Sediment Transport in Cache Creek Drainage Basin in the Coast Ranges West of Sacramento, California

GEOLOGICAL SURVEY PROFESSIONAL PAPER 562-A

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

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By LAWRENCE K. LUSTIG *and* ROBERT D. BUSCH

SEDIMENT TRANSPORT IN ALLUVIAL CHANNELS

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By Lawrence K. Lustig and Robert D. Busch

ABSTRACT

This report treats the sediment-transport characteristics of streams in the Cache Creek drainage basin during the 1960–63 period and the relations of these characteristics to environmental factors. The general geology of the area is shown on a map compiled from several sources. The rocks that crop out in the basin range in age from Late Jurassic to Recent. Pliocene and Pleistocene continental deposits are apparently a major source of sediment in the basin; erosion of these deposits has resulted in badland topography, indicative of their silt-clay content.

The upper part of the basin, to the north, receives as much as 50 inches of precipitation each year, but this annual rainfall decreases to the south, and the middle part of the basin receives less than half this amount. The occurrence of badland topography and gullying, combined with the decrease in annual precipitation, is probably the cause of a marked increase in sediment yield in the middle part of the basin.

Because precipitation and runoff were deficient during the 1960–63 period, relative to the long-term period of record, a qualitative analysis of flow-duration data is presented. Although estimates of sediment discharge based upon 1960–63 observations must be low relative to the long-term sediment discharge, the deviation is probably not great.

Sediment-transport curves for each of five sediment stations are shown as least-squares regression lines of best fit. The exponents of water discharge, which are a measure of the rate of increase of suspended-sediment discharge with an increase in water discharge, show that the streams in the upper, middle, and lower parts of the basin have distinctive sediment-transport characteristics. Sediment discharge increases downstream, but the rate of increase is much greater in the middle part of the basin than in the upper part. The rate decreases between Capay and Yolo because artificial controls at Capay induce sediment deposition through surface-water diversion.

The total suspended-sediment discharge for the 1960–63 period was 476,700 tons from North Fork Cache Creek, 174,800 tons from Bear Creek, 2,261,000 tons from Cache Creek above Rumsey, 3,320,000 tons from Cache Creek near Capay, and 2,132,000 tons from Cache Creek at Yolo.

Total sediment discharge is computed (1) by substitution of daily mean water-discharge values in a regression equation that relates instantaneous water discharge and bedload discharge, and addition of the bedload discharge thus obtained to the suspended-sediment discharge, and (2) by adjustment of instantaneous sediment-discharge values to daily mean values through the method of subdivision of days. Bedload discharge comprises approximately 7 percent of the total sediment discharge by these methods. Total sediment discharge at the Yolo sediment station for the 1960–63 period was approximately 2,300,000 tons.

The trap efficiency of the settling basin is estimated from data on suspended-sediment concentration at the weir of the basin and water-discharge values at Yolo. The results indicate that the trap efficiency is at least 50 percent and may be as great as 60 percent.

Various difficulties inherent in procedures for sampling of suspended sediment and the computation of both suspended and total sediment discharge lead to possibility of error but do not invalidate the results of the investigation.

INTRODUCTION

The development of a comprehensive water plan for a given basin is often a complex problem; the solution must often satisfy the varied water needs of different parts of the basin. This observation clearly applies to the Cache Creek drainage basin. The upper part of the basin contains Clear Lake, the largest natural lake located wholly within the boundaries of the State of California, and an ideal lake in many respects for recreational purposes. The primary water need in this area is stabilization of the lake level, which is dependent on both the rainfall-runoff input and the water discharge at the outlet of the lake.

Other water needs must be served, however. The outlet of Clear Lake is Cache Creek, which flows from the lake through the lower part of the basin. Because this area is primarily agricultural, a major water need in the lower part of the basin is to minimize both the frequency and magnitude of flood stages on Cache Creek and thus prevent the inundation of cultivated fields and orchards. The California State Department of Water Resources is considering several alternate plans of control and improvement within the drainage basin in an attempt to meet these and other water needs.

The efficient evaluation of these plans, which may include the construction of dams, reservoirs, and settling basins, requires information on sediment transport in the Cache Creek drainage basin.

Accordingly, the investigation reported here was undertaken to determine the quantity and distribution of the sediment transported by streams of the Cache Creek drainage net. Although a few observations were made in previous years, the data in this report pertain to the 1960–63 period. During this period, suspended-sediment samples were collected at five sediment stations within the drainage basin. Additional samples were obtained at the outlet of an existing settling basin in the lowermost part of the drainage basin, and seven total sediment-discharge measurements were made on Cache Creek at the Yolo sediment station.

These data are used to estimate the suspended-sediment discharge at each of the five sediment stations, and the total sediment discharge at the Yolo station. A geologic map of the basin has been compiled from several sources to indicate the probable sources of sediment. The effect of the net sediment transport on the settling basin below the Yolo station is also considered.

The operation of sediment stations in the drainage basin and the analysis and computation of data were performed by personnel in the Sacramento District Office of the Quality of Water Branch, in cooperation with the California State Department of Water Resources, and under the direct supervision of George Porterfield. The authors gratefully acknowledge the valuable counsel provided by Mr. Porterfield on many aspects of data interpretation and report preparation. Constructive criticism on these matters was also provided by Charles H. Hembree, Thomas Maddock, Jr., Paul C. Benedict, and James M. Knott.

LOCATION AND EXTENT OF THE AREA

The Cache Creek drainage basin (pl. 1) extends from the highlands north and northeast of Clear Lake to the Yolo Bypass, adjacent to Sacramento, Calif. It lies within Lake, Yolo, and Colusa Counties in the Coast Ranges of northern California. The northwest trend of the basin conforms to the regional trend of the Coast Ranges and to the coastline of California in these latitudes.

The marked elongation of this basin is unusual for so large a drainage basin. The overall length is approximately 100 miles, whereas the width ranges from 6 miles near Rumsey to more than 30 miles in the upper (northern) part of the basin. This configuration is determined by both structure and topography.

The total drainage area of the basin is difficult to ascertain. An extensive network of sloughs, canals, and levees, some of which are shown on plate 1, occur below Capay, in the lower part of the basin. Because these channels both enter and leave the general area, the drainage divide cannot be located with certainty. That part of the basin boundary that lies between a point to the north of Capay and Knights Landing is particularly uncertain, and any computation of total drainage area is therefore dependent on the judgment of the researcher. The area shown on plate 1 reflects the considered opinion of the authors and is approximately 1,300 square miles.

ENVIRONMENTAL CONDITIONS AFFECTING SEDIMENT TRANSPORT

The sediment-transport characteristics of streams in the Cache Creek drainage basin are strongly affected by environmental conditions. In fact, a later section of this report will show that the sediment-transport characteristics of the streams are, in part, directly dependent on their location within the basin. For the present, only the broader features of the upper, middle, and lower parts of the basin will be discussed. Climatic conditions will be indicated only in general terms, because precipitation and runoff will be discussed separately in a later section.

UPPER PART OF THE BASIN

The upper part of the basin, as here defined, is the area above the junction of Cache Creek and Bear Creek (pl. 1). Clear Lake and its tributaries are omitted from this discussion because the sediment transported to the lake is virtually trapped, and the area therefore contributes little to the sediment discharge from the basin.

North Fork Cache Creek drains a large region in which rocks of the Franciscan Formation crop out (pl. 1). This region includes the highlands, where the Coast Ranges attain elevations of about 4,000 feet. Because of heavy orographic precipitation, the rugged hillslopes are covered by dense vegetation. Stream channels contain much coarse debris, and channel gradients are commonly greater than 100 feet per mile. The valleys are generally narrow and deep, but they widen in some places, particularly at pronounced stream meanders. Within such stream reaches the valley floors are covered with coarse alluvium; the view shown in figure 1 is typical of the terrain.

Near the sediment station on North Fork Cache Creek (pl. 1) the stream flows through an alluvial valley bounded by hills that are much lower than those in the headwaters. The Pliocene and Pleistocene continental deposits are drained in this area and probably yield much sediment. The deposits range from alternating

FIGURE 1.—View of a tributary stream of North Fork Cache Creek, showing stands of pine on the steep slopes and the general density of vegetation, which includes much manzanita. The wide flat area on the valley floor is a point bar of coarse gravel; it is on the concave side of a stream meander in this upstream view.

layers of silt-clay, sand, and gravel to heterogeneous mixtures of sediment of these size classes. The topography in this lower reach of North Fork Cache Creek includes many steep bluffs dissected by badland-type gullies. Areas of intense erosion, such as the area shown in figure 2, occur where the silt-clay content of the deposits is fairly high; the bluff shown in the view contains about 30 percent silt-clay.

Cache Creek proper flows from the outlet of Clear Lake (pl. 1) to the junction with North Fork through terrain similar to that in the upper reaches of North Fork. Both the relief and the channel gradient of Cache Creek are somewhat less, however, than they are in North Fork. A view downstream from the dam located a short distance below the Clear Lake outlet is shown in figure 3. Coarse debris abounds in the stream channel and, as a consequence, flow tends to be turbulent. Because vegetation occurs along the banks of the stream channels in the upper reaches of both Cache Creek and North Fork, save near pronounced meander bends, high stages of flow will not necessarily transport proportionally great quantities of sediment. Above the junction of the two streams, however, Cache Creek flows through the Plio-Pleistocene deposits and their associated badland-type topography. The availability of sediment by erosion and entrainment during large runoff events increases markedly in this region.

In its upper reach, Bear Creek (pl. 1) flows through an alluvial valley bounded by low hills on the east and by the rugged highlands on the west. The valley is approximately 10 miles long and 1 mile wide, and the gradient is gentle. Apparently, the sediment transport characteristics of Bear Creek are strongly influenced by this valley. The Bear Creek channel contains coarse bed material, but its width-depth ratio is large (fig. 4); because the gradient is gentle, much of the coarse bed material must be reduced in size before it can be transported under the present flow regime. It is significant that the Bear Creek drainage system transports about 1,800 tons of suspended sediment per square mile, whereas North Fork Cache Creek transports more than 2,400 tons per square mile. The difference may be due to the highly erodible terrain in the drainage area of North Fork Cache Creek. Certainly, however, the ultramafic rocks and associated serpentine zones in the Bear Creek drainage area (pl. 1) would yield equally large quantities of sediment if the environmental conditions were more favorable to transportation of material.

Below the alluvial valley, Bear Creek flows through steep canyons for approximately 12 miles. The stream and its tributaries primarily drain Lower Cretaceous marine rocks in this lower reach, and environmental conditions are similar to those of Cache Creek and Bear Creek above the confluence of the two streams. A view of the junction of these streams (fig. 5) shows that steeply dipping sedimentary units crop out along the valley walls and channel banks, forming bluffs that are relatively barren of vegetation. These easily erodible sedimentary formations provide large amounts of sediment for transport at high as well as low stages of flow.

Summary.—The environmental conditions in the upper part of the basin change progressively downstream. Decrease in precipitation, owing to orographic control, is accompanied by a general decrease in the abundance of vegetation, particularly bordering the stream channels. These conditions, together with the high erodibility of the Pliocene and Pleistocene continental deposits and the Lower Cretaceous marine formations, tend to increase both sediment availability and sediment discharge downstream. They supplement the normal increase in sediment discharge downstream due to the increase in drainage area and water discharge.

FIGURE 2.—View of badland-type topography in the drainage area of North Fork Cache Creek. This topography is associated with outcrops of Pliocene and Pleistocene continental deposits, particularly in areas where the silt-clay content of the sediments is high. The badlands shown in this view contain approximately 30 percent silt-clay.

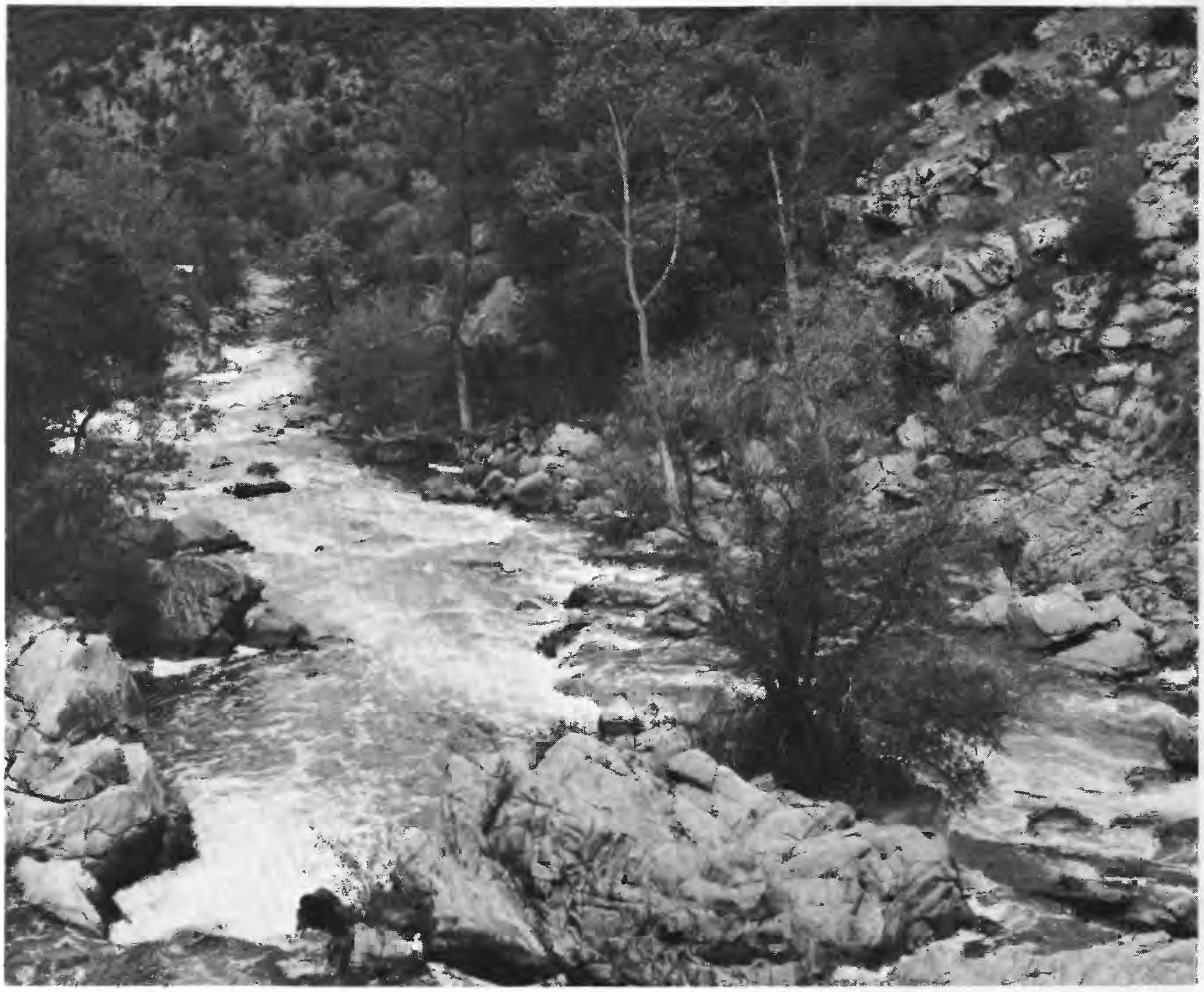

FIGURE 3.—View of the Cache Creek channel from the dam below the Clear Lake outlet, showing coarse debris in the channel and the growth of vegetation along the channel banks.

MIDDLE PART OF THE BASIN

Below the junction of Cache Creek and Bear Creek (fig. 5) a sequence of Upper Cretaceous marine formations crops out, capped in some places by younger gravels. The sedimentary rocks are predominantly sandstone, and they dip moderately to steeply. In several places Cache Creek flows across ledges of these clastic units; the channel appears to rest virtually upon bedrock. This condition prevails between the junction of Cache Creek and Bear Creek and the head of the alluvial valley near Rumsey (pl. 1). The view in figure 6 shows Cache Creek along one such reach above Rumsey. The massive sandstone unit shown at the right in the photograph contributes large blocks of debris directly to the channel, thus promoting turbulent flow in the stream. This condition is similar to that prevailing in much of the upper part of the basin, as previously described, but the valley here is much wider than, for example, the valley of Cache Creek below the Clear Lake outlet (fig. 3).

Precipitation is lower here than in the northern highlands, and there is a corresponding decrease in the number and size of conifers. Thus, the hillslope area exposed to erosion is greater, and there is higher sediment yield from these slopes and from bank cutting by the stream (fig. 6).

FIGURE 4.—View downstream of the channel and valley of Bear Creek. Cattle in the channel, in the left middle distance, indicate the scale.

