Sediment Transport in the Western Tributaries of the Sacramento River, California

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1798-J

Prepared in cooperation with the California Department of Water Resources

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By B. L. JONES, N. L. HAWLEY, *and* J. R. CRIPPEN

SEDIMENTATION IN SMALL DRAINAGE BASINS

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SEDIMENT TRANSPORT IN THE WESTERN TRIBUTARIES OF THE SACRAMENTO RIVER, CALIFORNIA

By B. L. JONES, N. L. HAWLEY, and J. R. CRIPPEN

ABSTRACT

The western tributaries of the Sacramento River, from Clear Creek in the north to Putah Creek in the south, drain an area of more than 7,000 square miles. Major impoundments in the area at present have a combined storage capacity of about 2.5 million acre-feet, and proposed impoundments would add 3–7.5 million more acre-feet of storage. About 960,000 acre-feet of water is imported to the region from the Trinity River annually, and plans call for the annual importation in the future of 700,000–950,000 acre-feet from the Eel River basin. Most of this imported water will be conveyed to areas of water deficiency south of the study area.

The quantity of sediment carried by streams and deposited by them may affect both the quality of water and the operational regimen of reservoirs. Because of these possible problems, data on sediment transport have been analyzed to provide planners and engineers with estimates of the quantities involved in the fluvial sediment processes of the study area.

In the basins studied, average annual yields of suspended sediment range from less than 100 tons to more than 3,000 tons per square mile, and bedloads range from 2 to 7 percent of the total sediment discharge. Suspended-sediment yield shows a general correlation with geologic province—the highest yields are from the basins draining the Coast Ranges province, the lowest yields from the Great Valley of California province, and the intermediate yields from the Klamath Mountains province.

Total average annual yield of suspended sediment from the study area is probably about 4.7 million tons. A substantial part of this, perhaps 30 percent, is retained by entrapment as deposits in lakes and reservoirs within the region; the remaining 70 percent is transported from the regions, most of it during relatively short periods of high streamflow.

INTRODUCTION

The western tributaries of the Sacramento River yield large quantities of good-quality water. Extensive development of the area's water resources is either underway or planned (California Department of Water Resources, 1970) to control floods and provide water for irrigation, recreation, municipal supply, and wildlife enhancement. Each development plan includes several impoundments, as well as other engineering works that will affect the regimen of streamflow. The western tributaries are the subject of this report because the quantity of available data together with the need for information concerning the region make a separate report appropriate. Sediment yield from the eastern tributaries is relatively low, and sediment from that part of the basin has therefore posed fewer problems. The limited data from the eastern tributaries have not been analyzed.

This report summarizes and analyzes much of the available sediment data gathered from the western tributaries. Hopefully, the information provided here will be valuable in the design and operation of the water-development system. The sediment-transport characteristics of streams may be an important factor in the selection of reservoir sites. The deposition of large quantities of sediment can shorten the useful life of a reservoir, and fine sediment particles remaining in suspension in a reservoir can cause persistent turbidity downstream. The creation of large mainstream reservoirs can bring about pronounced changes in downstream fluvial processes. For example, the trapping of coarse sediment by a reservoir may leave the unladen stream with a renewed ability to erode, and thereby result in degradation of the downstream channel; on the other hand, the reduction of floodflows may reduce the gross competency of the stream and cause aggradation downstream.

A sediment-sampling program has been conducted by the Water Resources Division of the U.S. Geological Survey in cooperation with Federal, State, and local agencies, as part of the Survey's appraisal of the Nation's resources. Data collected in the course of this program were used to develop estimates of the long-term transport of suspended sediment from the basins in the study area.

This study was conducted by personnel of the Water Resources Division, U.S. Geological Survey, in cooperation with the California Department of Water Resources. The work was under the direct supervision of Willard W. Dean, chief of the Sacramento subdistrict, and under the general supervision of R. Stanley Lord, district chief in charge of water-resources investigations in California.

DESCRIPTION OF THE AREA

The study area includes the basins of the western tributaries of the Sacramento River from Putah Creek in the south to Clear Creek in the north. The area, about 7,070 square miles, is shown in figure 1. The streams drain the east flank of the Coast Ranges and the southeastern Klamath Mountains and are tributary to the Sacramento River, either directly or by way of one of the floodways which parallel the river. Data used in this report were collected at the sites listed in table 1; locations of the sites are shown in figure 1.

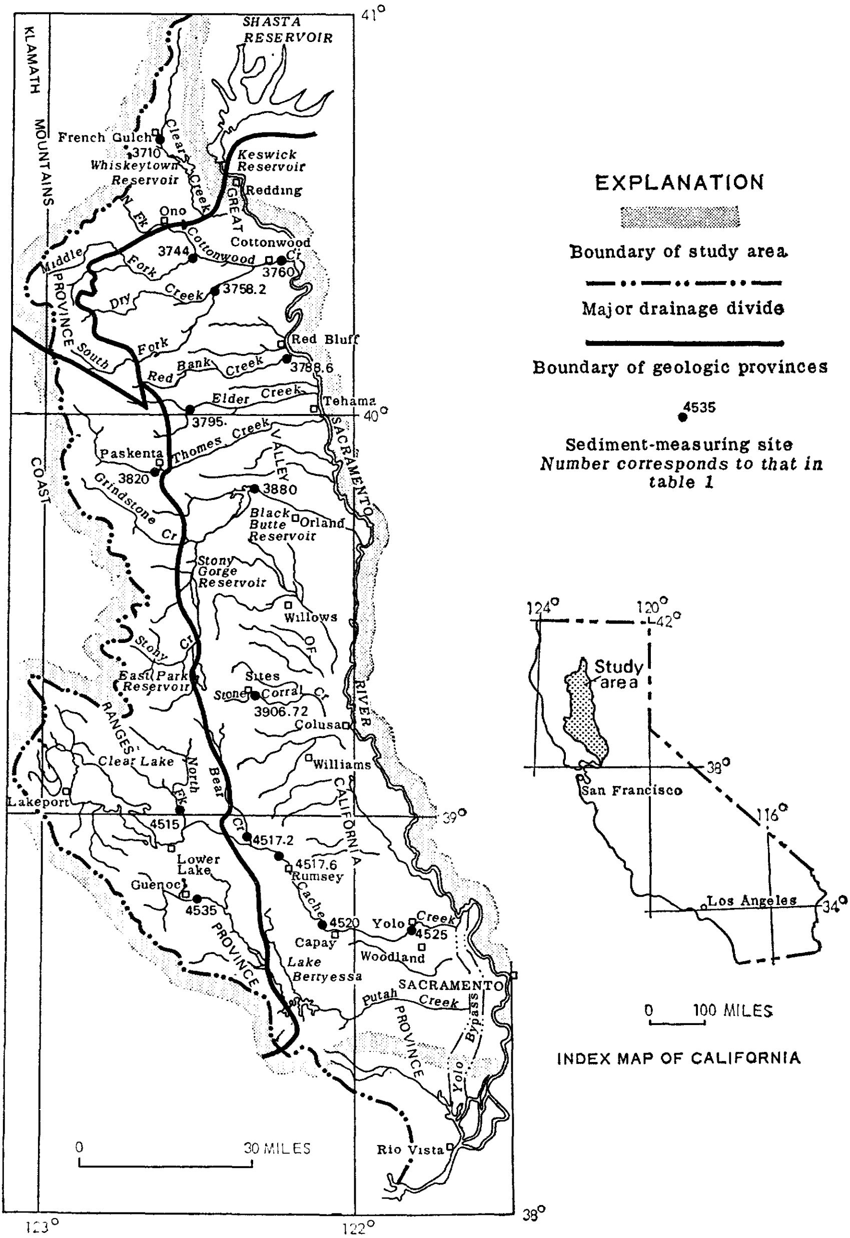

FIGURE 1.—Map of study area showing geologic provinces. Geologic provinces from Jenkins (1943).

