Sedimentation of Lake Pillsbury Lake County California

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1619-EE

Prepared in cooperation with the State of California Department of Water Resources

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By G. PORTERFIELD *and* C. A. DUNNAM

CONTRIBUTIONS TO THE HYDROLOGY OF THE UNITED STATES

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SEDIMENTATION OF LAKE PILLSBURY, LAKE COUNTY, CALIFORNIA

By G. Porterfield and C. A. Dunnam

ABSTRACT

A study of sedimentation of Lake Pillsbury was undertaken in May 1959 to determine the quantity, character, and distribution of sediment deposited in the reservoir since the storage of water began in December 1921.

The drainage area of Lake Pillsbury is in the steep rugged mountains of the Coast Ranges in northwestern California, and elevations range from 1,828 (maximum lake elevation) to about 7,000 feet mean sea level. The vegetal cover throughout the basin is generally medium to dense and includes several species of grass, brush, fir, pine, and oak.

Precipitation varies with season and location in the Pillsbury drainage area, and available data are insufficient to define the average rainfall for the entire basin. At the lake, the monthly precipitation ranges from 0 to about 18 inches, and annual precipitation ranges from about 20 to 75 inches. The average annual precipitation at the Hullville station near the lake for the period 1907–36 was 47.62 inches. Temperatures range from about 15° to 107°F.

The reservoir formed by Scott Dam has a surface area of 2,280 acres. The average depth is 38 feet and the maximum depth, near the dam, is about 100 feet. The original reservoir storage capacity of 94,400 acre-feet has been reduced to 86,780 acre-feet during the 37.5 year period (December 1921—May 1959).

The loss of capacity represents a sediment deposition of 7,620 acre-feet, which is 8.1 percent of the original storage capacity, or an average annual loss of 0.22 percent.

Most of the sediment in Lake Pillsbury is deposited in the upper reaches of the Eel River and Rice Fork Eel River arms. This distribution of sediment is attributed primarily to the properties of the sediment, the reservoir shape and operation, and the ratio of the reservoir capacity to inflow.

The dry specific weight of the sediment deposited in the reservoir ranged from 41 to 87 pounds per cubic foot; the lowest specific weights are in the deep water in the main body of the reservoir, and the specific weight generally increased with distance upstream from the dam. The weighted-mean dry specific weight of sediment for the entire lake was 73 pounds per cubic foot.

INTRODUCTION

LOCATION AND GENERAL FEATURES

Lake Pillsbury, formed by Scott Dam on the Eel River, is in northern Lake County, Calif., 22 miles northeast of Ukiah and 17 miles north of Upper Lake. The drainage basin comprises the upper 288 square miles of the Eel River basin and lies wholly within the boundaries of the Mendocino National Forest.

Most of the land within the drainage basin is owned by the U.S. Government and is administered by the Forest Service. The lake and some of the adjoining land are privately owned. Lumbering and grazing are the principal pursuits on both private and public lands, and little, if any, land is in cultivation. The lake is operated as a holdover-storage facility, and the water is utilized for power and irrigation; minimum releases are made as required to support fish and wildlife. The lake is also a popular recreation area having private and public facilities available.

PURPOSE AND SCOPE

The purpose of this study was to determine the quantity, distribution, and properties of sediment deposited in Lake Pillsbury, and to provide a summary of the major physical and cultural features of the area that affect sedimentation of the reservoir. Very little information on reservoir sedimentation in the Coast Ranges of northwestern California is available, and data are needed to assist in planning and designing certain facilities of the California Water Plan (California Department of Water Resources, 1957). In addition, the results of the survey will make possible a revision of the capacity tables for Lake Pillsbury and will result in more accurate water records and more effective operation of the reservoir.

ACKNOWLEDGMENTS

The cooperation of the Pacific Gas and Electric Co., owner and operator of the dam and reservoir, is acknowledged. Company personnel furnished maps and data of the original survey, details of the dam and reservoir operation, and a boat for use during the field survey. The Upper Lake District of the U.S. Forest Service furnished facilities at the lake for the survey party's use. The owners of private resorts at Lake Pillsbury allowed full use of their facilities by the survey party. Rainfall records were furnished by Mrs. J. M. Cartwright of the Rice Fork Lodge and by Mr. Harold Boyd of Lake Pillsbury Pines.

DRAINAGE BASIN

PHYSIOGRAPHY AND SOILS

The Lake Pillsbury drainage area of 288 square miles is in the steep, rugged terrain of the Coast Ranges of northwestern California. Elevations within the drainage basin range from 1,828 (maximum lake elevation) to approximately 7,000 feet msl (mean sea level), and the lengths of the major tributaries to the reservoir range from a few to 26 miles. The average slope of the Eel River above the dam is 160 feet per mile, and the average slope of the Rice Fork Eel River is 200 feet per mile. The Eel and Rice Fork Eel Rivers have slopes of 1,560 and 2,110 feet per mile, respectively, between 4,000 and 5,000 feet elevation. The longitudinal profile of the principal tributaries to the reservoir are shown in figure 1.

The Lake Pillsbury drainage basin is underlain principally by rocks of the Franciscan Formation (fig. 2). The Franciscan consists of shale, greenstone, chert, conglomerates, and lesser amounts of sandstone and limestone; it has been complexly folded and faulted, and metamorphosed, and has been eroded and aggraded. The acclivities adjacent to the lake are composed of easily erodable deposits of reworked Franciscan material that include Recent alluvium, terrace deposits, and landslide debris.

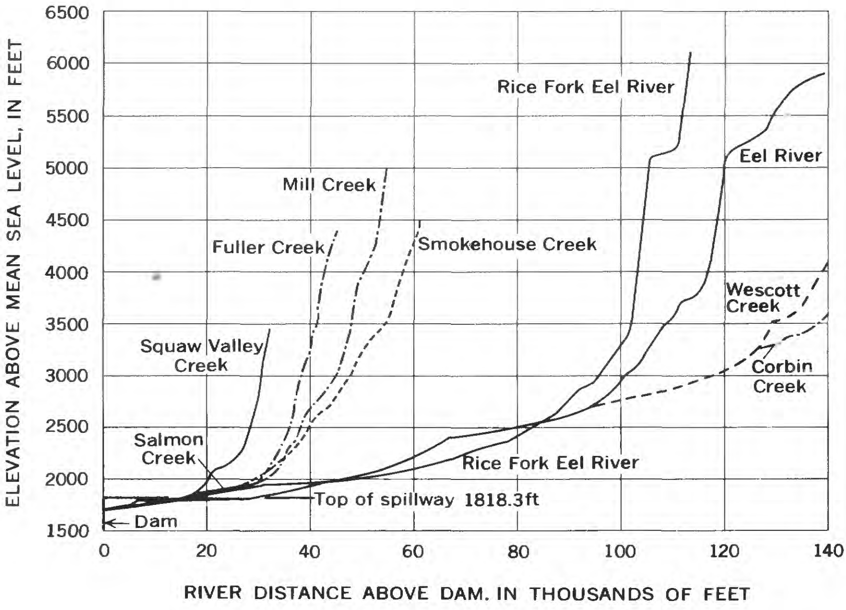

FIGURE 1.—Longitudinal profile of streams tributary to Lake Pillsbury.

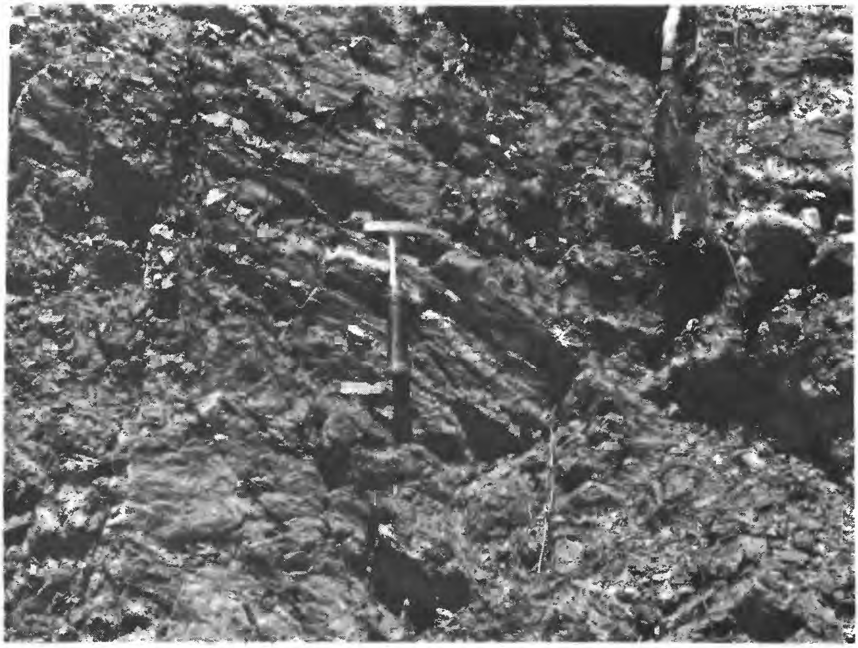

FIGURE 2.—Erosion-resistant material near elevation of 3,500 feet on Hull Mountain road.

The soils of the drainage basin are fertile and well drained, and the resulting good vegetal cover is responsible, to a large degree, for the small amount of sheet and gully erosion. The primary source of sediment entering the reservoir is the loosely consolidated conglomerates which comprise the streambanks and reservoir banks at the lower elevations and which are more subject to erosion and slides than are the soils at higher elevations.

CLIMATE

The Lake Pillsbury drainage area is characterized by warm dry summers and cool damp winters. Most of the precipitation, in the form of snow and rain, falls during the months of November to February; occasional storms occur as late as April or May.

Very few climatological data have been collected for the Lake Pillsbury drainage basin. The U.S. Weather Bureau precipitation station nearest the basin is at Potter Valley powerhouse, 10 miles southwest of Scott Dam and at an elevation of 1,014 feet above mean sea level. The mean annual precipitation at the Potter Valley location, based on a 48-year period of record through 1959, is 43.70 inches.

A U.S. Weather Bureau continuous-record precipitation station was operated near the present reservoir area from 1907 to 1936 (U.S.

Weather Bureau, 1936). During this 29-year period, the mean annual precipitation was 47.62 inches and the monthly precipitation ranged from 0 to 18.10 inches. The temperature range during the same period was from 15° to 107°F.

Precipitation data for the lake area was furnished by two local residents. One of these records, collected on the Rice Fork Eel River near the west end of sedimentation range 35 (pl. 1), covers the period from December 1955 to May 1959; the other record, collected on the east bank of the north arm of the lake between ranges 57 and 58, covers the period September 1957 to March 1959. The mean annual precipitation at the Rice Fork location was 52.48 inches and at the north arm location, 56.61 inches.

Rainfall in the Lake Pillsbury basin is variable, and such climatological data as are available may not be representative of weather conditions in remote areas of the drainage basin.

VEGETATION

Vegetal cover of the Lake Pillsbury basin includes several species each of grass, brush, fir, pine, and oak. The basin has medium to dense cover except for a few burn and minor slide areas.

The lower elevations have mixed stands of pine, redwood, brush, and oak. Relatively flat areas near the lake and areas in the basin that were formerly ravaged by fire are predominantly brush covered—principally chamise and manzanita—interspersed with mountain oak. Intermediate and higher elevations have stands of sugar and ponderosa pines and redwood (fig. 3).

Logging is one of the principal industries in the Lake Pillsbury basin. The logging operations and the roadbuilding incidental to those operations may well be the major source of sediment produced by cultural activities.

DAM AND RESERVOIR

DAM

Fowler (1923) describes the dam thus: "During the summer of 1920 the Company began the construction of a cyclopean concrete dam with straight crest and ogee gravity section at the outlet of Gravelly Valley. The elevation of the river bed at this point is 1,795 feet, and the spillway level of the dam now under construction is 1,900 feet above the sea * * * . It was originally intended to construct the dam with a straight crest with a spillway section 485 feet long at an elevation of 1,900 feet, with abutments at either end rising 10 feet higher, the

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FIGURE 3.—Typical terrain and ground cover in Eel River basin.

total crest length being 679 feet. After the dam had been completed to a distance of 515 feet from the north abutment, it was decided to connect with the south abutment by constructing the remainder of the dam at an angle of 44° with the original structure, the distance to solid rock being shorter on this line than on the original."

The original spillway elevation of 1,900 feet (1,818.3 msl (mean sea level))[1] was 105 feet above the streambed. In 1922 the maximum capacity of the reservoir was increased by the installation of 6-foot flashboards. About 1925 the 6-foot flashboards were replaced with 10-foot timber gates. In October 1939 the timber gates were removed, and five of them were replaced with radial gates 32 feet long and 10 feet high; the remaining timber gates were replaced with 10-foot steel-slip gates. Thus, the original spillway elevation has remained unchanged. No major change in gate elevation occurred from about 1925 to 1959.

[1] Datum used for original survey was 81.7 feet below datum used for 1959 survey.

DATUM

During the original survey (1906), the elevation of the initial point for the high-water contour line was established by aneroid barometer. This datum was used during the construction of the dam. It has continued in use as the base for referencing the various features of the dam and for recording the daily fluctuations of the lake level as published in the U.S. Geological Survey Water-Supply Paper series.

Levels in May 1959 established the mean sea level elevation of the dam as 81.7 feet below the elevation assumed for the initial point in 1906. The May 1959 sediment survey of Lake Pillsbury was made using mean sea level elevation, which is the datum used throughout this report.