In a later part of this report it will be shown that the sediment yield from the region between Rumsey and the Capay sediment station (pl. 1), here defined as the middle part of the basin, is much greater than would be predicted on the basis of drainage area alone. Here approximately 100 square miles of land contributes more sediment than does an area twice as large in the upper part of the basin. Because the number of tributary streams, total stream length, and water discharge are all determined by the extent of the drainage area, a disproportionate sediment yield indicates that the middle part of the basin must differ environmentally from the other parts.

The view across the Cache Creek valley shown in figure 7 illustrates certain significant environmental conditions. First, wide areas of Pliocene and Pleistocene deposits again crop out along the valley walls; vegetation is scanty and numerous badland zones occur where the silt-clay content of the rocks is high. Second, the orchards visible in the distance are representative of more extensive cultivation in this part, tending to increase erosion of the valley floor. Additional factors not shown in the figure are the several tributary channels that drain Upper Cretaceous and Tertiary sedimentary rocks on the west side of the valley (pl. 1), and the precipitation distribution in the region.

The sediment contribution from the tributary streams and waterways is difficult to assess. The channels are indistinct where they cross cultivated fields, but several of the larger channels undoubtedly carry runoff during widespread storms in the narrow belt of hills in which the tributary streams head. The primary cause of the disproportionate sediment yield, however, is thought to be the decrease in quantity and frequency of precipitation. Although mean annual precipitation is approximately twice as great in the upper part of the basin, empirical rules (Langbein and Schumm, 1958) indicate that sediment yield increases as the precipitation decreases to about 12 inches per year.

FIGURE 5.—View of the junction of Cache Creek and Bear Creek. The view is across Bear Creek and up Cache Creek; the junction of the two streams is at lower left. Steeply dipping sedimentary units in the left foreground and right middle distance are relatively bare of vegetation, providing a ready source of sediment in this area.

Summary.—The middle part of the basin has lower relief, less precipitation and vegetation, more gentle gradients (about 10–15 ft per mile), and greater sediment yield than the upper part of the basin. The increase in sediment yield is due to a combination of environmental conditions rather than solely to an increase in drainage area and stream discharge. These conditions include badland topography, land cultivation, and a decrease in mean annual precipitation.

LOWER PART OF THE BASIN

The lower part of the basin is here defined as the area below the sediment station near Capay (pl. 1). The station is on a reach of Cache Creek that flows through Upper Cretaceous marine rocks; the land is largely grass covered and is similar in appearance to much of the Coast Ranges at lower elevations (fig. 8). Trees are relatively few, but they tend to grow in groves; the local hydrologic environment favors such growth conditions.

Sediment load from this terrain reaches the streams in two ways. First, sheetflow over the grasslands transports moderate quantities of sediment to the streams. Second, and more important, surficial slump and soil creep gradually create gullies; runoff concentrates in the gullies, erosion is accelerated, and sediment yield increases. Two conspicuous areas of surficial slump in the lower part of the basin are shown in figure 9. The steplike topography results from soil saturation and subsequent downslope movement along planes that are concave upward. The gradual growth of such features produces a gully. Certain gullies, such as the one in figure 10, have grown headward to the crests of the hills. In this instance, tree roots have been exposed to a depth of nearly 5 feet.

FIGURE 6.—View upstream of the Cache Creek channel above Rumsey. Valley width tends to increase in this upper reach of the middle part of the basin. The stream flows across bedrock here. The coarse material in the channel is derived from the massive sandstone formation shown at the right. There is some suggestion of bank cutting by the stream at higher stages of flow than that shown in this view.

At Capay, below the sediment station (pl. 1), a series of small dams and other artificial controls diverts the surface flow from Cache Creek, and sediment deposition occurs over a wide area on the flat alluvial plain (fig. 11). The natural channel regains good definition a few miles downstream, however, and continues beyond the Yolo sediment station (fig. 12) to the settling basin and the Yolo Bypass (pl. 1). The area below Capay is a large alluvial fan with a high gravel content, over which Cache Creek meandered before the settling basin and other controls were established. The channel shown leading to Knights Landing (pl. 1) was a former path of flow.

Summary.—The lower part of the basin consists of an upper reach in which Upper Cretaceous sedimentary rocks crop out and the processes of surficial slump and creep occur, and a lower reach that is a flat plain with scattered low gravel hills. Both elevations and precipitation values are lower than elsewhere in the basin, and deposition rather than erosion of sediment is the dominant process. Much gravel and sand is transported to the lowermost boundary of the basin, however.

GEOLOGY

The Cache Creek drainage basin (pl. 1) lies within the Coast Ranges of northern California. The ranges are structurally controlled, and the regional trend, including both topographic expression and the strikes of all major faults and folds, is approximately N. 30° W.

The general geology of the area was well summarized by Lachenbruch (1962), and much of the discussion here is derived from his work.

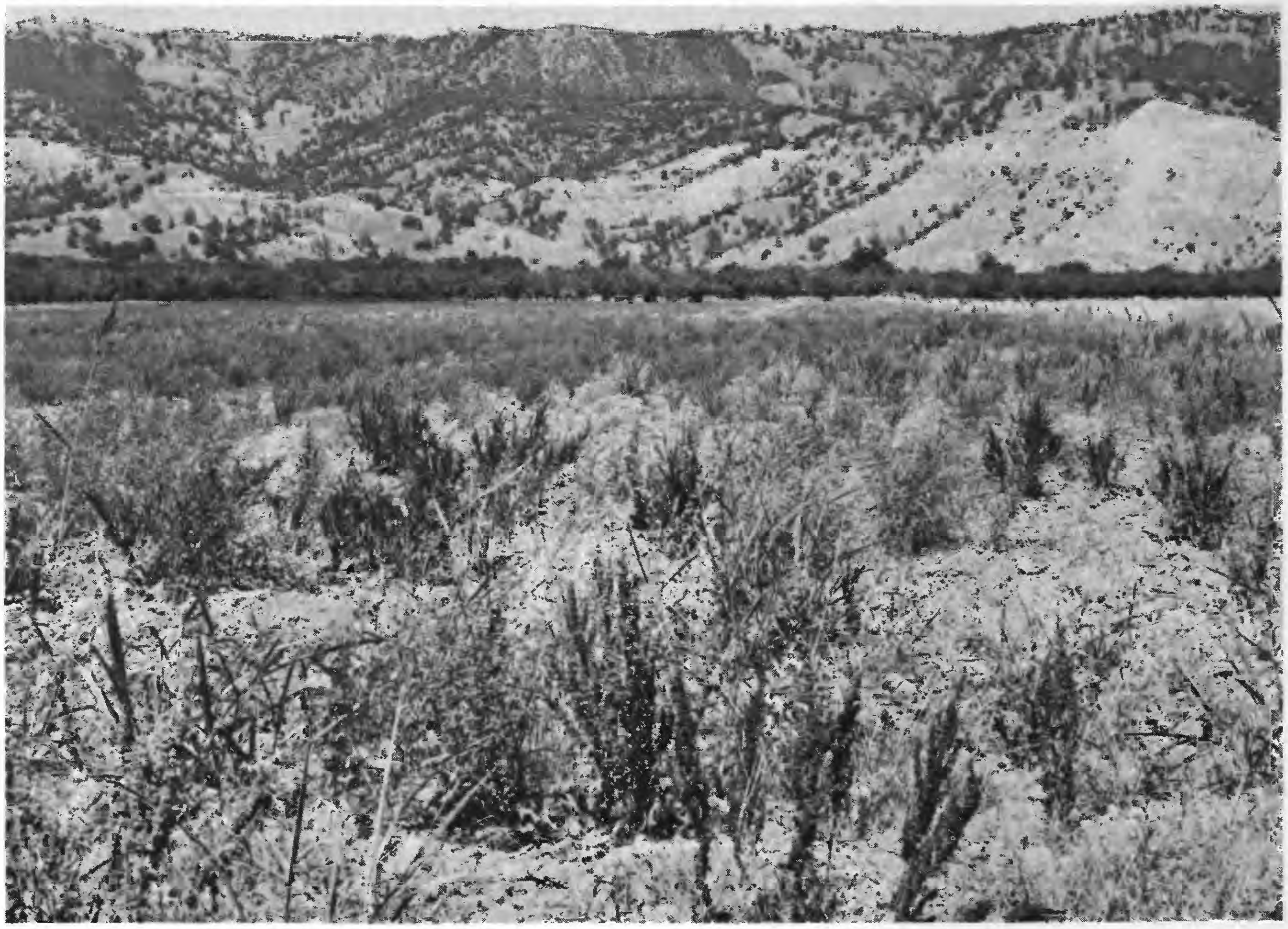

FIGURE 7.—View across the Cache Creek valley between Rumsey and Capay. Pliocene and Pleistocene continental deposits crop out on the far side of the valley in this area. Badland topography, akin to that shown in figure 2, is ubiquitous, and the sediment derived from it is transported directly into Cache Creek. The stream parallels the range of hills but is obscured in this view by the orchards in the middle distance. Cultivation of land is extensive in this part of the basin, as suggested by the tilled soil in the foreground.

The Franciscan Formation forms the core of much of the Coast Ranges, but in the Cache Creek basin these rocks crop out only in the upper part of the basin. The group consists of a heterogeneous assemblage of clastic marine sedimentary rocks, mafic volcanic rocks, and mafic and ultramafic intrusive rocks that exhibit varying degrees of metamorphism. Chert and limestone occur in lesser abundance. The lithologic and structural complexities of the Franciscan Formation and the scarcity of fossils have prevented precise correlation of units of the group with one another and with other Mesozoic rocks in the area; however, the rocks are thought to range in age from Late Jurassic to Late Cretaceous.

Aside from the partly serpentinized ultramafic rocks (pl. 1), which are both regionally and locally fractured and sheared, the Mesozoic rocks in the Cache Creek basin are shales, sandstones, and conglomerates. Many of the sandstones contain a micaceous matrix and are therefore graywacke. These rocks have noticeable current and slump features, particularly in the Upper Cretaceous marine sequence that crops out between Bear Creek and the general area of Guinda (pl. 1).

The eugeosynclinal deposits described above are overlain by early Tertiary and Quaternary deposits to the east of Clear Lake and in the middle part of the basin (pl. 1). Outcrops of Paleocene and Eocene rocks consist predominantly of massive sandstones which show better sorting than the older rocks, and interbedded conglomerates and silty shales. The Pliocene and Pleistocene continental deposits, as previously described, consist of silt-clay, sand, and gravel and occur both as discrete units and as heterogeneous mixtures. The younger overlying alluvium is similar to these continental deposits but is generally not as coarse.

FIGURE 8.—View of the Cache Creek valley near the sediment station at Capay. The general aspect of the landscape in this area is typical of the appearance of the Coast Ranges at lower elevations. Grasslands are broken by scattered bedrock outcrops, as shown in the foreground.

PRECIPITATION AND RUNOFF

The movement of storms from the Pacific Ocean to the east and south produces precipitation, primarily rain, in the Cache Creek drainage basin. Approximately 85 percent of the precipitation occurs from November to March.

Precipitation records in the area, several of which date from 1900 or earlier, reveal that although considerable fluctuation in precipitation may occur at a given station, the mean annual precipitation reflects orographic control. Near Knights Landing (pl. 1), in the lowest part of the basin, the mean annual rainfall ranges from 16 to 18 inches. Near Capay and Rumsey, where elevations range from about 250 to more than 400 feet, the mean annual rainfall is between 21 and 24 inches. In the vicinity of Clear Lake, where elevations are about 1,500 feet, the mean annual precipitation is 37 inches; in the northern highlands, where elevations are about 3,000–4,000 feet, precipitation totals 50 inches or more per year.

The fluctuations in mean annual precipitation that can occur in the basin are illustrated by the maximum rainfalls of record, which range from 32 inches per year in the lower part of the basin to more than 100 inches in the northern highlands. These maximum values are approximately double the long-term mean precipitation at a given station.

It is therefore not surprising that fluctuations in mean annual runoff have also occurred in the basin. Table 1 lists the mean annual water discharge at three stations within the basin for the period of record and for the 1960–63 period covered by this report. These data show that the mean annual runoff during the 1960–63 period was less than the long-term mean runoff at each of these stations and was probably deficient elsewhere in the basin as well. The lesser surface runoff corresponds partly to a diminution in precipitation and partly to an increase in surface water diversion and ground water use for agricultural purposes; such use must necessarily increase when precipitation decreases, because consumptive requirements do not vary greatly. Fluctuations in water discharge, in themselves, are not the primary concern of this report. Sediment discharge is related to water discharge, however, and the probable effect of treating a period that is not representative of long-term conditions must be considered.

TABLE 1.—*Mean annual water discharge at three stations in the Cache Creek drainage basin for the period of record and for the 1960–63 period*

Station	Length of record (years)	Mean annual discharge for period of record (acre-feet)	Mean annual discharge for 1960–63 (acre-feet)	Net change in mean annual discharge (acre-feet)
North Fork Cache Creek	32	133,900	94,200	−39,700
Cache Creek at Capay	20	420,600	326,300	−94,300
Cache Creek at Yolo	60	367,100	206,630	−160,470

EFFECT OF THE RUNOFF DEFICIENCY UPON SEDIMENT DISCHARGE

The usefulness of an investigation of sediment discharge within a given drainage basin is limited, to some extent, by the degree to which extrapolation of the results is justifiable. If, for example, sediment-discharge data are intended to provide criteria for the design of reservoirs, the designer will wish to extrapolate the results of a short-term investigation over a period of perhaps 50–100 years into the future. For such purposes, the period of observation must adequately represent long-term phenomena. If it can be shown, for example, that a relation exists between water discharge and sediment discharge, and if the water discharge for the period of observation is not significantly disproportionate to previous long-term water discharge values, then it can reasonably be argued that the sediment discharge during the period of observation approximates the long-term sediment discharge. Extrapolation of results

FIGURE 9.—View of surficial slump and creep on hillslopes near Capay. Two zones of slumping are visible in the left foreground, on the far bank of Cache Creek, and similar features are visible on the higher parts of the slopes to the right.

would, therefore, be justifiable. Unfortunately, one can never predict at the outset of an investigation whether a given period of observation will indeed be representative of long-term periods. The period of observation of the Cache Creek drainage basin is known to have included several years during which the annual runoff was significantly less than the mean for the long-term period of record (table 1). To evaluate this variation in runoff, so as to qualify the results of this report if necessary, flow duration curves for both the period of observation and the long-term period were plotted for each sampling station.

Flow duration curves for streamflow stations on North Fork Cache Creek, Cache Creek near Capay, Cache Creek at Yolo, Cache Creek above Rumsey, and Bear Creek are shown in figures 13 through 17, respectively. The location of each station is shown on plate 1. These frequency curves show the percentage of time that any given water discharge is equaled or exceeded. Because data on the water discharge of Bear Creek (fig. 17) include only a single year prior to the period of observation covered by this report, and because no previous data are available for Cache Creek above Rumsey (fig. 16), duration data cannot be compared with a long-term record at these two stations. The three remaining stations adequately depict the flow characteristics in the drainage basin, however, because they are located in the upper, middle, and lower parts of the basin, respectively.

The flow-duration curves for stations on both North Fork Cache Creek and Cache Creek near Capay (figs. 13, 14) show that the data for the 1960–63 period plot to the left of the long-term mean at high water-discharge values and, following intersection with the long-term duration curves, plot to the right at low water-discharge values. The discharge value at the initial point of intersection is approximately 40 cfs (cubic feet per second) for North Fork Cache Creek (fig. 13) and 80 cfs

FIGURE 10.—View of the head of a gully in Upper Cretaceous sedimentary rocks near Capay. The extent of gullying in the lower part of the basin near Capay is illustrated in this view. This gully may have originated through slumping far downslope, such as that shown in figure 9.

for Cache Creek near Capay (fig. 14). That is, these discharge values were equaled or exceeded less often during the period of observation than during the long-term period of record, whereas lower discharge values occurred more often during the period of observation. The curves for Cache Creek near Capay (fig. 16) intersect again at a discharge value below 80 cfs, but this results, in part, from complications introduced by surface-water diversions and is, in any event, unimportant in principle.

The flow-duration data for Cache Creek at Yolo (fig. 15) show no intersection between the curves that represent the 1960–63 and long-term periods. That is, at the outlet of the drainage basin, the deficiency in runoff during the period of observation is represented by a decrease in the frequency of occurrence of any given water discharge.

Because sediment discharge is a function of water discharge, and because water discharge was deficient relative to the long-term period of record at each of these stations, it is clear that the estimates of sediment discharge provided by this report must be regarded as minimum values. Although the flow-duration data for stations on Cache Creek near Capay and North Fork Cache Creek show an increase in the frequency of occurrence of low-water flows during the 1960–63 period, this increase cannot compensate for the deficit of high-water flows, which account for a much larger proportion of sediment transport than the low-water flows.

FIGURE 11.—View of the Cache Creek channel below Capay showing the extensive area of deposition in the reach below the point of stream diversion. The channel proper extends across this view in the middle distance. It is subject to surface flows during times of controlled release of water from upstream, and during the winter rainy season. The tree trunks show that at high stream stages much of this entire area is subject to inundation.