The area includes parts of three geologic provinces (fig. 1) as defined by Jenkins (1943). The headwaters of all streams discussed in this report are in the Klamath Mountains province or the Coast Ranges province. The lower reaches of all streams in the study area traverse the dissected uplands and alluviated plain of the Great Valley of California province. Excellent discussions of the geological aspects of each province may be found in Bailey (1966).

TABLE 1.—*Sampling points and precipitation and runoff in the study area*

Station No. (fig. 1)	Station	Drainage area (sq. mi).	Mean annual [1] runoff		Mean annual precipitation (inches)	Runoff as percentage of precipitation	Period of available record (water years)	
			(Acre-feet)	(Inches)			Streamflow	Sediment
11-3710	Clear Creek at French Gulch.	115	145,000	24	59	41	1951–68	1956–67
11-3744	Middle Fork Cottonwood Creek near Ono.	249	165,000	12	40	30	1957–68	1962–68
11-3758.2	South Fork, Cottonwood Creek near Cottonwood.	217	120,000	10	36	28	1963–68	1963–68
11-3760	Cottonwood Creek near Cottonwood.	922	586,000	12	37	32	1941–68	[2] 1956–67
11-3788.6	Red Bank Creek near Red Bluff.	109	38,000	6.5	22	30	1965–67	1964–68
11-3795	Elder Creek near Paskenta.	92.9	68,000	14	33	42	1949–68	1963–68
11-3820	Thomes Creek at Paskenta.	194	[3] 209,000	20	49	41	1921–68	[2] 1962–68
11-3880	Stony Creek at Black Butte damsite near Orland.[4]	741	400,000	10	30	33	1952–62	1957–62
11-3906.72	Stone Corral Creek near Sites.	38.2	3,500	1.7	19	9	1959–64, 1966–68	1965–68
11-4515	North Fork Cache, Creek near Lower Lake.	197	[3] 145,600	14	37	38	1931–68	1957–66
11-4517.2	Bear Creek near Rumsey.	100	26,500	5.0	24	21	1959–67	1960–67
11-4517.6	Cache Creek above Rumsey.	955	(5)	----------	34	----------	1960–67	[2] 1960–67
11-4520	Cache Creek near Capay.	1,044	(5)	----------	32	----------	1943–68	1959–62
11-4525	Cache Creek at Yolo.	1,139	(5)	----------	30	----------	1904–68	[2] 1958–67
11-4535	Putah Creek near Guenoc.	113	[3] 147,700	25	44	57	1931–68	1962–68
	East Park Reservoir.[6]	102	61,100	11	27	41	----------	----------
	Stony Gorge Reservoir.[6]	301	166,000	10	29	34	----------	----------

1 Observed or estimated for 1941–65.
2 Daily records of sediment transport were gathered at these stations for some or all of the record period.
3 Discharge of Thomes Creek for 47 years, 196.900 acre-feet; of North Fork Cache Creek for 37 years, 136,800 acre feet; and of Putah Creek for 39 years, 149,100 acre-feet.
4 Station continued with different name after dam was built.
5 Flow of Cache Creek is affected by the storage and release regimen of Clear Lake (drainage area, 528 square miles) and by evaporation from the lake.
6 From Knott and Dunnam (1969). Data referenced to long-term periods with streamflow regimens similar to that of 1941–65.

Major impoundments in the study area are Lake Berryessa, Clear Lake (a natural lake with controlled storage), East Park Reservoir, Stony Gorge Reservoir, Black Butte Reservoir, and Whiskeytown Reservoir. The total storage capacity of these impoundments is approximately 2,500,000 acre-feet. Impoundments that have been proposed in the study area would add 3,000,000–7,500,000 acre-feet of storage. Water from Trinity River is presently imported to Whiskeytown Reservoir at an average rate of 960,000 acre-feet per year. Development plans for the future envision importation of 700,000–950,000 acre-feet per year from the Eel River basin to the Central Valley. Detailed information on water development in the study area may be found in two reports of the California Department of Water Resources (1969, 1970). Also pertinent is the U.S. Army Corps of Engineers report on Cottonwood Creek (1970, pls. I and III). Construction of Dutch Gulch Reservoir (1,100,000 acre-feet) on Cottonwood Creek and Tehama Reservoir (900,000 acre-feet) on South Fork Cottonwood Creek was authorized by Congress in December 1970.

CLIMATE

In general the entire study area has cool wet winters and hot dry summers. More than 80 percent of all precipitation occurs during the 6 months from November to April, and it is mostly from general regionwide storms. Prevailing winds are from the west. In the winter, when the land is cooler than the ocean, the moisture-laden airmass produces rain or snow as it moves inland; in the summer, when the land is warmer than the ocean, the moisture-laden airmass becomes relatively dry as it moves inland, so summertime precipitation is very light or entirely absent.

Altitude and latitude modify the quantity of precipitation that may occur. At the highest altitudes in the northern part of the study area, precipitation may exceed 100 inches in some years; at the lowest altitudes in the southern part of the area, precipitation in dry years may be less than 10 inches. Annual precipitation may vary greatly from one year to another at all locations. Mean annual precipitation for the basins of the study area, based upon isohyetal maps prepared by the California Department of Water resources (1966, pl. 1), is shown in table 1.

Temperatures in the study site are equable. The accompanying table shows representative temperatures at several selected sites.

Weather station [1]	Daily average temperature in ° F.			
	July 1968		January 1968	
	Maximum	Minimum	Maximum	Minimum
Whiskeytown Reservoir	97.3	64.0	52.8	33.1
Red Bluff Airport	97.4	64.7	53.3	32.9
Stony Gorge Reservoir	97.2	60.7	54.1	30.4
Lake Berryessa	93.6	60.8	55.5	34.8
Sacramento Airport	94.5	57.9	52.2	34.5

[1] From the annual summary of the Environmental Science Services Administration. Sacramento Airport is about 50 miles east of Lake Berryessa.

The seasonal range is influenced by the upwind proximity of the Pacific Ocean, therefore the extremes vary less than those that occur farther inland where the continental rather than the maritime regimen is dominant. As the table shows, the maximums and minimums in the study region do not vary greatly from place to place. The maximum temperatures shown for Sacramento (which has the lowest altitude and also is the southernmost of the stations listed) are not as high as one might expect; probably the cooling is caused by the inflow of maritime air entering through the wind gap formed by San Francisco Bay and the Sacramento–San Joaquin Delta.

VEGETATION AND SOILS

The low level bottom lands of the Sacramento Valley and of many areas along the lower reaches of some tributary streams have deep fertile alluvial soils. Good crops of grain are grown by dry-farming methods, and with irrigation a wide variety of vegetables and fruits is grown. The gentle slopes and good cover allow only small losses of soil—indeed, the greatest sediment problem in many areas may be the addition of soil layers by deposition during flood periods.

Soils on the steep slopes and ridges of the foothill areas are generally shallow and infertile, contrasting sharply with the deep, rich soils of the valley bottom. The semiarid foothills support only brush, scrub oak, or grass. During the summer months the dry grass provides poor soil cover; then, in the wet months of winter and spring new growth occurs.

In the mountains, land slopes are generally steep and soil is likely to be shallow and infertile. Despite this, and probably because of favorable humidity that is more prevalent at high altitudes than at low altitudes, stands of timber grow on many north-facing slopes that are higher than 2,000 feet. In mountain valleys that have alluvial soil and on slopes that are not steep, there is likely to be well-established herbage and brush that provide some protection against erosion. In general, however, loose soil in the mountains erodes rapidly.