RESERVOIR

Scott Dam is immediately below the confluence of the Rice Fork Eel River, Salmon Creek, and Squaw Valley Creek with the Eel River, all of which drain directly into the reservoir. The orientation and shape of the lake are shown in Plate 1.

For the purpose of this study, the lake was considered in four sections or arms: the north arm, Eel River arm, Rice Fork arm, and the main body as shown in Plate 2.

The north arm is that part of the lake north of range 52; it has Squaw Valley Creek and Salmon Creek as tributaries. The north arm drains 12 percent of the Lake Pillsbury basin and constitutes 54 percent of the surface area of the lake and 41 percent of the total lake volume. The east and west shores of the north arm are generally steep; the north shore is gently sloping. A large part of the north arm is above water each year during the period of maximum drawdown. At maximum water level (1,828.3 msl), this arm of the lake is about 11,000 feet long and reaches a width of almost 8,000 feet at its widest point.

The Eel River arm is that part of the lake east of range 8 and is formed by the Eel River valley. It drains 55 percent of the Lake Pillsbury basin and constitutes 28 percent of the surface area and 32 percent of the volume of the lake. At maximum water level, the width of the Eel River arm is 3,000 feet at the widest point, and the length is about 24,000 feet. The upper Eel River arm is a narrow winding canyon; the lower part is a relatively wide, steep-banked section. The unusual shape of the lake, produced by the emergence of the river from the canyon to the wide section, is a factor that affects the distribution of sediment in the Eel River arm.

The Rice Fork arm is that part of the lake south of range 29. It drains 33 percent of the Lake Pillsbury basin and contains 7 percent of the surface area and 6 percent of the volume of the lake. At maximum water level the Rice Fork arm is a narrow winding canyon about 16,000 feet in length; it seldom exceeds 400 feet in width until it nears its junction with the Eel River.

The main body of the lake is bounded by the dam, ranges 52, 8, and 29. It has a negligible drainage area and constitutes 11 percent of the surface area and 21 percent of the volume of the lake. At maximum water level this section of the lake is about 5,000 feet in length and averages about 2,000 feet in width.

RESERVOIR USE

Lake Pillsbury is operated as a holdover-storage facility for power generation and irrigation. The water yield of the basin above Scott Dam, less evaporation and seepage losses, is 380,800 acre-feet per year (35-year average, 1923–58), and the maximum capacity of the reservoir (May 1959 survey) is 86,780 acre-feet. Spillway overflow and water releases from Lake Pillsbury flow down the Eel River to Van Arsdale Dam; from there 147,700 acre-feet per year is diverted through a tunnel to Potter Valley powerhouse; below the powerhouse, part of the water is used for irrigation and the remainder flows into East Fork Russian River. Complete records of the quantity of water stored at Lake Pillsbury, spillway overflow and releases, and the quantity of water diverted for irrigation and power are available in U.S. Geological Survey Water-Supply Papers of the series "Surface Water Supply of the United States, part 11, Pacific Slope Basins in California."

RESERVOIR OPERATION

In the course of the normal reservoir operation, the lake contents are reduced during the usually dry months of April to November, the annual low occurring from September to January. Lake contents during the annual low usually range from about 10,000 to 40,000 acre-feet. Maximum drawdown occurred Dec. 9–10, 1931, when only 10 acre-feet of water was available above the outlet sill. The maximum lake contents recorded for the annual low was 56,900 acre-feet on Nov. 14, 1942.

During the fall and winter, the reservoir fills to spillway elevation (1,818.3 feet msl). The radial gates are usually open during the winter storms to prevent excessive water-surface elevations of the lake. After the winter storms pass, the radial gates are closed and the reservoir is allowed to fill to elevation 1,828.3 msl. The maximum recorded water-surface elevation was 1,829.1 feet msl on May 13 and 16, 1925. Only in a few years has the reservoir failed to fill at some time during the year.

The annual drawdown and resulting low water levels of the reservoir at the start of the winter runoff have a pronounced effect on the distribution of sediment and the quantity of sediment that will pass through the reservoir. In at least 35 months during the period 1921–58 the monthly outflow exceeded the total storage capacity of the reservoir. The maximum monthly outflow was 350,100 acre-feet in February 1958.

RESERVOIR SEDIMENTATION

GENERAL

The useful life of a storage facility is partly dependent on the rate that the storage capacity is lost because of the sediment brought into the reservoir by the streams. The design of a dam and appurtenant structures, and therefore the initial cost of a project, may also be influenced because of sedimentation. Economic loss due to silting may be greater than that measured by the initial cost of the reservoir (Eakin and Brown, 1939), for the original reservoir is generally constructed at the most favorable and economic site and a replacement storage facility would be more costly than the original.

Reservoir sedimentation is a complex process dependent on many factors, and the interaction of the factors may make the sedimentation of each reservoir a case unto itself. The quantity of suspended sediment and bed material that moves down a stream can be determined, in most cases, with a fair degree of accuracy, and this knowledge should be utilized prior to the design and construction of any reservoir. However, reservoir sedimentation rates computed strictly from volume of sediment entering the reservoir may be in error (Lane, 1953) because some of the material may flow through the reservoir without deposition, and some of the deposition may take place above the spillway elevation of the reservoir. The origin, transportation, and deposition of sediment in reservoirs is discussed by Witzig (1943).

The distribution of the sediment, in addition to volume of sediment deposited, may shorten the life of, or damage, a reservoir. The factors commonly associated with the distribution of sediment in a reservoir are reservoir operation, reservoir shape, wave-action deposits, capacity of the reservoir in relation to amount of inflow, density currents, and properties of the sediment. Additional factors associated with distribution of sediment in a particular reservoir are narrow necks within the reservoir area, vegetation in the delta areas, heavy sediment-contributing streams entering the reservoir area, and the water-surface elevation at the time of maximum sediment inflow.

How sediment is deposited in reservoirs is illustrated in figure 4 (Lane, 1953). The bottomset beds are composed of fine material that

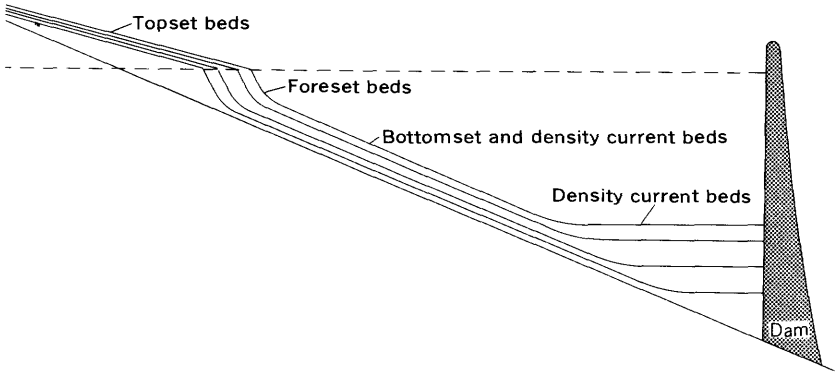

FIGURE 4.—Longitudinal cross section through a reservoir showing various types of deposits.

is carried into the lake in suspension and settles slowly and somewhat uniformerly over the bottom. The density currents, or gravity flow, will move some of the fine material along the bottom far into the reservoir and will produce an additional accumulation near the dam. The foreset beds are composed of coarser material and are inclined downward in the direction of flow. Generally, the angle of inclination of the foreset beds is greater with very coarse sediment than with moderately coarse sediment. The topset beds are composed of the coarsest sediments and extend from the point in the stream where the backwater effect of the lake becomes negligible to the edge of the foreset beds.

LAKE PILLSBURY

In each tributary of Lake Pillsbury, the longitudinal profile (figs. 5–8) shows well-defined topset, foreset, and bottomset beds and appropriate changes in size composition of the material. There is a small increase in the thickness of the deposit near the dam, possibly the result of density currents.

The reservoir contents are greatly reduced before each storm season and the first winter storm tends to establish foreset beds well downstream in the reservoir and at a low lake level. For the rest of the storm season, the water surface is kept near spillway level, and later inflow tends to build thin foreset beds at spillway elevation.

Because the shape of a reservoir affects the distribution of sediment, the open expanse of the Lake's north arm is a factor in producing the high waves that make terraces in the banks in that part of the reservoir. The narrow, crooked shape of the Rice Fork arm

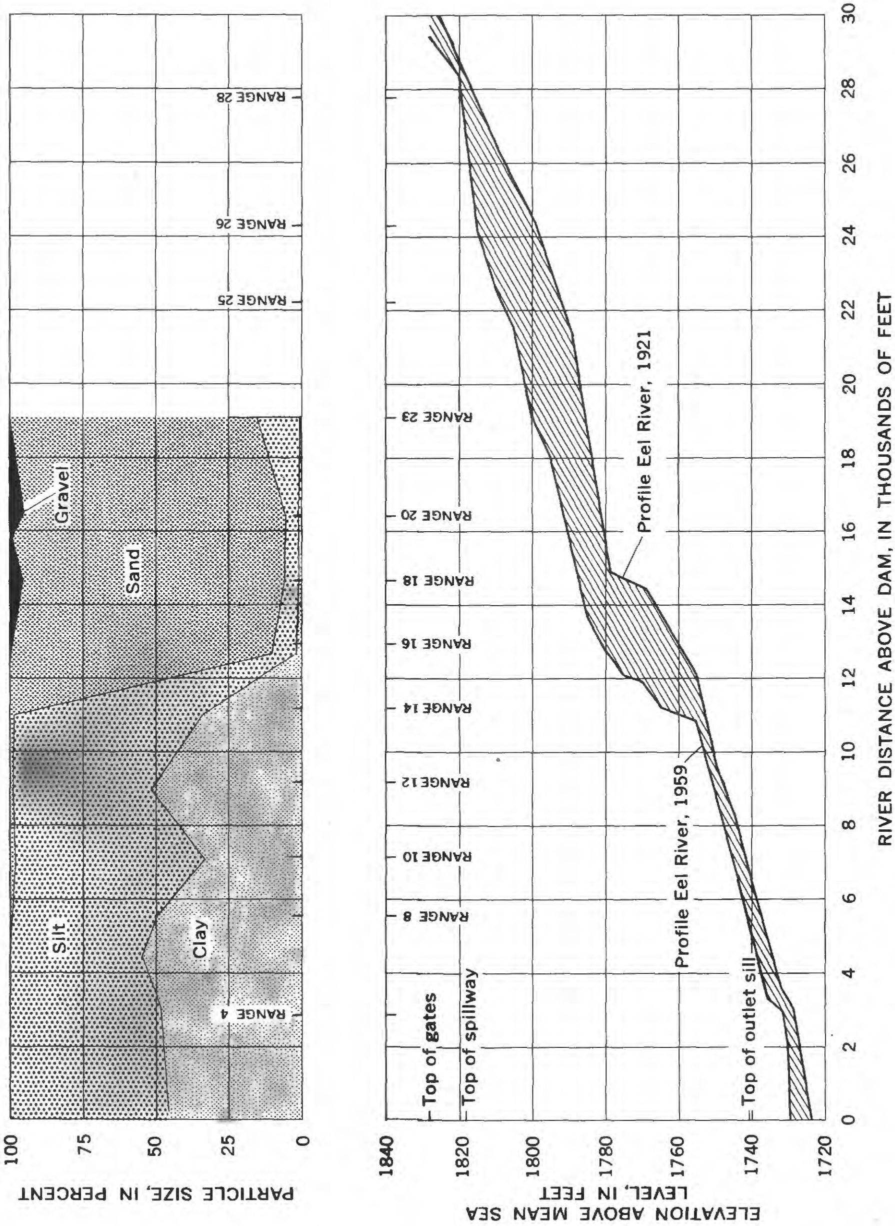

FIGURE 5.—Longitudinal profile of Eel River and particle size of deposited material.

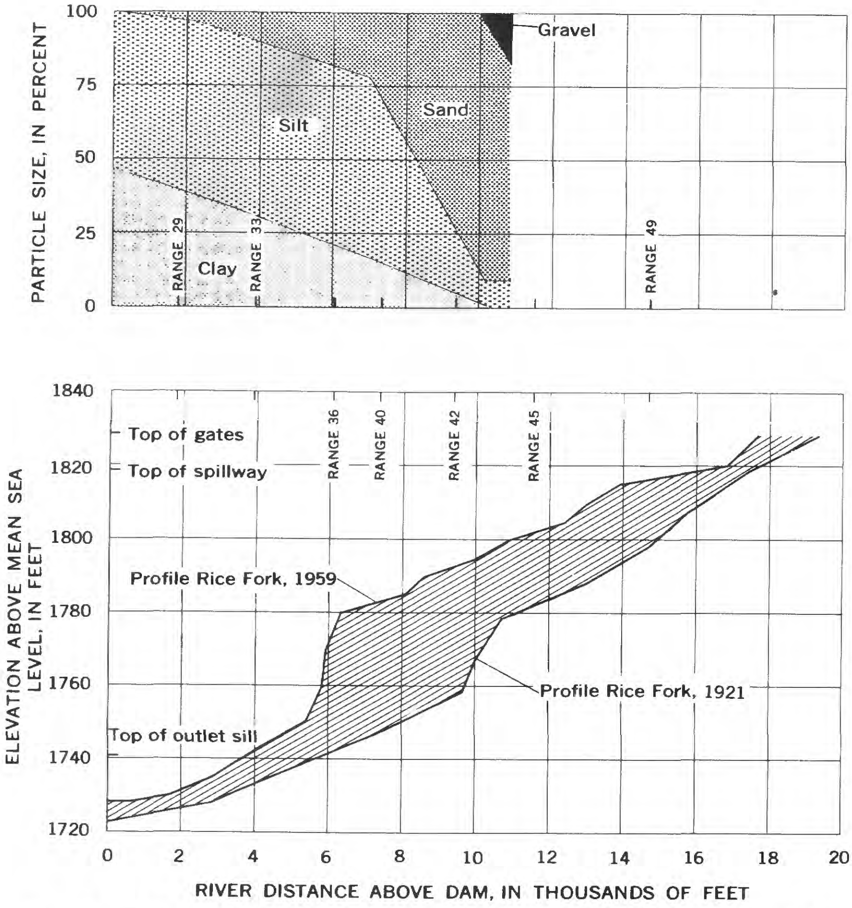

FIGURE 6.—Longitudinal profile of Rice Fork and particle size of deposited material.

adds to bank erosion and helps lower the velocity of water entering the lake. The lower velocity keeps the coarse sediment from being carried far into the lake. The Eel River flows from a narrow restricted channel near range 20, spreads out, and deposits some of its suspended load.