FIGURE 12.—View of the Cache Creek channel near the Yolo sediment station. Note the abundance of gravel on the bed of the channel in this reach, which is in the lower part of the drainage basin. The undulations of the bed suggest a pool and riffle sequence of broad amplitude. The trapezoidal cross section at the station is approximately 135 feet wide and about 40 feet deep.

SEDIMENT DISCHARGE OF STREAMS

Evaluation of the sediment discharge of streams in the Cache Creek drainage basin is a major aim of this investigation. Before treating the basic sediment data and their interpretation, however, it is pertinent to consider some of the problems that arise in the sampling of sediment in streams and the computation of records. In the section which follows below, problems associated with the estimation of total sediment discharge are omitted; these will be discussed in the section of this report entitled "Total Sediment Discharge."

PROBLEMS OF SAMPLING AND COMPUTATION

The sampling of streams and computation of data were accomplished in conformance with standard procedures of the U.S. Geological Survey. Suspended sediment was sampled with the U.S. D–49 sampler, or "fish" as it is commonly designated, at all but low flows. A 3/16-inch-diameter nozzle was used with this sampler. Low flows were sampled using the U.S. DH–48 hand sampler equipped with a 1/4-inch-diameter nozzle. In both types of sampling, the first question that arises is whether any particles of greater diameter than the nozzles were in suspension at the time of sampling. If this occurred then such particles were unmeasured, thus producing an erroneous determination of the size distribution and the concentration of suspended sediment. Although it is thought to be unlikely, the occurrence of such particles in suspension is possible and this source of error should be recognized.

The D–49 sampler is so designed that the entrance velocity of the water-sediment mixture is equal to the instantaneous velocity of flow. Because velocity of flow varies with time and is a function of depth, determination of the true sediment concentration in a given volume of water within a vertical section of the stream is not possible. Also, because the velocity-depth relation may vary somewhat among different streams, the reported concentrations, which are weighted according to discharge, are not strictly comparable.

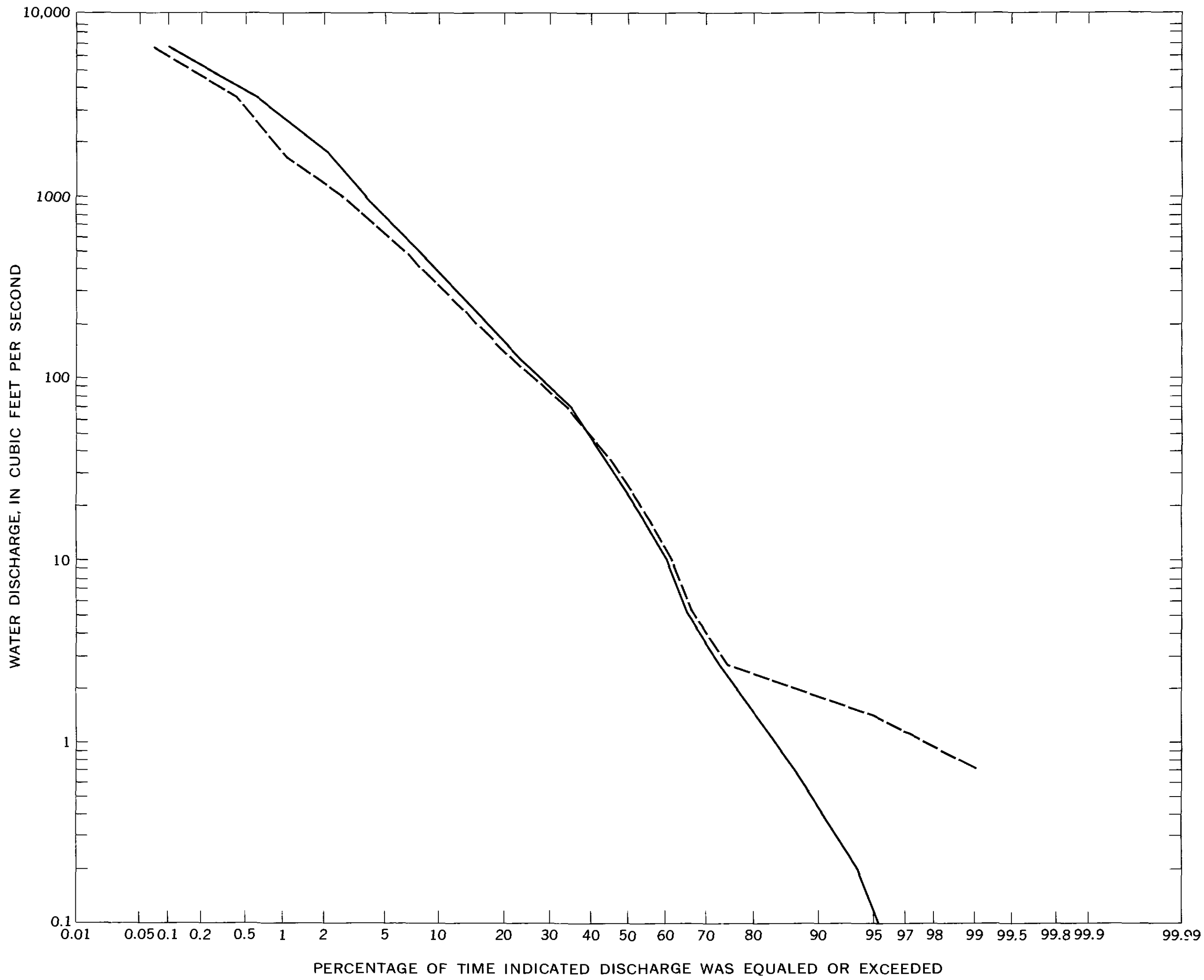

FIGURE 13.—Flow-duration curves of North Fork Cache Creek. The dashed curve represents the 1960–63 period: the unbroken curve represents the long-term period of record (1931–63). The fact that the curves intersect at a water discharge of 40 cfs indicates that greater water-discharge values occurred more frequently during the long-term period of record than during the 1960–63 period, and lesser values occurred more frequently during the 1960–63 period than during the long-term period of record.

The problem is compounded because the reported suspended-sediment concentration at a given cross section is derived from the concentrations measured at several vertical sections. In the Cache Creek drainage basin, the number of verticals where sediment-discharge measurements were made of streams ranged from three to nine, and depended on the stage at the time of sampling. Changes in bed form, bed roughness, and turbulence with stage, however, render any choice of the number of vertical sections that are required somewhat arbitrary. The basic problem is that the absolute concentration, whether weighted for discharge or not, is never known; and the degree of accuracy of the usual sampling procedures cannot, therefore, be stated with certainty.

If, however, the sediment-concentration measurements at a given cross section are assumed to be highly reliable, then a problem of extrapolation of these results arises. In most investigations of sediment transport, including the present study, the goal is to determine the sediment-transport characteristics of streams that are many miles in length. Information gained at a cross section must therefore be extrapolated to a reach, and the reach, in turn, must be representative of many miles of that stream. Such extrapolation assumes that the principle of continuity prevails during the period of sampling or record.

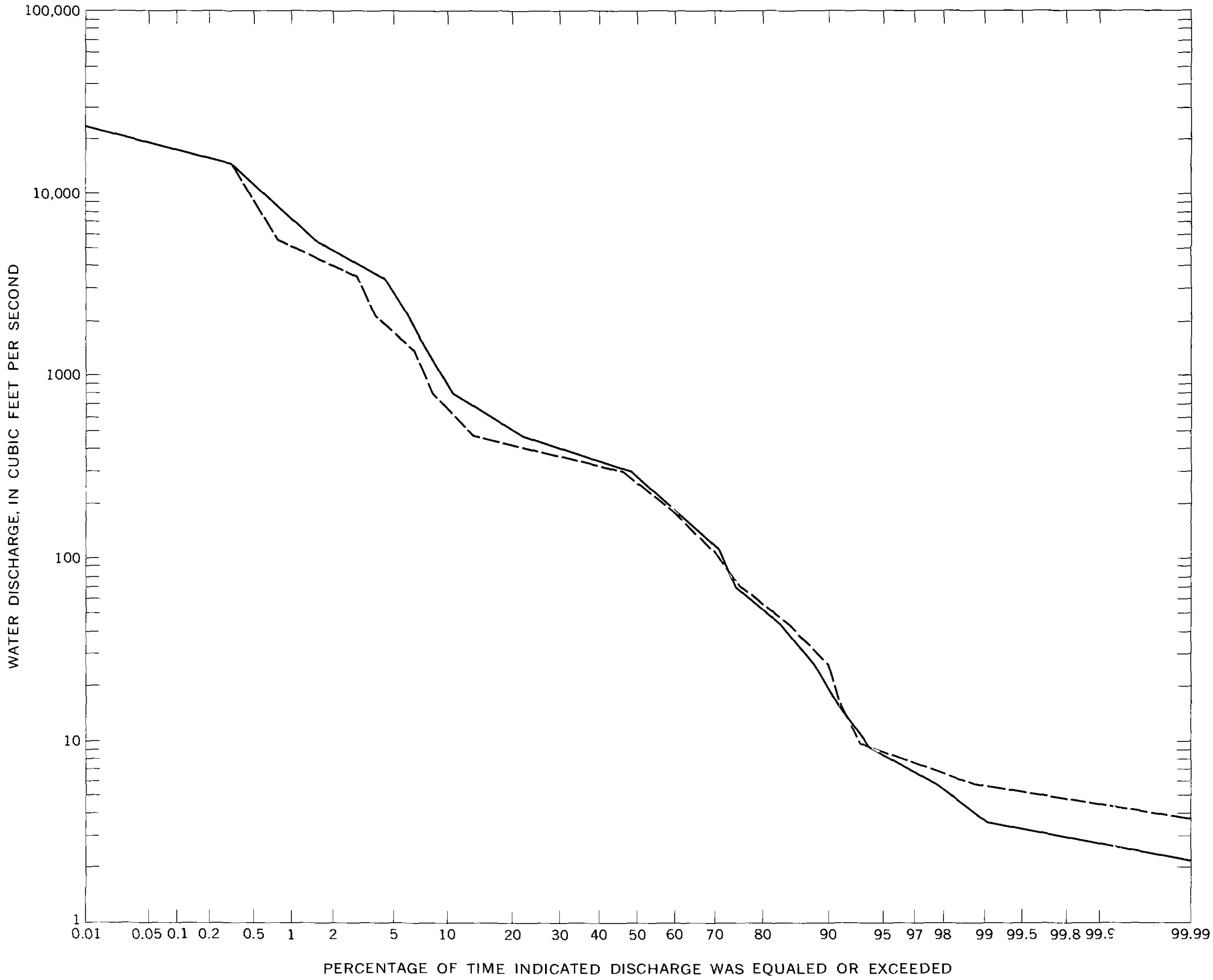

FIGURE 14.—Flow-duration curves of Cache Creek near Capay. The dashed curve represents the 1960–63 period; the unbroken curve represents the long-term period of record (1943–63). Note that water-discharge values greater than approximately 80 cfs occurred more frequently during the long-term period of record than during the 1960–63 period and that lesser water-discharge values generally occurred with greater frequency during the 1960–63 period.

Continuity, as applied here, means that for each unit of sediment that enters a stream above a given station, an equal unit, not necessarily the same one, must pass the station and be discharged in a downstream direction. A given unit of sediment, however, may at different times be derived from hill-slope erosion in headwater reaches of the basin, from stream terraces, from bank caving, or from erosion of the bed and banks of the channel. Because of the diversity of the possible sources of sediment, changes in channel morphology above and below a given station may occur. The principle of continuity clearly must prevail over the long term. During a 4- or 5-year sampling program, however, it is quite possible that the vagaries of local erosion and aggradation within the channel may cast doubt on the extrapolation of data from a given cross section.

A major problem in sampling sediment in streams is depth limitation. The suspended-sediment sampler is so constructed that samples cannot be obtained within approximately 0.4 foot of the water-sediment interface.

The quantity of suspended sediment in this region can be computed, in part, from the general relation of the suspended sediment distribution with depth, namely

$$cw = -k\frac{dc}{dy},$$

where

c = local concentration,
w = fall velocity,
k = a factor that involves the eddy-viscosity coefficient, and
y = depth.

Upon integration, an expression can be obtained that relates the concentration of sediment of a given size range at any depth to the concentration at known depths. Some fraction of the sediment that is in saltation or suspension within 0.4 foot of the bottom must

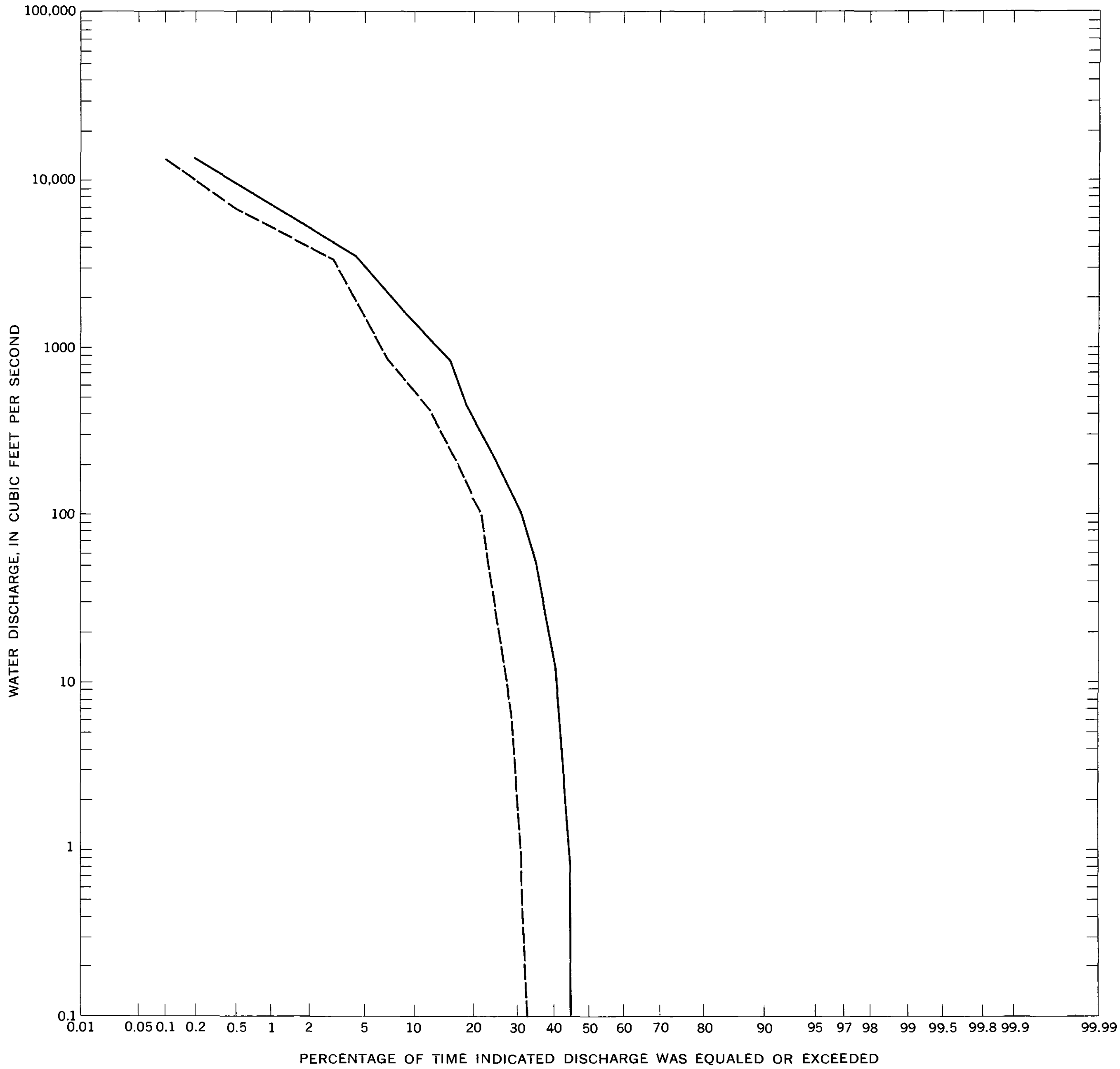

FIGURE 15.—Flow-duration curves of Cache Creek at Yolo. The dashed curve represents the 1960–63 period; the unbroken curve represents the long-term period of record (1904–63). Flows of any given water discharge occurred more frequently during the long-term period of record than during the 1960–63 period.

still be assigned, however, to that portion of the total sediment discharge that is transported as bedload. This fraction may be small or large, but whether or not it is negligible depends upon the particular characteristics of a given stream and its sediment load. This element of uncertainty in the sampling of the suspended-sediment load in its entirety affects the determination of both the suspended-sediment and the bedload discharge.