Erosion rates in the study region often are influenced by the distinct separation of wet and dry seasons. During the dry season, annual grasses die, soils harden and crack, and a layer of loose dust may develop. If the onset of the wet season is a period of gentle rain and moderate temperatures, considerable grass cover may develop and later periods of more intense rainfall may cause little erosion. If, on the other hand, the first storms of the season are protracted and intense or if low temperatures discourage the growth of cover, erosion may be severe. Deep gullies may be cut, and there may be mudflows or landslides on the steeper slopes. Poor cover conditions produced by the wet-dry cycle may, in areas having impermeable soils and easily erodible rocks, produce badland topography such as exists in parts of the Cache Creek, Thomes Creek, and Grindstone Creek basins.

Some of the activities of man may affect the soil and the vegetation, and thus affect erosion rates. Logging, farming, grazing, roadbuilding, and mining are common activities which may change cover conditions, disturb or compact the soil, and make large quantities of loose soil or rock available for erosion and transport.

STREAM DEVELOPMENT

Some of the study streams such as upper Stony Creek, North Fork Cache Creek, and Bear Creek follow fault zones or other linear structural features; thus they parallel the north-south trend of ridges for part of their length and exhibit a crude trellis drainage pattern. To the north and west, shorter tributaries draining highlands that have more homogeneous lithology show modified dendritic patterns.

Streams draining the east flanks of the Coast Ranges flow first in bedrock channels in the high mountains, then in the foothills through narrow valleys with shallow coarse alluvial fill, over broad alluviated valleys of the dissected uplands, onto the deep alluvium of the low plains or fans, and finally into the river flood plains and channels (Poland and Evenson, 1966). The low-lying alluvial plains and fans are flat or gently undulant and were formed during the present depositional cycle. The Sacramento River and the lower reaches of some tributaries have formed level flood plains or overflow lands on which parallel flowage routes form during flood periods. Most streams south of Stony Creek terminate as distinct entities in these overflow lands and do not have discernible channels that enter the low-flow channel of the Sacramento River.

STREAMFLOW

The considerable variation of precipitation that occurs in the study basins is reflected in the runoff characteristics. Table 1 shows the wide variation of average annual streamflow from basin to basin and the highly variable relation between runoff and precipitation. Runoff ranges from 9 to 57 percent of precipitation, indicating that there are vast differences among the basins in precipitation, evapotranspiration, permeability of soils, and channel and aquifer storage.

The quantity of sediment transported from a region in a given year is a function of many variables, but dominant among them is streamflow. Streamflow throughout the region of this study varies greatly from year to year, and therefore the yearly sediment yield varies greatly. By estimating the average annual yield, we are implying that the value arrived at is typical for a long period of time, not for a specific short period that may or may not be representative of the long term. We must therefore insure that the period used is typical for the long term, and we can do this by using streamflow data from (or adjusted to) a period of time when the flow regimen closely resembles the pattern exhibited by the longest records available. Inspection of the data shows that this can be done in the area described in this study by adopting the 25-year period, 1941–65, as a base period. The streamflow data are separated into annual periods or water years that end September 30 of the indicated calendar year.

DESCRIPTION OF INDIVIDUAL STREAMS

CLEAR CREEK

Clear Creek rises in the Klamath Mountains province at an altitude of about 5,250 feet, flows southwestward for about 20 miles, then southeastward to the community of French Gulch, and thence to Whiskeytown Reservoir. From Whiskeytown Reservoir (drainage area, 200 square miles), Clear Creek flows southeastward to its junction with the Sacramento River about 6 miles south of Redding. The length of Clear Creek is about 44 miles; from source to mouth its fall is 4,800 feet, with 3,000 feet of the fall occurring in the first 6 miles. Total drainage area is 250 square miles. Suspended sediment was sampled at the gaging station Clear Creek at French Gulch (sta. 11–3710). Storage of water in Whiskeytown Reservoir (an artificial impoundment with capacity of 241,000 acre-feet) began in May 1963.

COTTONWOOD CREEK

Cottonwood Creek proper is formed by the joining of its Middle Fork (the largest tributary) with its North Fork. Suspended-sediment data from the main basin and from two subbasins have been used in this report.

Middle Fork Cottonwood Creek rises on the east slope of the Coast Ranges at an altitude of about 4,000 feet, flows eastward for about 30 miles, and then joins the North Fork. The sampling station on Middle Fork (11–3744) is near the community of Ono, about 0.4 mile upstream from the confluence, and is at an altitude of 550 feet.

South Fork Cottonwood Creek rises at about 5,000 feet altitude and is about 45 miles long. It joins Cottonwood Creek some 10 miles downstream (eastward) from the confluence of the Middle and North

Forks. The South Fork is sampled at station 11–3758.2, about 10 miles upstream from its junction with Cottonwood Creek and at about 525 feet in altitude.

The main basin is sampled at station 11–3760, Cottonwood Creek near Cottonwood, about 2 miles upstream from the mouth and 15 miles downstream from the confluence of the Forks. The altitude of the gage is about 364 feet. The drainage area at the mouth is about 940 square miles.

The authorized Dutch Gulch Dam and Reservoir (1,100,000 acre-feet) would be located on Cottonwood Creek about 11 miles west of the town of Cottonwood. The authorized Tehama Dam and Reservoir (900,000 acre-feet) would be located on South Fork Cottonwood Creek about 9 miles southwest of the town of Cottonwood.

RED BANK CREEK

The headwaters of Red Bank Creek are in the Klamath Mountains and on the east slope of the Coast Ranges, at an altitude of about 4,000 feet. The creek flows southeastward for about 20 miles to join the Sacramento River 2 miles downstream from Red Bluff. From origin to mouth, Red Bank Creek falls about 3,500 feet. The gaging station and sampling site (sta. 11–3788.6) is about 3 miles south of Red Bluff. Total drainage area of the basin is about 115 square miles.

ELDER CREEK

Elder Creek rises on the eastern slope of the Coast Ranges at an altitude of about 7,000 feet. The stream flows eastward for about 40 miles to its confluence with the Sacramento River. Nearly 4,690 feet of the total 6,400 feet of fall from headwaters to mouth occurs in the first 8 miles of the channel length and about 1,000 feet of fall occurs in the next 10 miles. Sediment samples are collected near Paskenta (sta. 11–3795). Total drainage area of the basin is about 140 square miles.

THOMES CREEK

Thomes Creek originates on the east slope of the Coast Ranges at an altitude of more than 6,000 feet. It flows south for about 22 miles, follows a northeasterly direction for 35 miles, and then joins the Sacramento River. The total fall of the main stem is 5,800 feet, and the total drainage area of the basin is about 300 square miles. Many small tributaries, some unnamed, flow into the main stem. Sediment samples are collected at the Paskenta gage (Thomes Creek at Paskenta, sta. 11–3820).

STONY CREEK

Stony Creek originates in the Coast Ranges northeast of Clear Lake at an altitude of more than 6,000 feet. The stream is about 90 miles long. There are three large reservoirs in the basin: East Park, Stony Gorge, and Black Butte. Black Butte Reservoir is the largest, newest, and farthest downstream of the three; it was completed in 1963 and has storage capacity of roughly one-third of the average annual flow of the creek. The drainage area at the outlet of Black Butte Reservoir is 740 square miles, and the total drainage area of the Stony Creek basin is 778 square miles.

Principal tributaries to Stony Creek are Little Stony Creek, draining the southwestern part of the basin, Briscoe Creek and Grindstone Creek in the west-central part, and North Fork Stony Creek, draining the northern part of the basin. Grindstone Creek is of special interest because of plans to use a part of the channel to convey water from the Eel River basin into a storage complex in the Sacramento River basin (California Department of Water Resources, 1970).