Another important effect of shape (Lane, 1953) which may apply to Lake Pillsbury is produced when a dam is constructed below the confluence of two streams. In such instances, the useful life of the reservoir may be dependent on the rate of sedimentation of the stream carrying the largest load. The valley of the stream transporting the largest load will fill first, and deposition will then advance toward the dam. The remaining arms of the lake may be isolated and form other lakes, and much of the water in the isolated lakes may not be

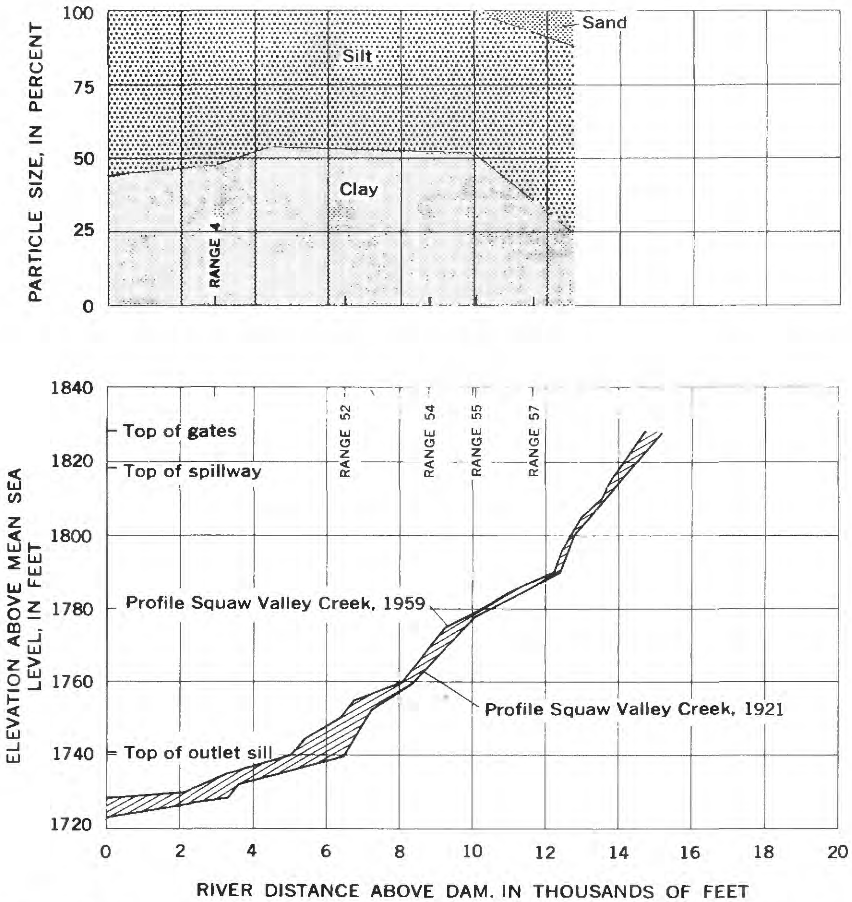

FIGURE 7.—Longitudinal profile of Squaw Valley Creek and particle size of deposited material.

available for release from the dam. The Rice Fork arm, for example, comprises only 6 percent of the total reservoir volume as compared with 32 percent within the Eel River arm, 41 percent within the north arm, and 21 percent within the main body of the reservoir. Thus, a substantial loss of volume in the Rice Fork arm and main body of the reservoir, a total of only 27 percent of the present capacity, could isolate and adversely affect the usefulness of the remaining reservoir capacity, at least for the present reservoir operation. Although this loss of capacity will not occur in the near future, it should be noted that the north arm, containing 41 percent of the present reservoir capacity, is collecting sediment at an extremely low rate relative to the other arms of the reservoir. Complete filling of the Rice Fork

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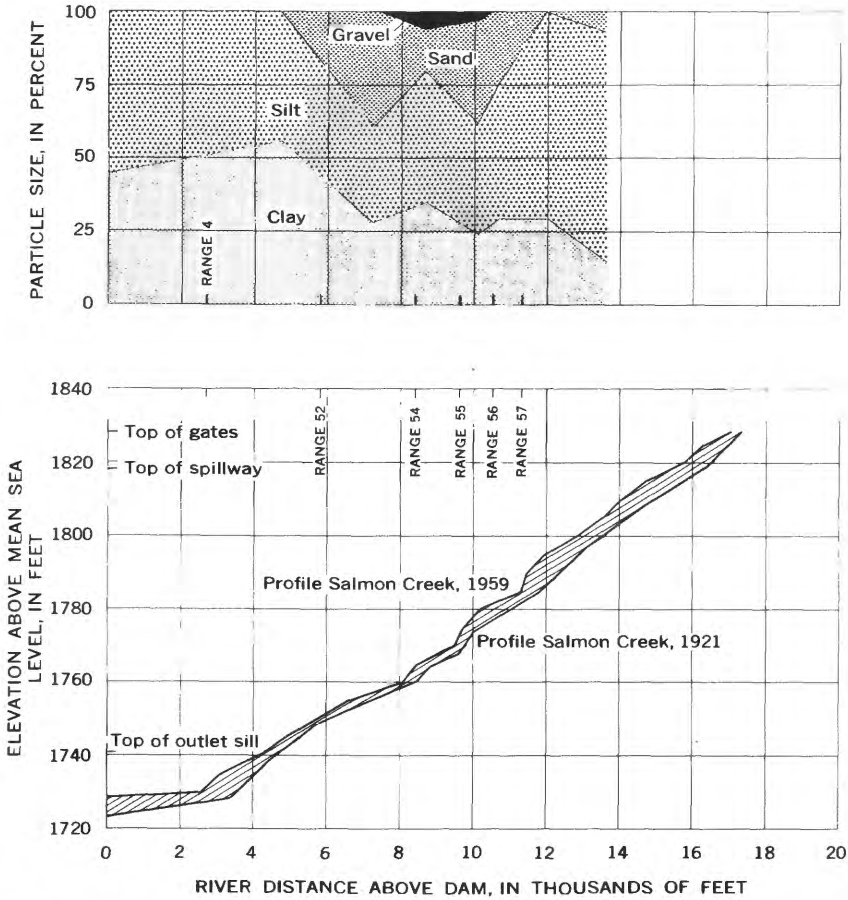


FIGURE 8.—Longitudinal profile of Salmon Creek and particle size of deposited material.

and Eel River arms will nullify the effectiveness of the reservoir even though the north arm is still relatively free of sediment. This fact should be considered when estimating the remaining useful life of the reservoir.

Wave action in the open expanse of the lake, and bank slides in the narrow arms of the lake are factors in the sedimentation of Lake Pillsbury. The effect of wave action on bank erosion is conspicuous in the north arm and main body of Lake Pillsbury, although the quantity of sediment moved into the lake by such action may be relatively minor. High wind and waves occur frequently from January to June while the lake levels are high. The material in the steep banks is loosely consolidated and subject to erosion (fig. 9).

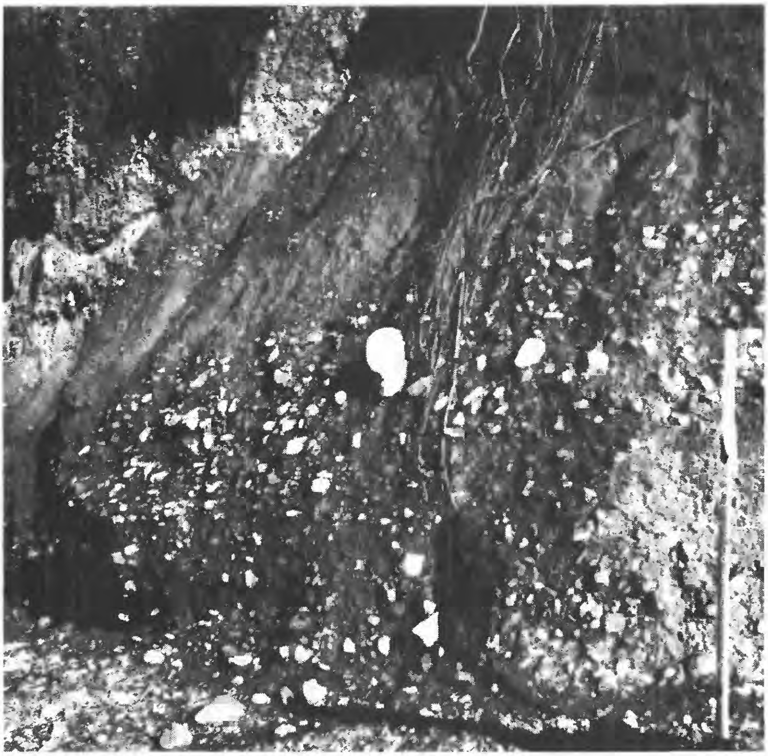
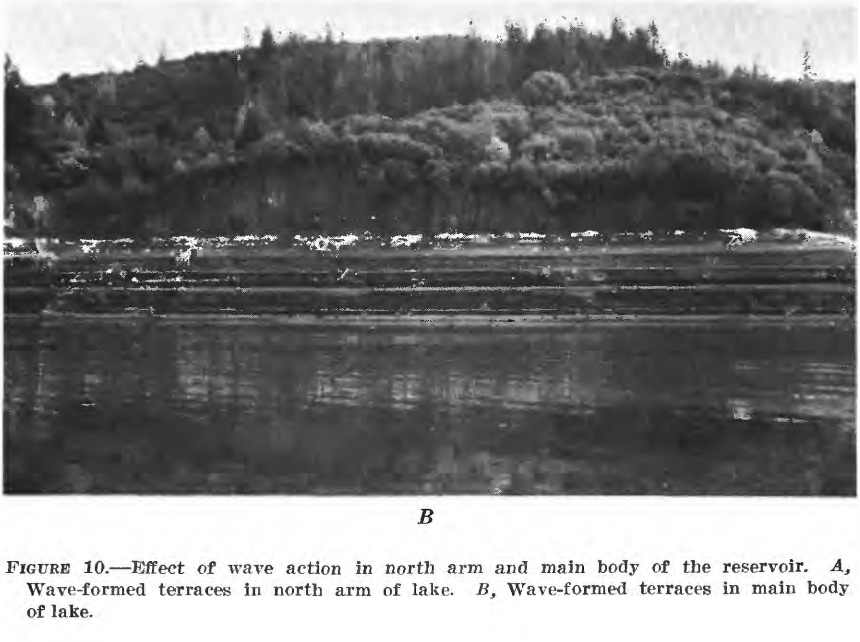


FIGURE 9.—Photograph of reservoir shoreline in north arm of lake showing loosely consolidated alluvium in banks above high water. Photographer's cap in center of picture.

The reservoir bank in the north arm of the lake near the east end range 53 consists of a series of terraces below spillway elevation (1,818 msl). These terraces are about 4 feet high and 4 feet wide. Fine material eroded from the banks has been transported into the main body of the lake and the coarse material was scattered over the terraces from elevation 1,818 msl to, and possibily below, elevation 1,776 msl. No measurements were made to determine the distance that the banks in the north arm have receded owing to bank erosion. However, stumps of trees that formerly grew on the banks are visible evidence that the banks have not changed appreciably since storage of water began (fig. 10).

Other factors that affect sedimentation in Lake Pillsbury, such as bank slides, reservoir operation, properties of the sediment, and ratio of capacity to inflow are discussed in the section on distribution of sediment.

A



B

FIGURE 10.—Effect of wave action in north arm and main body of the reservoir. *A*, Wave-formed terraces in north arm of lake. *B*, Wave-formed terraces in main body of lake.

RESURVEY OF LAKE PILLSBURY

METHOD OF SEDIMENT SURVEY

Two survey methods are in general use to determine the quantity of sediment deposited in a reservoir, the contour method and the range method. The method chosen for use will depend on the quantity and distribution of sediment in the reservoir and on the availability and accuracy of previous base maps (Eakin and Brown, 1939, p. 153–167).

The contour method requires sufficient control and mapping to draw an accurate contour map and requires that a previous contour map be available. The accuracy of the sediment survey is dependent on the accuracy of the individual maps. An original base map, prepared by the lake owners as a part of an application to the Federal Power Commission for a project license, was available for use in the Lake Pillsbury resurvey.

