a very small proportion of the total inflow. Even in the year of greatest annual precipitation, 1941, the quantity contributed to the reservoir was considerably less than 1 percent of the measured inflow from tributaries.

EVALUATION OF BANK STORAGE

The annual changes in reservoir contents shown in table 9 are similar in amount to those representing the differences between inflow and outflow. If all items of the budget had been accounted for and accurately measured, the quantities in these two columns would be identical. Actually there are significant differences

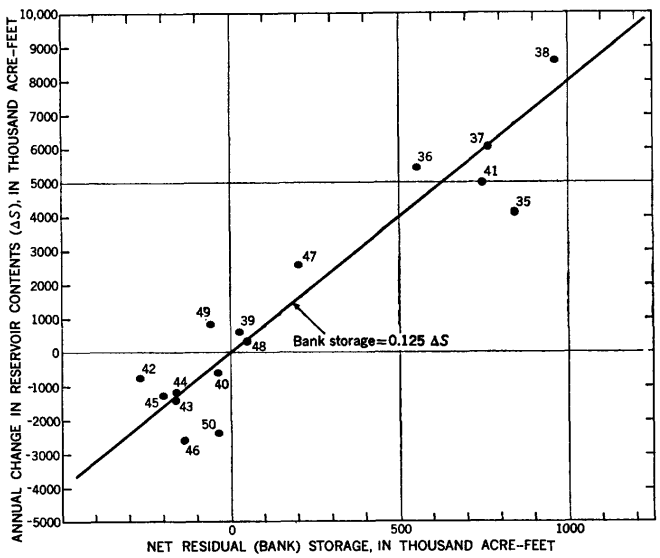

FIGURE 20.—Relation of net residual (bank storage) to annual change in reservoir contents.

in most years, and these differences are listed as "residuals." They vary in magnitude and sign, in a manner quite comparable to the net changes in reservoir contents. These residuals are plotted against the annual change in reservoir contents on figure 20. Although each residual, being the difference between two large figures, parts of which are estimates, is subject to large relative errors, nevertheless the points on figure 20 show a consistency which indicates that the actual errors are not large. The conclusion may be drawn that on an annual basis more water enters into or is withdrawn from storage than is indicated by the capacity table. In other words, Lake Mead has a significant amount of storage space in addition to the volumes which were calculated from the hydrographic survey of 1948–49, or even the original reservoir survey of 1935.

The unsurveyed storage in Lake Mead is the volume in which water can be stored in the banks or bottom of the reservoir, as determined during the hydrographic survey of 1948–49. It corresponds to bank storage along a river, with all the phenomena of filling and draining of interstices as the lake rises and recedes. It includes the water in the volume that has been filled by sediment during the interval from 1935 to 1948, and it includes voids in the gravel and sand and other rock materials that underlie the sides of the reservoir. Inasmuch as all this unsurveyed storage is in the banks of the reservoir, it is properly classed as ground-water storage, of the kind generally known as bank storage.

The magnitude of this bank storage is indicated in table 9 by comparison of the reservoir storage at end of year as indicated by capacity table, and the total storage as given by the cumulative difference between inflow and outflow. The data from both columns are plotted in figure 21 against corresponding lake stages. The gross storage, computed from the difference between outflow and inflow, indicates the total detention in the Lake Mead basin, subject to errors of estimation and measurement as explained. Since the inflow includes the volume of the solid particles of the suspended sediment, the detention necessarily includes sediment plus water. The sediment solids (about 2,000 million tons) occupy a volume of about 550,000 acre-feet; the bulk volume (1,426,000 acre-feet) is the sum of the sediment solids volume plus the volume of the interstitial water.

As of September 30, 1941, when the highest year-end stage was reached, the total storage computed from inflow-outflow differences was 33,216,000 acre-feet. compared with reservoir contents of 29,357,000 acre-feet as computed from the original capacity curve. The difference of about 3,859,000 acre-feet is presumed to represent the bank storage plus sediment storage. As shown in chapters N to T, the sediment particles carried into the reservoir between 1935 and 1948 have a total estimated volume of 550,000 acre-feet. The water storage beneath the reservoir sides and bottom when the lake is filled to capacity is therefore of the order of 3,300,000 acre-feet.

Not all the 3,300,000 acre-feet of ground-water storage is usable storage. About 875,000 acre-feet is held within the interstices of the sediments deposited within the lake, of which about 40 percent lie below the dead storage level. The effect of continued sedimentation below this level will be to reduce the proportion of water in existing sediment by compaction, but to increase the over-all quantity of interstitial water at the expense of reservoir dead storage.

The bank storage is not available during short-period changes in water level. It takes time for the water to permeate and drain the sediments containing this storage, and only a small proportion is available during the usual seasonal change in reservoir contents. Detailed analyses of bank storage associated with monthly or seasonal fluctuations in reservoir levels cannot be made until more is known of the distribution of evaporation and unmeasured inflow during the year. However, preliminary studies indicate that bank storage of the extent indicated is available only for year-to-year changes in reservoir contents.

