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SEDIMENT TRANSPORT IN THE FEATHER RIVER, LAKE OROVILLE TO YUBA CITY, CALIFORNIA

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WATER-RESOURCES INVESTIGATIONS 78-20

PREPARED IN COOPERATION WITH THE
CALIFORNIA DEPARTMENT OF WATER RESOURCES

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Feather River

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For additional information write to:

District Chief
Water Resources Division
U.S. Geological Survey
345 Middlefield Rd.
Menlo Park, Calif. 94025

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CONVERSION FACTORS

English units are used in this report. For the benefit of readers who prefer metric units, the conversion factors for the terms used herein are listed below:

Multiply English unit	*By*	*To obtain metric unit*
acre-ft (acre-feet)	1.233×10^{-3}	hm^3 (cubic hectometers)
acre-ft/mi (acre-feet per mile)	7.663×10^{-4}	hm^3/km (cubic hectometers per kilometer)
(acre-ft/mi^2)/yr (acre-feet per square mile per year)	4.762×10^{2}	(m^3/km^2)/yr (cubic meters per square kilometer per year)
acre-ft/yr (acre-feet per year)	1.233×10^{-3}	hm^3/yr (cubic hectometers per year)
ft (feet)	3.048×10^{-1}	m (meters)
ft/mi (feet per mile)	1.894×10^{-1}	m/km (meters per kilometer)
ft/s (feet per second)	3.048×10^{-1}	m/s (meters per second)
ft^2 (square feet)	9.290×10^{-2}	m^2 (square meters)
ft^3/s (cubic feet per second)	2.832×10^{-2}	m^3/s (cubic meters per second)
(ft^3/s)·d (cubic feet per second-day)	2.447×10^{3}	m^3 (cubic meters)
lbs/ft^3 (pounds per cubic ft)	1.602×10^{1}	kg/m^3 (kilograms per cubic meter)
mi (miles)	1.609	km (kilometers)
mi^2 (square miles)	2.590	km^2 (square kilometers)
tons (short)	9.072×10^{-1}	Mg (megagram)
ton/d (tons per day)	9.072×10^{-1}	Mg/d (megagram per day)
ton/yr (tons per year)	9.072×10^{-1}	Mg/yr (megagram per year)
ton/ft (tons per foot)	2.976	Mg/m (megagram per meter)
ton/mi^2 (tons per square mile)	3.503×10^{-1}	Mg/km^2 (megagram per square kilometer)
(ton/mi^2)/yr (tons per square mile per year)	3.503×10^{-1}	(Mg/km^2)/yr (megagram per square kilometer per year)
yd (yards)	9.144×10^{-3}	hm (hectometer)
yd^3 (cubic yards)	7.646×10^{-7}	hm^3 (cubic hectometers)

Abbreviations used:

mg/L (milligrams per liter)
mm (millimeters)
°C (degrees Celsius)

SEDIMENT TRANSPORT IN THE FEATHER RIVER, LAKE OROVILLE TO YUBA CITY, CALIFORNIA

By George Porterfield, R. D. Busch, and A. O. Waananen

ABSTRACT

Regulation of the Feather River by Oroville Dam (beginning in 1967) changed the streamflow and sediment discharge downstream from the dam. Changes in channel geometry to adjust to the new regimen were still in process in 1975. Streamflow and sediment concentration and discharge had decreased. Median streamflow at Feather River near Gridley and Feather River at Yuba City, 27 miles and 49 miles downstream from the dam, had not changed, although the frequency of flow rates less than median increased and the frequency of flow rates greater than median, and which transport most sediment, decreased.

An estimated average total sediment discharge of 3,730 tons is trapped daily by Oroville Dam. This was the amount of material historically (1902-62) furnished to the channel downstream from the dam, and it influenced channel morphology. Surveys of selected channel cross sections downstream from Oroville Dam indicate net scour since 1911 and an apparent increase in rate of scour in the period 1965-70. Sediment- transport data indicate an increase in sediment yield (tons per square mile) from the 1965-67 period to the 1968-75 period in the basin downstream from Gridley to Yuba City, although the quantity of sediment transported was reduced owing to removal of sediment by storage behind Oroville Dam and to reduced streamflow. The increase in yield, assuming no change in tributary inflow, may be attributed partly to channel erosion accelerated by the clear-water releases and partly to the change in frequency and magnitude of flow rates.

The relation between water and sediment discharge (sediment-transport curve) changed at Gridley because of a decrease in sediment concentration during larger streamflow rates and an increase in sediment concentration during smaller streamflow rates. A trend analysis of sediment concentration for larger streamflow rates shows a continued declining trend in the quantity of fine material transported in suspension, although no declining trend is indicated for the suspended-sand fraction of suspended sediment. The relation between water and sediment discharge at Yuba City indicates that the concentration of suspended sediment has not decreased significantly during larger streamflow rates, and no change is apparent during smaller streamflow rates. A trend analysis shows no trend, to date, toward a decreasing concentration of suspended sediment nor toward a decrease in the sand fraction of the suspended sediment.

Changes in mean values of width, depth, and velocity of flow--hydraulic geometry--at Feather River near Gridley indicate a general decrease in the competence of the Feather River at Gridley to transport suspended sediment and an increase in competence to transport bedload. Changes at Feather River at Yuba City indicate that competence to transport suspended sediment, including the sand fraction of suspended sediment, has increased.

INTRODUCTION

The Feather River is a major stream in California. Tributaries drain the northern Sierra Nevada and join near Oroville (fig. 1) to form the main stream. Downstream from Oroville the Feather River discharges onto the generally flat and featureless floor of the Sacramento Valley at an elevation less than 150 ft above msl (mean sea level) and flows southerly about 55 mi to the Sacramento River at Verona.

Lake Oroville (fig. 1), formed on the river by Oroville Dam 4.2 mi east of Oroville, has a storage capacity of 3,538,000 acre-ft of water and is a key feature of the long-range California water plan.

Historically, sediment eroded and transported by the Feather River tributaries has been deposited in the lower reaches of the Feather River basin or discharged to the Sacramento River. The Feather River and numerous other tributaries of the Sacramento River are the sources of sediment deposited in the low-lying parts of the Sacramento Valley, and this sediment is one of the key factors responsible for the morphology of the lower reaches of that stream.

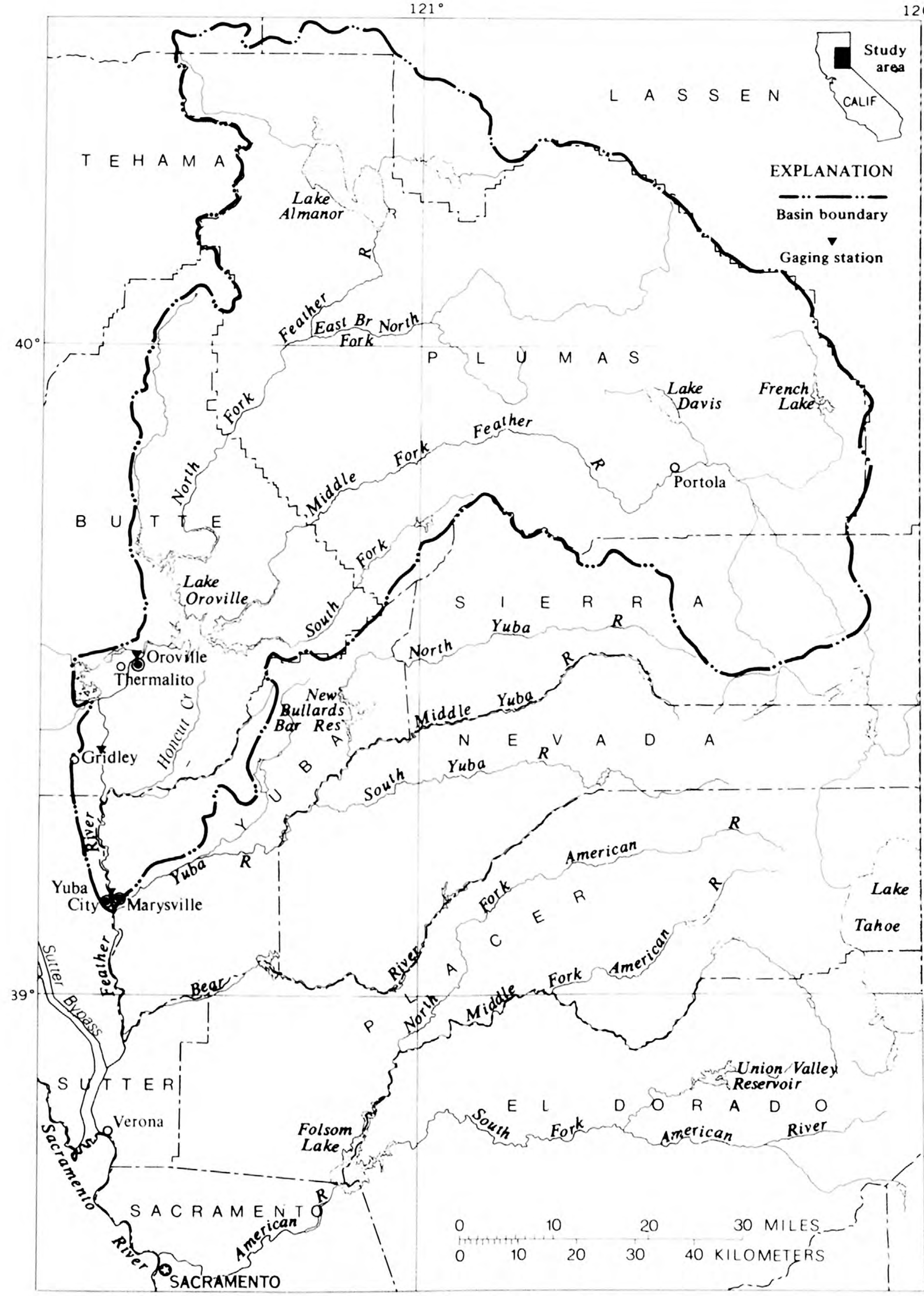


FIGURE 1.--Report area.

The construction of dams and impoundments on streams affects the natural patterns of sediment transport. The entrapment of sediment by a reservoir affects the potential useful life of the reservoir; but, further, the combination of sediment entrapment and flow modification downstream by diversions or by alteration of flow rates affects the stream channels downstream. The distribution and pattern of streamflow and the quantity and grain size of sediment transported are major factors influencing river morphology. The transport capabilities of the flows discharged to downstream channels may cause scour or deposition of sediment and corresponding channel changes as the streams adjust to the modified flow conditions. Thus, the construction of Oroville Dam and the formation of a large reservoir such as Lake Oroville, completed in 1968, caused significant changes in the characteristics of the flow downstream. The effects of these changes may continue over an extended period of time.

The U.S. Geological Survey, in cooperation with the California Department of Water Resources, began to collect sediment data for the Feather River at Oroville in November 1956 to obtain information for estimating the effect of sediment inflow on the life and operation of the proposed Oroville reservoir. Data collection for the Feather River near Gridley and at Yuba City began in October 1964 to document pre-dam streamflow, sediment transport, and channel conditions downstream and to estimate the effect of planned flow releases from Lake Oroville on the channel. The California Department of Water Resources obtained data on the stream profile and geology of selected cross sections in the reach downstream from Gridley in the period 1965-70.

The purpose of this report, prepared in cooperation with the California Department of Water Resources, is to present a summary of data obtained by the Geological Survey and to evaluate changes and trends in sediment transport and channel geometry since completion of Oroville Dam. Information on such changes provides a basis for evaluating the effects of the reservoir operation on the channel downstream.

PHYSIOGRAPHY

The Feather River, a major tributary of the Sacramento River, is formed by the confluence of the Middle Fork and South Fork Feather Rivers 5.4 mi upstream from Oroville Dam, and 11 mi upstream from the gaging station at Oroville. The North Fork Feather River joins the Feather River 3 mi downstream. All three tributaries flow into Lake Oroville.

The North, Middle, and South Forks of the Feather River flow generally southwestward. These tributaries have steep slopes and flow mostly in narrow, deeply incised canyons. The Middle Fork Feather River canyon, about 27 mi upstream from Oroville, has walls that rise more than 2,000 ft above the streambed and that slope about 0.9 ft/ft. The river slope at this point is 0.0125 ft/ft, or 66 ft/mi. The South Fork Feather River canyon, about 28 mi upstream from Oroville, has walls that rise more than 1,000 ft above the streambed and that slope about 0.75 ft/ft. The river slope at this point is 0.067 ft/ft, or 354 ft/mi. Basin elevation is 135 ft at Oroville, 35 ft at Yuba City, and 10,453 ft at Lassen Peak in the southern Cascade Mountains. Selected physiographic data for the Feather River upstream from Yuba City are listed in table 1, and profiles of the Feather River and principal tributaries are shown in figure 2. Selected physiographic data for these tributaries are in table 2.

The Feather River leaves the Sierra Nevada foothills at Oroville, flows for about 8 mi southwestward in a flat-bottomed, terraced valley, and turns sharply to flow almost due southward to join the Sacramento River at Verona.

The slope of the river channel decreases abruptly as the river leaves the foothills and enters the Sacramento Valley; thus, the river velocity is decreased and sediment deposition is accelerated. The Sacramento Valley is a broad structural trough that contains rocks ranging in age from Early Cretaceous to Holocene. Continental deposits of post-Eocene age and ranging in thickness from almost zero near the margins of the valley to about 3,500 ft beneath the south-central part (Page, 1974, p. 1) contain fresh water. The continental deposits underlying the Feather River from near Gridley to Yuba City range from about 400 to 1,200 ft in thickness (Page, 1974, p. 7).