The contour method allows computation of vertical and horizontal distribution of sediment and the plotting of capacity curves.

The range method is used when the actual thickness of sediment deposits can be penetrated and measured with a sampling spud and when no previous base maps of required accuracy are available. The direct measurement of thickness of sediment deposits in Lake Pillsbury would be difficult because of unfavorable sampling conditions created by either the excessive water depths, the great thickness of the sediment deposits, or the coarse texture of the sediments in delta areas.

The range method does not furnish data to compute the vertical distribution and only partly delineates the horizontal distribution of sediment.

Although the 1959 sediment survey of Lake Pillsbury was made using the contour method, ranges were established and identified. The ranges facilitated the survey, the construction of the map, and the field check of the map. The ranges will also facilitate future surveys and will provide a basis for more precise measurement of the increase in thickness of the sediment deposits.

CONTROL FOR SEDIMENT SURVEY

Preliminary to the sediment survey, a 5,179.5-foot base line was established in the relatively flat, clear area of the north arm of the lake. The base line (pl. 1), which was referenced to established section corners, is marked with 4-foot by ¾-inch steel reinforcing rods driven to a depth of 3 to 3.5 feet. The base line markers are inundated at maximum water level but are exposed when the water level is below about 1,817 feet msl.

The base line, described above, was used for the triangulation of range-end points in the north arm (ranges 52 to 58) and in the main body of the lake (ranges 2 to 8). Some additional range-end points in the Eel River arm and in the Rice Fork Eel River arm were also checked by triangulation. All range-end points were located above the high water mark and as near as practicable to the shoreline. Wherever possible, the range-end points were located on a prominent point of the lake shoreline that could be located and identified by use of the base map prepared from this survey. The range-end points were marked with 3.5-foot by ¾-inch steel rods driven to a depth of about 3 feet. The original base map furnished by the lake owners was used as the control for preparing the new contour map. The configuration of the shoreline was improved by use of an aerial photograph of the same scale. The scale of the original base map and that of the new base map is 1 inch=400 feet.

SURVEY PROCEDURE

TRANSIT-STADIA SURVEY

In November 1958, a transit-stadia survey was made of the north arm of the lake above elevation 1,786 feet msl. The data from the transit-stadia survey were used to construct the contour lines of the central part of the north arm of the lake. Elevations obtained later with the echo-depth sounder in the north arm of the lake were compared with the contour lines drawn from the transit-stadia survey. This comparison served, to some extent, as a check on the accuracy of the data obtained with the echo-depth sounder.

ECHO DEPTH-SOUNDER SURVEY

In May 1959, the lake surface was at maximum elevation. All ranges shown in plate 1 were surveyed with an echo sounder during that month.

The echo sounder used to survey Lake Pillsbury was a portable battery-operated echo depth-recording instrument operating at a fixed acoustic frequency of 200–220 kc at a power of less than 40 watts. This unit was chosen because the relatively high transmitting frequency and low power combine to give sharp definition of the sediment surface in clear water and at the depths found in Lake Pillsbury.

Accuracy of the basic unit is ±0.5 percent when operated at normal battery voltage. Variations of input voltage and temperature usually cause an error of less than 2 percent. However, a manually controlled variable-frequency power supply allows compensation for variations in water temperature, salinity, and changes in sound velocity in water, and enables the accuracy under all conditions of normal operation to be maintained within 0.5 percent.

The echo sounder measures the distance from the transducer (combination transmitter and receiver) to the lake bottom and records that distance on a calibrated chart moving at a fixed speed through the recorder. This equipment is mounted in a boat and the transducer is at a known distance below the water surface.

The echo sounder was calibrated several times each day to compensate for variations due to temperature, input voltage, and operating depths. A metal plate "check-bar" was lowered to an accurately measured distance below the water surface, and the depth reading of the check bar on the graph was adjusted to the measured distance by varying the frequency of the power supply. Frequent calibration of the echo sounder by means of the check bar eliminated the necessity for corrections of the chart to compute lake-bottom elevations.

Further descriptions of echo sounders and their use for sediment surveys are given by Smith (1958) and Blaisdell (1960).

To prepare for sounding each range, the boat was maneuvered in place at one end of the range and the echo sounder put into operation. The boat was then maneuvered at a constant speed to the opposite end of the range while the operator of the echo sounder kept the recorder adjusted to obtain a clear record of depth and to obtain "fixes" at each important change in bottom elevation.

The location of the boat at the time of each fix was obtained by two transitmen. One transitman, stationed at the range end opposite the starting point, directed the boat operator on course by use of hand and radio signals. The skill of the boatman usually prevented the boat from deviating more than 2 boat-widths from course, and course changes were held to a minimum. A given range was rerun if the boat deviated from course during the sounding of that range. The boat speed varied from range to range but was held constant for each range. The speed used for each range varied with the shape of the lake bottom, length of the range, and impeding effect of the wind and waves.

The second transitman was stationed at a position, preferably at the end of a nearby range, where accurate bearings of the sounding boat could be obtained. This transitman tracked the boat and obtained a bearing or fix on the boat for each fix signaled by the operator of the echo sounder. At the time each fix was signaled, the operator marked the fix on the recorder chart. Later, the bottom elevation at the point marked was plotted on the map at the location determined from the bearings obtained by the transitman.

The number of points marked on the chart and located by the transitmen varied from range to range. A short range or rough bottom topography required more frequent fixes. The echo-sounder operator usually requested a transit fix at each major change in bottom topography.

CONSTRUCTION OF CONTOUR MAP

Elevations obtained by the transit-stadia and echo-sounder surveys were plotted on the base map, and contour lines were drawn at 5-foot intervals.

The general configuration of the lake bottom (pl. 2) as defined by the May 1959 survey agreed with the configuration of the original base map.

Several field checks of the completed contour map were made during the winter of 1959 while the lake levels were low. All checks indicated good accuracy and, in general, contour intervals of 1 foot could be justified from the echo-sounder data.

COMPUTATION OF LAKE VOLUME

The lake area was divided into 25 segments, and the surface area for each segment at each 5-foot elevation was obtained with a planimeter. The segment areas at each 5-foot contour line were totalled to obtain the surface area at each elevation. The areas were plotted against elevation, and a curve was drawn to define the relation of elevation to surface area. From this curve a table was prepared to show area versus depth for each 1-foot increment of elevation. The areas thus obtained were used to compute capacity by the end-area method. Figure 11 shows the 1959 area and capacity curve and the original capacity curve.

COMPUTATION OF SEDIMENT VOLUME

The difference between the original capacity curve and the 1959 capacity curve at any elevation represents the volume of sediment deposited in the reservoir below that elevation. A graphical summary of the vertical distribution of sediment in Lake Pillsbury is shown in figure 12.

The accuracy of sediment computation by differences in the capacity curves is dependent upon the accuracy of the individual capacity curves. This method of sediment computation also precludes the direct measurement of sediment thickness and computation of sediment distribution by segments. The recorded profile of each range established during the 1959 survey may be used in the future as an

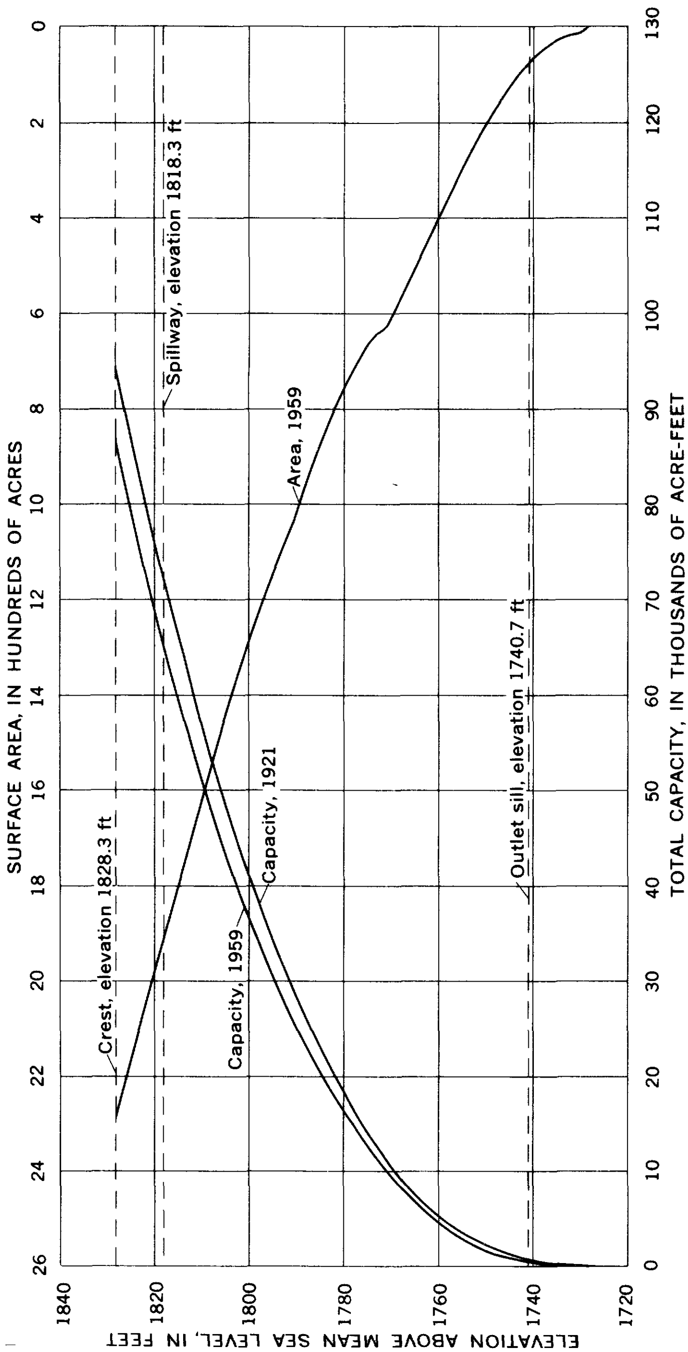


FIGURE 11.—Area-capacity curves, Lake Pillsbury.

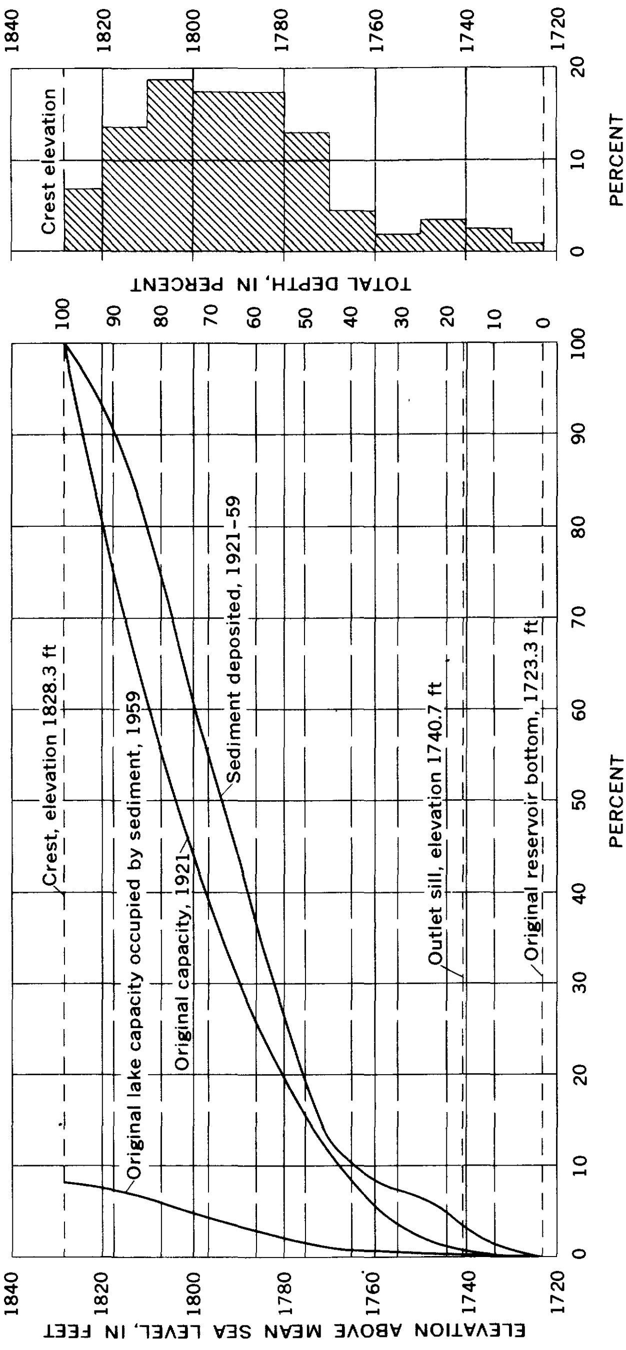


FIGURE 12.—Vertical distribution of sediment.

accurate basis for determining the thickness of sediment deposited during the period between surveys.

TRAP EFFICIENCY

All sediment transported into a reservoir may not be deposited in that reservoir. The quantity of deposited material in Lake Pillsbury represents the sediment inflow for the period of storage less that amount of material that passed through the reservoir. The ratio of the total sediment deposited in the reservoir to the total sediment inflow, expressed in percentage, is known as the trap efficiency.