The fact that the fall velocities of particles are significant in sediment transport leads to still another possibility of error. When suspended-sediment samples are analyzed, a dispersing agent is commonly added before pipet determinations of particle-size distribution are made. The arbitrary size classes established for sediment analysis are not entirely applicable to stream transport evaluation, however, because the sediment in the stream moves according to hydraulic principles. The percentage of clay in a sample analyzed after addition of a dispersing agent may not be a true indication of the actual percentage of particles of clay size that are transported by the stream. Clay that is in transport in the flocculated state is hydraulically equivalent to silt and, perhaps, even to sand. This possible source of error in the determination of particle-size dis'ribution is difficult to avoid. It can seriously affect the results of any sediment investigation.

In the computation of sediment discharge, problems of interpretation frequently arise. Some of the possible circumstances are the following:

1. Malfunction of a stream recorder will produce gaps in the hydrograph.
2. Certain runoff events may, in part, be produced by the controlled release of water upstream. This will complicate the interpretation of water-sediment relations.
3. Gage-height readings may be unavailable for all runoff events, and missing water-discharge values must then be estimated.
4. Multiple-peak events complicate the water-sediment relationship; increases in water discharge after the initial rise may not carry increased quantities of sediment because much of the available sediment has already been transported.
5. Sediment samples may be available for rising or falling stages but not for the peak of a given runoff event. Interpretation and estimation are then re-

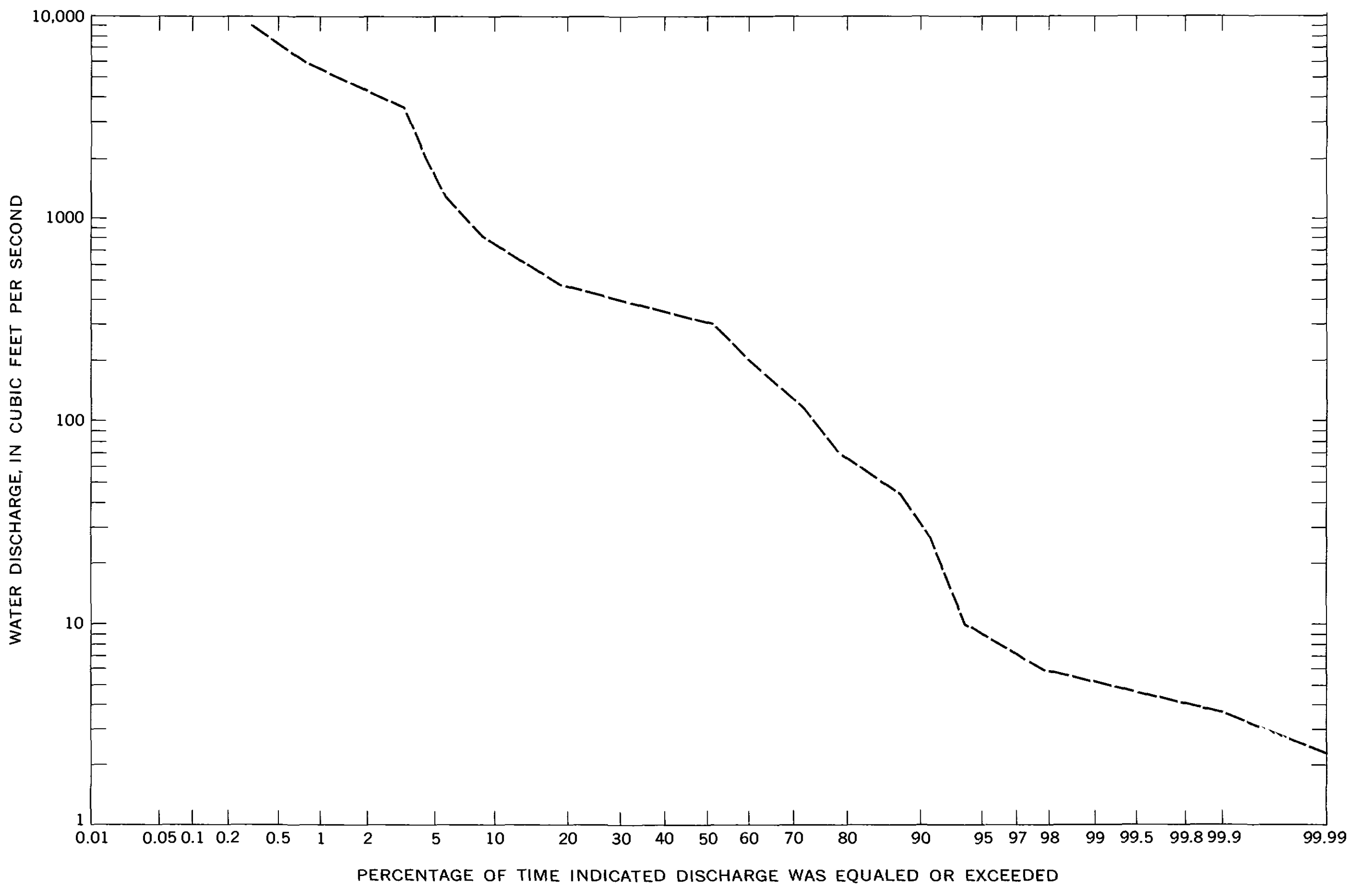

FIGURE 16.—Flow-duration curve for Cache Creek above Rumsey, 1960–63.

quired for determination of water-sediment relations.

6. The available instantaneous values for water and sediment discharge may not adequately approximate daily mean values. This will greatly complicate the computation of total sediment discharge, and in certain circumstances will effectively prevent computation.

The problems that are inherent in both sampling and analytical procedures do not invalidate the results of this report. As previously stated, the sampling and computation in this investigation conform to the standards of the U.S. Geological Survey, and the results are, accordingly, the best that can be obtained at present. The problems mentioned are common to nearly all sediment investigations, and the sound consideration of any set of data requires awareness of the possible sources of error.

SUSPENDED-SEDIMENT DISCHARGE

The sediment stations on streams within the Cache Creek drainage basin (pl. 1) are well distributed for the detection of differences in sediment-transport characteristics. As previously stated, the streams of the drainage net flow through a basin that varies in geologic, topographic, and climatic conditions. Conceivably, these variations might be reflected by corresponding variation of the suspended-sediment discharge of the streams. The correspondence is in fact demonstrated by the size distribution of suspended sediment, the sediment-transport and sediment-duration curve, and the suspended-sediment discharge at each station. These data, for the 1960–63 period, are discussed below.

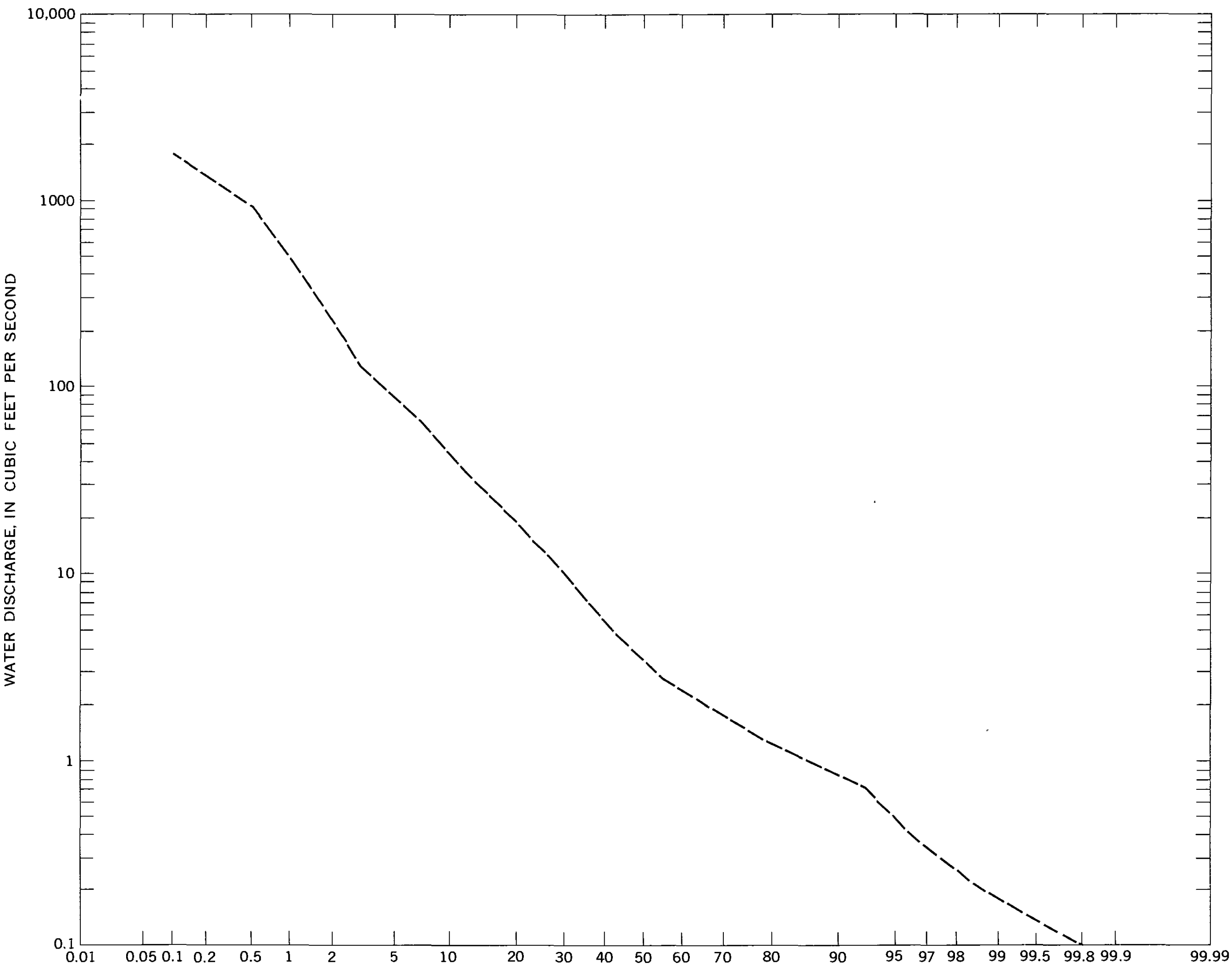

FIGURE 17.—Flow-duration curve for Bear Creek, 1960–63.

The mean particle-size distribution of suspended sediment at stations on North Fork Cache Creek, on Bear Creek, and on Cache Creek above Rumsey, near Capay, and at Yolo (pl. 1) is shown in figure 18. The size distribution of sediment that passes through the settling basin below Yolo is also shown.

Although the size distribution curves are similar, they are reasonably distinct. The data show that, in general, a larger percentage of fine sediment is in suspension in Cache Creek near Capay and at Yolo than above Rumsey or on North Fork Cache Creek. At the first two stations, for example, Cache Creek transports only 13–16 percent sand-size particles in suspension, whereas above Rumsey and on North Fork Cache Creek, 22–33 percent of the sediment in suspension is in this size range. This distinction reflects the fact that coarser sediment makes up a greater percentage of the available supply in the upper part of the basin. The data from Bear Creek belie this as a general rule, however. Bear Creek transports only 17 percent sand-size particles as suspended sediment, despite the fact that it traverses the upper part of the basin. The difference is partly explained by the fact that water discharge is lower and that much of the available sediment in the Bear Creek valley, as previously noted (fig. 4), may be too coarse for transportation under present conditions.

The size distribution of suspended sediment at the weir of the settling basin below Yolo will be described in a later discussion of deposition of sediment in the settling basin. It can be seen, however, from the size-distribution curve shown in figure 18, that virtually all sediment transported in suspension through the area is in the silt-clay size range.

Sediment-transport curves for the five sediment stations discussed above are shown in figure 19. These curves demonstrate the relation between daily mean sediment discharge and water discharge, and the regression equation for each curve is a least-squares fit of the data. The data used to compute the regression equations include only the actual measurements of water and

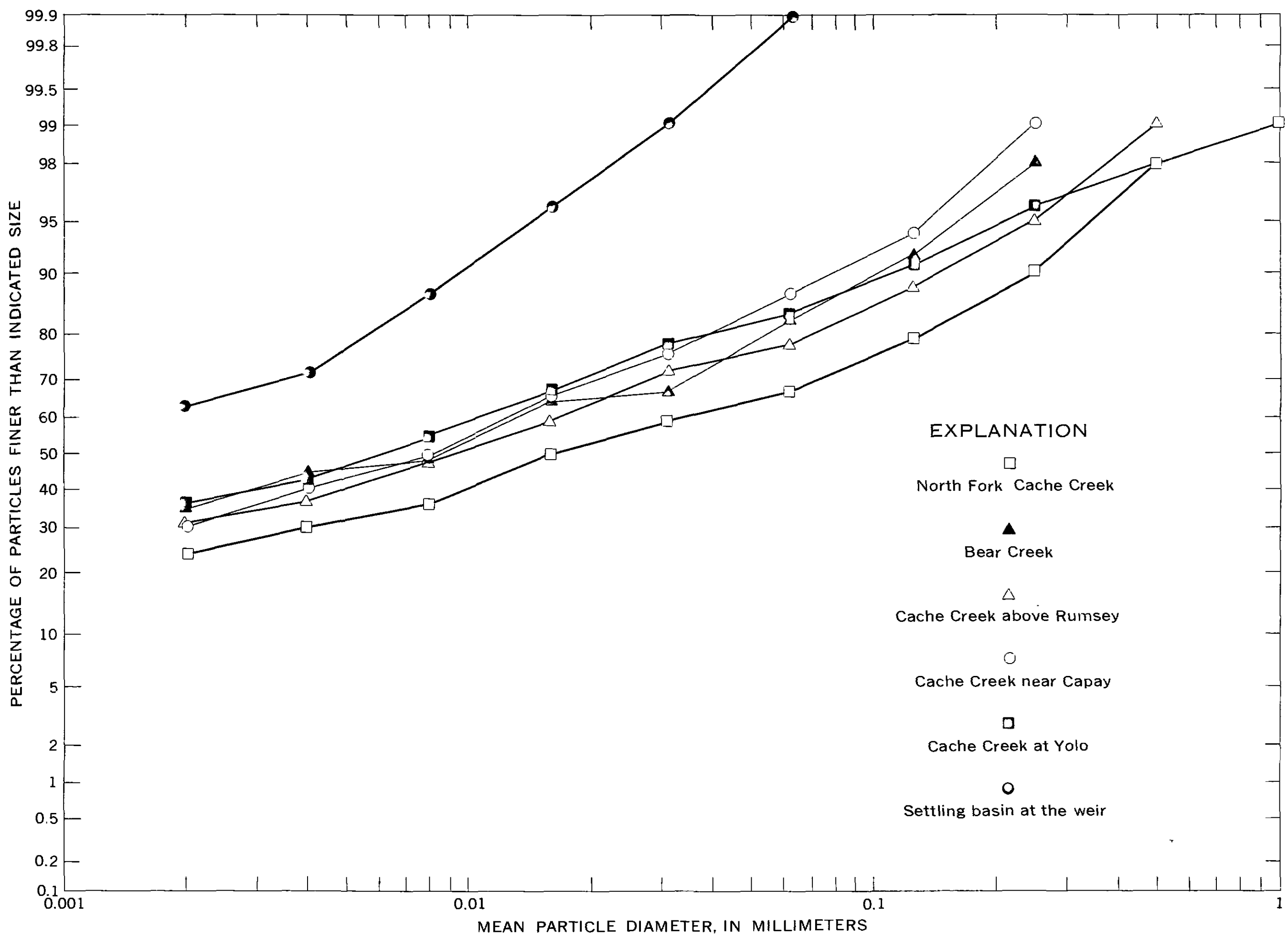

FIGURE 18.—Size-distribution curves of suspended sediment in streams of the Cache Creek drainage basin and from the settling basin at the weir.

sediment discharge during the 1960–63 period. Estimated values were omitted because such values must be derived from the actual sample data and hence should not be allowed to affect the relationship determined. The curves are based upon 82 samples from North Fork Cache Creek, 60 samples from Bear Creek, 646 samples from Cache Creek above Rumsey, 38 samples from Cache Creek near Capay, and 470 samples from Cache Creek at Yolo, and the respective water-discharge values.

Sediment-transport data commonly do not plot as a single straight line on logarithmic paper. Mathematically, this would suggest that water and sediment discharge are related by some function other than a power function, or perhaps are not related at all. Experience has shown, however, that sediment-transport data do plot as straight lines on such paper within a given range of discharge values; that is, the relation at both high and low discharge values is that of a power function, but the rate of increase of sediment discharge with water discharge, or the slope of the curve, is different for these high and low values. Accordingly, there are three approved ways of presenting sediment-transport data: (1) as a scatter diagram, (2) as a graph of two straight lines of different slope, or (3) as shown in figure 19, a simple least-squares fit of the discharge data. The last method was chosen for this report because neither the scatter of the plotted data nor an apparent break in slope at low discharge values is excessive, and because the essential purpose of inclusion of the data is to demonstrate the gross distinctions in sediment-transport characteristics among the streams.