Discovery of gold 7,000 ft downstream from the confluence of the Middle and South Forks in 1848 started placer and hydraulic mining in the Feather River basin. Debris from hydraulic mining subsequently caused a great increase in the quantity of material available for transport by the river and affected its geometry between Oroville and Yuba City. Gilbert (1917, p. 47) estimated mining deposits in the Feather River basin within the Sierra Nevada as 15,000,000 yd^3 and quoted an estimate by W. H. Hall (California State Eng. Rept. for 1880, p. 10-11) that piedmont deposits were 18,256,222 yd^3. The piedmont deposits on the Feather River start at the canyon mouth at Oroville and extend downstream about 25 mi, ending in the slack water caused by the debris brought to the Feather by the Yuba River.

From Oroville to Gridley the Feather River flows through a flood plain of loamy soil underlain by coarse gravel. The flood plain has been greatly changed by gold dredging that piled up great mounds of gravel and completely changed the local topography. The gravel mounds also stabilize the streambanks and serve as levees to contain some floodflows. Large quantities of gravel were mined from areas adjacent to the river for use in the construction of Oroville Dam. These areas now make up part of the Oroville Wildlife Area.

TABLE 1.--*Selected physiographic data for the Feather River*

Location	Drainage area[1] (mi^2)	Elevation above mean sea level (ft)	Intervening reach			Distance upstream from Yuba City gage (1,000 ft)
			Change in altitude (ft)	Length (1,000 ft)	Slope (ft/ft)	
Confluence Middle Fork and South Fork Feather Rivers	--	330	--	--	--	288
Confluence North Fork Feather and Feather Rivers	--	230	100	15	0.0067	273
Oroville Dam	3,607	210	20	13.5	.0015	259.5
Feather River at Oroville gage	3,624	135	75	29	.0026	230.5
Feather River near Gridley gage	3,676	80	55	113	.00049	117.5
Feather River at Yuba City gage	3,974	35	45	117.5	.00038	0

[1]609 mi^2 of the basin upstream from Feather River at Oroville are assumed to be noncontributing.

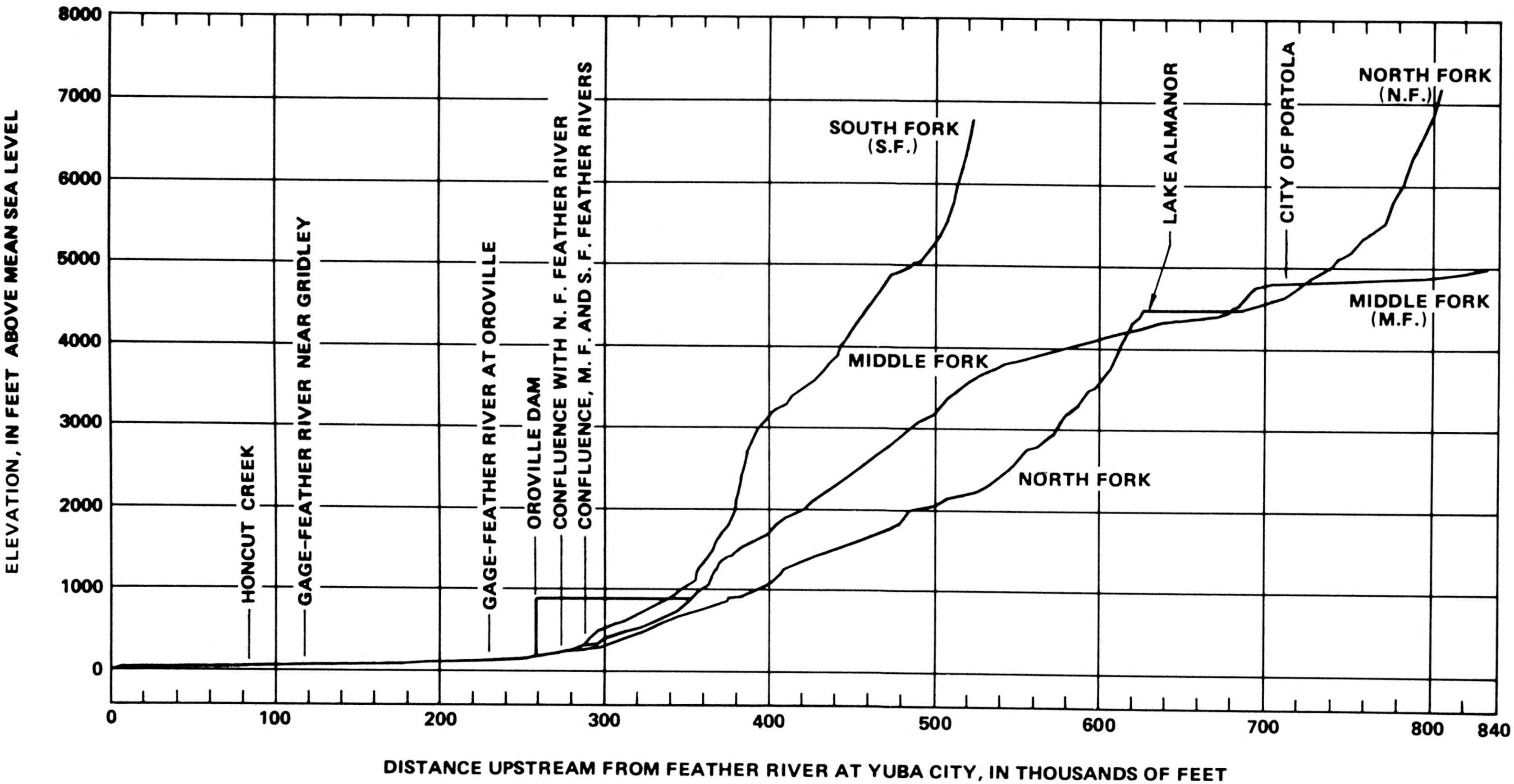


FIGURE 2.--Profiles of Feather River and principal tributaries upstream from Yuba City.

TABLE 2.--*Physiographic data for principal Feather River tributaries*

Stream	Elevation above mean sea level (approximate)		Length (thousands of feet)	Mean slope (ft/ft)
	Minimum (ft)	Maximum (ft)		
North Fork Feather River	230	7,200	531	0.0131
Middle Fork Feather River	330	5,000	548	.0085
South Fork Feather River	330	6,800	234	.0276

From Gridley to Yuba City the Feather River meanders between both artificial and natural levees. The slope of the river decreases and the material in the bed becomes finer downstream. Honcut Creek, which rises in the foothills of the Sierra Nevada, enters the Feather River 16 mi upstream from Yuba City. The Yuba River, which drains more than 1,340 mi^2 of the Sierra Nevada, enters the Feather River 0.7 mi downstream from the Feather River gaging station at Yuba City. Although the Yuba River enters the Feather River below the study area, it is significant because backwater during high flows affects the relation between depth of flow and water discharge in the Feather River at Yuba City and reduces the stream velocity, which in turn reduces the competence of the river to transport sediment. Gilbert (1917, p. 28, 47, 52) noted that the piedmont deposit of the Yuba River (because of hydraulic mining) was the largest single body of mining debris outside of the bays (San Francisco Bay system) and that this deposit extended to and was continuous with deposits in the Feather River.

STREAMFLOW AND SEDIMENT DATA

Streamflow and suspended-sediment data are available for many sites in the Feather River basin. An inventory of streamflow data for California through September 30, 1970, was listed by the U.S. Geological Survey (1971), and an inventory of sediment data through September 30, 1970, was given by Porterfield (1972a). A summary of data at the three sites on the Feather River used in this study is given in table 3.

Streamflow data for the gaging station Feather River at Oroville have been available since October 1901. Data for Feather River near Gridley since January 1944 and Feather River at Yuba City since July 1964 have been collected by the California Department of Water Resources; data prior to October 1964 were published in reports of that agency.

TABLE 3.--*Summary of water and sediment discharge for selected periods at three sites on the Feather River*

Station			Period of record		Water discharge (ft^3/s)			Suspended-sediment discharge				
Number	Name	Location	Water years	Number of years	Maximum day	Minimum day	Daily mean	Maximum day (tons)	Minimum day (tons)	Daily mean: Tons	Daily mean: Ton/mi^2 [1]	Average water-weighted concentration (mg/L)
11407000	Feather River at Oroville	Lat 39°31'18" Long 121°32'48"	1902-67	66	187,000	577	5,834					
			1902-62	61	187,000	577	5,790			[2]3,264	[2]1.083	[2]209
			1957-62[3]	6	95,800	872	4,918	365,000	3.0	1,142	.379	86
			1965-67	3	156,000	704	6,921	711,000	7.6	3,669	1.217	196
			1968-75	8	53,300	222	1,062	7,660	.6	42.5	2.50	15
			1974-75	2	37,300	369	1,213	1,110	1.1	23.6	1.39	7
11407150	Feather River near Gridley	Lat 39°22'00" Long 121°38'46"	1965-67	3	149,000	117	5,970	409,000	1.4	3,355	1.094	208
			1968-75	8	71,800	366	5,521	42,100	2.4	280	4.06	19
			1974-75	2	54,000	1,100	7,438	3,930	21	278	4.03	14
11407700	Feather River at Yuba City	Lat 39°08'20" Long 121°36'17"	1965-67	3	156,000	166	6,325	334,000	12	3,806	1.131	223
			1968-75	8	74,500	410	5,889	54,100	18	1,815	4.95	114
			1974-75	2	55,300	1,250	7,905	35,800	56	2,432	6.63	114

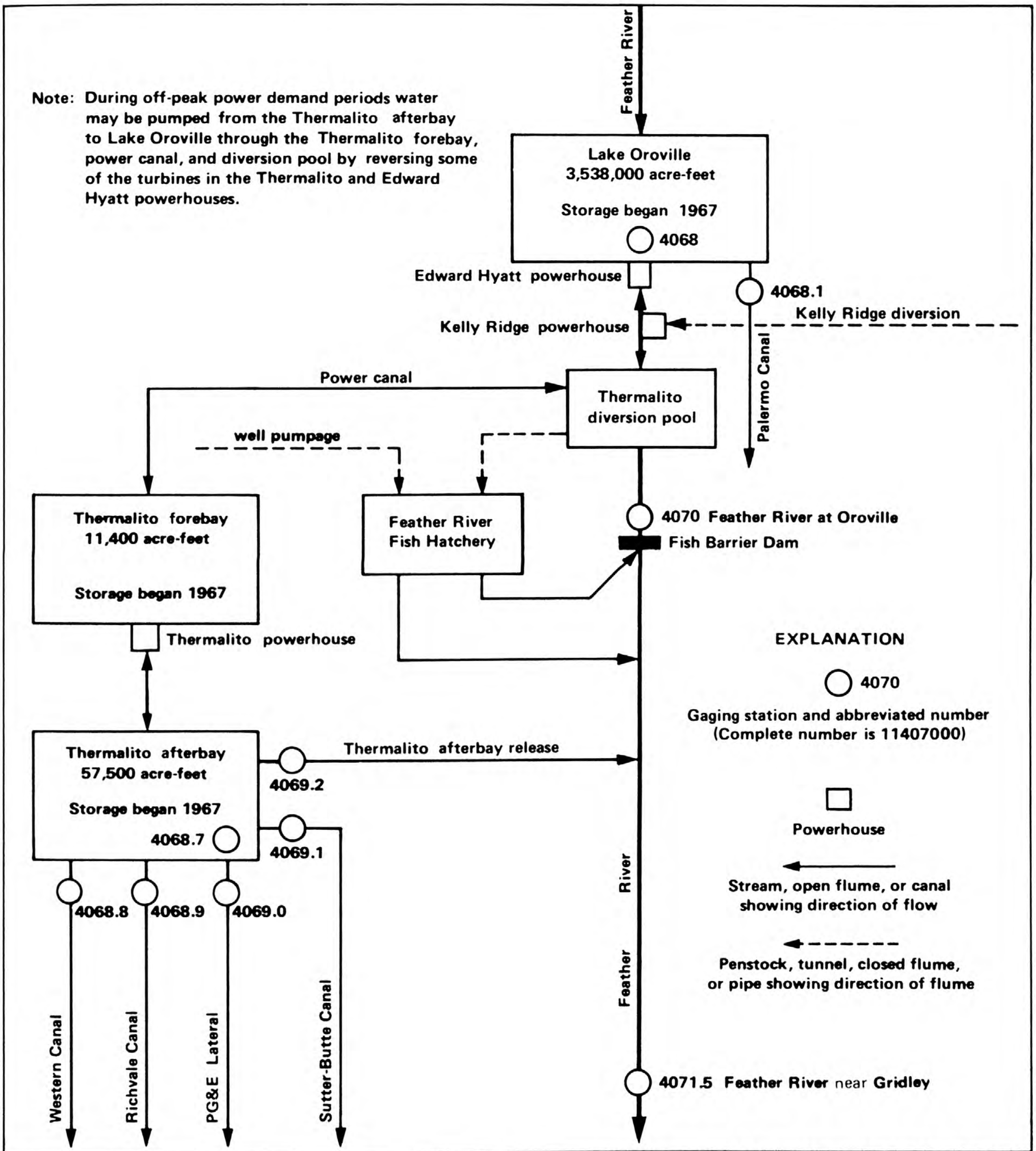
[1]After 1968 the effective drainage area is assumed to be equal to the area downstream from Oroville Dam.
[2]Estimated.
[3]Does not include October 1956.

Collection of suspended-sediment data began in November 1956 for Feather River at Oroville and in 1956 and 1957 for selected sites in the upper Feather River basin to determine the effect of sediment transported by the river on the life and operation of Lake Oroville. Data collection began in October 1964 for Feather River near Gridley and at Yuba City to determine changes in regimen downstream resulting from the construction and operation of Oroville Dam. These data include depth-integrated suspended-sediment samples collected daily, or more often, at Oroville, Gridley, and Yuba City during periods of storm runoff and 2 to 5 days each week during periods of low, clear flow. A description of sampling equipment and methods is found in Guy and Norman (1970, p. 5-19) and U.S. Inter-Agency Committee on Water Resources (1963). Daily values of sediment discharge were computed by methods described by Porterfield (1972b), and are published annually by the U.S. Geological Survey.