The trap efficiency is dependent on the many factors affecting deposition of sediment in reservoirs, such as the properties of sediment, shape of reservoir, ratio of inflow to capacity, salinity of water, turbidity currents, and reservoir operations.

For Lake Pillsbury, the ratio of the average annual inflow (35 years) to the initial capacity is about 4, and most of the inflow occurs during the winter months. In 38 months during the 35 years preceding this survey, the monthly flow passing over the spillway equaled or exceeded the total reservoir capacity. The peak monthly discharge, that of February 1958, exceeded the initial reservoir capacity by a factor of 3.7. Large quantities of water passing through the reservoir in a relatively short time interval will reduce deposition of the fine sediment and will contribute to the flushing of the fine sediment accumulated during periods of low runoff. The trap efficiency of the reservoir could be computed if the quantity of fine material flushed through the reservoir were known, or the quantity of sediment transported into the reservoir were known. Unfortunately, no outflow or inflow data are available for Lake Pillsbury for the period preceding the 1959 resurvey.

Most, if not all, of the sediment in the sand-size range and larger is deposited in the upper part of the Eel River and Rice Fork arms figs. 5, 6) and the trap efficiency for this material will approach 100 percent. Some of the fine material, in the silt- and clay-size range, is deposited in the reservoir; however, an unknown amount of the fine material passes through the reservoir and the trap efficiency for this fine material cannot be computed. The trap efficiency of an individual reservoir may be extrapolated from known trap efficiencies of nearby reservoirs if it exhibits similar runoff charactertics. Brown and Thorpe (1947) developed a curve, for several reservoirs in the Sacramento-San Joaquin basins, that related the trap efficiency to the storage capacity per square mile of drainage basin. By that relation, the trap efficiency of Lake Pillsbury is 94 percent. This trap efficiency may be high considering the high ratio of inflow to capacity for Lake Pillsbury and the large amount of fine material that is probably flushed through the lake. A larger reservoir near Lake Pillsbury will have a trap efficiency of at least that of Lake Pillsbury.

DISTRIBUTION OF SEDIMENT

NORTH ARM

The north arm of the lake constitutes 54 percent of the entire surface area of the lake, and the combined drainage area of the two major tributaries to the north arm, Salmon Creek and Squaw Valley Creek, comprise 12 percent of the Lake Pillsbury drainage basin. Sediment inflow to the north arm is low and is confined principally to the channels of the two major tributaries. The longitudinal profiles of Squaw Valley Creek and Salmon Creek (figs. 7, 8) indicate sediment depths that rarely exceed 8 feet. Measurements of sediment depth at the location of core samples 24, 23, and 19 (pl. 1) show 0.2, 1.25, and 2.5 feet respectively.

The large area of the north arm of the lake that lies between the narrow and well-defined channels of Salmon and Squaw Valley Creeks is virtually devoid of any lake-deposited sediment. This area was above water (water-surface elevation 1,786) during the initial phase of the survey in November 1958 and also when a field check was made of the completed contour map in December 1959. The depths of deposited sediments rarely, if ever, exceeded 0.1 to 0.2 foot in depth and, in most places, the gravel that originally covered the area is still partly exposed. The stumps of the trees cleared from the area during the construction period and prior to inundation, which are still in place, verify the premise that only minor sedimentation has occurred in the large central part of the north arm.

The amount of sediment in the channels of Squaw Valley Creek and Salmon Creek may be explained, in part, by the small sediment contribution from the two creeks and by the reservoir bank erosion. The fine silt deposited in the large central part of the north arm is probably transported by backwater during the high flows of the Eel River and Rice Fork Eel River. The percentage of the total lake volume in the north arm of the lake (41 percent in 1959) will, in all probability, increase in the future as the remainder of the reservoir continues to receive sediment at a rate higher than that of the north arm.

EEL RIVER ARM

The Eel River arm, which includes Horsepasture Gulch and Salt Spring Creek, constitutes 32 percent of the 1959 lake capacity and 28 percent of the lake surface area; it receives inflow from 55 percent of the lake drainage area.

The longitudinal profile of the Eel River (fig. 5) shows that deposits of sediment range from 9 to 18 feet in depth between ranges 14 and 28. Below range 14 the sediment is deposited in a fairly uniform layer, 3 to 5 feet deep, and consists predominantly of fine material in the silt- and clay-size range.

The unusual shape of the longitudinal profile of the sediment in the Eel River arm is attributed to the combined influence of several factors. Inspection of the topographic map of the area reveals that, before the construction of Scott Dam, the Eel River above range 20 was in a narrow, deeply incised channel having an average slope of about 18 feet per mile. At range 20 the stream entered a wide valley and at range 8 it again entered a deep, narrow channel before emerging into what is now the main body of the lake and its confluence with Squaw Valley Creek, Salmon Creek, and the Rice Fork Eel River. Figure 5 (1921 profile) shows the influence of the topography upon the river profile. As the stream entered the wide valley at range 20, its velocity was reduced and part of its suspended load was deposited. Deposition had advanced the leading edge of the foreset beds into the valley to range 18 and had reduced the slope between range 18 and range 25 to about 10 feet per mile. Above range 25 the slope was about 20 feet per mile. Below the delta, at range 18, the slope had stabilized at about 16 feet per mile.

After the construction and closing of the dam, the profile of the river adjusted to the new conditions imposed by the impoundment of water in the reservoir. The usual operation pattern for the reservoir results in low lake levels preceding the initial winter storm runoff (fig. 13) ; the initial rise will move sediment into the large part of the Eel River arm before deposition occurs. Evidence of this pattern is the continuing advance of the foreset beds from range 18 in 1921 to range 14 in 1959. During the winter storms, the usual operating procedure is to open the gates and to hold the lake level at an elevation of 1,818.3 feet or 10 feet below maximum capacity. After the storm runoff has abated, the gates are closed and the reservoir is filled to maximum level. The 1959 longitudinal profile of the Eel River reflects this operational procedure as is shown by the decrease in slope below range 28, about 1,818 feet msl, where the flow of the Eel River enters the lake and deposits the larger suspended material, and thus forms a small delta near range 26.

The particle size and other properties of the sediment from the drainage basin above the Eel River arm are additional factors which explain the manner in which the sediment is deposited in the reservoir. Mechanical analysis of soils from the riverbanks (fig. 14) immediately above the reservoir show 89 percent of the material to

A

B

FIGURE 13.—Sediment deposits in the Eel River arm. *A*, Eel River upstream from range 20. *B*, Enroachment of delta into Eel River arm.

FIGURE 14.—Photograph of typical sediment-producing area along Eel River above the reservoir showing loosely consolidated material on banks of Eel River.

be sand and gravel (0.062–8.000 mm) and the remaining 11 percent to be silt and clay (less than 0.062 mm).

Some of the silt and clay will pass through the reservoir, especially during periods of high flow when the crest gates of the dam are open. The remainder of the fine material explains the relatively thin, uniform veneer of material below range 14 and in the main body of the reservoir.

The coarser fractions of the available materials are the chief constituents of the sediment deposits in the upper reaches of the Eel River arm.

The banks of the Eel River arm are very steep and the soils consist of coarse, loosely consolidated alluvium, predominantly of sand and gravel composition. The annual variation of the reservoir water level and the resultant wetting and drying of the banks probably contribute to the sloughing of the banks. Many large bank slides are visible in the Eel River arm, especially in the narrow canyon above range 20 (fig. 15). Most of the fine material from the bank slides is transported further into the lake during the winter storms; the course sand and fine gravel remain in place. Much of the material deposited in the narrow reaches of the upper Eel River arm may be attributed to bank erosion. Fifty percent of the total sediment in the reservoir is deposited above the 1,794-foot contour, and over 90 percent of the sediment is deposited above the 1,760-foot contour (fig. 12).

RICE FORK ARM

The Rice Fork arm is a narrow, steep-walled canyon that contains 7 percent of the surface area and 6 percent of the total volume of the reservoir. The Rice Fork Eel River drains 33 percent of the total drainage area of Lake Pillsbury and may contribute a like percentage of the annual inflow.

The 1921 longitudinal profile of the Rice Fork arm shows that the slope was 30 feet per mile for the upper 8,000 feet of the reservoir and that a sharp increase in slope existed between ranges 44 and 42. Below

FIGURE 15.—Bank slides in Eel River arm near range 25.

range 42 the slope gradually decreased as the Rice Fork canyon became wider and the stream approached the main stem Eel River.

The May 1959 survey revealed that the sediment deposits in the Rice Fork arm ranged in depth from 5 to 38 feet. The slope of the longitudinal profile decreased in the upper reaches of the Rice Fork arm during the period 1921–59. The low lake levels at the beginning of the high winter inflow allowed the suspended material to move into the lake and advanced the delta 4,000 feet further down the channel, to range 36.

A similarity exists between the 1959 profiles of the Eel River and the Rice Fork Eel River near the 1,818-foot contour as well as near the 1,780-foot contour. Reservoir operation appears to effect similar changes in the profiles of the two streams. The initial rise of the storm season will bring about a deposition of material at the delta front near the 1,780-foot contour, and further deposition will occur upstream as the lake level rises.

Below range 43 the particle size of the deposited sediment becomes finer in the downstream direction, and below range 36 most of the deposited material is in the silt and clay range. Material deposited on the surface of the lake bed in the steep-walled section above range 42 is sand and gravel, and as in the upper reaches of the Eel River arm, the principal source of the material is the banks of the stream. Because of the small original volume of lake capacity in the Rice Fork arm, this arm undoubtedly is the greatest loser of volume, percentagewise, from sedimentation.

SEDIMENT DEPOSITS

METHODS OF INVESTIGATION

CORE SAMPLES

The deposited sediment was sampled with a split-core sampler suspended by boat-mounted streamflow-measuring equipment. The split-core sampler consists of a precisely machined hollow cylinder that is split longitudinally to allow easy removal of the sediment core. The lower end of the core sampler is fitted with a cutting head to assure an accurate core diameter and a relatively undisturbed sample. The upper end of the sampler is fitted with a ball valve to allow water to pass out of the cylinder as the sample enters and to hold the sample in the cylinder as the sampler is brought to the surface. The boat-mounted suspension equipment facilitated the use of the sampler, and the calibrated counter on the sounding reel made possible the accurate measurements of water depth and sampler penetration.

Attempts to get an undisturbed sample at each location were unsuccessful. The deposited sediment of low specific weight was frequently washed out of the sampler before reaching the surface, and the sediment of high specific weight was not always penetrable to the full length of the sampler. Core samples were carefully preserved in water-tight containers for transfer to the laboratory for analysis. Specific weight was determined for all relatively undisturbed core samples. Determinations of specific gravity and particle-size distribution were made on most core samples collected at the locations shown in plate 1.

SEDIMENT-DENSITY PROBE

Measurement of inplace densities of bottom sediment was made with the battery-operated portable Model 497 Probe furnished by Federal Inter-Agency Sedimentation Project [2] (fig. 16).

The Model 497 Probe has a gamma-ray source of 3 millicuries of radium 226. The number of these gamma rays scattered back to the probe detector per unit of time is proportional to the density of the material surrounding the source, and thus the probe can be calibrated as a direct measure of density. The probe is designed to measure the density in a 13-inch interval between the gamma-ray source and the geiger tube. A low reading is obtained if the probe is incompletely submerged in the sediment. Theory, development, and tests of the probe are discussed by Caldwell (1960).

The probe was suspended from the boat by the same equipment used to suspend the split-core sampler. The boat was anchored at the sample location, and the probe was lowered into position in the sediment preparatory to obtaining the reading. At least 2 counts of 2 minutes duration each were obtained for the density determination at each location. Generally, the depth of the probe was 1 to 2 feet below the sediment surface at the time the reading was obtained.

Several factors prevented exact determinations of the depth of sediment penetrated by the probe. These factors include the high wind and waves sometimes encountered in the open expanses of the lake and the deep water in the main body of the lake. Near the dam the probe could not be lowered to the desired depth because only 100 feet of coaxial cable was furnished with the probe.

Advantages of the inplace density measurements by gamma-ray scattering are obvious. The difficult and sometimes impossible task of obtaining an undisturbed core sample is eliminated. Determinations of density are accurate and are quickly made, and the results are

[2] Federal Inter-Agency Sedimentation Project, St. Anthony Falls Hydraulic Laboratory, Hennepin Island and Third Ave., SE., Minneapolis, Minn.