Sediment information for the Stony Creek basin was derived from several sources. Knott and Dunnam (1969) reported sediment accumulations in Stony Gorge and East Park Reservoirs and computed the mean annual sediment yield, using suspended-sediment samples collected from Stony Creek at Black Butte damsite (sta. 11–3880). Sediment samples also were collected at a station on Grindstone Creek near Elk Creek and just upstream from Stony Creek; however, data from that station were not easily adjusted to the base period used and therefore are not shown separately.

STONE CORRAL CREEK

Stone Corral Creek rises in the foothills east of East Park Reservoir at an altitude of about 1,000 feet. It flows eastward in a very irregular course into the floodway of the Sacramento River. Streamflow occurs only during the rainy season. Sediment samples were collected near Sites (sta. 11–3906.72), about 16 miles upstream from the mouth. The drainage area at the gage is 38.2 square miles.

Stone Corral Creek in its lower reaches serves as a collector of the flow of several west-side tributaries. These channels are not distinctly separated from each other in the low, flat overflow plain of the Sacramento River valley so the actual drainage area of Stone Corral Creek at its mouth has not been determined.

CACHE CREEK

Cache Creek drains a 1,290-square-mile basin in the Coast Ranges and Great Valley of California; this basin is mostly east and southeast of Clear Lake. Cache Creek proper originates as the outlet of Clear Lake. The drainage area tributary to the lake is 458 square miles and the surface area of the lake is about 70 square miles. The length of Cache Creek, from Clear Lake outlet to its mouth at Yolo Bypass, is about 80 miles. The principal tributaries are North Fork Cache Creek and Bear Creek.

Water is diverted from Cache Creek for irrigation at many points near and downstream from the community of Capay, where the stream debouches onto the flat valley floor. Here in the lower reaches of Cache Creek the sediment settles over a wide area forming a large alluvial fan (Lustig and Busch, 1967).

Sediment samples were collected at five stations: North Fork Cache Creek near Lower Lake (11–4515), Bear Creek near Rumsey (11–4517.2), Cache Creek above Rumsey (11–4517.6), Cache Creek near Capay (11–4520), and Cache Creek at Yolo (11–4525).

PUTAH CREEK

Putah Creek originates in the Coast Ranges south of Clear Lake at an altitude of about 4,000 feet. The length of the main stream is about 80 miles, and the total basin area is 810 square miles. Of this, about 244 square miles is downstream from Lake Berryessa.

The topography of the Putah Creek basin upstream from Lake Berryessa is extremely rugged, with poor thin soil; only the alluvium of the valley floor is tilled. In contrast, the lower part of the basin is characterized by brush-covered foothills and farther downstream by a large area of rich farmland on the alluvium of the Sacramento Valley.

Sediment samples are collected at the station near Guenoc (11–4535), upstream from Lake Berryessa.

FLUVIAL SEDIMENT TRANSPORT

Fluvial sediment is material that is suspended, transported, or deposited by water. Disintegrated rocks of the earth's crust are the source of most sediment. Gully and sheet erosion of soil is the dominant upland source of fine sediment; other sources include reworked older deposits, landslides and mudslides, bank and channel cutting, and direct contribution of sediment to the stream by wind, by volcanic action, or by precipitation as dust particles.

Fluvial-sediment discharge generally can be categorized in terms of the mode of transport. Suspended sediment is that part of the stream sediment load that moves essentially as part of the streamflow; it is maintained in suspension by the upward components of turbulent flow or by colloidal suspension. Bedload is that part of the sediment load that moves by rolling, skipping, and sliding along or very near the streambed.

Suspended sediment makes up only a small part of the flow of streams; however, the total quantity of streamflow is so great that the annual load of suspended sediment is large. The quantity of sediment moved as bedload, on the other hand, is relatively small—generally much less than the total load of suspended sediment.

Bedload depends in part on the size of the bed material and in part on variables such as depth, slope, and velocity of flow. Suspended-sediment discharge is closely related to the availability of fine sediment and to the pattern of runoff from upland areas; bedload discharge is closely related to the size of bed material and to stream hydraulics. Suspended-sediment discharge is usually determined by direct stream sampling. Bedload discharge is usually computed by one of several procedures. Bedload samplers have been devised, but they are not widely used at the present time ([U.S.] Inter-Agency Committee on Water Resources, 1963).

Total sediment discharge is the sum of suspended-sediment discharge and bedload discharge. Suspended-sediment discharge is computed from measurements taken with equipment that cannot sample the zone within 0.3 or 0.5 foot from the streambed. The unsampled near-bottom stratum of flow contains the bedload material and suspended material that is present in concentrations probably higher than those indicated by sampler data. Thus, the sampling and computing process yields results that are biased to the extent that extrapolation to the unsampled zone is in error. Inaccuracies having this origin vary with the stream and with hydrologic conditions; usually the error is a very small percentage of the computed suspended-sediment discharge.

Estimates of the total sediment discharge can sometimes be checked by comparing it with the total accumulation of deposited sediment; this total can be determined by periodic surveys of reservoir bottoms.

COMPUTATION OF SEDIMENT TRANSPORT AND YIELD

The following sections discuss the methods by which values of average annual sediment yield were computed for this report. The basic data for the computations are published in reports of the U.S. Geological Survey; either the water-supply paper series, "Quality of Surface Waters of the United States, Parts 9–14," or the reports "Water Resources Data for California, Part 2, Water Quality Records." The data on sediment accumulation in the two reservoirs on Stony Creek are taken from an earlier report by Knott and Dunnam (1969).

SUSPENDED-SEDIMENT DISCHARGE

The estimates of average annual suspended-sediment discharge shown in this study are made by the flow-duration sediment-transport curve method described by Miller (1951). Available data of suspended-sediment discharge are of two types: (1) Daily records with sediment discharge computed for each day of streamflow; and (2) instantaneous data based upon samples taken when appropriate and when possible—sometimes often enough to be quite descriptive of sediment transport throughout one or more periods of high flow, but frequently not. Miller's method requires that a curve be developed that relates sediment discharge to water discharge; this is the sediment-transport curve. Such a curve was developed for each station in this study; an example is shown in figure 2. The relation was based upon daily values for stations if available, but for most stations only instantaneous values were available.

To compute long-term suspended-sediment yield, the sediment-transport curves must be used in conjunction with duration curves of daily discharge for the corresponding streams. The duration curves, in turn, must be representative of the long-term distribution of flows of various magnitudes. Many of the records do not include all years of the base period (1941–65) that was chosen; if the records were thus deficient, the required duration values were estimated by use of the method recommended by Searcy (1959). The method consists of relating the flow regimen of station B (with a short term of record) to that of station A (having a long record) during the period of record at station B, then using the relation of short-term to long-term characteristics of the flow regimen of station A to estimate the long-term characteristics of the flow at station B. Figure 3 shows a typical duration curve for the base period. The base-period-duration curve and the sediment-transport curve together provide the data shown in table 2, an example of the computation of mean annual sediment discharge.

The most accurate results are probably for those stations with long-term records of both streamflow and suspended sediment that have daily computations of suspended-sediment transport. The estimates of long-term average suspended-sediment discharge derived from very short records of flow and instantaneous samplings of suspended-sediment concentrations have more possibility for error, but no definite limits can be assigned.

Column 5 of table 2 shows the suspended-sediment discharge that accompanies the appropriate water discharge in the duration table. When each element of column 5 is multiplied by the percentage of time from column 2, the sum of the products is the mean daily suspended-sediment discharge (column 6). This sum multiplied by the number of days in a year (365.25) is the mean annual suspended-sediment discharge (the average total quantity annually transported from the basin).