Total sediment discharge in Feather River near Gridley was determined from data obtained at selected intervals from October 1964 to May 1965. These data included samples of bed material and provided the information needed to appraise bed-material movement and to compute unsampled sediment discharge by a method described by Colby and Hembree (1955). During this period the California Department of Water Resources constructed river profiles and geologic sections in the reach downstream from Gridley.

OROVILLE DAM AND LAKE OROVILLE

Oroville Dam is on the Feather River 5.5 river mi upstream (east) from Oroville. Construction began on the embankment of this earthfill dam in July 1962, and the concrete chute-type sidehill spillway was completed May 13, 1968. Storage in Lake Oroville began November 14, 1967, although temporary detention of Feather River flow and attenuation of flood peaks occurred at times during dam construction, notably during the December 1964 flood. Lake Oroville has a usable capacity of 2,686,000 acre-ft between elevation 640.0 ft and the normal maximum pool elevation of 900.0 ft. Total capacity at normal maximum pool elevation is 3,538,000 acre-ft. Water is released from the lake to the Feather River through a powerhouse by way of a penstock in the left abutment of the dam and to Palermo Canal through a concrete tunnel also in the left abutment. Thermalito diversion dam, 0.4 mi upstream from the Feather River gage at Oroville, diverts part of the flow through the Feather River Fish Hatchery and part into the Thermalito forebay for power generation. Flow through the fish hatchery is returned to the river downstream from the Oroville gage. Part of the flow into the Thermalito forebay is returned to the river downstream from Oroville and part is diverted into a series of canals. Power-generating turbines at Thermalito and at Oroville powerhouses may be reversed, and some water is pumped upstream during periods of low power demand and reused to generate power during peak-demand periods. A schematic diagram (fig. 3) shows diversions from and storage in the Feather River at Lake Oroville.



Modified from U.S. Geological Survey, (1973, fig. 13).

FIGURE 3.--Schematic diagram showing diversions from and storage in Feather River at Lake Oroville.

Effects of Sediment on Reservoirs

The useful life of a reservoir depends on the rate and distribution of storage capacity lost, which in turn depends on the quantity and distribution of sediment brought into the reservoir. Sediment-transport data provide the information needed to estimate the number of years before sediment deposits will interfere with reservoir operation and the period before the useful life of the reservoir will be terminated. The distribution of sediment, in addition to the volume of deposited sediment, may shorten the life or reduce the operating potential of the reservoir. Sediment may deposit in the upper end of a reservoir and deplete the storage capacity between certain elevations of a useful operating pool. Factors controlling the distribution of sediment in a reservoir include reservoir operation, reservoir shape, wave action, capacity of the reservoir in relation to quantity of inflow, density currents, and the grain size of the sediment entering the reservoir. Additional factors associated with distribution of sediment in a particular reservoir are narrow necks within the reservoir area, vegetation in the delta areas, heavy sediment contribution by streams entering the reservoir area, and the water-surface elevation at the time of maximum sediment inflow.

All sediment entering a reservoir may not be deposited there. The quantity of deposited material represents the difference between total sediment inflow and the sediment that passes through the reservoir. The ratio of the deposited sediment to sediment inflow, expressed in percentage, is defined as the trap efficiency. Trap efficiency is dependent on factors such as basin and reservoir shape, method of operation and type of outlets, ratio of capacity to inflow, density currents, and particle-size distribution of sediment entering the reservoir. Brune (1953) developed a relation between capacity-inflow ratio and trap efficiency after analyzing factors affecting trap efficiency for 44 reservoirs. On the basis of his results the trap efficiency of a reservoir with a capacity-inflow ratio similar to Lake Oroville should range from 94.5 to 100 percent with a mean value of about 96 percent. This value is for a normal ponded reservoir which Brune defines as a conventional reservoir, as distinguished from desilting basins and dry reservoirs, and operated without any special efforts to sluice sediment (via density currents through the reservoir). Because of the large potential trap efficiency of Lake Oroville, the trap efficiency is assumed to be 100 percent and no adjustments are made to estimated sediment deposition in the reservoir nor to sediment transport downstream from Lake Oroville.

Sediment Inflow to Lake Oroville

The impact of sediment inflow on Lake Oroville can be determined by a study of sediment records and updated by periodic reservoir surveys. Sediment-inflow quantities determined from daily samples of suspended sediment generally are more accurate for a stream the size of the Feather River than those determined from reservoir surveys; however, distribution of sediment in a reservoir is more accurately determined from a reservoir survey.

Suspended-sediment inflow to the Lake Oroville site from November 1956 to September 1962 can be determined from published records of sediment discharge for Feather River at Oroville. Sediment data collected during the period June 1962 to the beginning of storage November 14, 1967, were affected by construction and therefore are not representative of the probable long-term sediment inflow to Lake Oroville. A method for estimating the long-term sediment discharge, based on 1956-62 sediment data and the 1902-62 streamflow record (Jorgensen and others, 1971), is described in the following paragraphs.

The relation between daily values of suspended sediment and water discharge (the sediment-transport curve) is shown in figure 4. Each point on the curve represents the average value of suspended-sediment discharge for the small range of water discharge shown in the suspended- sediment computations shown in table 4. Average values of water discharge (col. 4) and suspended-sediment discharge (col. 5) are those shown in figure 4. This group-averaging procedure yields results superior to those from the "flow-duration, sediment-transport curve" method, although the basic assumptions are similar for both procedures. The transport curve, based on group averages, more nearly approximates the relation between water and sediment discharge and is superior to a straight line relation (logarithmic plotting) derived from a visual fit or by a least squares regression fit, because the relation is seldom linear except for small ranges in water discharge. The accuracy with which the transport curve (fig. 4) represents the 1957-62 data may be determined by comparing sediment discharge computed from the curve with published discharge. The difference, or error, is 1.2 percent.

The relation between suspended-sand discharge and water discharge (fig. 4) is based on group averages of suspended-sand transport determined by particle-size analyses of selected samples of suspended sediment.

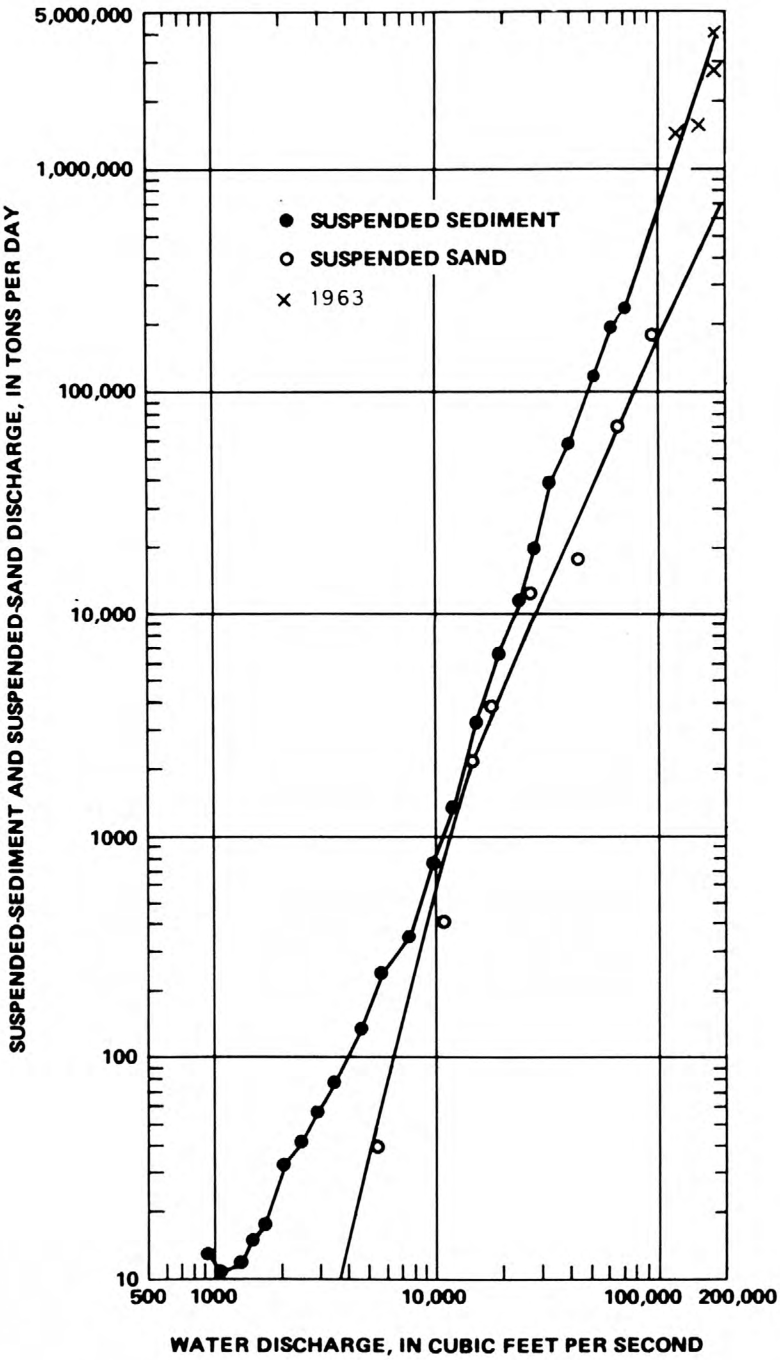


FIGURE 4.--Relation between streamflow and suspended-sediment and suspended-sand discharge, Feather River at Oroville, 1957-62 water years.

TABLE 4.--*Computation of suspended-sediment discharge, Feather River at Oroville, 1902-62 water years*

Lower limit of discharge range (ft³/s)	Number of days discharge in range		Average water discharge (ft³/s)	Average suspended-sediment discharge (ton/d)	Average suspended-sand discharge (ton/d)	Suspended-sediment discharge (tons)		Suspended-sand discharge (tons)	
	1957-62	1902-62	1957-62	1957-62	1957-62	1957-62	1902-62	1957-62	1902-62
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
0	0	0	0	0	0				
577	0	23	[1]630	[1]5	.01		115		0.23
690	0	54	[1]750	[1]7	.02		378		1.1
810	4	206	943	13	.04	52	2,680	0.16	8.2
970	63	627	1,080	11	.07	693	6,900	4.4	44
1,200	60	933	1,310	12	.16	720	11,200	9.6	149
1,400	80	1,411	1,500	15	.28	1,200	21,200	22	395
1,600	169	2,498	1,700	18	.47	3,040	45,000	79	1,170
1,900	239	3,042	2,080	33	1.0	7,890	100,000	239	3,040
2,300	307	2,034	2,500	42	2.1	12,900	85,400	645	4,270
2,700	290	1,627	2,920	56	3.9	16,200	91,100	1,130	6,350
3,200	145	1,083	3,530	77	8.3	11,200	83,400	1,200	8,990
4,600	288	1,798	4,680	133	26	38,300	239,000	7,490	46,700
5,400	121	1,026	5,920	242	70	29,300	248,000	8,470	71,800
6,500	136	1,835	7,630	355	190	48,300	651,000	25,800	349,000
9,100	58	939	9,960	763	570	44,300	716,000	33,100	535,000
11,000	47	773	12,100	1,340	1,100	63,000	1,040,000	51,700	850,000
15,000	74	1,153	15,500	3,220	2,530	238,000	3,710,000	187,000	2,920,000
18,000	42	460	19,900	6,560	4,540	276,000	3,020,000	191,000	2,090,000
22,000	18	271	23,900	11,400	6,920	205,000	3,090,000	125,000	1,880,000
26,000	8	181	28,900	19,700	10,800	158,000	3,570,000	86,400	1,960,000
31,000	3	92	33,600	40,100	14,400	120,000	3,690,000	43,200	1,320,000
36,000	4	78	40,500	59,300	22,000	237,000	4,630,000	88,000	1,720,000
43,000	0	43	[1]46,800	[1]90,000	32,300		3,870,000		1,390,000
61,000	3	53	62,500	197,000	55,300	591,000	10,400,000	166,000	2,930,000
73,000	0	12	[1]79,200	[1]270,000	107,000		3,240,000		1,280,000
86,000	1	13	95,800	[1]365,000	164,000	365,000	4,740,000	164,000	2,130,000
100,000	0	4	[1]110,000	[1]580,000	185,000		2,320,000		740,000
120,000	0	6	[1]130,000	[1]1,040,000	300,000		6,240,000		1,800,000
140,000	0	3	[1]155,000	[1]2,100,000	490,000		6,300,000		1,470,000
172,000	0	1	[1]172,000	[1]3,100,000	620,000		3,100,000		620,000
187,000	0	1	[1]187,000	[1]4,000,000	750,000		4,000,000		750,000
Total	[2]2,160	22,280	[3]10,620,000			[4]2,436,000	72,720,000	1,180,000	26,880,000

[1]Estimated.

[2]**Does not include October 1956.**

[3]Published water discharge is 10,621,955 (ft³/s)·d.

[4]Published sediment discharge is 2,466,610 tons.