It is clear from the data that the five sediment stations, each of which is assumed to be representative of many miles of streambed, can be placed in three separate categories. This classification is based on the regression equations, particularly the exponent of water discharge. As shown on the curves (fig. 19), this exponent is approximately 1.8 and 1.9 for Bear Creek and North Fork Cache Creek, respectively, whereas it ranges from about 2.0 to 2.5 for Cache Creek at the Rumsey and Capay stations. That is, although sediment discharge increases with an increase in water discharge at each of the four stations, the rate of increase of sediment discharge is considerably greater near the Rumsey and Capay stations. This difference reflects the fact that the Bear Creek and North Fork stations are nearer to the headwaters of the Cache Creek drainage basin. Both the smaller drainage area above these stations and the greater percentage of stream reaches in rocky terrain mitigate against a great increase in suspended-sediment discharge with increased water discharge. Moreover, the mean annual water discharge of perennial streams is always greater in the lower or downstream part of a given drainage basin because of an increase in drainage area and a concomitant increase in the number of stream tributaries.

On the basis of the data just given and the assumption that the effects of other factors are equal, the rate of increase of suspended-sediment discharge with an increase in water discharge should be greater at the Yolo station than near the Rumsey and Capay stations, which are farther upstream (pl. 1). The sediment-transport curve for Cache Creek at the Yolo station, however, shows that the effects of other factors are apparently unequal (fig. 19). The exponent of water discharge in the regression equation is approximately 1.5; that is, at this lowermost station in the drainage basin, the rate of increase of suspended-sediment discharge with water discharge, is lowest rather than highest. The reason for this seeming anomaly is the diversion of the surface water of Cache Creek above Yolo, at Capay, as previously mentioned. A series of small dams there have a twofold effect on the sediment-transport characteristics of Cache Creek at Yolo. First, these barriers promote sediment deposition above Capay; and second, the periodic, controlled release of water from Capay to a large network of canals and sloughs, some of which are shown on plate 1, causes additional sediment to be diverted from its natural path to Yolo. The effect of these various works of man is to reduce not only the rate of increase of suspended-sediment discharge with water discharge at Yolo from the normal value, but also the absolute value of the suspended-sediment discharge; it will be shown later in this report that the total annual tonnage of suspended sediment passing the Yolo station is actually less than that passing the station near Capay.

Summary.—The sediment-transport data show that the rate of increase of suspended-sediment discharge with an increase in water discharge rises downstream. This rise would normally be greatest at Yolo, near the drainage outlet for the basin, but the artificial barriers at Capay have reduced this value to the lowest in the drainage basin.

This difference in sediment-transport characteristics among streams in the Cache Creek drainage basin is also borne out by sediment-duration data. The sediment-duration curves for stations on North Fork Cache Creek, Bear Creek, and Cache Creek above Rumsey, near Capay, and at Yolo are shown in figures 20–24, respectively. These curves are similar to flow-duration curves in that they show the frequency with which a given suspended-sediment discharge is either equaled or exceeded.

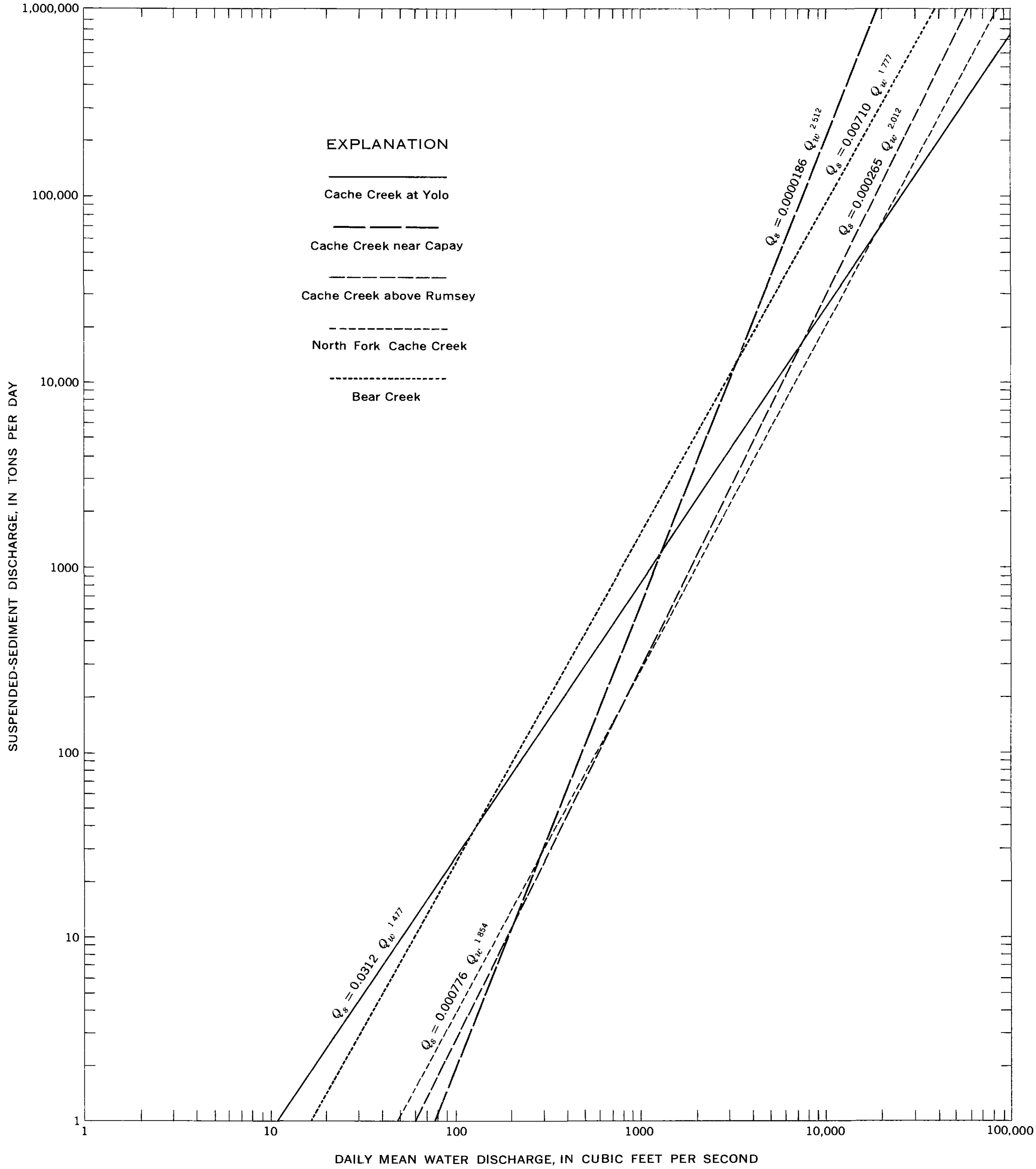

FIGURE 19.—Sediment-transport curves of streams in the Cache Creek drainage basin, 1960–63 period. The curves are least-squares regression lines of the sample data. Note that the rate of increase of suspended-sediment discharge with an increase in water discharge is greater for Cache Creek above Rumsey and near Capay than for North Fork Cache Creek and Bear Creek; the rate of increase is least for Cache Creek at Yolo.

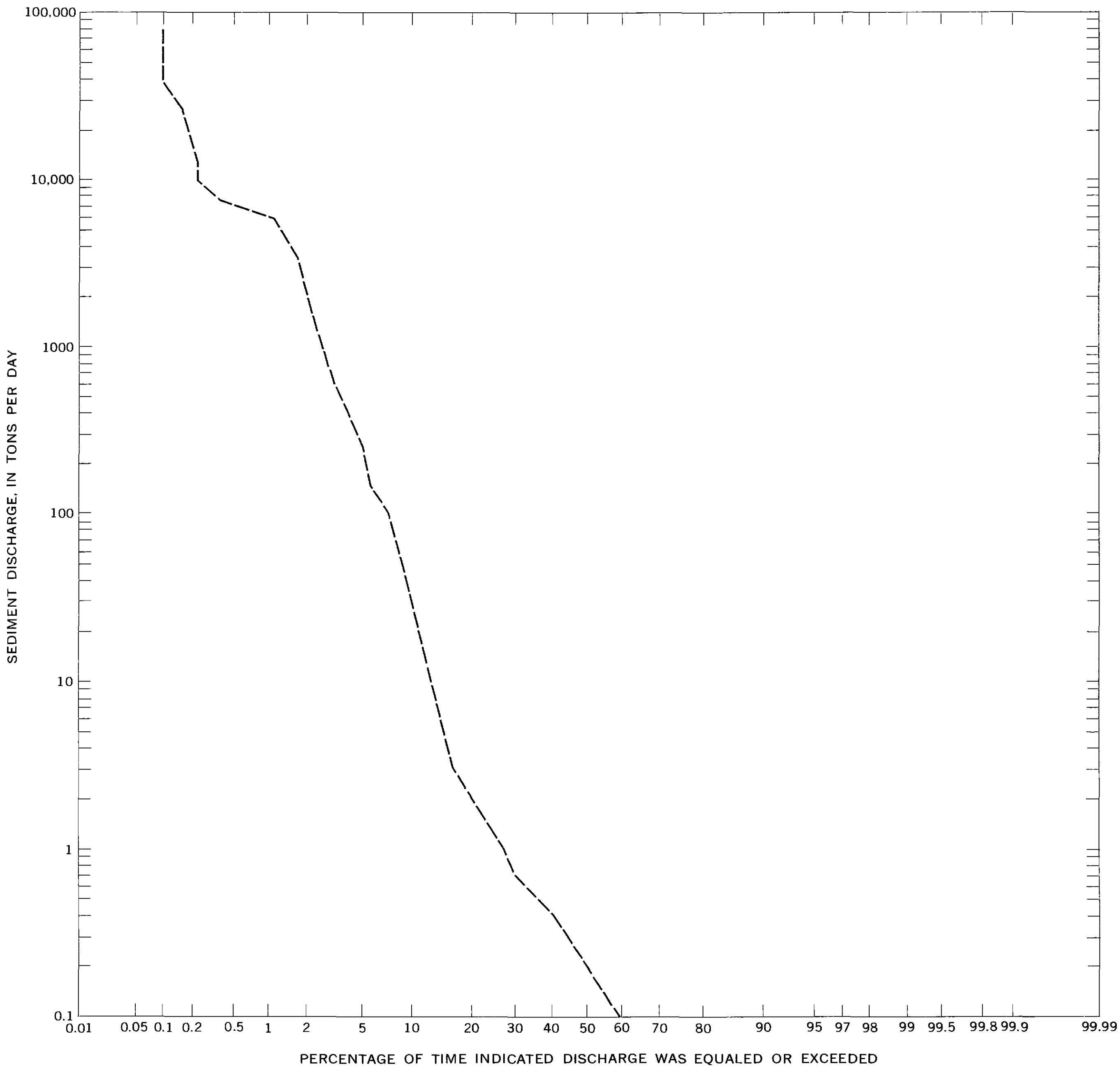

FIGURE 20.—Sediment-duration curve of North Fork Cache Creek, 1960–63.

These data clearly indicate that the same classification of stations pertains. North Fork Cache Creek and Bear Creek show similar sediment-transport characteristics, which are distinctly different, however, from those of a second pair of stations, namely Cache Creek above Rumsey and near Capay. A suspended-sediment discharge of 1,000 tons per day, for example, is equaled or exceeded about 2 percent of the time at the uppermost pair of stations and 7 percent of the time at the stations on Cache Creek above Rumsey and near Capay, which are farther downstream. At a suspended-sediment discharge rate of 10,000 tons per day, the respective frequency values are approximately 0.4 and 3.0 percent.

The effects of artificial conditions again are evident from a comparison of the sediment-duration data for Cache Creek near Capay (fig. 23) and at Yolo (fig. 24). For any given value of suspended-sediment discharge, the frequency of occurrence is greater at Capay than at Yolo, whereas under natural conditions the reverse would be true. A second example of departure from sediment-transport characteristics that would be expected under pristine conditions is afforded by the marked breaks in the slope of the duration curves for Cache Creek above Rumsey (fig. 22) and near Capay (fig. 23). These breaks result from the controlled release of water from Clear Lake (pl. 1). This water flow periodically removes much of the available sediment that would normally be transported in suspension from the upstream rocky channel, thus reducing the concentration of suspended sediment in subsequent natural runoff events

Finally, the absolute magnitude of the suspended-sediment discharge during the 1960–63 period suggests differences in sediment-transport characteristics at these stations, in the effects of man, and in certain geologic controls. The estimated magnitude of the suspended-sediment yield for each of the 4 years of observation is shown in table 2. Also listed is the drainage area above each station. The total suspended-sediment-yield data

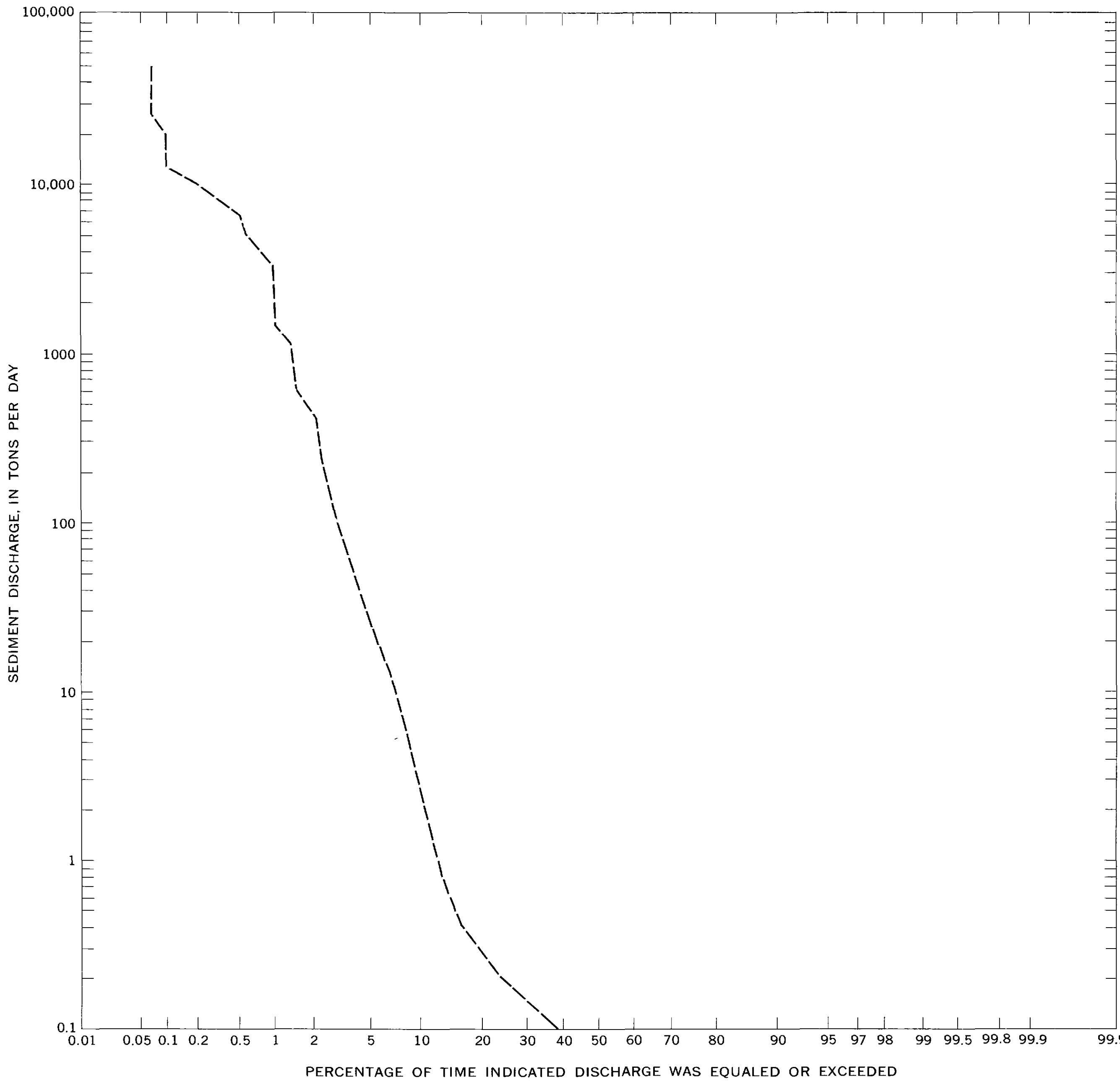

FIGURE 21.—Sediment-duration curve of Bear Creek, 1960–63.