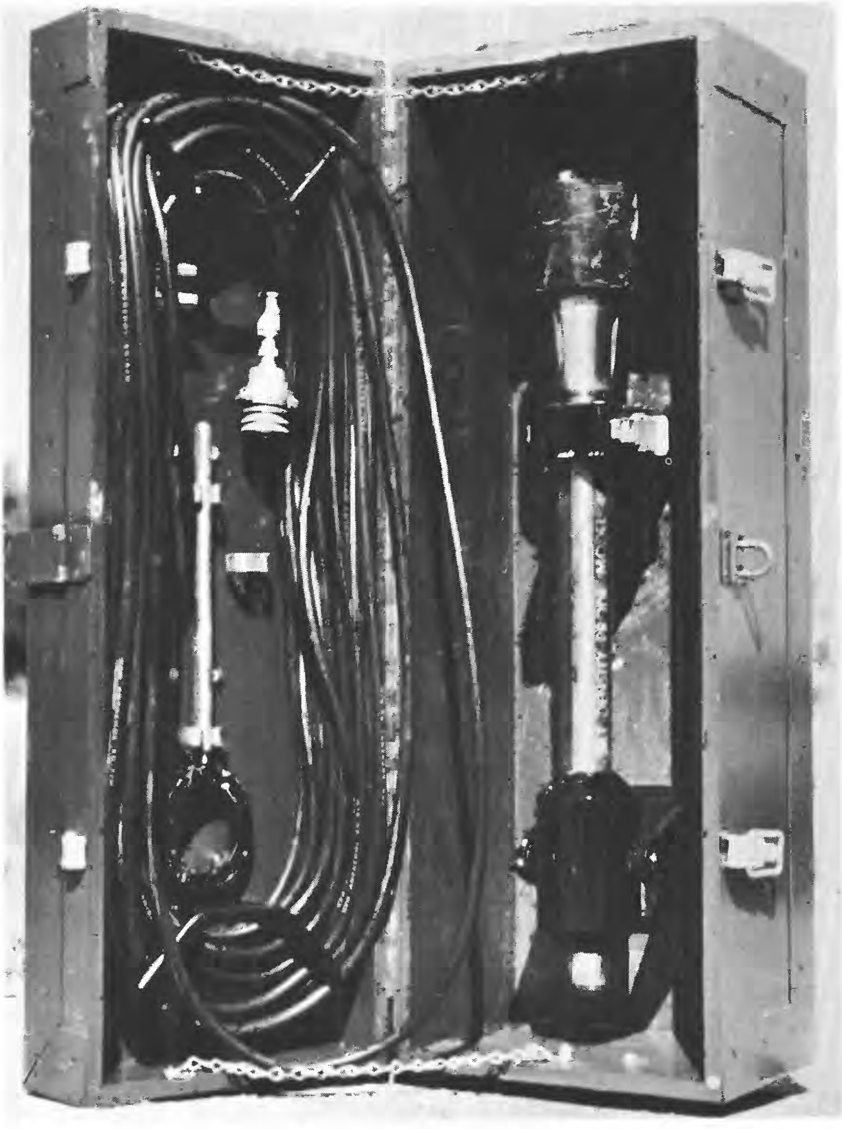


FIGURE 16.—Gamma-ray density probe in shielded carrying case.

available in the field without additional calculations. The density gradient of the deposited sediment can be determined by obtaining readings at various depths below the sediment surface.

CALIBRATION OF SEDIMENT-DENSITY PROBE

The factory calibration curve for the sediment-density prcbe (fig. 17) was checked in the field to determine its accuracy in the type of

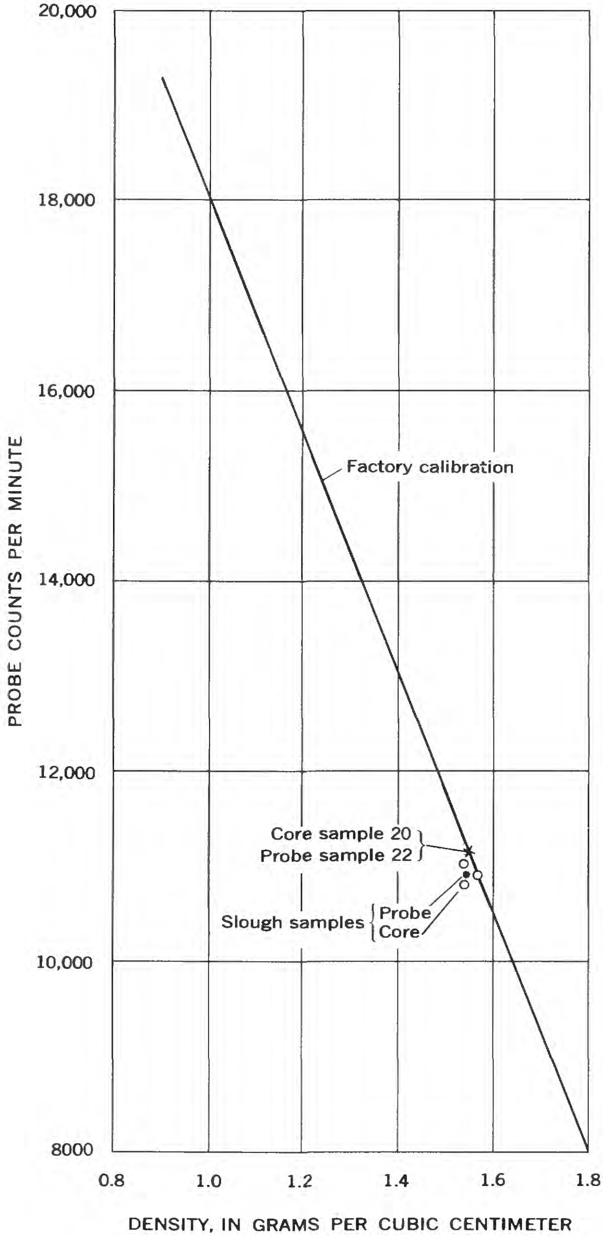


FIGURE 17.—Density-probe calibration curve.

sediment found in Lake Pillsbury. The check was made by obtaining a sample with the split-core sampler (sample 20, pl. 1) and by a determination with the sediment-density probe (sample 22, pl. 1) at as near the same location as possible. The wet specific weight of the material at the point of the calibration sample was 96.7 pounds per cubic foot by each method. Because no bottom sediment of lower specific weight was found in Lake Pillsbury at convenient working depths, no calibration samples could be taken to check the remainder of the calibration curve.

Three calibration samples were taken in sloughs near Sacramento, but they were also of high specific weight (fig. 17). The average value for each of these three samples varied from the calibration curve by 0.3, 1.3, and 1.9 percent, respectively. In this calibration test the core samples were taken with a special split-core sampler that contained brass inserts in 6-inch lengths. Thus, the core was removed and sealed in 6-inch sections, and specific weight could be determined independently for each 6-inch increment. Core samples were taken on each side of, and as near the probe as practicable, so that the core samples consisted of the same material as that in which the probe determination was made.

Results of the core samples show that the wet specific weight of sediment between 0.5 and 1.0 foot in depth varied from 101.1 to 105.5 pounds per cubic foot, and the sediment in the 0.5 foot nearest the surface varied from 86.1 to 91.1 pounds per cubic foot.

In each test the probe was positioned so that the gamma-ray source was located 1.0 foot below the sediment surface to obtain the probe count of the material collected in the top two inserts of the split-core sampler. The specific weight of the material varied laterally and vertically, but the mean value of core-sample determinations agreed closely with the probe determination at each location.

DETERMINATION OF RESULTS

SPECIFIC WEIGHT

The specific weight of a sediment sample is the ratio of the weight of the sample to its volume. The ratio of the weight of an undisturbed sample of the sediment-water mixture to the volume of the sediment-water mixture is referred to in this text as the wet specific weight; the ratio of the weight of the dry solids contained in the water-sediment mixture to the volume of the mixture is referred to as the dry specific weight. Determinations of specific weight made on core samples are given in table 1.

Additional determinations of specific weight of the bottom sediment were made with the gamma-ray density probe. These determinations were made for two reasons: First, to develop an operational procedure for use of the probe, and second, to compare the results obtained with the probe to those obtained with the core sampler.

The probe is calibrated to give the wet specific weight of the deposited sediment in grams per cubic centimeter. These values can be converted to pounds per cubic foot and compared directly with the values of wet specific weight determined from the core samples. To compare values of dry specific weight the probe values were converted to dry specific weight by the following equation: $D=\frac{S(W-62.4)}{S-1}$,

where D is the dry specific weight of the lake bottom sediment,

S is the specific gravity of the sediment particle, and

W is the wet specific weight of the sediment.

This equation was used by the U.S. Bureau of Reclamation (1957) in a study of the use of radio-isotopes for measuring the density of saturated submerged sediment deposits.

Some of the determinations of specific weight by the probe are probably in error due to poor penetration of the bottom sediment. The dense sediment of well packed, coarse material in the upper reaches of the reservoir were not penetrable with the cable-suspended instrument, and water depths near the dam were too great to allow complete or sufficient penetration by the probe.

Specific weights of bottom sediment measured with the probe are given in table 2.

TABLE 1.—*Specific weight and specific gravity of core samples*

[Arm of lake: MB, main body; E, Eel River; R, Rice Fork; S, Salmon Creek; SV, Squaw Valley Creek]

Core sample (pl. 1)	Date	Specific gravity	Water temperature (°F)	Arm of lake	Specific weight (lbs per cu ft)	
					Wet	Dry
1	May 28, 1959	2.72	63	MB	90.8	45.4
2	do	2.71	64	MB	91.1	49.4
3	do	2.72	64	MB	93.0	48.5
4	do	2.72	64	E	92.4	48.8
5	do	2.72	64	E	89.0	42.0
6	do	2.70	64	E	83.6	43.4
7	do	2.71	64	E	96.1	53.9
8	Dec. 3, 1959			E	106.0	69.3
9	May 29, 1959	2.70	64	E	115.0	84.0
10	do	2.73	65	E	117.0	87.0
10A	Nov. 23, 1958	2.72		E		83.6
11	May 29, 1959	2.72	65	E	117.0	86.0
12	do	2.72	66	E		
13	do	2.69	63	R	93.0	53.7
14	do	2.68	64	R	100	61.1
15	do	2.69	65	R		
16	do	2.72	64	MB	92.4	46.2
17	do	2.69	62	S	91.1	50.6
18	do	2.70	62	S	93.7	49.7
19	Dec. 2, 1959			S	99.9	56.9
20	May 29, 1959	2.71	65	S	96.7	56.5
21	Nov. 24, 1958			S		60.6
22	do			S		72.9
23	Dec. 2, 1959			SV	85.2	40.6
24	Nov. 24, 1958			SV		64.5

TABLE 2.—*Specific weight of deposited sediment by sediment-density probe*
[Arm of lake: MB, main body; E, Eel River; R, Rice Fork; S, Salmon Creek; SV, Squaw Valley Creek]

Sediment-density probe (pl. 1)	Date (May 1959)	Arm of lake	Specific weight (lbs per cu ft)	
			Probe determination	Computed dry weight
1[a]	29	MB	77	23
2[a]	29	MB	76	22
3	29	MB	97	54
4	29	MB	96	53
5	29	MB	99	57
6	30	E	96	53
7	30	E	96	54
8	30	E	99	58
9	30	E	97	55
10	30	E	99	57
11	30	E	102	62
12	30	E	100	59
13	30	E	107	70
14	30	E	105	67
15	29	R	100	59
16	29	R	95	52
16A	29	R	101	62
17	30	R	100	60
18	30	R	106	70
19	29	MB	97	55
20	29	S	81	30
21	29	S	95	52
22[b]	29	S	97	54
23[c]	29	S	74	18
24	29	SV	92	46

[a] Doubtful penetration.
[b] Calibration sample. See core sample 20.
[c] Low penetration.

PARTICLE SIZE

Determinations of size distribution were made on all core samples. Analyses of the coarse materials (larger than 2.00 nm) were made by the dry-sieve (Rotap) method. Both the dry- and wet-sieve methods were used for the analysis of the material in the sand range (0.062–2.00 mm), and the pipette method was used for the analysis of the silt and clay (less than 0.062 mm). The results of these particle-size analyses and the results of an analysis of a soil sample from the bank of the Eel River upstream from the maximum water level are given in table 3.

SPECIFIC GRAVITY

Specific-gravity determinations were made for most of the core samples collected at Lake Pillsbury. The pycnometer method, described by Krumbein and Pettijohn (1938), was used to make the specific-gravity determinations. Results show a small range in values, from 2.68 to 2.72. The results are given in table 1 and are also shown on plate 1.

TABLE 3.—*Particle-size analyses of core samples*

Core sample (pl. 1)	Percent finer than indicated size, in millimeters—											Median diameter (millimeters)
	0.002	0.004	0.008	0.016	0.031	0.062	0.125	0.250	0.500	1.000	2.000	
1	33	45	67	87	99	100	------	------	------	------	------	0.0047
2	33	48	71	90	98	100	------	------	------	------	------	.0042
3	36	54	78	92	98	100	------	------	------	------	------	.0035
4	33	49	71	89	97	99	100	------	------	------	------	.0041
5	------	33	------	87	------	98	99	99	100	------	------	.0058
6	34	52	73	91	98	99	100	------	------	------	------	.0037
7	31	34	58	83	96	99	100	------	------	------	------	.0064
8	2	2	4	5	7	10	34	86	97	99	99	.1500
9	------	1	------	2	------	6	20	56	84	92	96	.2250
10	------	1	------	2	------	6	23	74	93	98	99	.1800
10A	3	3	5	6	12	22	64	93	99	100	------	.1000
11	------	1	------	2	------	6	12	34	76	91	96	.3200
12	------	1	------	4	------	15	50	94	98	99	100	.1250
13	25	34	39	61	87	97	100	------	------	------	------	.0110
14	------	17	------	37	------	78	97	100	------	------	------	.0240
15	------	1	------	4	------	10	25	60	84	92	95	.2050
16	39	56	80	95	99	100	------	------	------	------	------	.0031
17	23	28	40	49	56	61	81	99	100	------	------	.0180
18	------	35	------	70	------	80	84	89	92	93	94	.0072
19	20	24	35	45	53	62	74	89	96	97	97	.0250
20	21	29	41	60	71	76	89	99	100	------	------	.0110
21	17	29	46	78	98	100	------	------	------	------	------	.0087
22	14	15	21	41	76	93	100	------	------	------	------	.0185
23	41	52	74	87	95	100	------	------	------	------	------	.0035
24	16	25	37	59	78	88	99	100	------	------	------	.0120
Bank sample	1	2	2	4	7	11	28	61	84	91	94	.2000

SPECIFIC WEIGHT OF LAKE-BOTTOM SEDIMENT

Generally, the specific weight of the sediment deposited in Lake Pillsbury, as determined from core samples, increased in the upstream direction from the dam as was expected (pl. 1); however, the material near the dam was more compacted than had been anticipated. This compaction was indicated by echo-sounder measurements which indicated an absence of soft upper layers of low-density sediment. The absence was verified by a sample of the lake water collected just above the surface of the compacted sediment. A Foerst sampler, designed for the collection of water or water-sediment mixture at any predetermined depth, was used in this verification. The concentration of the sediment in the sample was 86 parts per million.