The estimated long-term sediment discharge for Feather River at Oroville, 1902-62, is 72.7 million tons (col. 8), or 1.19 million ton/yr. This value was computed by summing the products of the number of days in the range of water discharge (col. 3) and the average suspended-sediment discharge for the range (col. 8). It is also the probable discharge for the ensuing 61 years (until 2023) assuming no change in conditions that affected sediment yield and transport during the base period of record 1957-62. The accuracy of an estimate based on this method is dependent on the representativeness of the transport curve for the period for which it was prepared and of the sampled flow events. The long-term estimate is evaluated as being fair to good because the transport curve is based on daily sampling, on annual records which are rated good, and, although the period of record is for only 6 years, on sufficient items being sampled in the low and medium water discharge ranges to produce a smooth curve for the period. In contrast, figure 5 shows the erratic form of annual transport curves. Because the distribution of sediment-discharge values for a narrow range of discharge is generally skewed and has a large standard deviation, many years of data are needed to provide a sufficient number of samples to define the mean sediment discharge for a given range of water discharge. Sufficient high-flow events did not occur, however, during 1957-62 to define the transport curve for the larger streamflow rates, and the curve was extrapolated above about 100,000 ft^3/s on the basis of a few 1963 data (fig. 4). The large probable error inherent in extrapolating the transport curve is demonstrated by the large quantity of sediment transport, 36 percent of the total (col. 8, table 4), that occurred in 15 days, or in 0.07 percent at the time, during 1902-62.

An indication of the range of discharge sampled and the frequency of events sampled during the two periods may be obtained by comparing the cumulative flow-frequency curves (flow-duration curves) in figure 6.

The estimated suspended-sediment inflow to the site of Lake Oroville, 1957-62 and 1902-62, is summarized in table 5. The sediment discharge at Oroville was adjusted to that at the reservoir site on the basis of drainage area and on the assumption that 609 mi^2 of the Feather River basin upstream from Oroville are noncontributing. This value for the noncontributory area was used by the California Department of Water Resources in their initial estimate of sediment inflow to Lake Oroville (E. F. Serr, written commun., 1959).

The quantity of suspended sediment transported by a stream is usually determined by weight. To provide an estimate of the volume the sediment will occupy in a reservoir, the weight of transported sediment must be converted to volume.

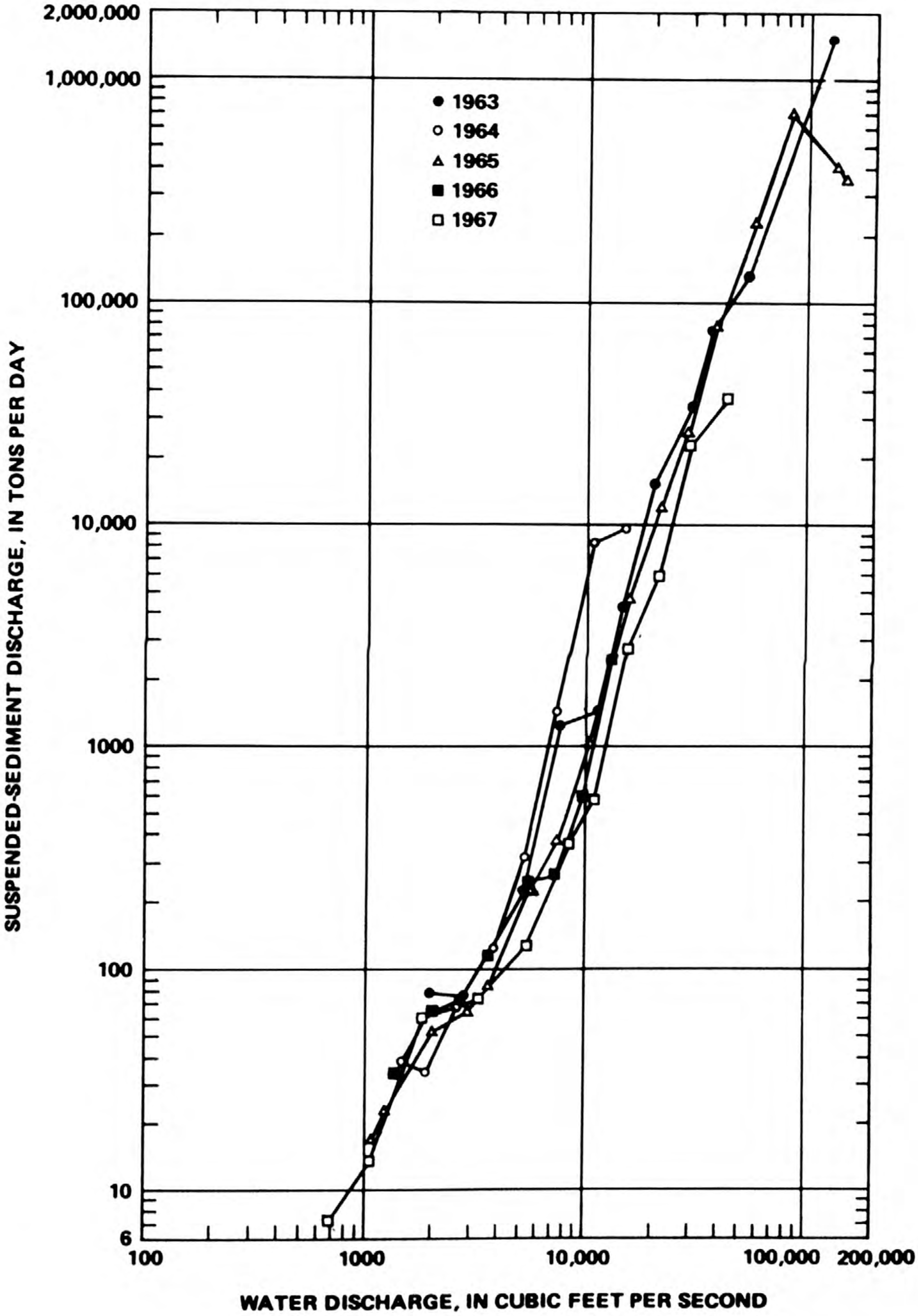


FIGURE 5.--Relation between streamflow and suspended-sediment discharge in Feather River at Oroville, 1963-67 water years.

TABLE 5.--*Volume of suspended-sediment discharge, Feather River at*

Period (water year)	Number of years	Feather River at Oroville (contributory area, 3,015 mi^2)				
		Suspended sediment				
		Tons	(Ton/mi^2)/yr	Acre-ft, Unit weight (lb/ft^3) 56	68	80
1957	1	627,600	208	515	424	360
1958	1	809,800	269	664	547	465
1959	1	107,400	35.6	88.1	72.5	61.6
1960	1	587,100	195	481	396	337
1961	1	57,840	19.2	47.4	39.1	33.2
1962	1	276,900	91.8	227	187	159
1957-62[1]	6	2,467,000	136	2,023	1,666	1,416
1902-62[2]	61	72,720,000	395	59,620	49,100	41,740

[1]Suspended sand, Feather River at Oroville: 1,180,000 tons or 576 acre-ft at a unit weight of 94 lb/ft^3.

[2]Suspended sand, Feather River at Oroville: 26,880,000 tons or 13,130 acre-ft at a unit weight of 94 lb/ft^3. Suspended sand, Feather River at Oroville damsite: 26,730,000 tons or 13,060 acre-ft at a unit weight of 94 lb/ft^3.

A value of 68±12 lbs/ft^3 (1.09 specific gravity) was determined as the initial unit weight of deposited sediment. This value was computed by a procedure presented by Lara and Pemberton (1963) that utilizes the particle-size distribution, which for Feather River at Oroville is 34, 41, and 25 percent sand, silt, and clay, and regression coefficients determined from an analysis of results of about 1,300 reservoir surveys. Computations of volumes in table 5 were made for unit weights of 56, 68, and 80 lbs/ft^3 to provide an envelope of one standard deviation and a reasonable estimate of the minimum, mean, and maximum volumes of sediment deposits at the site of Lake Oroville.

Suspended-sand discharge at the damsite for 1902-62 was 26.7 million tons. The volume of sand, 13,060 acre-ft, is based on a unit weight of 94 lb/ft^3 (specific gravity, 1.51), the value determined as the weight of well-graded Sacramento River sand.

Oroville and at Oroville damsite, 1957-62 and 1902-62 water years

Feather River at Oroville--Continued			Feather River at Oroville damsite (contributory area, 2,998 mi^2)			
Suspended sediment--Continued						
(Acre-ft/mi^2)/yr			Tons	Acre-ft		
Unit weight (lb/ft^3)				Unit weight (lb/ft^3)		
56	68	80		56	68	80
0.171	0.141	0.119	624,100	512	421	358
.220	.181	.154	805,200	660	544	462
.029	.024	.020	106,800	87.6	72.1	61.3
.160	.131	.112	583,800	479	394	335
.016	.013	.011	57,510	47.2	38.8	33.0
.075	.062	.053	275,300	226	186	158
.112	.092	.078	2,453,000	2,011	1,656	1,408
.324	.267	.227	72,310,000	59,290	48,820	41,500

The unsampled sediment discharge for Feather River at Oroville (and damsite) is estimated to be about 485 ton/d, or 13 percent by weight, of the total sediment discharge This estimate is based on comparison of streamflow and suspended-sediment concentration and discharge for Feather River at Oroville and near Gridley during the concurrent periods of record 1965-67. These data, although affected by construction activities and diversions, indicate that most sediment in transport at Oroville is moved past Gridley and that flow frequencies at Gridley (1902-62) probably are comparable to those at Oroville at the larger flow rates.

The total sediment discharge for Feather River at Gridley, 1902-62, therefore may be assumed to be approximately equal to the total sediment discharge at Oroville plus material eroded from the bed and banks of the stream and from local inflow. Material eroded from the bed and banks of the stream, assuming that changes in the cross section at mile 18 (fig. 11) are representative of the reach from Oroville to Gridley, is an estimated 200 ton/d; and the suspended-sediment inflow to the reach is an estimated 90 ton/d.

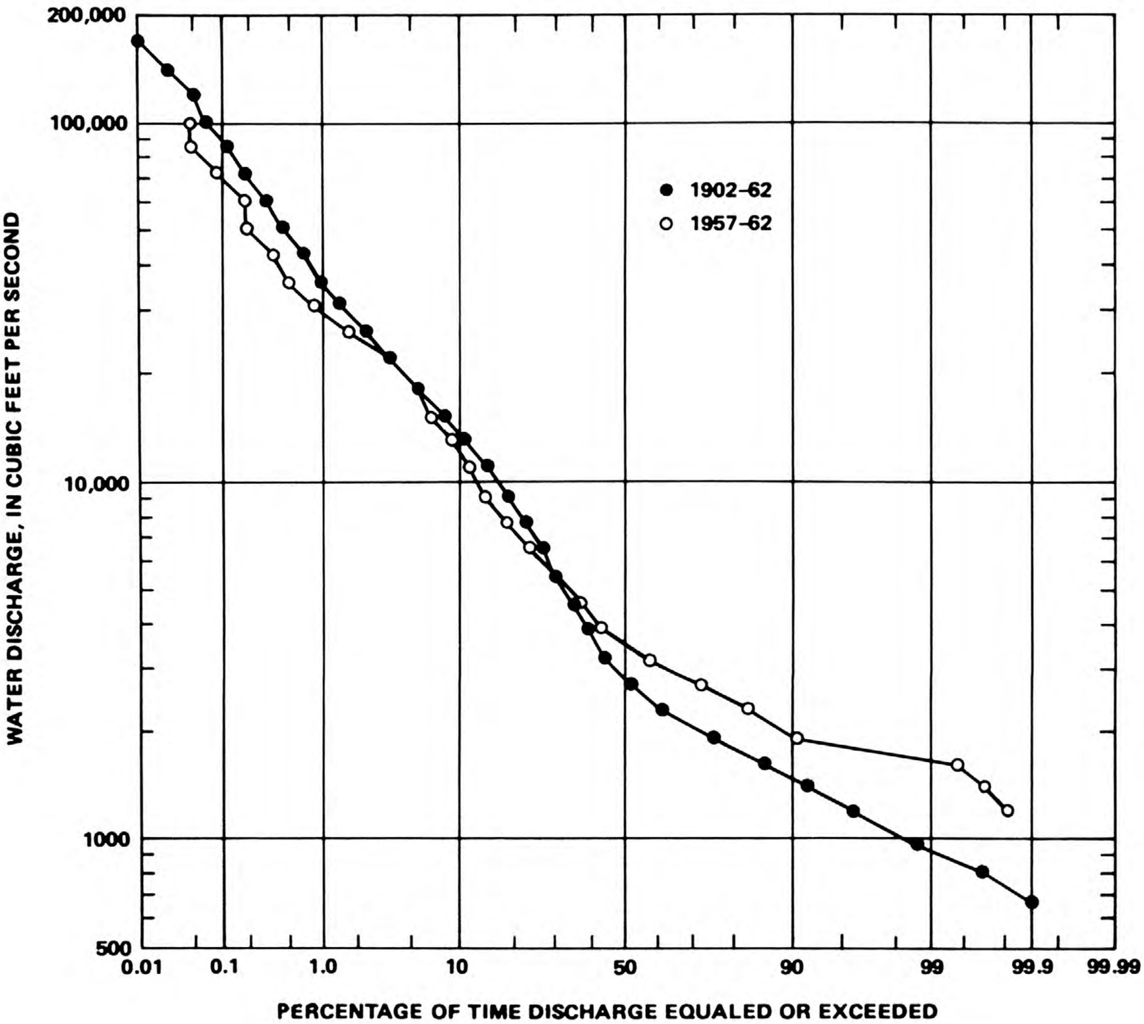


FIGURE 6.--Cumulative flow-frequency curves for Feather River at Oroville, 1902-62 and 1957-62 water years.