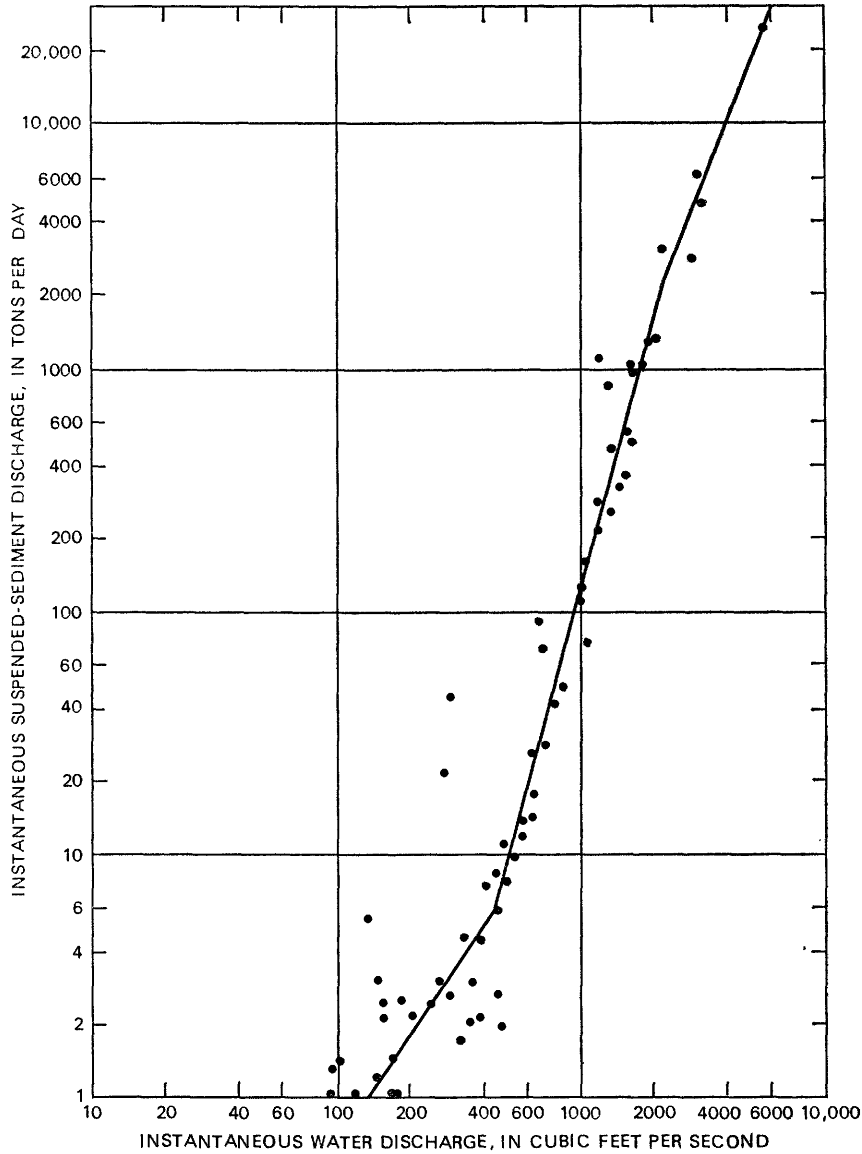

Figure 2.—Suspended-sediment transport curve, Clear Creek at French Gulch.

SUSPENDED-SEDIMENT YIELD

We have discussed the methods used to estimate the long-term average annual transport of suspended sediment from a basin. Knowledge

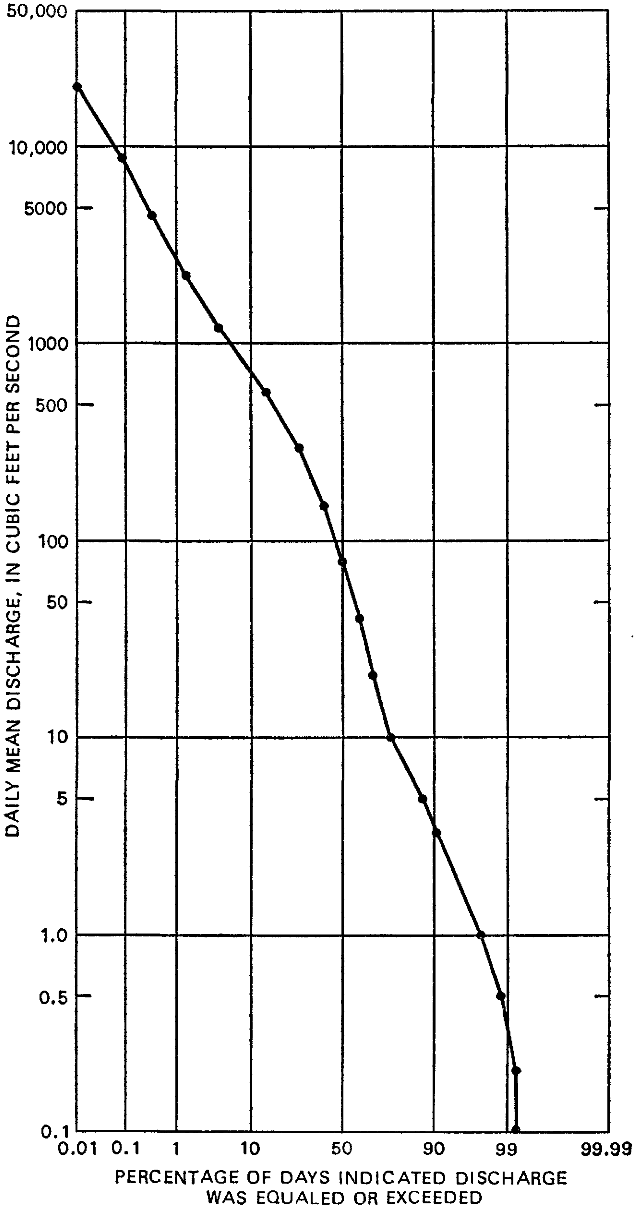

FIGURE 3.—Flow-duration curve, Thomes Creek at Paskenta, October 1940–September 1965.

of the quantity transported is useful in itself, but the data can be analyzed yet further to determine the variations in sediment yield among the regions studied.

TABLE 2.—*Example of computation of mean annual suspended-sediment discharge*

[Data are from sediment-transport curve and duration curve of daily discharges of Clear Creek at French Gulch]

Cumulative time (percent)	Time in increment (percent)	Mean of increment (percent)	Streamflow (cubic feet per second)	Suspended-sediment discharge (tons per day)	Mean daily suspended-sediment discharge [1] (tons)
(1)	(2)	(3)	(4)	(5)	(6)
0. 02	0. 02	0. 01	5, 900	30, 000	6. 00
. 10	. 08	. 06	4, 200	12, 000	9. 60
. 20	. 10	. 15	3, 300	6, 400	6. 40
1. 0	. 80	. 60	2, 300	2, 500	20. 00
3. 0	2. 0	2. 0	1, 360	400	8. 00
5. 0	2. 0	4. 0	890	85	1. 70
9. 0	4	7	610	21	. 84
15	6	12	400	5. 2	. 31
25	10	20	250	2. 5	. 25
35	10	30	160	1. 3	. 13
45	10	40	110	0	0
55	10	50	70	--------	--------

Total mean daily suspended-sediment discharge..........tons.. 53. 23
Mean annual suspended-sediment discharge.............tons.. [2] 19, 000

[1] Column 6=column 2×column 5.
[2] Rounded.