The values of wet and dry specific weights ranged from 84 to 117 and from 41 to 87 pounds per cubic foot respectively (table 1). The average dry specific weight of sediment in Lake Pillsbury was 73 pounds per cubic foot. This value was computed by weighting the average specific weight of the sediment for each 10-foot contour interval with the quantity of sediment deposited in that interval. In general, the average specific weight determined and computed from core-sample values was used as a basis for computing the average specific weight. The probe values for samples near the dam and in the upper reaches of the reservoir were considered to be too low. It should be noted that the average value of 73 pounds per cubic foot represents the weighted value of samples taken near the surface of the deposited sediment in Lake Pillsbury and that no correction was made to allow for compaction of sediment due to weight of the overburden, age of deposits, or operation of the reservoir.

Specific weights of the bottom sediment in the Eel River arm of the lake are shown in figure 18. The probe values, except those at locations 1 and 2 (pl. 1), are higher below range 14 than are the core-sample values. Above range 14 this relation is reversed.

Core-sample values of specific weight of the sediment upstream from range 18 are higher than those obtained with the probe. The higher values are considered reliable because the dry specific weight of core samples 10 and 10A (near range 20), collected at different water levels and with different samplers, agree closely. Samples 10 and 11, collected with the split-core sampler during high lake levels, have specific weights of 87 and 86 pounds per cubic foot, respectively. Sample 10A, collected with a hand sampler during the low lake levels, has a specific weight of 84 pounds per cubic foot. The difference between core sample and density probe values are due partly to sampling difficulties and partly to the difference in location of the sampling sites.

The relation of median particle size to specific weight of sediment deposited in reservoirs can be used to estimate the initial specific weight of reservoir deposits. A chart showing general relation was prepared by Hembree and others (1952) from data from many reservoirs; the relation represents an average of values based on a wide range of reservoir conditions (fig. 19).

The relation of median particle size (table 3) to dry specific weight (table 1) for core samples from Lake Pillsbury was also plotted (fig. 19). In general, the values from Lake Pillsbury agree well with those from other reservoirs.

The weighted median particle size of core samples from Lake Pillsbury is 0.93 mm. Application of this median particle size to the relationship curve (fig. 19) indicated a specific weight of 77 pounds per cubic foot, which is slightly higher than the weighted average specific weight (73 pounds per cubic foot) as determined from the core samples.

PARTICLE SIZE OF LAKE-BOTTOM SEDIMENT

The sediment in the main body and Eel River arm of the lake below range 14 is of uniform particle-size distribution. Above range 14 on the Eel River arm and above range 29 on the Rice Fork arm the particle size of the sediment deposits increases appreciably in the upstream direction. In general, the particle size of the bottom

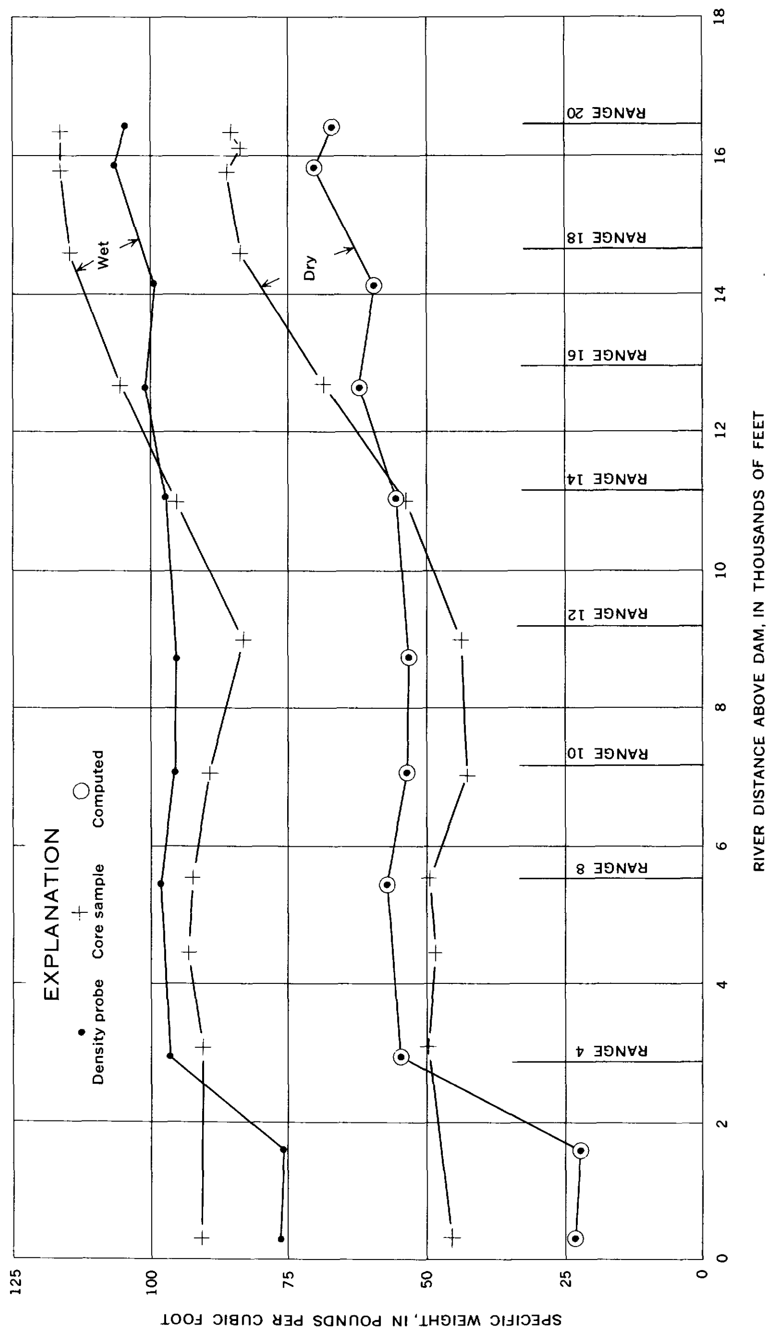


FIGURE 18.—Specific weight of deposited sediment in the Eel River arm.

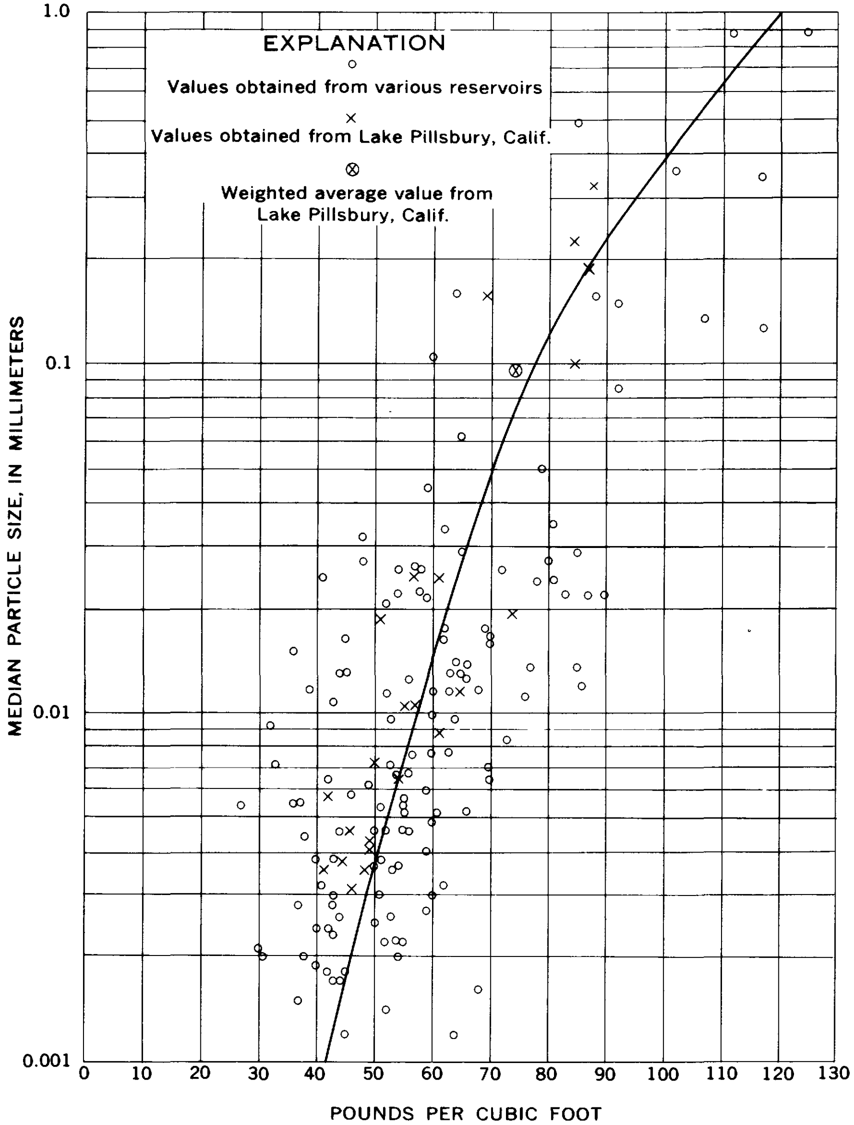


FIGURE 19.—Relation of specific weight of sediments deposited in reservoirs to median particle size. From Hembree and others (1952).

sediment in the canyon part of the Eel River arm and Rice Fork arm of the lake ranges from fine sand to gravel.

The channels of the Eel and Rice Fork Eel Rivers are mostly gravel above the high water level of the lake. The distance that the gravel extends into the lake was not determined. Most of the gravel is probably above the 1,820-foot contour and constitutes a small percentage of the material deposited in the lake.

The results of particle-size determinations are given in table 3. The relation between particle size and river profile changes is shown in figures 5 to 8. The particle-size distribution of each sample is plotted in relation to its distance upstream from the dam. Effects of particle size of the lake-bottom sediment on sediment distribution in the reservoir were discussed in a previous section.

PREDICTING SEDIMENT DISTRIBUTION IN RESERVOIRS

A knowledge of the previously discussed factors affecting sediment distribution in reservoirs and of the sediment loads of the tributary streams is necessary to predict the sediment distribution for reservoir design purposes. Several methods for predicting sediment distribution and the application of those methods are described by Borland and Miller (1958).

Figures 20 and 21, taken from Borland and Miller (1958), show the curves that are a part of the Van't Hul method for the selection of a design curve for distribution of sediment in reservoirs. This method embodies a means for associating a particular reservoir with one of four groups, based on one factor—reservoir shape. The groups are described as gorge (type IV), hill (type III), flood plain (type II), and lake (type I). The gorge-type reservoir is associated with a shape that would have a small increase in capacity with depth, and the lake-type reservoir is associated with a shape that would have a large increase in capacity with depth. Figure 20 gives the slope (n), and the reciprocal of the slope (m), of the capacity curve associated with each type of design-disposition curve. Figure 21 shows the shape of the various design-disposition curves.

Admittedly, it is easier to use the measured volumes of sediment in Lake Pillsbury, as found in the May 1959 survey, and theorize why they were thus distributed than it would have been to use the data that would be available during the planning stage to predict the future sediment distribution. No attempt was made here to use basic data available only at the planning stage to predict the distribution because the predicted results would obviously be biased toward the known values. However, a predicted sediment distribution based only on reservoir shape (Van't Hul method) is compared to the distribution existing at the time of the May 1959 survey.