Based on an average unit weight of 68 lbs/ft^3, the estimated suspended-sediment inflow is 48,800 acre-ft and the unsampled sediment, at 94 lbs/ft^3, is 5,280 acre-ft in 61 years. Assuming the reservoir capacity for sediment storage to be equivalent to that for water storage, about 3,990 years would be required to fill the 3.538 million acre-ft reservoir. Mackin (1948) pointed out that if this assumption of sediment storage capacity were true, then, when the delta front (of Lake Mead) reaches the dam, the river must transport its detrital load from the head of the reservoir to the delta on a surface of no slope. Sediment transport could not occur under such a condition. Obviously then, when the reservoir is filled with sediment the surface of the sediment must slope upstream from the dam and the sediment-storage capacity for a reservoir therefore would be greater than the water-storage capacity.

Conversely, the distribution of the sediment in a reservoir may shorten the life or reduce the operating potential of the reservoir before the reservoir is filled with sediment. The survey of Lake Mead, Ariz., in 1948-49 (Ames, Kennon, and Langbein, 1960, p. 93) showed that about 16 percent of the sediment in the reservoir had deposited in the upper 17 percent of the total reservoir depth. This upper segment contained 42 percent of the original 32.544 million acre-ft of storage capacity. A survey of Lake Pillsbury, Calif., (Porterfield and Dunnam, 1964) showed that over 50 percent of the sediment had deposited in the upper 30 percent of the reservoir depth that had contained more than 55 percent of the original 94,400 acre-ft capacity. Hence, a large percentage of the sediment inflow is deposited in the upper levels of the lake and reduces the capacity of the power pools.

Assuming distribution of deposited sediment similar to that described for Lake Mead, Lake Oroville, with about 38 percent of the reservoir capacity above an elevation of 800 ft and in the upper 100 ft segment of depth, should have a long operating lifespan but considerably shorter than the 3,990 years indicated by the computed ratio of sediment inflow to lake volume.

Survey of Lake Oroville in 1971

The California Department of Water Resources established 24 permanent sediment ranges at Lake Oroville in 1968. The sediment ranges are precisely determined cross sections about normal to the original stream course or reservoir shoreline and extend above the operating level of the reservoir. They provide a permanent and accurate base from which to measure and monitor sediment deposition and distribution.

The initial sediment survey, July 26-28 and August 9-11, 1971, made after 2 years of high inflow (1969 and 1970), was limited to the sediment ranges near the reservoir headwaters (California Department of Water Resources, 1971). The survey showed that very little sediment had been deposited since storage of flow began in 1967. The only measurable material was found near the upstream sediment range on the Middle Fork Feather River, and traces of this material disappeared 0.4 mi downstream. Sediment had deposited to a maximum depth (at the thalweg) of 22 ft at this range, which had an original bottom, or thalweg, elevation of 808 ft. Most sand and silt may deposit in a reservoir at the elevation where velocity of tributary inflow initially decreases and near the reservoir levels most often occurring immediately prior to and during periods of most sediment inflow. The minimum water-surface elevation of Lake Oroville in 1969 was 750 ft and in 1970-73 ranged from 824 to 833 ft.

No deposition was found, nor expected, at the upstream range of the South Fork Feather River. The thalweg elevation of 540 ft for this range is considerably lower than the elevation at which material was deposited in Middle Fork Feather River and is also lower than the minimum elevation of usable capacity (640 ft). No deposition was found at the upstream range of the North Fork Feather River, thalweg elevation 771 ft.

Effects of Reservoirs on Channel Regimen and Geometry

The downstream effects of reservoir operation on sediment transport and on the quantity and distribution of flow should be considered during the planning phase, as well as the effect of sediment inflow and deposition within a reservoir. Frequently, however, less effort is devoted during the initial studies and planning for dams and reservoir operation to estimating downstream effects of reservoir operation and providing solutions to these complex problems than is devoted to the effect of sediment deposition and distribution in the reservoir. Many examples of downstream changes attributable to reservoir operation are cited in the literature. Examples are reported in the Proceedings of the Federal Inter-Agency Sedimentation Conference (Coldwell, 1948, p. 142-161; Stanley, 1948, p. 163-167) and the Proceedings of the Conference on Sediment Problems in California (Einstein and Johnson, 1956).

The effects of diverting 6 million acre-ft of water from the Colorado River, a sand-bed stream, into the All-American Canal and leaving the sediment in the river to be transported by the remaining flow of 1.5 million acre-ft was described by Borland (Einstein and Johnson, 1956, p. 65-78). The stream could not transport the sediment remaining in the river together with the additional sediment brought into the stream by tributary inflow, and it began to meander in the aggrading channel. Costly engineering solutions were necessary to alleviate the flooding and drainage problems.

Regulation of a stream attenuates peak flows and changes the historical flow frequencies instrumental in channel formation. The larger flows, which occur only a small percentage of the time, transport most sediment because transport of suspended sediment increases generally at a rate of about the square of the streamflow, and transport of bed material increases in a sand-bed stream at a rate of about the cube of the stream velocity. The median discharge, which is the flow commonly associated with the formation of the channel, is frequently changed by regulation, although the mean discharge may remain unchanged.

The characteristics of channel shape at a given cross section, the width and depth, and, therefore, the velocity, change in response to changes in water discharge. The depth and width, as well as velocity, also are functions of the quantity of sediment transported in the channel. The characteristics of channel shape--the width and depth, and therefore, the velocity--change in response to changes in water discharge. A reduction in flow reduces the competence and capacity of the stream to transport sediment, which then leads to a reduction in the capacity of the channel to convey water; thus, sediment and flooding problems are created.

The released flows also are low in sediment concentration, as most sediment is impounded in the reservoir. This clear water has a greater potential for erosion and transport than the original water-sediment mixture, and scour may occur in the reach downstream from the dam, followed by fill farther downstream. Whether scour or fill results immediately downstream or whether the slope initially increases immediately downstream is dependent partly on the size of the bed material below the dam and whether the particle size of the bed material increases or decreases in the downstream direction.

Coldwell, (1948, p. 153-156) presented several examples of the effects of releases on a sand channel. In one example, at Denison Dam on the Red River, Texas and Oklahoma, he estimated that in the 17-mi reach below the dam 2,900 acre-ft, or about 150 yd^3 per yard of river length, was removed in a little more than 3 years. He reported deepening of the channel near the outlet works, which increased the power head, deepening of the narrow part of the river, severe bank caving, and shifting of the flow from one side of the channel to the other.

The U.S. Army Engineer District, Tulsa, Okla., in a report on the second resurvey of Denison Dam and Reservoir (U.S. Army Corps of Engineers, 1960), noted that more than 36,000 acre-ft of material that had been scoured from the river channel, 1942-58, had been derived from bank caving as well as deepening of the river channel. The volume of material removed was equivalent to about 358 acre-ft per river mile for the 101-mi reach downstream from Denison Dam. In a study of channel degradation in the 17-mi reach downstream from Denison Dam, the Engineer District determined that rates declined from 1,278 acre-ft per year in 1943 to 668 acre-ft per year between 1943 and 1945 and to 450 acre-ft per year between 1945 and 1958. This study indicated that removal of material downstream from a dam is much more rapid in the period shortly after closure of the dam than in later years.

Degradation of a channel downstream from a reservoir is limited by the increase in grain size of the bed material that accompanies selective erosion and transport of the finer material. The bed can become armored--resistant to erosion by the released flows--when erosion reaches gravel underlying the streambed. Armoring can also occur if some coarser materials, sand and gravel, are mixed in the bed material, because selective sorting and removal of the finer particles of the bed tend to concentrate the coarser material and slow or stop degradation at a lesser depth than would otherwise be expected.

Stanley (1948, p. 168), in reporting on the effect of operation of Lake Mead on the Colorado River channel, noted that when Hoover Dam was closed the slope of the riverbed for about 100 mi downstream averaged 1.5 ft/mi. Twelve years later the slope was 2.1 ft/mi for the first 13 mi, 1.9 ft/mi for the next 13 mi, and 1.7 ft/mi in the following 39 mi. In the succeeding 30 mi the slope had been reduced to 1.3 ft/mi, but in the next 10-mi reach in the swampy valley near Needles, Calif., the river was flowing on an average slope of 1.8 ft/mi. The Colorado River experience showed that if the bed material becomes progressively finer downstream, or depths to coarse material increase with distance downstream from the dam the ultimate slope in the scoured area will be steeper than the initial slope; that if the material is uniform in character at various depths and distances the ultimate slope should be about the same as the initial; and that only if the material is fine for considerable depth near the dam, and coarseness increases with distance from the dam, will the final slope in the scoured area be less than the initial slope.

These examples demonstrate the effects that dams on some large streams have had on the channels downstream. They are indicative of the possible effects of sediment entrapment in reservoirs, namely release of flows with low sediment content and subsequent erosion and scouring of channels downstream.

TOTAL SEDIMENT DISCHARGE

General

Total sediment discharge is the total quantity of all sediment passing a section. It may be defined according to the type of material, mode of transport, or the method of measurement; however, a single set of definitions cannot be applied to all elements of sediment transportation and measurement because of the complex interrelation among factors affecting sediment transport and the physical limitations of sampling equipment.

Total sediment discharge may be divided into two parts on the basis of type of material or general relation to flow; namely, fine-material discharge and bed-material (or coarse-material) discharge. Fine-material discharge consists of particles finer than those normally found in the streambed. Bed-material discharge is composed of particles found in appreciable quantity in the streambed. Bed material may be transported both as bedload and intermittently as suspended sediment.

Total sediment discharge may be divided into two parts also on the basis of transportation; namely, suspended sediment, whose weight is supported entirely by the surrounding fluid, and bedload, whose weight is supported primarily by the streambed. The suspended material usually consists of both fine material and bed material.

Further, total sediment discharge may be divided into two parts also on the basis of method of measurement, because of the physical limitations of sampling equipment. The parts consist of the sampled discharge (the discharge in the zone traversed by the sampler) and the unsampled discharge (Colby and Hembree, 1955, and Colby, 1957). Unsampled discharge may also be divided into (1) the sediment transported in suspension within 0.3 to 0.5 ft of the bed and (2) the bedload, which is transported in nearly continuous contact with the streambed. Depth-integrating samplers, used to sample concentrations of suspended sediment, normally traverse the depth from the water surface to within 0.3 to 0.5 ft of the bed. The sampled discharge may consist of both fine material and bed material in suspension, and the unsampled discharge consists of both fine material and bed material transported in suspension and of bed material transported as bedload. Unsampled-sediment discharge, in the final computation, may be defined as the part of the total-sediment discharge exceeding that determined from the discharge-weighted concentration in the sampled zone.

Sampled discharge, on the basis of method of measurement, is the fraction of total-sediment discharge generally referred to as suspended- sediment, or sediment, discharge and whose values are published annually by the U.S. Geological Survey.

Total sediment discharge was computed for Feather River near Gridley for the 1965 water year. The methods used and the results obtained from the Gridley data are discussed in the following section. No other total sediment discharge data are available in the Feather River basin.

Feather River near Gridley, 1965 Water Year

Total sediment discharge measurements of Feather River made near Gridley include determination of water discharge, mean velocity, width and depth of the stream, water temperature, concentration of suspended sediment, and particle-size distribution of suspended sediment and of bed material. These include the data required to compute total sediment discharge by the procedure outlined by Colby and Hembree (1955). A summary of the data and computations is given in table 6, particle-size analyses are listed in table 7, and bed-material distributions are given in figure 7.

TABLE 6.--*Total-sediment-discharge measurements, Feather River near Gridley, 1965 water year*

Date	Time (hours)	Discharge (ft^3/s)	Area (ft^2)	Width (ft)	Mean velocity (ft/s)	Mean depth (ft)	Sediment discharge						
							Suspended (sampled)	Unsampled				Total	
							Tons	Percent sand[1]	Tons	Percent of total	Tons per foot of width	Tons	Percent sand[1]
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
Oct. 6, 1964	1250	2,030	2,950	238	0.69	12.39	16	19	0	--	--	16	19
Nov. 5	1000	1,700	2,880	234	.59	12.29	23	2	0	--	--	23	2
Nov. 10	1320	4,710	3,320	240	1.42	13.81	382	13	13	3.3	0.05	395	16
Dec. 2	--	5,340	3,550	242	1.50	14.69	231	16	6	2.5	.02	237	18
Jan. 5, 1965	1215	30,500	5,980	288	5.10	20.75	42,200	61	10,100	19.3	35.1	52,300	69
Feb. 2	1205	11,400	3,620	304	3.15	11.92	1,720	57	1,100	38.9	3.62	2,820	74
Mar. 4	1345	6,640	3,210	302	2.07	10.63	251	25	55	18.0	.18	306	38
Apr. 5	--	7,470	3,370	305	2.22	11.05	444	41	115	20.6	.38	559	53
May 5	1245	9,740	3,750	306	2.60	12.25	894	29	406	31.2	1.33	1,300	51

[1]Larger than 0.062 mm.

TABLE 7.--*Particle-size analyses of suspended sediment and bed material, Feather River near Gridley, 1965 water year*

[Method of analysis: sieve, except as noted]

Date of collection	Time (hour)	Water temperature (°C)	Discharge (ft^3/s)	Sediment concentration (mg/L)	Sediment discharge (ton/d)	Percentage finer than indicated size in millimeters: Suspended sediment (sampled zone)						Bed material						
						0.062	0.125	0.250	0.500	1.000	2.000	0.062 Silt	0.125 Sand	0.25	0.50	1.0	2.0	4.0 Gravel
1964																		
Oct. 6	1250	19.5	2,030	3	16	81	89	93	100	--		4	9	34	84	100	--	--
Nov. 5	1000	11.5	1,700	5	23	98	98	100	--	--		3	9	37	75	98	100	--
Nov. 10	1320	11.5	4,710	30	382	87	95	100	--	--		2	8	35	86	99	100	--
Dec. 2	--	8.5	5,340	16	231	84	92	98	100	--		3	8	37	77	99	100	--
1965																		
Jan. 5	1215	8.0	30,500	513	42,200	[1]39	[1]56	[1]75	[1]100	--		--	--	14	94	100	--	--
Feb. 2	1205	6.5	11,400	56	1,720	43	53	64	73	100		--	--	3	34	84	98	100
Mar. 4	1345	8.5	6,640	14	251	75	91	100	--	--		--	--	6	51	93	100	--
Apr. 5	--	10.0	7,740	22	444	59	67	75	92	100		--	--	8	47	90	99	100
May 5	1245	11.0	9,740	34	894	71	86	98	99	100		--	1	6	41	94	99	100

[1]Method of analysis: visual-accumulation tube.