Suspended-sediment yield is usually expressed as tons per square mile per year and is computed from mean annual suspended-sediment discharge (in tons per year) by dividing by the size of the drainage area in square miles. Obviously, the value thus obtained is an average for the entire basin; rarely does such an average rate of suspended-sediment yield actually exist over any substantial area. In a basin that includes a large lake such as Berryessa or Clear Lake, much of the suspended sediment that is carried into the lake by tributaries will settle out as the water becomes quiescent. Lake outflow commonly carries in suspension a relatively small quantity of very fine material, perhaps 5–30 percent of the total sediment that enters the lake. Any basin where a lake thus detains suspended sediment blocks the continuity in movement of the material. The discontinuity must be recognized and appropriate adjustments made in order to translate data on suspended-sediment transport (gathered at a station downstream from the lake) into estimates of basinwide yield.

Because of the great variations in yield that occur for many reasons, the sources of suspended sediment must be determined by as small areas as possible. For a set of data such as is available, for example, from the Cottonwood Creek basin where there are two stations on tributaries and one on the main stream, the yields of three distinct areas (the basins of the two tributaries and the intervening area that contributes to the downstream station) can be computed separately. The computations assume a continuity of sediment movement—that is, all sediments passing the upstream sites also pass the downstream site, and the difference between the total load passing the upstream site and the load passing the downstream site represents all the sediments produced from the intervening area. This assumption, although never perfectly true, is probably valid for most conditions over a long period of time. However, during a short period there may be a relatively large quantity of deposition within any specific reach, and the true yield of the intervening area may therefore not be exactly the same as the computed residual indicates. The residual value obtained by subtraction is actually a net sediment yield; if the net sediment yield thus computed is small compared to the measured values from which it is derived, then it can be in error by a high percentage. Nevertheless, the method can be used to advantage in studying sediment-yield characteristics of a region. Table 3 sum-

TABLE 3.—*Mean annual transport and yield cf suspended sediment*

Identification symbol		Basin	Area (sq mi)	Estimated mean annual quantities of suspended sediment	
Station No. (fig. 4)	Basin letter			Transported from basin (tons)	Yield (tons per sq mi)
3710	A	Clear Creek at French Gulch	115	19,000	165
3744	B	Middle Fork Cottonwood Creek near Ono	249	260,000	1,040
3758.2	C	South Fork Cottonwood Creek near Cottonwood.	217	230,000	1,060
	D	Intervening area, E− (B+C)	456	320,000	702
3760	E	Cottonwood Creek near Cottonwood	922	810,000	
3788.6	F	Red Bank Creek near Red Bluff	109	93,000	853
3795	G	Elder Creek near Paskenta	92.9	125,000	1,350
3820	H	Thomes Creek at Paskenta	194	650,000	3,350
	j	East Park Reservoir	102	46,000	451
	J	Intervening area, k−j	199	69,000	347
	k	Stony Gorge Reservoir	301	115,000	
	K	Intervening area, L−k	440	445,000	1,010
3880	L	Stony Creek at Black Butte damsite near Orland.	741	560,000	
3906.72	M	Stone Corral Creek near Sites	38.2	3,800	99
4515	N	North Fork Cache Creek near Lower Lake	197	215,000	1,090
4517.2	O	Bear Creek near Rumsey	100	62,000	620
	P	Intervening area, Q− (N+O)	130	[1] 453,000	3,480
4517.6	Q	Cache Creek above Rumsey	[2] 955	880,000	
	R	Intervening area, S−Q	89	270,000	3,030
4520	S	Cache Creek near Capay	1,044	1,150,000	
	T	Intervening area, U−S	95	0	0
4525	U	Cache Creek at Yolo	1,139	1,150,000	
4535	V	Putah Creek near Guenoc	113	130,000	1,150

[1] Assuming 150,000 tons per year of suspended sediment leaves Clear Lake. This assumption is based upon a poorly defined sediment-transport rating, applied to long-term data of daily lake outflow; the results are compatible with reasonable rates of sediment yield and trap efficiency.
[2] Includes the three preceding basins (N, O, P) and the 528 square miles tributary to Cache Creek at the outlet of Clear Lake.

maries the suspended-sediment yields of the component subareas within the study area, and figure 4 is a map showing a generalized interpretation of the yield characteristics of the region.

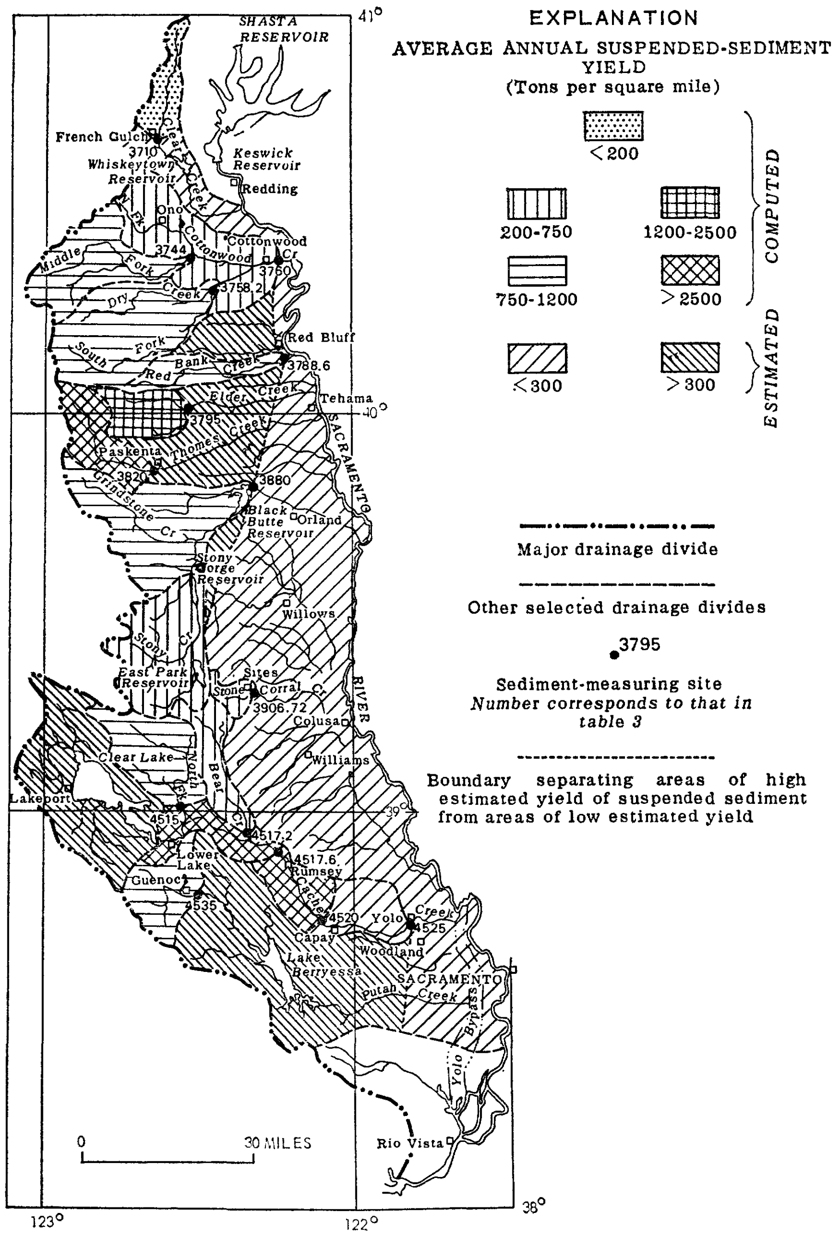

FIGURE 4.—Map showing average annual yield of suspended sediment in the study area.

The information shown in table 3 and figure 4 indicates that the highest sediment yields of the study area are from the Coast Ranges province (fig. 1), particularly from areas underlain by sedimentary rocks of the Franciscan Formation (Bailey, 1966). Lowest yields occur in the foothills and flatlands. Generally, high suspended-sediment yields seem to be related to high runoff (or at least they seem to be coincidental in areas of occurrence), although the Clear Creek basin is an exception.