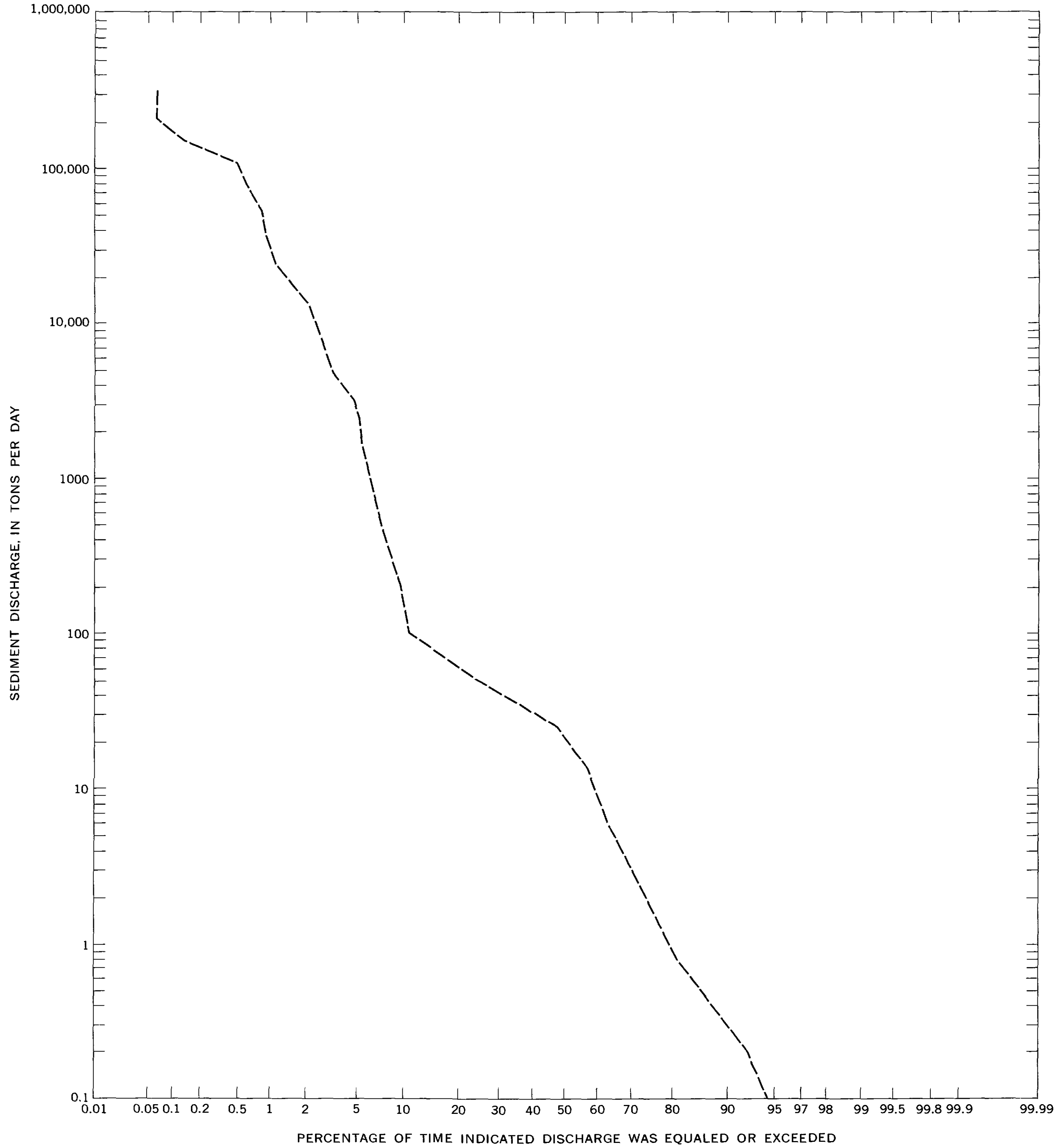

FIGURE 22.—Sediment-duration curve of Cache Creek above Rumsey, 1960–63.

show, once again, that although the yield of North Fork Cache Creek is greater than that of Bear Creek, these upstream stations exhibit similar transport characterics if differences in drainage area are considered. The sediment yield increases markedly downstream and the 2- to 3-million-ton sediment yield at the Rumsey and Capay stations clearly distinguishes this pair from the upstream stations. As previously noted, the sediment yield between Capay and Yolo decreases by more than 1 million tons for the 4-year period. This decrease may be attributed to artificial controls; most of it must be the result of deposition above the controls at Capay, but some fraction of the total amount of sediment is probably transported into the distributary network of canals and sloughs in the lower part of the basin. Part of this decrease may also result from deposition below Capay and subsequent removal of some of the sediment through gravel quarrying for commercial purposes.

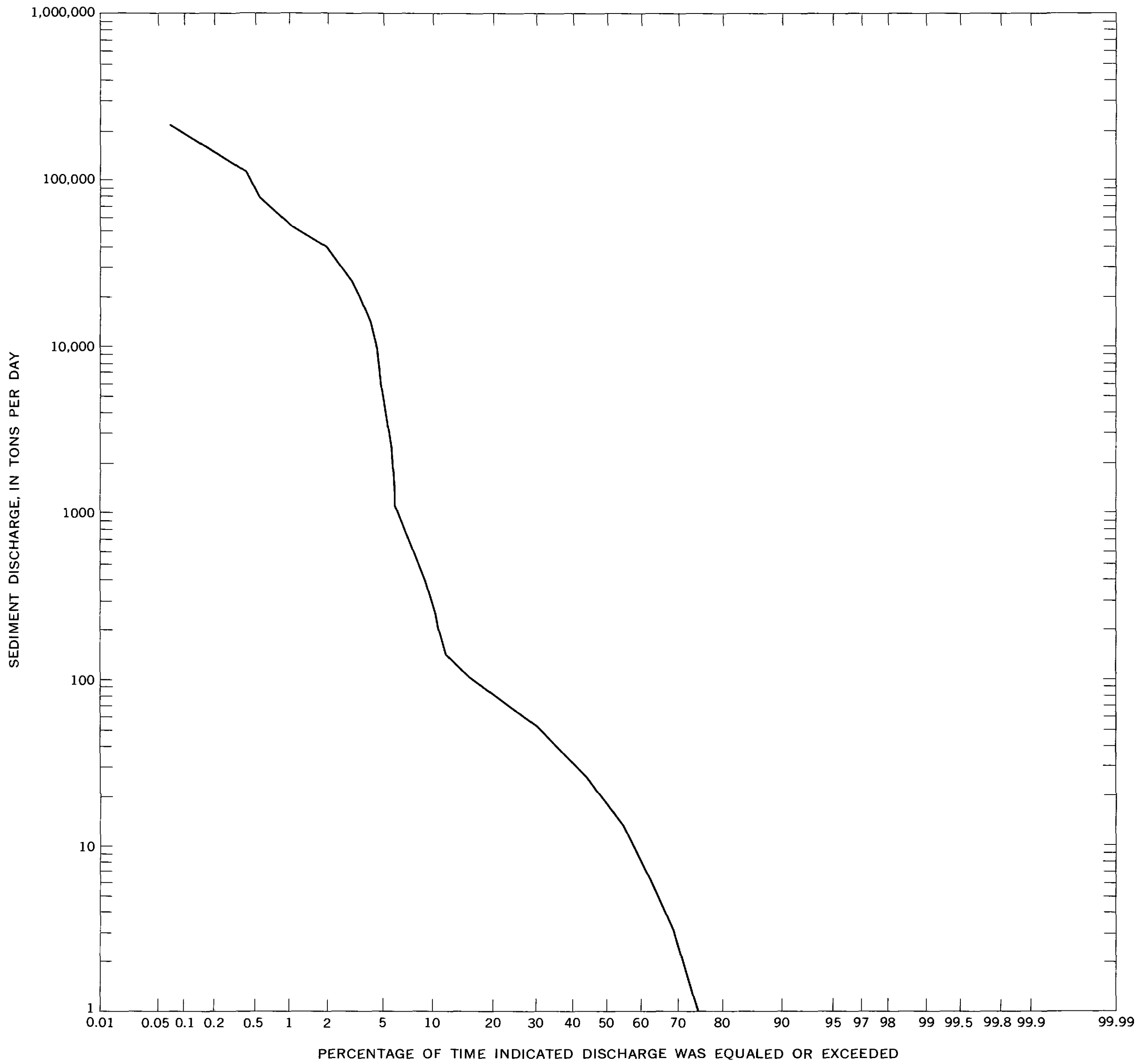

Figure 23.—Sediment-duration curve of Cache Creek near Capay, 1960–63.

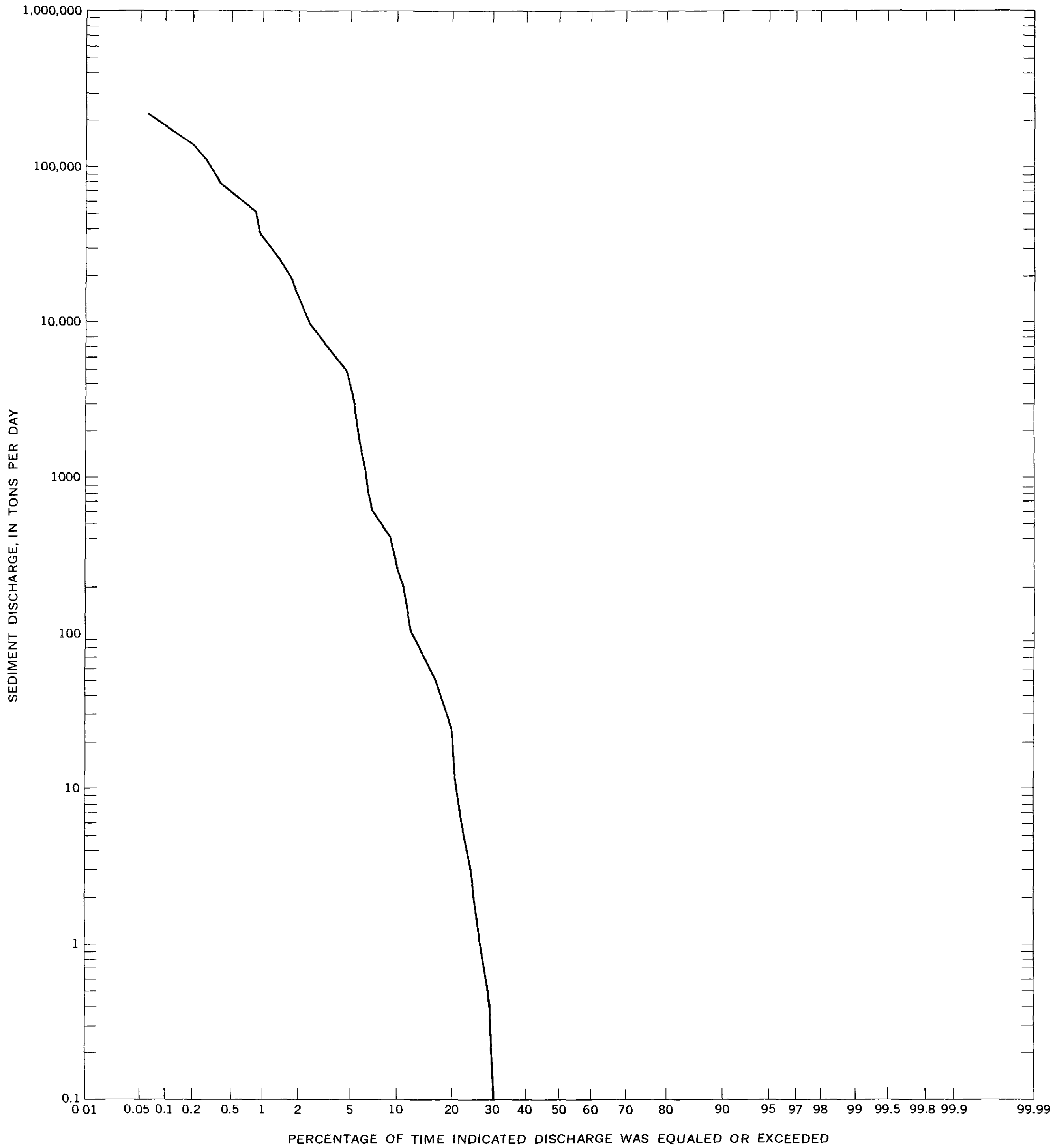

FIGURE 24.—Sediment-duration curve of Cache Creek at Yolo, 1960–63.

TABLE 2.—*Annual suspended-sediment yield, in tons, at sediment stations in the Cache Creek drainage basin*

[Contributory drainage area above each station is given in parentheses]

Water year	North Fork Cache Creek (198 sq mi)	Bear Creek (96.8 sq mi)	Cache Creek above Rumsey (954 sq mi)[1]	Cache Creek near Capay (1,052 sq mi)	Cache Creek at Yolo (1,137 sq mi)
1960	140, 885	17, 550	284, 090	363, 911	260, 446
1961	16, 868	6, 388	148, 517	85, 692	84, 263
1962	110, 960	54, 236	653, 999	791, 575	652, 052
1963	207, 958	97, 957	1, 174, 218	2, 078, 905	1, 134, 971
Total	476, 700	174, 800	2, 261, 000	3, 320, 000	2, 132, 000

[1] Includes the Clear Lake drainage area (528 sq mi), which contributes sediment to the lake proper. The effective drainage area above this station is 426 square miles.

The data in table 2 clearly indicate the effects of geologic conditions. The sediment yield of Cache Creek near Capay exceeded that of Cache Creek above Rumsey by 1,059,000 tons during the period of observation. The approximate difference in drainage area above each station, however, is only 98 square miles. If the area that is tributary to Clear Lake (pl. 1), which contributes sediment that accumulates in the lake, is subtracted from the area above the Rumsey station, the data indicate that an effective drainage area of 426 square miles above the Rumsey station produced 2,261,000 tons of sediment during 1960–63 whereas the 98 square miles between the Capay and Rumsey stations contributed 1,059,000 tons. That is, the area between the stations contributed 2.04 times as much suspended sediment as might be predicted from drainage area alone. This difference in sediment yield per square mile may be attributable to the more highly erodible units that crop out in the valley above Capay, particularly the Pliocene and Pleistocene deposits in which many areas of badlands (fig. 2, 7) occur. This area of high sediment yield is a significant element in the choice of suitable locations for reservoirs in the basin; a structure above Rumsey, for example, would not reduce the annual sediment yield at Yolo by an amount that would be predicted on the basis of the drainage-area reduction.

TOTAL SEDIMENT DISCHARGE

The total sediment discharge of a stream may be defined as the sum of the sediment transported in suspension and the sediment transported as bedload during a given time interval. In accordance with this definition, the bedload discharge discussed in this report represents the difference between total sediment discharge and the observed suspended-sediment discharge. In this broad usage, bedload discharge includes that fraction of sediment near the streambed which is in suspension but is not sampled, as well as that fraction of sediment which is transported solely by traction.

Although the determination of total sediment discharge seems only to require that suspended-sediment and bedload discharges be observed at a given station and added, it is a complex problem. Because the bedload discharge of a given stream cannot be sampled and measured using present instruments, total sediment discharge must be determined by indirect methods.

One such method was provided by Colby and Hembree in 1955. They modified the bedload function devised by Einstein (1950) for computation of total sediment discharge from observations at a cross section of a stream. These observations include the hydraulic geometry of the cross section, the concentration of suspended sediment, and the particle-size distribution of the suspended sediment and of the material in the streambed. The estimate of total sediment discharge obtained by use of the modified Einstein method is improved if there is an overlapping of the sizes of sedimentary particles in suspension and in bedload transport. Because the total sediment-discharge data given in this report are based upon the modified Einstein method, it should be noted that such overlapping of size classes did occur during each total load measurement.

The modified Einstein method is one of the best procedures available for the computation of total sediment discharge, and it has been proved valid for sand-bed streams. Its applicability to streams that flow in sand and gravel channels, such as Cache Creek, remains somewhat uncertain, however. Another method might have been used, but one of the fundamental problems in sediment-transport studies is that the predictive efficiency of any total-sediment-discharge method cannot be ascertained unless the true bedload discharge of a given stream is known. And it is precisely this value which cannot be determined routinely with present instrumentation. Hence, one cannot determine which of several procedures provides the "best" answer.

Seven measurements of the total sediment discharge were obtained at the Yolo sampling station (pl. 1) between January 1959 and January 1964 (table 3). A wide range of instantaneous water-discharge values is represented, and this range should be sufficient to define the instantaneous water-sediment relations of Cache Creek at Yolo.

Instantaneous water discharge and total sediment discharge are related by the power function $Q_s = 0.00189\ Q_w^{1.981}$, as demonstrated by the graph in figure 25. Total sediment discharge, therefore, increases rapidly with an increase in water discharge, but figure 26 shows that this is accompanied by a decrease in the percentage of the total discharge that represents bedload discharge. As previously noted, bedload discharge is here considered as the difference between the total sediment discharge and the suspended-sediment discharge. Although the absolute quantity of sediment in the bedload fraction does not decrease (table 3), it represents a smaller percentage of the total sediment discharge, because suspended sediment makes up the bulk of the total load at high water-discharge values.