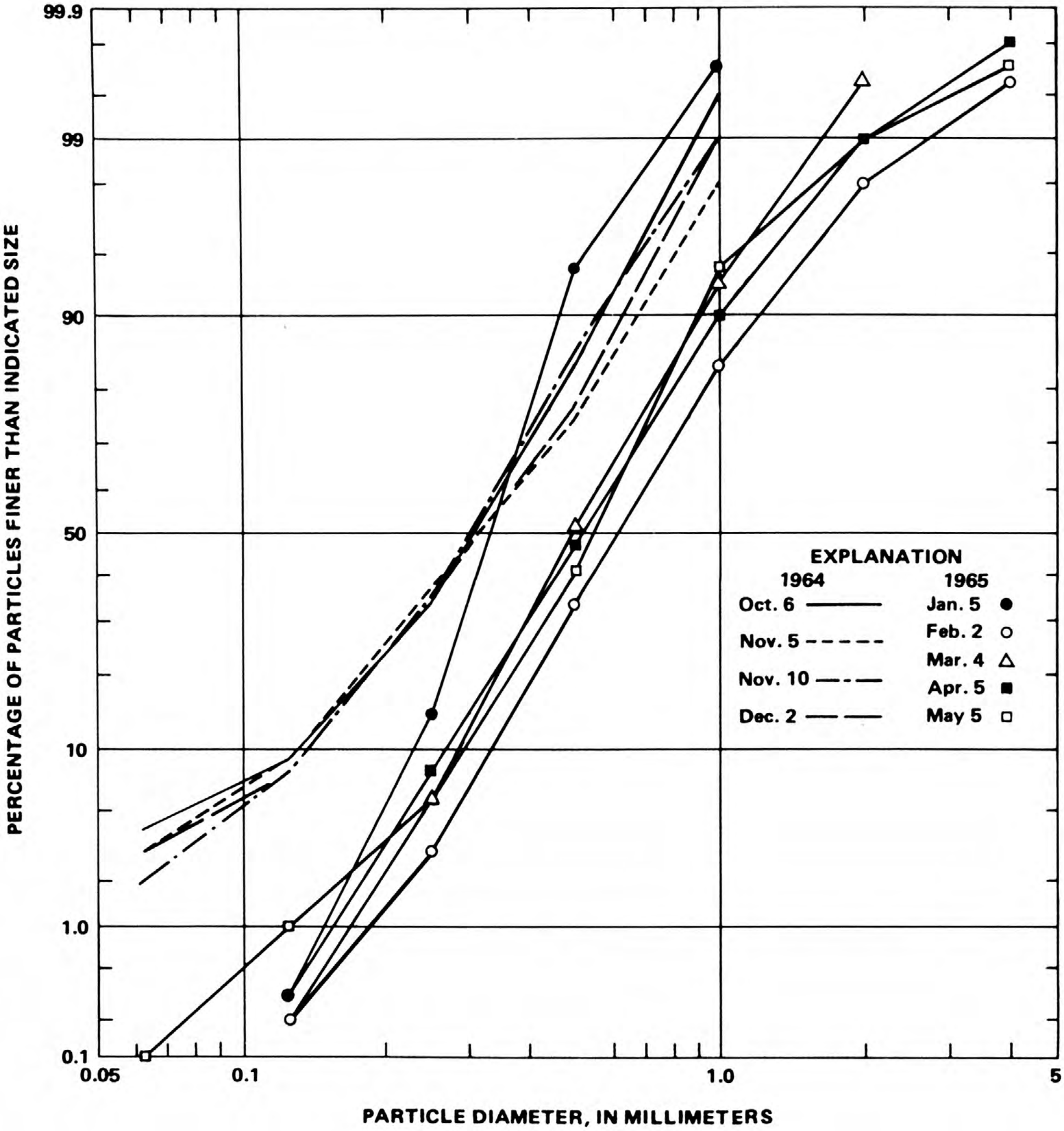


FIGURE 7.--Particle-size distribution of bed material in Feather River near Gridley, 1965 water year.

Computed values of total load include both the fine material and bed material (coarse material) transported in suspension and the bed material transported near or in contact with the streambed. Fine-material discharge is a function of basin characteristics, not flow variables, and is the variable usually responsible for the large scatter of points in a plot of water and sediment discharge. It cannot be computed with any degree of accuracy, hence frequent sampling of suspended sediment is required to accurately define the changes in concentrations relative to time. The bed-material (coarse material) discharge transported in the sampled zone is included also in the records of suspended-sediment discharge. Suspended-sediment discharge is a major fraction of the total-sediment discharge; therefore, adequate records of suspended sediment are a prerequisite to estimating total load.

Material transported in the unsampled zone and near the streambed is primarily coarse-material, or bed-material, discharge. A good relation usually exists between mean velocity of flow and unsampled discharge per unit of width (col. 6 and 12 in table 6). This relation (fig. 8) is used to compute daily values of unsampled discharge; the method used and the accuracy obtained generally depend on the correlation and predictability of streamflow and the mean width, depth, and velocity of the stream. Correlation among these hydraulic variables during the 1965 measurements was good, as indicated by the relation between streamflow and velocity (fig. 9). Curves showing average values of width, depth, and velocity for 1965 are shown in figure 25 in the section on hydraulic geometry.

The relation between water discharge and unsampled sediment discharge (fig. 10) was used to compute the daily value of unsampled sediment discharge for each value of daily mean streamflow. Total sediment discharge was determined by adding these daily values of unsampled discharge to the daily values of sampled suspended-sediment discharge published by the U.S. Geological Survey (1965, p. 221 and revisions 1974, p. 395). A monthly and annual summary of streamflow, suspended-sediment, and total sediment discharge is given in table 8. During 1965, the suspended-sediment discharge was only 81 percent of the total-sediment discharge. The unsampled discharge, 19 percent of the total, was probably larger in 1965 than for the average year at Feather River near Gridley, because of the larger flow rates that occurred during 1965 water year and because most unsampled sediment discharge is transported during the larger flow rates. The unsampled-sediment discharge, 1902-62, assuming that flow frequencies of the Feather River at Oroville, 1902-62, occurred also at Gridley, is estimated to be about 17 percent of total sediment discharge.

The total sediment discharge data obtained during 1965 and the relations shown in figures 8-10 are not necessarily representative of conditions existing since regulation and should not be used to predict sediment discharge for other periods. Changes that have occurred since 1965 in the relation of the mean velocity, width, and depth to streamflow are described in a following section. Changes probably have occurred also in the particle-size distribution of the bed material (fig. 7).

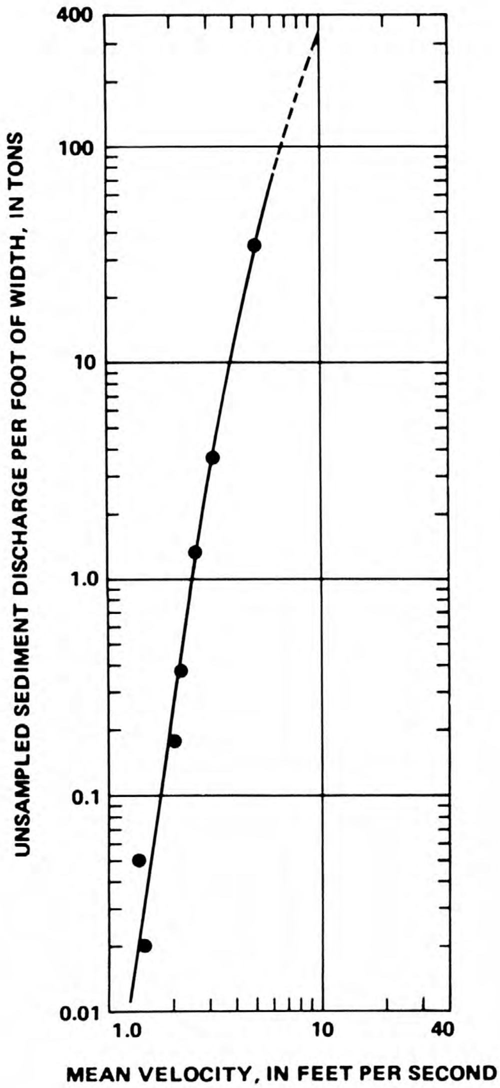


FIGURE 8.--Relation between mean stream velocity and unsampled sediment discharge, Feather River near Gridley, 1965 water year.

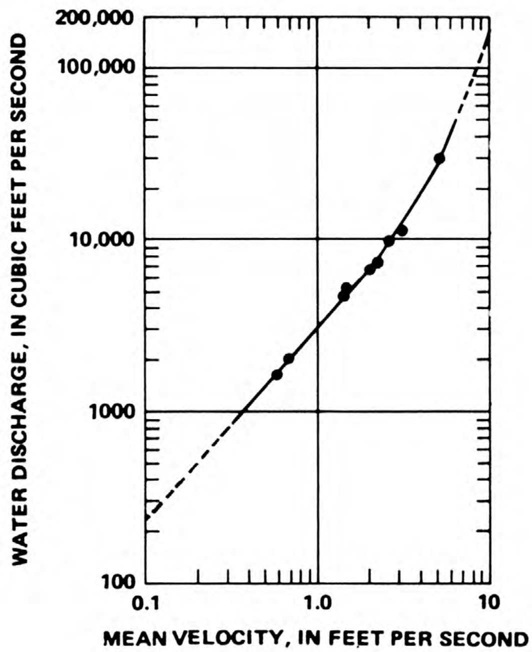


FIGURE 9.--Relation between streamflow and mean velocity, Feather River near Gridley, 1965 water year.

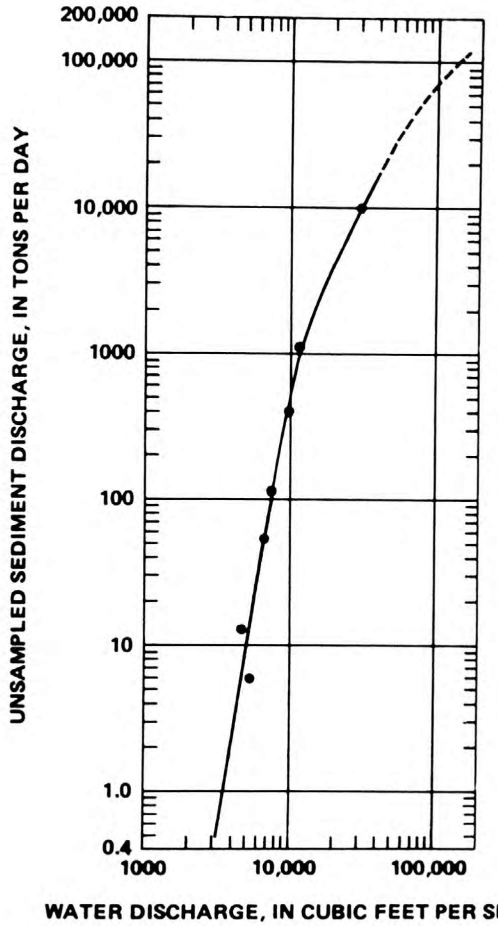


FIGURE 10.--Relation between streamflow and unsampled sediment discharge, Feather River near Gridley, 1965 water year.

TRENDS IN HYDRAULIC GEOMETRY AND SEDIMENT DISCHARGE

The impact of Oroville Dam on the geometry of the channel, streamflow, and sediment discharge downstream from the dam may be estimated from records of water and sediment discharge and from surveys and photography of the channel. The water and sediment discharge are considered to be factors, virtually independent of the stream channel, that depend on the nature of the drainage basin. The average river-channel system tends to develop in a way to produce an approximate equilibrium between the channel and the water and sediment it must transport (Leopold and Maddock, 1953).

Changes in variables in the Feather River basin that influence channel shape include changes in flow frequencies, streamflow rates, sediment-concentration frequencies, sediment discharge, and particle- size distribution of the suspended and bed material.

TABLE 8.--*Summary of total sediment discharge, Feather River near Gridley, 1965 water year*

Month	Water discharge [(ft^3/s)·d]	Sediment discharge, in tons		
		Suspended (sampled)	Unsampled	Total
1964				
October	66,080	1,047	0	1,050
November	88,263	2,245	24	2,270
December	833,750	2,243,553	464,000	2,710,000
1965				
January	564,850	505,780	136,000	642,000
February	247,420	35,079	11,100	46,200
March	214,040	10,661	2,410	13,100
April	405,390	175,326	60,700	236,000
May	225,360	18,387	8,260	26,600
June	97,210	3,673	61	3,730
July	41,662	575	0	575
August	41,310	627	0	627
September	53,120	975	0	975
Total	2,878,455	2,997,928	682,555	3,683,127

Historical Channel Changes

At the height of hydraulic-mining activity between 1857 and 1884, millions of cubic yards of material was washed from the hillsides and into the streams by large jets of water. This large quantity of material was in excess of the transport competence of the streams and thus was deposited in the channel and on the adjacent plains. This material caused, among other problems, flooding and damage to riparian lands. Thus, historical equilibrium was disturbed drastically by hydraulic mining. After mining decreased, following an injunction in 1884 and regulation in 1893, the Feather River probably began to redevelop equilibrium between streamflow and the sediment available for transport. The trend toward premining conditions and equilibrium was interrupted by channel and flood-plain changes resulting from dredge-mining operations between 1905 and 1952 and the construction of levees and training walls for flood control and reclamation. Additional changes resulted when new levees were built and when dredge tailings on the flood plain were used in the construction of Oroville Dam. Completion of the dam in 1968 initiated a new cycle in river morphology.