The data from the two most downstream stations on Cache Creek (Capay and Yolo) indicate that the same quantity of suspended sediment is transported past both stations. This relation results in a computed yield of zero from the intervening area. Two inferences follow: first, that the yield from the intervening area is relatively low—this conclusion seems reasonable, as the region is low and flat, and average annual precipitation is less than 20 inches; second, that the true difference in the quantities transported past the two stations is too slight to be significant when compared to the entire suspended load. To demonstrate the relative magnitudes that are involved: in the level semiarid region of 95 square miles that constitutes the intervening area, the net yield of suspended sediment is probably in the order of magnitude of 100 tons per square mile per year at the most, or a total of not more than 10,000 tons. The computed load at both Capay and Yolo is more than 1.1 million tons and at either station may easily be in error by 10 percent. Obviously, the quantity contributed by the intervening area cannot be meaningfully deduced from any residual that might be computed between such large values.

The sediment yields shown in figure 4 are the best estimates possible from the available data; however, it must be borne in mind that many of the data are from relatively short periods of record, and even the 25-year base period to which the data were adjusted may differ from truly long-term conditions. In most cases, the yields are averages for areas of more than 100 square miles. Sediment yield from markedly smaller areas within the study region or from any areas outside the sampled basins may be considerably different from the computed yields. In applying these data to specific design problems, onsite observations and additional data should be used to confirm or correct the information provided by this report.

BEDLOAD DISCHARGE

Bedload discharge can be estimated by several computational procedures, all of which utilize empirical relations among the size distribution of bed material, the physical characteristics of the stream channel, and the laws of hydraulics. In this report the Meyer-Peter and Muller equation, as modified by the U.S. Bureau of Reclamation (1960), was used. The equation is

$$G_s=1.606B\left[3.306\left(\frac{Q_s}{Q}\right)\left(\frac{D_{90}^{1/6}}{n_s}\right)^{\frac{3}{2}}dS-0.627D_m\right]^{\frac{3}{2}},$$

where

G_s=total bedload discharge, in tons per day.
B=bottom width of the stream channel, in feet.
Q_s=the water discharge that transports a specific bedload, in cubic feet per second.[1]
Q=total water discharge, in cubic feet per second.
D_{90}=particle size at which 90 percent of the bed material is finer, in millimeters.
n_s=Manning n value for the streambed.
d=depth of flow, in feet.
S=slope of the energy gradeline, in feet per foot.
D_m=effective size of bed material, in millimeters.

[$D_m=\frac{\Sigma D\Delta p}{100}$ where D is the geometric mean diameter of particles in a given size fraction and p is the percent by weight in that size fraction.]

The parameters of the size of bed material were determined from samples collected at three stations where the data defining channel and hydraulic parameters were available. Bedload discharge was computed for a variety of flow conditions, and this information was used to derive the transport curves of bedload shown in figure 5. The mean annual movement of bedload was computed in the same manner as the movement of suspended sediment was; that is, by use of the transport curves and the daily duration curves of the streams in question. The estimates of bedload transport at the three stations and at two additional locations in the study area (Stony Creek and Cache Creek where computations were previously made for use in another report) are summarized in table 4. Bedload yield of the basins ranged from 13 to 211 tons per square mile, and the bedload constituted 2–7 percent of the total sediment transported from the basins studied.

As has been mentioned, the several formulas that investigators have used for the computation of bedload transport differ from each other. One formula may be especially sensitive to variations in a particular characteristic of channel geometry, of streamflow regimen, or of particle-size distribution, and other formulas may be sensitive to other characteristics. In addition, measurements used in the computations are from only one site (or at most a limited number of sites) in each basin. For this reason bedload transport values computed from

[1] That is, total discharge except for the flow that has its carrying capacity associated with the banks of the channel rather than with the bed.

these formulas are imprecise; however, they do serve to indicate the relative magnitudes of materials moved as bedload.

VOLUME OF DEPOSITED SEDIMENT

When planning impoundments or other works of hydraulic engineering, the designer must be concerned with the quantity of storage space or flowage area which may be lost because of the deposition of sediment. In this report, therefore, the deposited unit weights and, from those, the deposited volumes of the sediment transported past

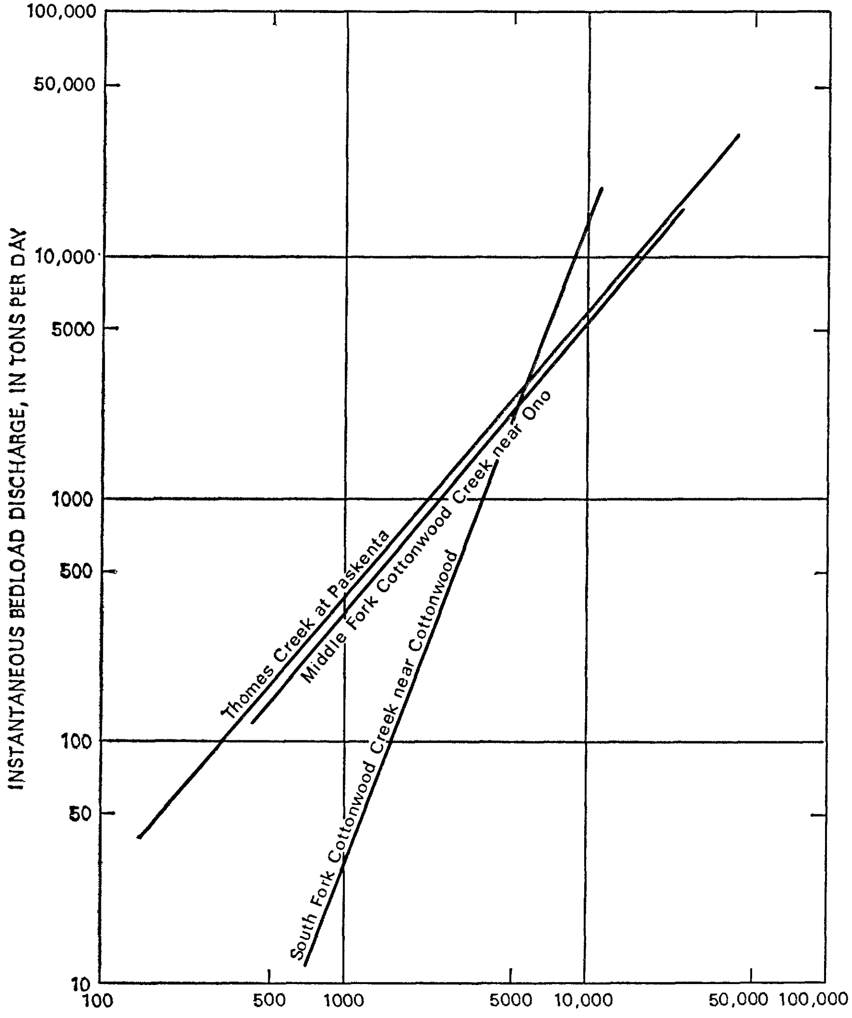

FIGURE 5.—Transport curves of bedload discharge at selected measuring sites.

the measuring sites were computed by use of a method described by Lara and Pemberton (1965). The initial unit weight of the deposited material was calculated from data on the relative percentages of clay, silt, and sand, using coefficients for each classification under assumed conditions of reservoir operation whereby the sediment is always or nearly always submerged (type I operation, in the Lara and Pemberton method). The equation used for deposited weight was

$$V=26\,P_c+70\,P_m+97\,P_s,$$

where P_c, P_m, and P_s are the percentage clay, silt, and sand, respectively, and V is the unit weight after deposition. Also unit weights were computed by using a relation based upon median particle size, which was developed by Welborn (1967). The results of the two methods agreed closely.