TABLE 3.—*Total sediment-discharge data from Cache Creek at the Yolo sediment station, for selected dates*

[Bedload discharge is determined by subtracting suspended-sediment discharge from total sediment discharge]

Date	Instantaneous water discharge (cfs)	Mean velocity (ft per sec)	Suspended sediment load (tons per day)	Bedload (tons per day)	Total sediment load (tons per day)
1959					
Jan. 15	276	1.96	118	58	176
Feb. 16	12,800	6.18	272,700	6,900	279,600
17	6,000	5.07	65,100	2,130	67,230
Mar. 18	109	1.65	3.5	18	22
1960					
Feb. 3	748	2.64	1,290	257	1,550
9	7,540	5.31	62,700	5,310	68,010
1964					
Jan. 28	396	2.54	96	24	120

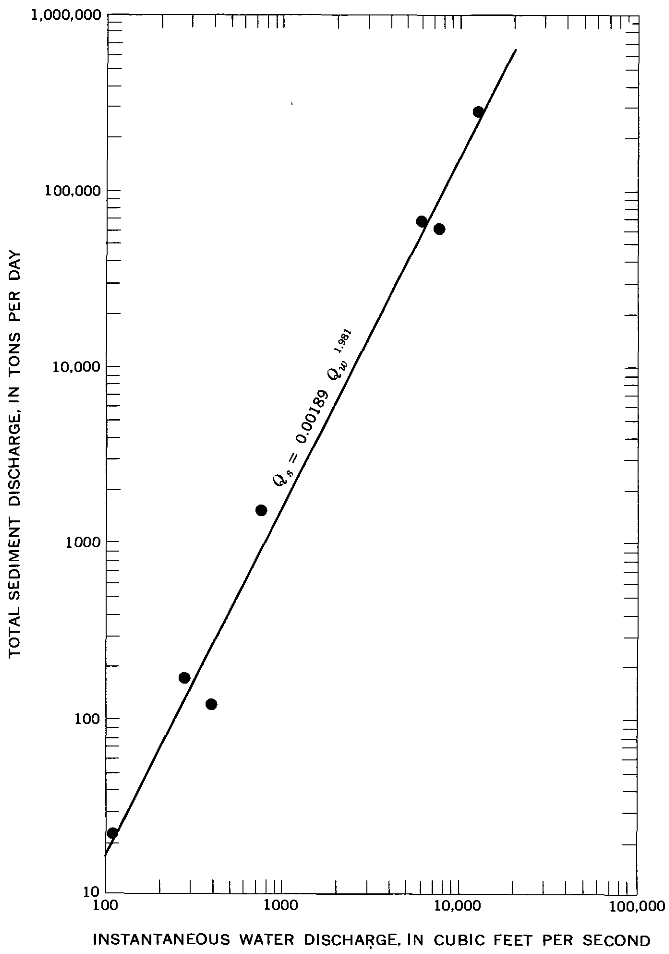

FIGURE 25.—Relation of total sediment discharge and instantaneous water discharge.

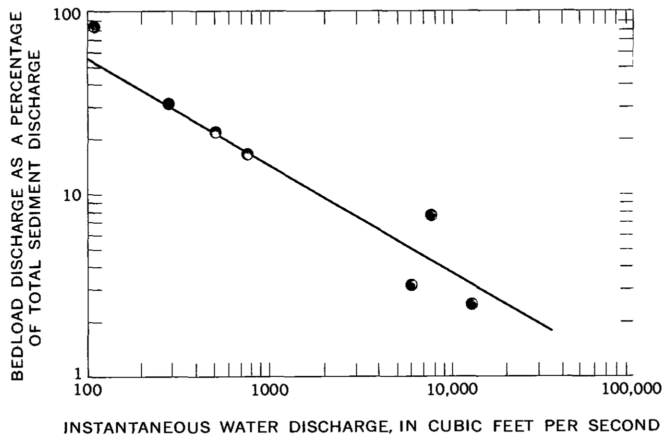

FIGURE 26.—Relation of bedload discharge, as a percentage of total sediment discharge, and instantaneous water discharge.

The data in table 3 also indicate that a relation exists between bedload discharge and the mean velocity of flow. The graph in figure 27 shows that these variables are also related by a power function. Bedload discharge may be expected to increase with an increase in velocity of flow, because as the mean velocity increases, the velocity at the streambed surface also increases, and consequently there is additional bedload transport. Moreover, the fact that water discharge is related to sediment discharge implies that a relation must exist between velocity and bedload. Because the width and elevation of the streambed are fairly stable at the sediment station, velocity tends to increase with water discharge.

The data discussed thus far are pertinent only to the dates and times of measurement of the total sediment discharge at Yolo. The water-discharge values given in table 3 and plotted in figures 25 and 26, and also the mean velocity values, are instantaneous. That is, they are values for a specific time of measurement and may or may not approximate daily mean values.

If one assumes that instantaneous values do approximate daily mean values, then a simple method of computing the total sediment discharge for each year of record may be used. A graph of instantaneous water discharge and bedload discharge is given in figure 28. The least-squares regression equation for this relation is $Q_{bl}=0.0246\ Q_w^{1.334}$. If daily mean water-discharge values are substituted in this expression for each day of flow, and then cumulated, a value of total bedload discharge for a given year can be obtained. Addition to the annual suspended-sediment discharge for that year will provide the required total sediment discharge. This procedure was followed in computing the data given in table 4. The mean value of the bedload of

Cache Creek at Yolo, as a percentage of the total load, is 6.7 by this method.

TABLE 4.—*Annual sediment-discharge data from Cache Creek at the Yolo sediment station*

[Bedload values computed with the assumption that instantaneous water-discharge values approximate daily mean values]

Water year	Suspended-sediment load (tons)	Bedload (tons)	Total sediment load (tons)	Bedload (percent)
1960	260,400	14,130	274,500	5.1
1961	84,260	7,470	91,730	8.1
1962	652,100	37,620	689,700	5.5
1963	1,135,000	94,850	1,230,000	7.7
Total	2,132,000	154,100	2,286,000	
Mean				6.7

As previously noted, instantaneous water-discharge values may not approximate daily mean values. Analysis of the data for Cache Creek for 1959, for example, reveals that the instantaneous values are approximately 30 percent greater than the corresponding daily mean values of water discharge at high stages of flow, and are about 10 percent greater at low stages of flow. This suggests that the relation shown in figure 28 provides too low an estimate of the annual bedload discharge and, therefore, of the total sediment discharge. Accordingly, an alternate method of computation would seem desirable.

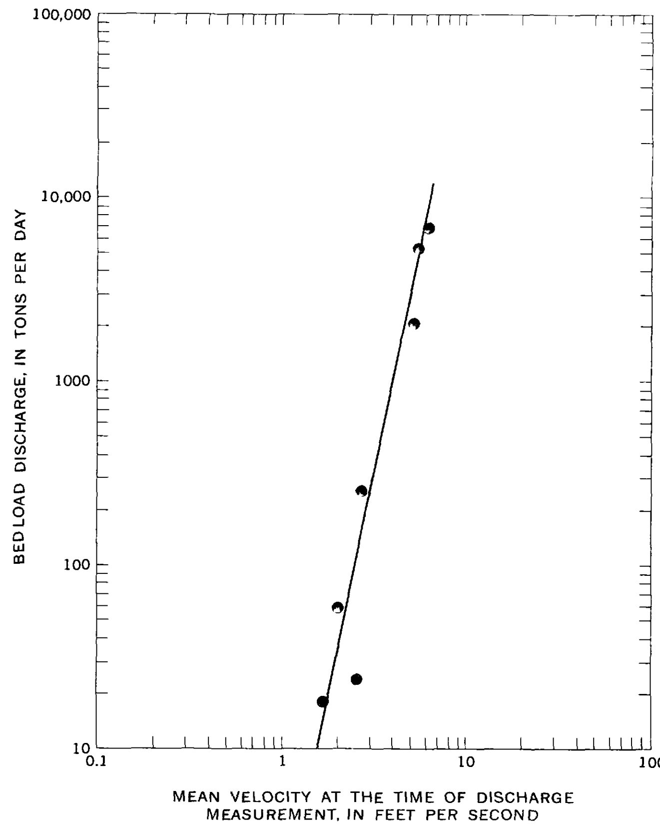

FIGURE 27.—Relation of bedload discharge and mean velocity of flow at the time of the water-discharge measurement.

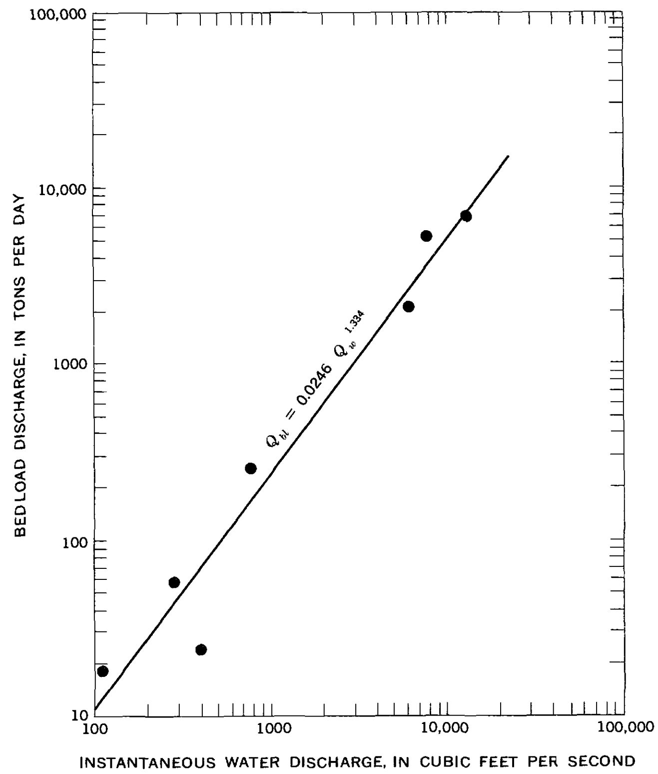

FIGURE 28.—Relation of bedload discharge and instantaneous water discharge.

The method used for this purpose is that of subdivision. This consists, principally, of (1) defining a bedload curve, for each day which has a wide range of water discharge, based on the water-sediment relations of the stream (fig. 28), (2) subdividing each day into a number of intervals, thus obtaining the bedload discharge during each interval, and (3) computing the total-sediment discharge by cumulation of the bedload during the intervals and adding this bedload to the suspended-sediment discharge for the day. The results of computing bedload by the subdivision method are given in table 5.

TABLE 5.—*Annual sediment-discharge data from Cache Creek at the Yolo sediment station*

[Bedload values computed by the method of subdivision]

Water year	Suspended-sediment load (tons)	Bedload (tons)	Total sediment load (tons)	Bedload (percent)
1960	260,400	14,720	275,100	5.4
1961	84,260	7,770	92,030	8.4
1962	652,100	38,400	690,500	5.6
1963	1,135,000	95,750	1,231,000	7.8
Total	2,132,000	156,600	2,289,000	
Mean				6.8

The additional correction because of subdivision is indicated on the plot shown in figure 29. These data show the differing values of bedload discharge that will be obtained, the difference depending upon the method of computation used. Specifically, it can be seen that the values obtained by the method of subdivision differ from the values obtained when subdivision is not employed. This is true because the slope of a line of best fit will depart slightly from 45°, which would indicate equality of bedload discharge values regardless of subdivision. The correction required by these data is approximately 2,500 tons for the 1960–63 period.

In the present instance, the adjustments described above produce a relatively minor change in the total sediment-discharge estimate. The total sediment load for the 1960–63 periods (table 4) increased by 2,500 tons (table 5), which represents a percentage increase of about 0.1 percent. The increase, of course, is due entirely to adjustment of bedload discharge values. Because the rate of increase of bedload discharge with an increase in water discharge is low, the initial approximation (table 4) appears sufficient for most purposes. If a given stream has a greater rate of increase of bedload discharge with an increase in water discharge than that indicated for Cache Creek, then adjustment by the method of subdivision will be required.

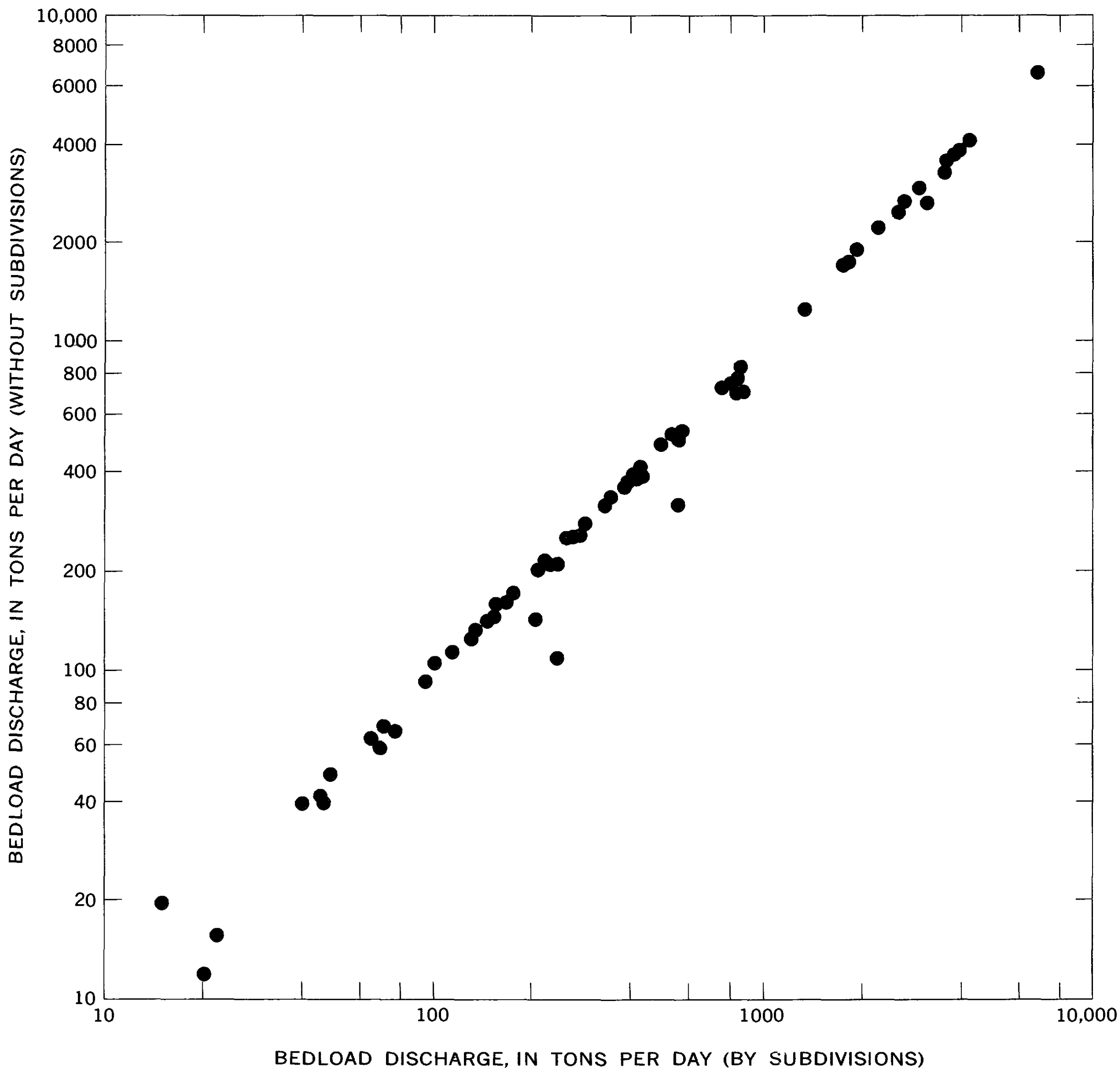

FIGURE 29.—Scatter diagram showing the differing values of bedload discharge that are obtained by the method of subdivision. These data pertain to Cache Creek at the Yolo sediment station for the 1960–63 period.

The several curves in figure 30 show the relation of various fractions of sediment discharge for Cache Creek at the Yolo station and also provide another simple, though less precise, method of determining the total sediment and bedload discharges listed in table 4. Curve 1 shows the relation of bedload discharge and water discharge, where bedload discharge is defined as the difference between total sediment discharge and suspended-sediment discharge. Curve 2 shows the relation of the mean suspended-sediment discharge for the 1960–63 period and water discharge. In this instance, the relation is plotted as two straight-line segments that differ in slope, because a precise rather than a gross relation is desired. The sum of curves 1 and 2 is curve 3, which represents the relation between the adjusted total sediment discharge and water discharge.