Levees and training walls built for flood control artificially controlled the width of the stream and the maximum flow in the stream, which in turn effected changes in the depth and velocity of the stream. Gilbert (1917) observed that the hydraulic principle most illustrated by results obtained from training walls on the Yuba River near Marysville was that the efficiency of a current may be increased by confining it laterally, so as to make the ratio of depth to width greater than under natural conditions on an alluvial plain; thus, a stream can carry its debris load on a gentler slope than would naturally be assumed. Colby (1961) commented that, (for a natural channel) at constant low mean velocity, an increase in depth reduces the discharge of bed material, but, at a constant high mean velocity, the effect of depth is reversed.

Because of the interest and activity generated at local, State, and Federal levels by the effect of mining debris on stream channels, many surveys that show channel shape and changes have been made. Blodgett (1972) showed changes in the Feather River main channel at selected cross section, 7.6, 26.1, and 30.6 mi downstream from Oroville Dam, based on surveys in 1909 and 1911 by the U.S. Army Corps of Engineers, and in 1965 and 1969 by the California Department of Water Resources (fig. 11). These surveys indicate channel scour ranging from 2 to 6 ft. The increase in channel size at these cross sections is summarized in table 9. This scour increased the capacity of the channel to carry floodflows and its competence to transport sediment.

Changes in Streamflow

The streamflow record integrates the effects of climate, topography, geology, and land use and gives a distribution of the flow in time and magnitude. When the flows are plotted according to frequency of occurrence, the resulting cumulative-frequency curve--a flow-duration curve--shows the integrated effect of factors that influence streamflow (Searcy, 1959). A flow-duration curve shows the percentage of time during which specified discharges were equaled or exceeded in a given period. It provides a means of presenting streamflow data and combines in one curve the flow characteristics of a stream throughout the range of discharge for the period upon which it is based.

Frequency of discharge is especially important in an understanding of the hydraulic geometry of an alluvial river system and the changes in width, depth, and velocity of rivers that occur in a downstream direction. Changes in frequency of flow rates, such as those caused by regulation of flow by Oroville Dam, will result in changes in width, depth, and velocity and the competence of the stream to transport sediment. These changes may include attenuation or elimination of floodflows that transport most sediment and supply new material to replace that eroded during the initial flood surge. Changes may also include severe adjustments in occurrence of low and median flows, which are primarily responsible for shaping the stream channel. The impact of these changes, therefore, may be modified or controlled, within operating limitations, by adjusting the flow frequencies through regulation.

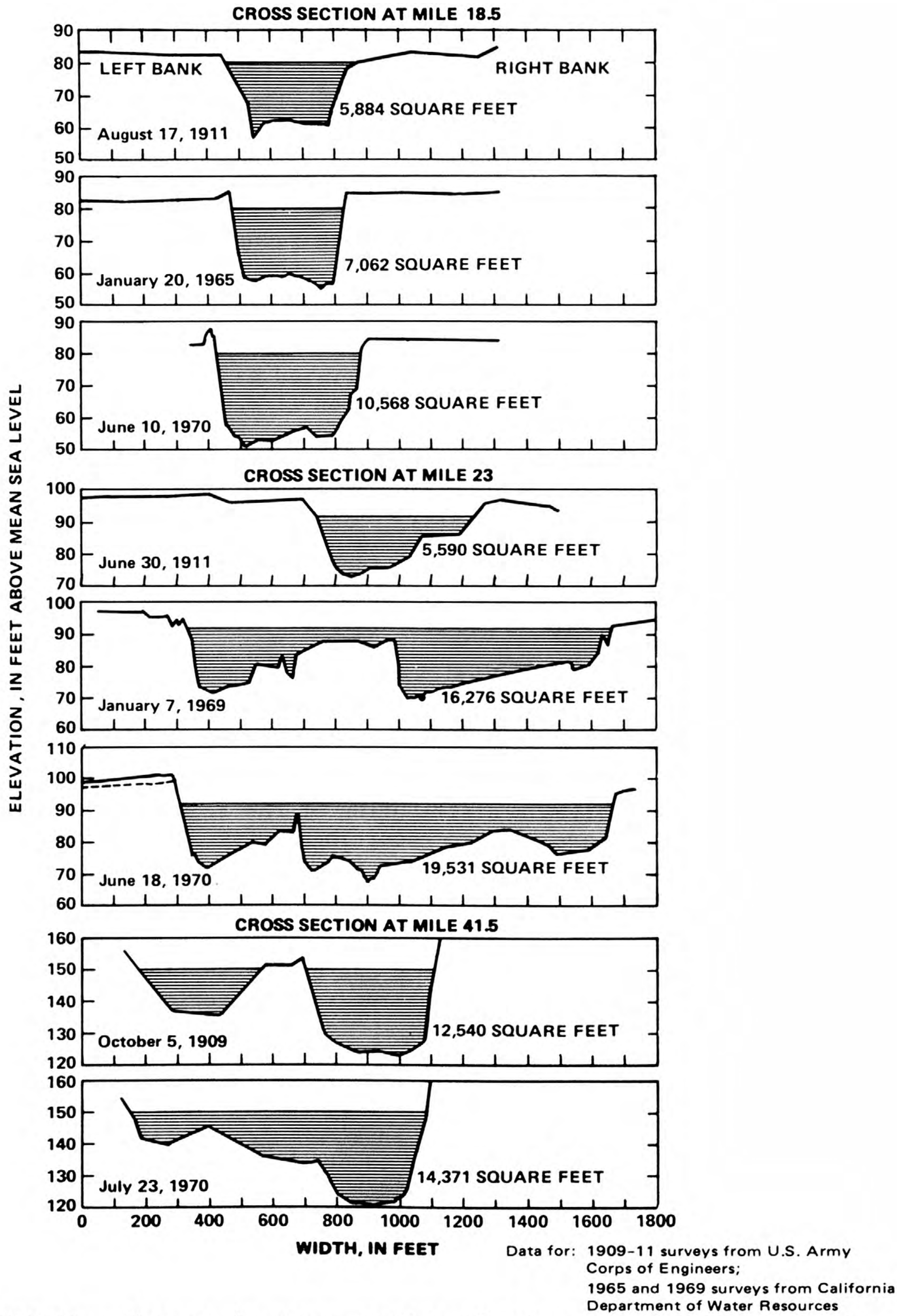


FIGURE 11.--Changes in cross section of main channel of Feather River at miles 18.5, 23, and 41.5 upstream from Yuba City (miles 30.6, 26.1, and 7.6 downstream from Oroville Dam), 1909-70. (After Blodgett, 1972.)

TABLE 9.--*Changes at selected cross sections in the main channel of Feather River upstream from Yuba City, 1909-70*

[after Blodgett, 1972]

Date of survey	Reference elevation (feet above mean sea level)	Cross section area below reference elevation (ft^2)	Percentage increase in cross-section area since 1909 or 1911	Elevation of thalweg (feet above mean sea level)
		At mile 18.5		
08-17-11[1]	80	5,844	--	56.6
01-20-65[2]	80	7,062	21	55.0
06-10-70	80	10,568	81	50.8
		At mile 23		
06-30-11[1]	92	5,590	--	73.1
01-07-69[2]	92	16,276	191	69.9
06-18-70	92	19,531	250	67.7
		At mile 41.5		
10-05-09[1]	150	12,540	--	122.8
07-23-70	150	14,371	14	120.4

[1]Data for 1909-11 obtained from surveys by the U.S. Army Corps of Engineers for the California Debris Commission.

[2]Data obtained from unpublished surveys by the California Department of Water Resources.

Flow-frequency data for the Feather River at Oroville for the unregulated period 1902-67 are shown in figure 12 and include the data in figure 6 that were used to estimate the sediment inflow to Lake Oroville. Frequency data for 1965-67 and 1968-75 are also shown. The 1965-67 data, obtained during the period of construction of Oroville Dam, indicate that flows for Feather River at Oroville were larger for the entire range of discharge than those during the long-term period 1902-67. This is due partly to the large floods during the 1965 water year. The influence of partial regulation during construction is indicated by the increase in low flows, and the increase in flows equaled or exceeded more than 50 percent of the time, over corresponding flows during 1902-67. The effect of total regulation and diversions is illustrated by the flows during 1968-75. Median discharge, the bankfull stage used as a base for channel morphology studies, decreased from 2,900 ft^3/s for the 1902-67 data period to 410 ft^3/s after regulation; average discharge decreased from 5,834 to 1,062 ft^3/s.

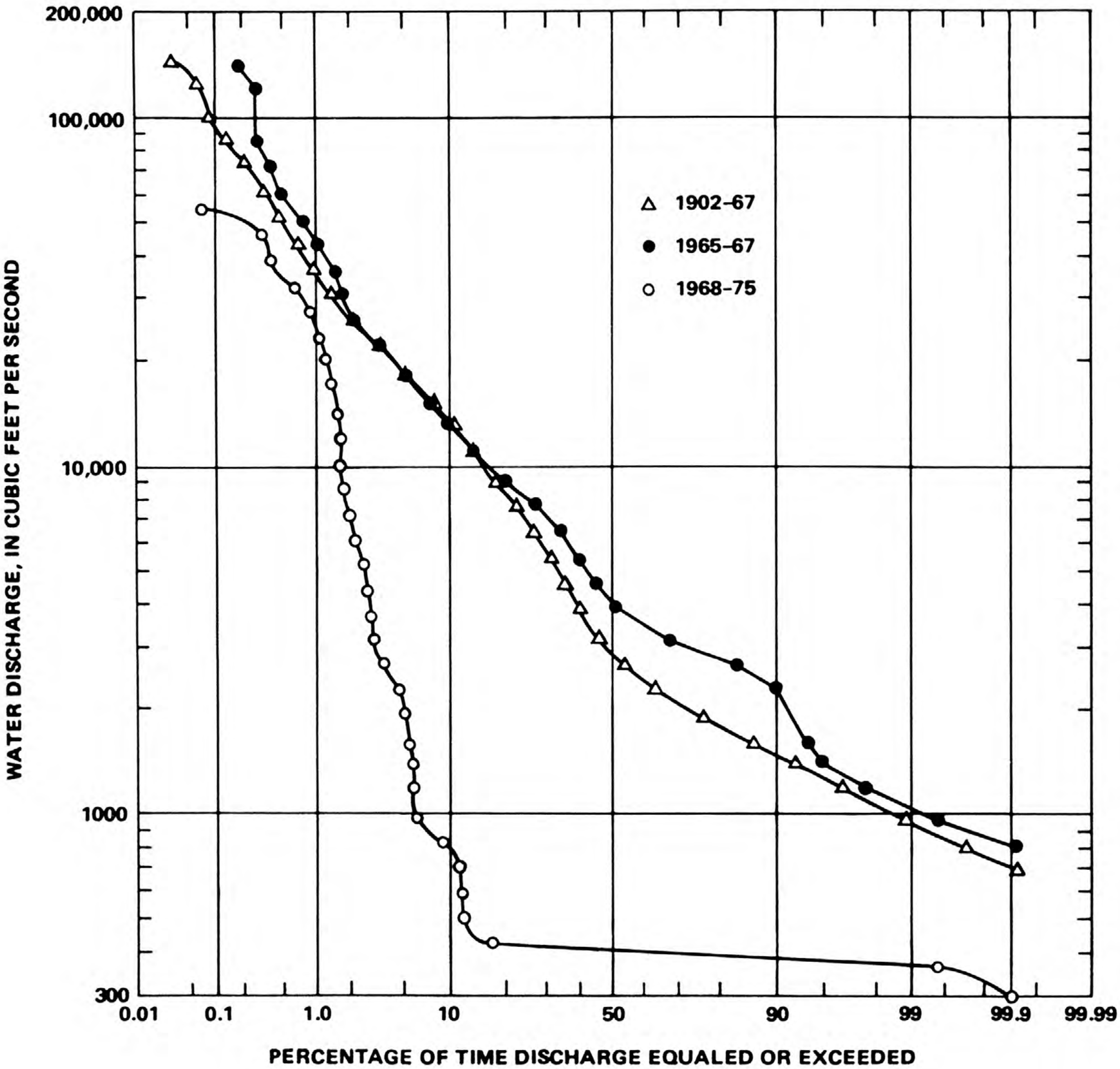


FIGURE 12.--Cumulative flow-frequency curves for Feather River at Oroville, 1902-67, 1965-67, and 1968-75 water years.

Flow-frequency data for the Feather River near Gridley and at Yuba City are given in figures 13 and 14. The influence of partial regulation on the low flows during construction of Oroville Dam is not as apparent at Gridley and Yuba City as at Oroville. Although long flow records are not available at these downstream stations, a relation between the 1965-67 data and the probable 1902-67 flow data can be inferred from the records at Oroville.