TABLE 4.—*Annual discharge of sediment as bedload in the study area*

Station		Average annual bedload discharge: Tons	Average annual bedload discharge: Tons per sq mi	Bedload as percentage of total transported sediment
11-3744	Middle Fork Cottonwood Creek near Ono.	25,000	100	7
11-3758.2	South Fork Cottonwood Creek near Cottonwood.	3,300	15	3
11-3820	Thomes Creek at Paskenta	41,000	211	6
11-3880	Stony Creek at Black Butte damsite near Orland.	[1] 9,800	13	2
11-4525	Cache Creek at Yolo	[2] 77,000	[3] 126	6.3

[1] From Knott and Dunnam (1969), adjusted to 1941-65 flow regimen.
[2] From Lustig and Busch (1967, p. A30), adjusted to 1941-65 flow regimen.
[3] Assuming no bedload from the 528 square miles of the basin tributary to the outlet of Clear Lake.

The average annual volume occupied by suspended sediment if it were deposited in reservoirs is shown in table 5. Deposited volumes of bed material were not computed; however, we can reasonably postulate that the bedload has a unit weight of perhaps 100 pounds per cubic foot. Therefore, a given weight of deposited bedload may occupy 0.6–0.8 of the volume occupied by an equivalent weight of deposited suspended sediment; from this, we can make a reasonable estimate of the deposited volume. Bedload weight in the study area ranged from 2 to 7 percent of the weight of suspended sediment; corresponding deposited volumes range from 1 to 6 percent of the volume of deposited suspended sediment. Judging from the data of the study area, at most locations the volume of deposited bedload would be less than 5 percent of the volume of deposited suspended sediment.

TABLE 5.—*Sediment measured at sampling sites: particle size, unit weight, and volume after deposition*

[Definition of terms: Clay=less than 0.004 mm; silt=0.004–0.062 mm; sand=0.062–2.0 mm; granules=2.0–4.0 mm; pebbles=4.0–64 mm]

Station	Particle size								Suspended sediment	
	Bed material				Suspended material					
	Percent				Percent					
	Pebbles	Granules	Sand	Median diameter (mm)	Sand	Silt	Clay	Median diameter (mm)	Computed unit weight (pounds per cubic foot)	Computed mean annual deposited volume, in acre-feet per square mile of drainage area
Clear Creek at French Gulch					23	41	36	0. 010	60	0. 13
Middle Fork Cottonwood Creek near Ono	65	16	19	6. 20	36	34	30	. 022	67	. 72
South Fork Cottonwood Creek near Cottonwood	47	11	42	3. 40	43	34	23	. 028	71	. 68
Cottonwood Creek near Cottonwood					15	44	41	. 007	56	. 72
Red Bank Creek near Red Bluff					18	53	29	. 012	62	. 63
Elder Creek near Paskenta	54	17	29	4. 50	24	51	25	. 011	65	. 95
Thomes Creek at Paskenta	41	18	41	2. 80	44	35	21	. 040	73	2. 12
Stony Creek at Black Butte damsite, near Orland					15	42	43	. 009	55	. 63
Stone Corral Creek near Sites					8	13	79	. 001	37	. 12
North Fork Cache Creek near Lower Lake	59	15	26	6. 00	30	42	28	. 022	66	. 76
Bear Creek near Rumsey	66	17	17	6. 20	12	35	53	. 004	50	. 57
Cache Creek above Rumsey					20	43	37	. 009	59	. 72
Cache Creek near Capay					22	41	37	. 009	60	. 85
Cache Creek at Yolo	45	13	42	3. 20	19	39	42	. 007	57	. 82
Putah Creek near Guenoc					26	44	30	. 014	64	. 83

DISCUSSION AND CONCLUSIONS

The available data indicate that the average annual suspended-sediment yield in the study area ranges from less than 100 to more than 3,000 tons per square mile. There seems to be a tendency toward a positive correlation of yield with precipitation and runoff; for example, the lowest computed sediment yield was from the basin having the least runoff (Stone Corral Creek). Thomes Creek and North Fork Cache Creek both have high runoff, and both are heavy sediment producers. However, the upper basin of Clear Creek has high runoff but low yield. Obviously, factors other than precipitation and runoff are involved. It seems reasonable to postulate that among these factors are: the presence or lack of sources of erodible material together with protective plant development, the nature of the topography of the basin, the regimen of precipitation, and the regimen of runoff.

The highest suspended-sediment yields in the study area come from basins draining the Coast Ranges province, particularly from the basins underlain by sedimentary rocks of the Franciscan Formation.

Data were available to enable computation of the bedload discharge at five sites in the study area. Bedload at these sites was found to range from 13 to 211 tons per square mile of basin area, and it represented 2–7 percent of the total transported sediment. Bedload is a function of the hydraulics of the stream in question as well as of the material available for movement; changes in the flow regimen of a stream can therefore cause great changes in the quantity of material the stream will transport as bedload. Under the natural conditions observed in this study and in others, it seems that bedload from many basins may be assumed to be usually 2–7 percent of the load carried in suspension.

The material carried in suspension by the study streams was found to have potential volumes, when deposited, ranging from 0.1 to 2.1 acre-feet per year per square mile of contributing area. Most streams in the central part of the study area transport large enough quantities of material so that the effect of sediment deposition may be important to engineering design. Lower sediment yields occur in the foothills and plains of the Great Valley of California province and in crystalline rocks of the Klamath Mountains province. In areas of low yield, the deposited volume of sediment may not be an engineering problem; however, knowledge of the characteristics of size distribution of suspended sediment may be important, as particle size is closely associated with the occurrence of persistent turbidity.

Two attributes of the regimen of sediment transport in the study area are strongly linked with regional characteristics of the precipitation regimen:

1. There is great variation from year to year. For example, in 1965, a wet year, about 800,000 tons of suspended sediment passed the station on North Fork of Cache Creek, or more than 3.5 times the average annual quantity. In contrast, the quantity transported during 1961, a dry year, was less than 7 percent of the average; the 1965 load was thus more than 50 times the 1961 load.
2. Much of the erosion (and the ensuing transport of sediment) occurs during short periods of time. In most of the study area, 90 percent of the sediment is transported during only 3 percent of the time, and this occurs during the rainy period from October to April.

The total annual production of suspended sediment of the entire study area can be estimated on the basis of the available data. In the total area from which the data were obtained (about 4,000 sq mi), sediment yield averages about 4.2 million tons annually. Of this about 1.3 million tons is trapped in four lakes if their trap efficiency is assumed to be about 90 percent. For the remaining part of the study area, about 3,100 square miles, there are no data. Judging from topographic and geologic similarities with measured areas, perhaps 600 square miles of this can be considered to yield relatively high quantities of sediment and the remaining 2,500 square miles to yield low quantities. Assigning arbitrary but reasonable values of 400 tons per square mile as high annual yield and 100 tons per square mile as low annual yield, the average annual yield of the 3,100 square miles is about 500 thousand tons; therefore, the total annual yield of the region averages about 4.7 million tons, of which about 3.4 million tons are transported to the Sacramento River.

The short period of record and the limited areal coverage of sediment data in the study area permitted only broad generalizations in the definition of source areas. It must be recognized that the computed mean annual yields are sufficiently accurate for design purposes only at locations that are in the vicinity of data collection sites. For estimates of sediment yields at other locations, the information in this report should be supplemented by additional sediment data, and conditions in the project area should be compared to known transport conditions in similar and adjacent basins. The systematic collection of suspended-sediment data, over relatively long periods of time, can provide vastly improved estimates of sediment yield from project areas.

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