In general, under present conditions and with the estimates now available for evaporation, precipitation, and unmeasured inflow, the annual change in gross

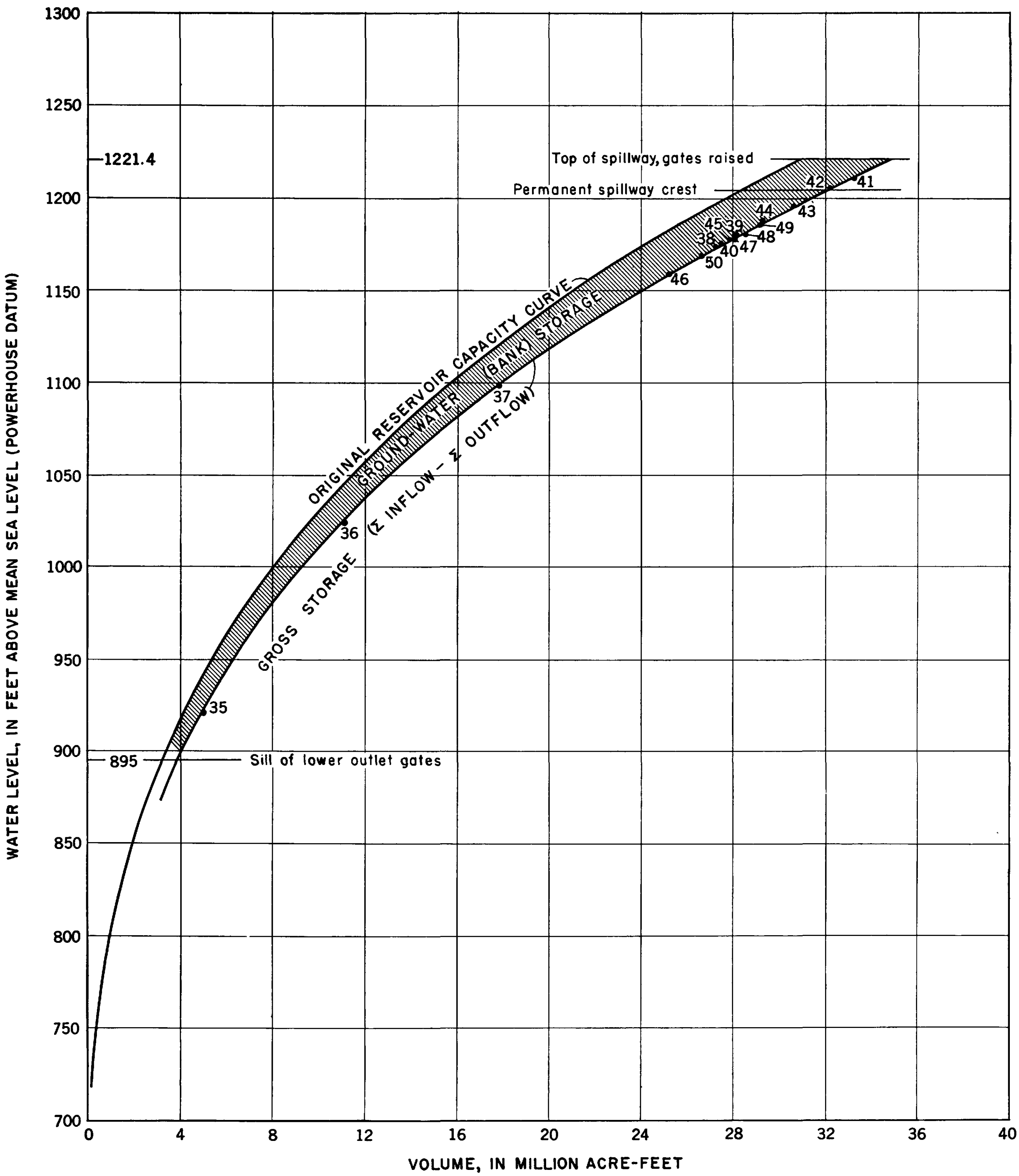

FIGURE 21.—Comparison of reservoir capacity curve with gross storage curve computed from difference between inflow and outflow.

storage averages about 12 percent more than the change in reservoir contents indicated by the capacity table, which adds materially to the degree of river regulation afforded by the reservoir. Thus, under present conditions, as shown by figures 20 and 21, there is a considerable variation in usable bank storage with change in lake levels. From September 1941 to September 1946 there was a net decline of 52.2 feet in reservoir level. Reservoir contents declined 7,140,000 acre-feet, but the gross storage contributing to the discharge at Hoover Dam amounted to 8,050,000 acre-feet, indicating a recovery of 910,000 acre-feet from bank storage during this 5-year drawdown.

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