The distribution of sediment and the original-capacity curve of Lake Pillsbury are shown in figure 12. The graph shows that 50 percent of the material deposited in Lake Pillsbury is below (or above) the

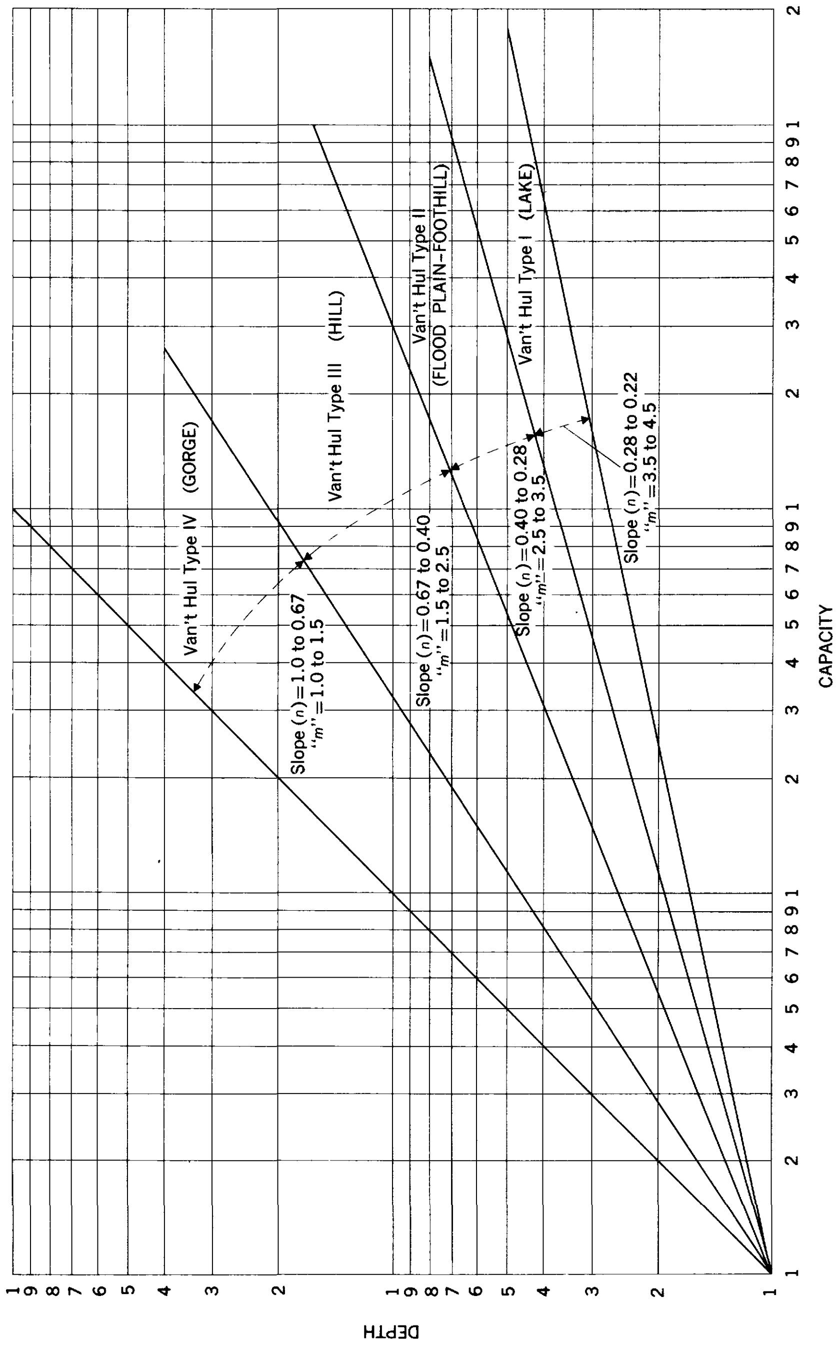


FIGURE 20.—Relations of capacity to depth associated with Van't Hul-type design-disposition curves. *m*, reciprocal of slope (*n*).

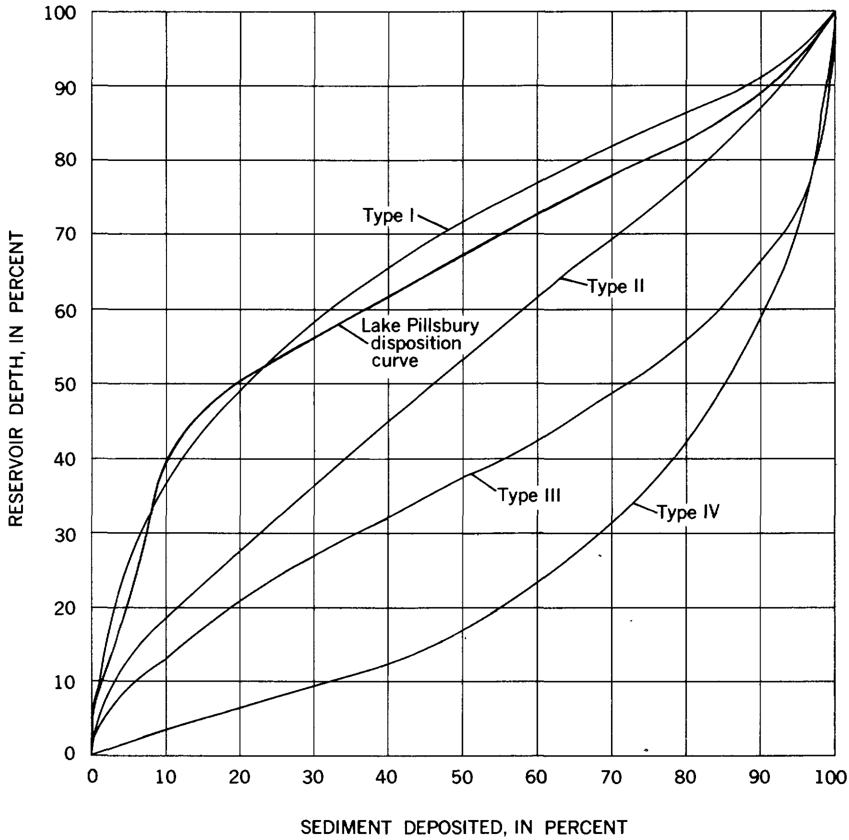


FIGURE 21.—Comparison of Lake Pillsbury disposition curve with Van't Hul-type design-disposition curves

1,794-foot contour, or is in the lower 67 percent (or upper 33 percent) of the total depth; and that 50 percent of the original capacity was below the 1,804-foot contour, or in the lower 77 percent of the total depth of the lake. The curve labeled "original lake capacity occupied by sediment in 1959" (fig. 12) indicates that 7,620 acre-feet of sediment occupies 8.1 percent of the original volume and that half of this sediment (3,810 acre-feet) occupies 4.0 percent of the original reservoir capacity and is deposited below the 1,794-foot contour.

The slope of the original-capacity curve of Lake Pillsbury representing the relation of capacity to depth and the slope of the capacity curve for 1959 are shown in figure 22. The original-capacity curve had a slope of about 0.3 and would be associated with the design-disposition curve for type II reservoirs (fig. 20). The 1959 curve has a slope of about 0.2 below the 1,760-foot contour and a slope of

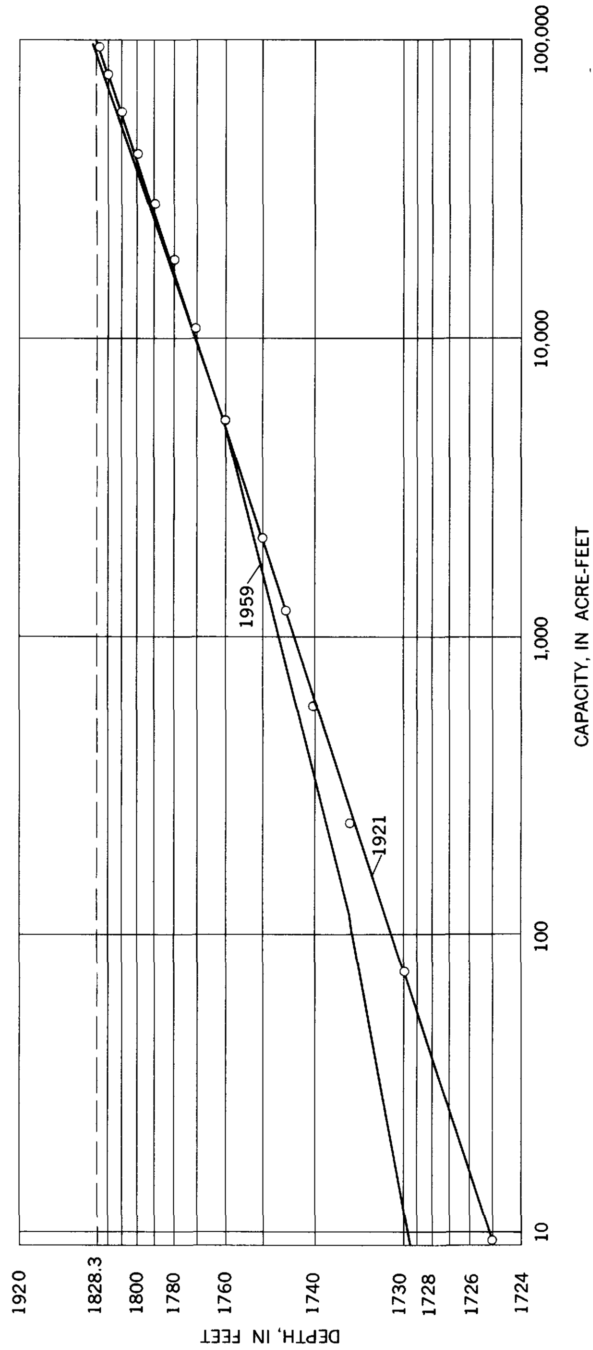


FIGURE 22.—Relation of capacity to depth of Lake Pillsbury.

about 0.35 above the 1,760-foot contour. These slopes indicate present design-disposition curves of types I and II, respectively.

Inspection of the 1959 disposition curve (fig. 21) shows that sediment is deposited in Lake Pillsbury according to the Van't Hul-type I disposition curve. The distribution of deposited sediment according to the type I disposition curve, rather than the type II curve indicated by the slope of the original-capacity curve, emphasizes the importance of variables other than reservior shape on the distribution of sediment in reservoirs. The properties of sediment, any unusual shape of the lake, probability of bank erosion, and reservoir operation should be used to modify the design-disposition curve; under the conditions existing at Lake Pillsbury, the first three of these variables would tend to cause sediment to be deposited higher in the reservoir, while the fourth variable would cause sediment to be moved lower into the lake. The properties of sediment, the unusual shape of the reservoir, and the occurrence of bank erosion were predominant variables affecting the distribution of sediment in Lake Pillsbury. The disposition curve should have been the type I.

SUMMARY

This report contains the results of the May 1959 sediment survey of Lake Pillsbury, Lake County, Calif. Construction of the dam was completed and impoundment of water was begun in December 1921. The age of the reservoir at the time of this study was 37.5 years.

The lake was resurveyed by a combination of transit-stadia mapping and echo soundings. The transit-stadia mapping was used for the relatively flat upper part of the north arm during a period of low water elevation in November 1958. Depths of the entire lake were measured by echo sounding in May 1959 when the water level was at maximum elevation. A contour map was constructed by plotting elevations obtained by the transit-stadia method and echo sounding. Accuracy of the contour map was verified by field checks of the map in December 1959.

The loss of reservoir capacity due to sediment accumulation was determined. The difference in capacity was computed from the original map prepared by the lake owner and the map prepared from the resurvey in May 1959. The accuracy of the computation of sediment accumulation was verified by measuring the thickness of the deposited sediment at selected points in the reservoir.

At maximum water lever (1,828.3 msl) the reservoir area and length of the various arms have changed very little by sediment deposition between 1921 and 1959. The volume, on the other hand, has been reduced from 94,400 acre-feet to 86,780 acre-feet, a loss of 7,620 acre-feet.

At spillway elevation (1,818 msl) the surface area, length of the lake arms, and volume have changed appreciably between 1921 and 1959. The surface area was reduced from 2,003 acres (Fowler, 1923) to 1,917 acres. The length of the Eel River arm was shortened by 1,900 feet, Rice Fork Eel River arm by 1,600 feet, Squaw Valley Creek part of the north arm by 300 feet, and Salmon Creek part of the north arm by 900 feet. The volume at this elevation was reduced from 72,717 to 65,761 acre-feet, equivalent to a loss of 6,956 acre-feet, during the 37.5 year period.

Total loss of storage due to sediment deposition averaged 203 acre-feet per year or 0.71 acre-feet per square mile of drainage area per year. A complete summary of pertinent data is given in table 4.

The distribution of the sediment in Lake Pillsbury was affected by many variables such as the physical properties of the sediment, reservoir operation, shape of the reservoir, and ratio of reservoir capacity to inflow. Fifty percent of the sediment was deposited above the 1,794-foot contour.

The sediment deposited in Lake Pillsbury ranges in dry specific weight from 41 to 87 pounds per cubic foot. The weighted average dry specific weight for the entire lake is 73 pounds per cubic foot.

The particle size of the deposited sediment ranged from clay to gravel with a weighted median diameter of 0.093 mm.

TABLE 4.—*Summary of pertinent data*

Dam:		
Height spillway above streambed	feet	105
Elevation top spillway (msl)	do	1,818.3
Elevation top gates (msl)	do	1,828.3
Elevation top walkway (msl)	do	1,838
Elevation outlet sill (msl)	do	1,740.7
Reservoir:		
Age (Dec. 1921–May 1959)	years	37.5
Surface area, top gates	acres	[1] 2,280
Total storage capacity:		
1921	acre-feet	94,400
1959	do	86,780
Storage capacity below outlet sill:		
1921	do	672
1959	do	397
Storage capacity per square mile drainage area:		
1921	acre-feet per square mile	328
1959	do	301
Drainage basin:		
Area	square miles	288
Runoff, 1923–58	acre-feet per year	380,800
Average slope:		
Eel River	feet per mile	160
Rice Fork Eel River	do	200

[1] At elevation 1,828.3 (msl)

TABLE 4.—*Summary of pertinent data*—Continued

Sedimentation:		
Sediment accumulated (1921–59):		
Total	acre-feet	7,620
Average per year	do	203
Per year per square mile drainage area	do	.71
Depletion of storage:		
Loss of original capacity:		
Average loss per year	percent	.216
Total loss	do	8.1

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