If curve 3 is used to compute total sediment discharge for the 1960–63 period by the flow duration method, the figure for total discharge of Cache Creek at Yolo as approximately 2,330,000 tons. If curve 2 is used to compute the bedload for the 1960–63 period, figure for the bedload discharge is 154,000 tons.

BED MATERIAL

The size limits of the bed material of a given stream can be variously defined, but any definition is dependent upon the flow regime at a given time. The lower size limit of material transported as bedload discharge is a function of the velocity of flow, the suspended-sediment discharge, and other factors. Hence, this lower size limit is variable through time.

For this report, some arbitrary lower limit must be chosen and therefore sedimentary particles coarser than 1.0 mm are here termed bed material. This size boundary is selected because material coarser than 1.0 mm was not found in the suspended-sediment samples obtained during the period of record. It is recognized, however, that at high velocities some particles of this size or larger may be in suspension, whereas at low velocities particles smaller than 1.0 mm may settle to the streambed or undergo transport by traction.

Size-distribution curves for the bed-material samples obtained from the streambed of Cache Creek at Yolo are given in figure 31. These samples were obtained at the time of each total-load measurement, and inspection of the curves shows that some material was finer than 1.0 mm in each case. The bed material coarser than 1.0 mm, however, ranges from 36 to 86 percent. This range corresponds to a considerable range of instantaneous water-discharge values, namely from 748 to 12,800 cfs.

The size distribution of bed-material samples affects the estimate of the total sediment discharge when the estimate is computed by the modified Einstein method. The samples are reliable, however, only if the streambed material at the times of sampling was representative of the average condition during the 1960–63 period. The question of whether instantaneous values of water discharge approximate mean values, which was raised previously, is also relevant.

A test of the reliability of bed-material sampling, however crude it might be, was desirable, and therefore composite samples of the bed material of the Cache Creek channel were collected at random cross sections over a 7-mile reach below the Yolo sediment station. This was done while the channel was dry, as shown in figure 12. The weight percentage of sediment coarser than 1.0 mm ranged from 57 to 86 over the 7-mile reach, and the mean value for a given cross section was 69 percent.

Because the sediment in the streambed below the Yolo sediment station can be assumed to represent the average size of the material that is transported past the station over a long-term period, the mean value of 69 percent is useful. Curve 4 in figure 30 shows the relation between water discharge and the material coarser than 1.0 mm transported by Cache Creek. Because curve 1 of this figure shows the relation of bedload discharge and water discharge, the percentage of the bedload discharge that is coarser than 1.0 mm can be computed. According to this method, approximately 48 percent of the bedload of Cache Creek is coarser than 1.0 mm.

The mean value of 69 percent, obtained as previously described, is probably greater than the actual value because it includes the effects of selective transport of finer sediment in this lowermost reach of the channel. These percentages appear to agree fairly well and the range of instantaneous values of the percentage of bed material coarser than 1.0 mm is probably representative of long-term conditions at the Yolo sediment station.

DEPOSITION OF SEDIMENT IN THE SETTLING BASIN

The Cache Creek settling basin below Yolo is shown on plate 1. Because of extensive artificial controls almost all the water in the stream passes the station at Yolo and continues directly to the settling basin, a distance of approximately 8 miles. The channel leading to Knights Landing, shown on plate 1, is natural but abandoned. Because flow is directed through the settling basin and over a weir that leads to the Yolo Bypass, an estimate of sediment deposition, or the trap efficiency of the settling basin, can be made from data on the sediment discharge at the Yolo station and at the weir of the basin. One of the goals of this investigation was to obtain an estimate of the trap efficiency

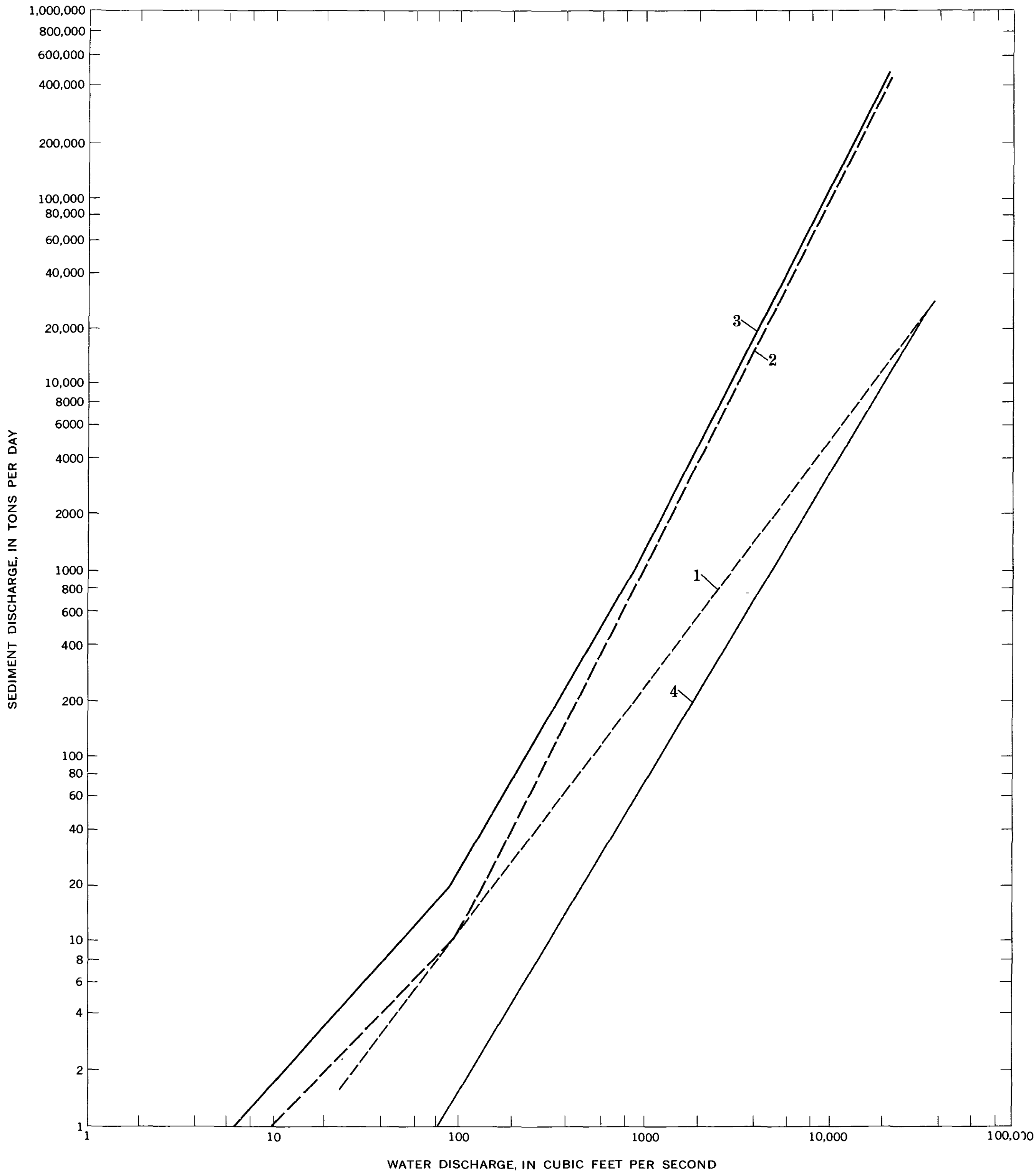

FIGURE 30.—Relation of various fractions of sediment discharge and water discharge for Cache Creek at the Yolo sediment station. Curve 1 shows the relation of bedload discharge and water discharge. Curve 2 shows the relation of the mean suspended-sediment discharge for the 1960–63 period and water discharge. Curve 3 shows the relation of the adjusted total sediment discharge and water discharge; it is the sum of curves 1 and 2. Curve 4 shows the relation of the discharge of particles coarser than 1.0 mm and water discharge.

in the settling basin; and for this reason, suspended-sediment samples were obtained at the weir whenever possible. During the 1960–63 period 27 samples were taken; much of the following discussion is based on these samples.

The size distribution of samples obtained at the weir was not discharge weighted because water-discharge data were unavailable. In order to estimate the suspended-sediment discharge at the weir, it is therefore necessary to combine the suspended-sediment concentration at the weir with the water discharge on the date of sampling at the Yolo station.

Implicit in this approach is the assumption that the water discharge at Yolo and at the weir are the same. Because most of the runoff events occur during the winter months, it seems improbable that any appreciable portion of the total runoff over the 8-mile reach of channel between Yolo and the weir is lost through evaporation. Possibly, however, the lowering of the water table in this area through ground-water pumping may be sufficient to cause some loss of surface flow by way of seepage into the surficial sediments. If so, the actual water discharge at the weir may be somewhat less than the water discharge at Yolo. The estimate of suspended-sediment discharge at the weir may thus be too high, and because trap efficiency is determined by the difference between the suspended-sediment discharge at Yolo and at the weir, the estimate of the trap efficiency of the settling basin may be too low.

The trap efficiencies discussed here, however, are predicated upon suspended-sediment discharge alone. Because no particles in the sand-size range pass over the weir, the settling basin must necessarily trap all the coarse sediment in transport that passes the Yolo station. As previously indicated, the true percentage of bedload discharge that passes Yolo is uncertain, but it is thought to be at least 7 percent of the total sediment discharge. Hence, the estimate of the trap efficiency of the settling basin should be increased by this amount, which probably exceeds greatly any reduction of the estimate because of water-discharge differences.

The difference between the suspended-sediment discharges at Yolo and at the weir, indicates that trap efficiency of the settling basin during the 1960–63 period ranged from 53 to 64 percent. The maximum water discharge that occurred at Yolo on the dates of sam-

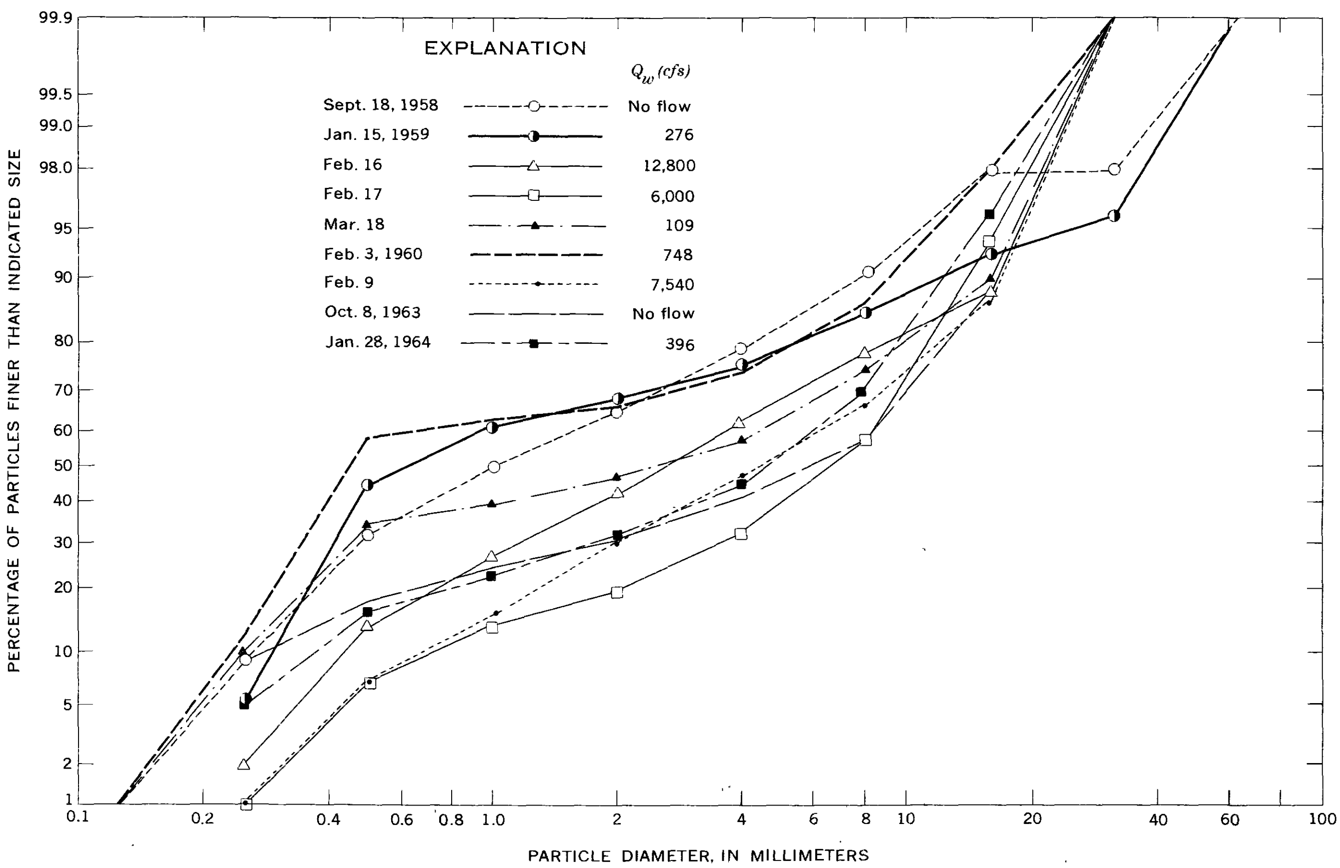

FIGURE 31.—Size-distribution curves of bed-material samples from Cache Creek at the Yolo sediment station. The samples were obtained at the time of each total-load measurement.

pling at the weir was 11,800 cfs. Because suspended-sediment discharge increases with water discharge, the trap efficiency computed for this date indicates the sediment deposition that results from large runoff events or, conversely, of the amount of sediment that passes through the settling basin and over the weir. The data show that 49 percent of the suspended sediment was trapped in the settling basin during this runoff event. It should be noted, however, that the moisture content of the settling basin immediately before large runoff events is of great importance; if the basin is almost dry, some net erosion of surface sediment may actually occur, thus markedly lowering the estimated trap efficiency.

More specific evaluation of the data is not possible because in addition to the qualification just noted, the absolute bedload discharge at Yolo and at the weir must be considered. The available data suggest, however, that approximately half of the suspended-sediment discharge, and perhaps 60 percent of the total sediment discharge, is trapped by the settling basin.

CONCLUSIONS

The mean annual runoff in the Cache Creek drainage basin during the 1960–63 period was 173,000 acre-feet less than the long-term, 60-year average. Flow-duration data show that there was an increase in the frequency of low-water flows in the upper and middle parts of the basin and a decrease in the frequency of high-water flows in all parts of the basin during the 1960–63 period. This runoff deficiency is a logical consequence of a precipitation decrease during the period of study. Therefore, if the estimates of sediment discharge provided in this report are extrapolated for planning purposes, they should be regarded as minimum values. This qualification assumes, of course, that the long-term climatic records are indeed indicative of future trends.

Both the rate and absolute magnitude of suspended-sediment discharge increase with an increase in water discharge downbasin. These normal sediment-transport characteristics are altered by artificial controls at Capay. Diversion of surface water at this point produces a reduction of sediment discharge below Capay.

During the 1960–63 period, the total quantities of suspended sediment transported by North Fork Cache Creek and by Bear Creek were 476,700 and 174,800 tons, respectively. The suspended-sediment load was more than 2 million tons above Rumsey and more than 3 million tons near Capay. The controls at Capay reduced the suspended-sediment load to slightly more than 2 million tons at Yolo.

Suspended-sediment discharge, and probably total sediment discharge as well, is affected by variations in environmental conditions within the basin. Apparently, because of geologic and topographic conditions, a 98-square-mile area between Rumsey and Capay contributes twice the quantity of sediment that would be expected from proportional computations based on drainage area alone. This suggests that any future controls within the basin above Rumsey will not reduce the sediment discharge of Cache Creek below the installation in strict accordance with such proportional computations.

The bedload discharge of Cache Creek at the Yolo sediment station is approximately 7 percent of the total sediment discharge. Similar results are obtained from computations based on the assumption that instantaneous values of water discharge approximate daily mean values, and computations that employ the method of subdivision and adjustment. Presumably this similarity exists because Cache Creek transports only a small percentage of its total load as bedload and, further, because the average water discharge is fairly high. At the average water discharge value of 881 cfs, the vast bulk of the load is transported as suspended sediment; hence adjustments that involve correction of the estimated bedload fraction have little influence on the estimated total sediment load.

The total sediment load of Cache Creek during the 1960–63 period was 2,289,000 tons. This total load estimate is limited primarily by the runoff deficit during the period of record; for extrapolation purposes it should be considered a slightly conservative estimate. The accuracy, however, is probably equal to that of the methods employed for sampling and computation.

The trap efficiency of the settling basin below Yolo was estimated by combining the concentration of suspended sediment that passed through the basin with the water discharge measured at the Yolo station. The results indicate that the settling basin traps approximately half of the suspended sediment that enters the basin, and, depending upon the true percentage of sediment that is transported as bedload, the trap efficiency may equal or slightly exceed 60 percent under normal conditions.

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