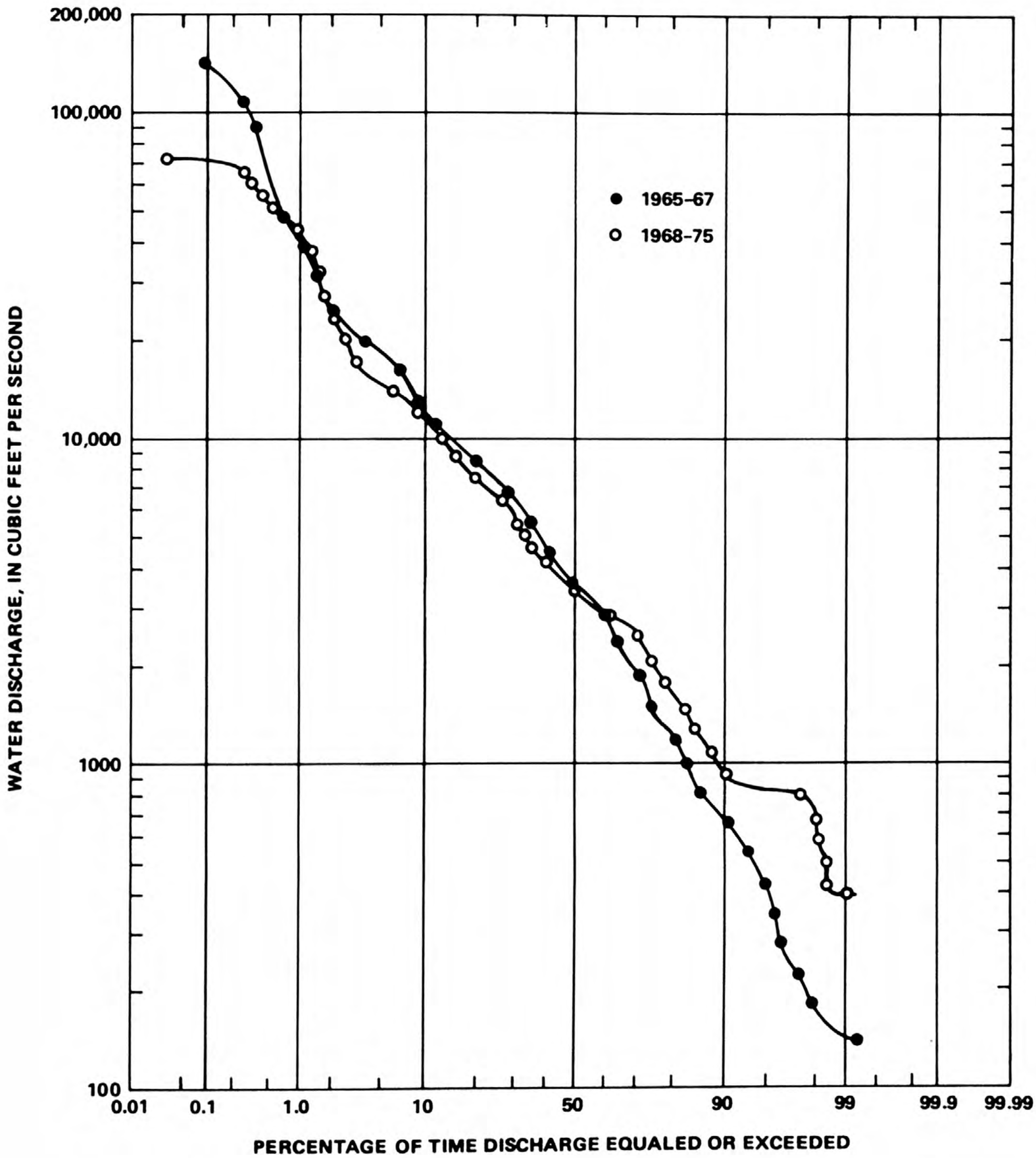


FIGURE 13.--Cumulative flow-frequency curves for Feather River near Gridley, 1965-67 and 1968-75 water years.

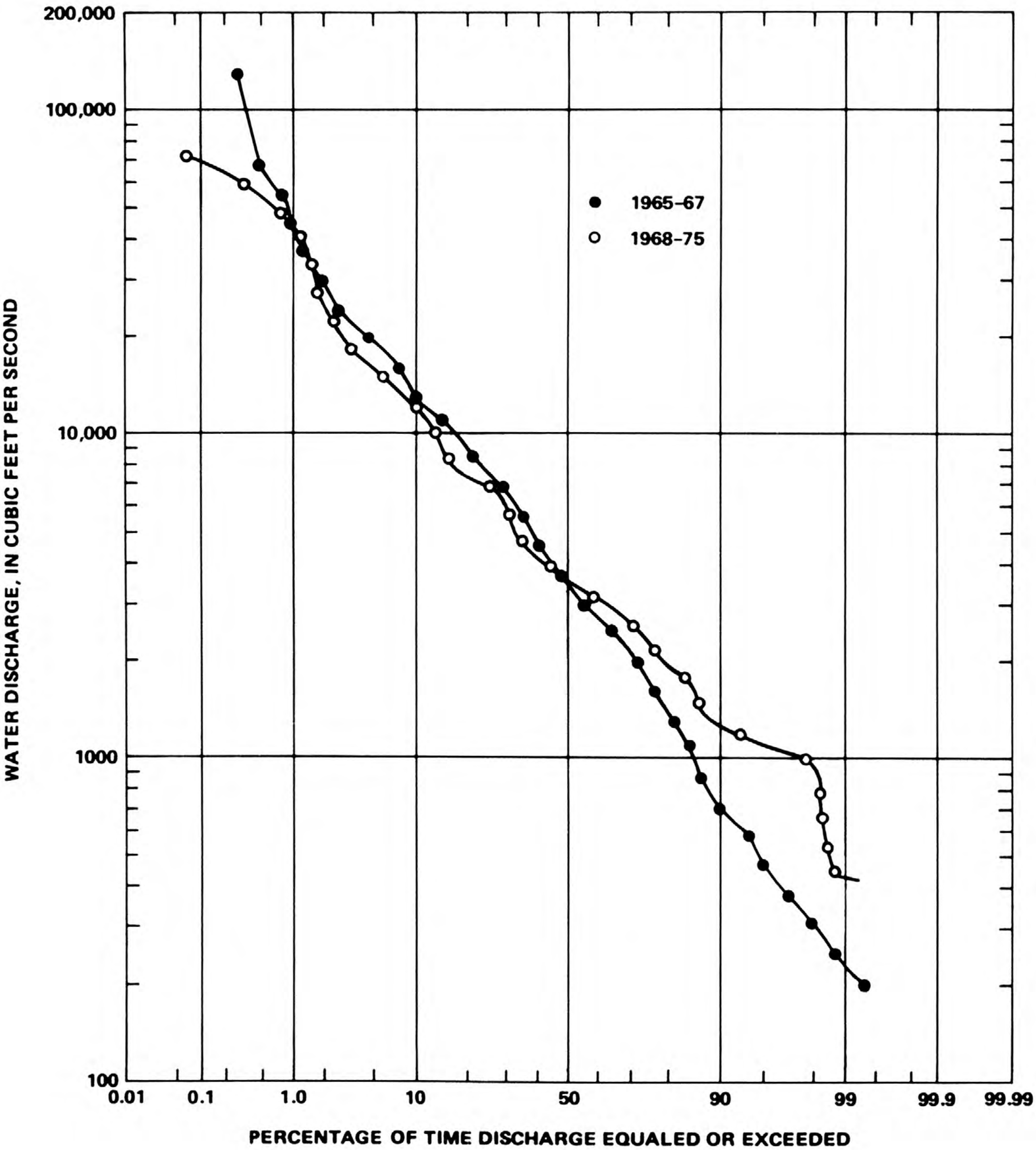


FIGURE 14.--Cumulative flow-frequency curves for Feather River at Yuba City, 1965-67 and 1968-75 water years.

Some of the flow diverted upstream from the Oroville gage is returned to the Feather River upstream from Gridley (fig. 3), and the average flow at the downstream stations, therefore, is greater than that at Oroville. Tributary inflow from Honcut Creek (fig. 2) influences flow at Feather River at Yuba City. Although the impact of regulation decreases in the downstream direction, there is obviously a decrease in the peak flows and probably a decrease in flows equaled or exceeded 50 percent of the time. Percentage occurrence of low-flow rates has increased over those for 1965-67 and probably is greater than for the 1902-67 low-flow rates. Average discharge decreased at Gridley from 5,970 ft^3/s for the period prior to regulation, to 5,521 ft^3/s during the regulated period; during the same period the average discharge at Yuba City decreased from 6,325 ft^3/s to 5,889 ft^3/s.

Changes in Concentration of Suspended Sediment

Daily values of suspended-sediment concentration are available for Feather River at Oroville since November 1956 and at Feather River near Gridley and at Yuba City since October 1964. Cumulative-frequency curves of daily mean concentration of sediment were prepared for selected periods and can be interpreted statistically, as was done for flow-duration curves. The frequency curves of concentration reflect the effect of all factors, artificial and natural, that influence erosion and transportation of sediment. The maximum concentration of sediment is not necessarily associated with the maximum streamflow; therefore, the sediment discharge of a stream is not simply the summation of the products of streamflow and concentration for comparative time intervals in the frequency curves. The relation between streamflow and sediment discharge is described in a later section.

Concentrations of suspended sediment in a natural channel system will normally decrease in the downstream direction (Leopold and Maddock, 1953, p. 22, and Rubey, 1933, p. 505), although individual rivers may differ in this respect (Mackin, 1948, p. 480). The concentration- frequency curves for Feather River at Oroville, Gridley, and Yuba City (figs. 15-17) indicate an increasing concentration in the downstream direction 99 percent of the time during the only concurrent period of record (1965-67) prior to regulation. The trend toward larger concentrations downstream from Oroville to Yuba City may be attributed, in part, to the topography and geology of the Feather River basin. Tributary inflow from the Sierra Nevada foothills, which the Feather River parallels from Oroville to Yuba City, has larger concentrations than flows originating higher in the Sierra Nevada, partly because the foothills contain more readily erodible material and because flows from higher elevations are partly regulated by many small lakes and diversion dams.

Concentration-frequency curves for the regulated period, 1968-75, show a considerable decrease in concentration at Oroville. The decrease is reflected in lesser degree at the downstream stations; however, the trend toward increasing concentrations downstream persists.

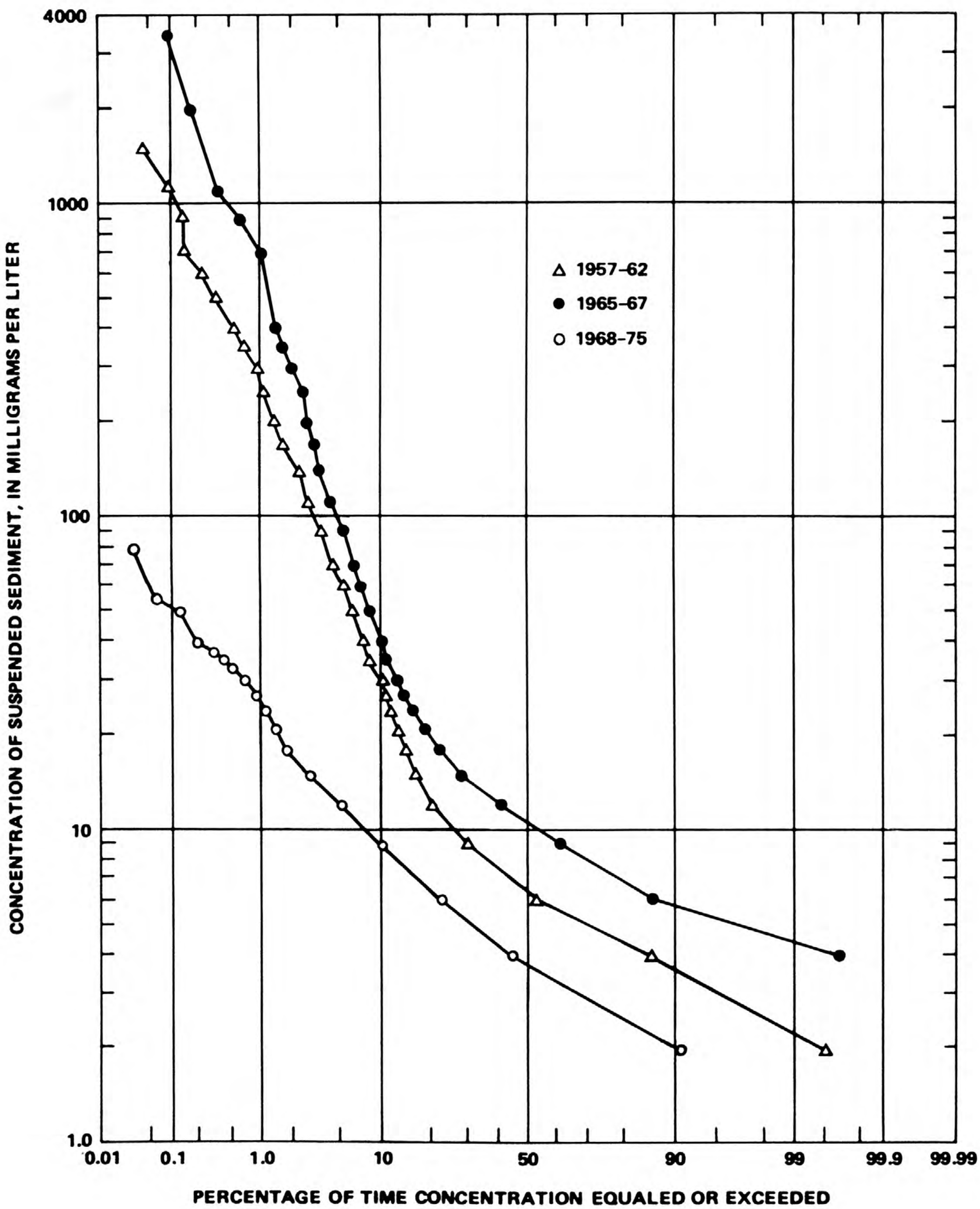


FIGURE 15.--Cumulative suspended-sediment concentration-frequency curves for Feather River at Oroville, 1957-62, 1965-67, and 1968-75 water years.

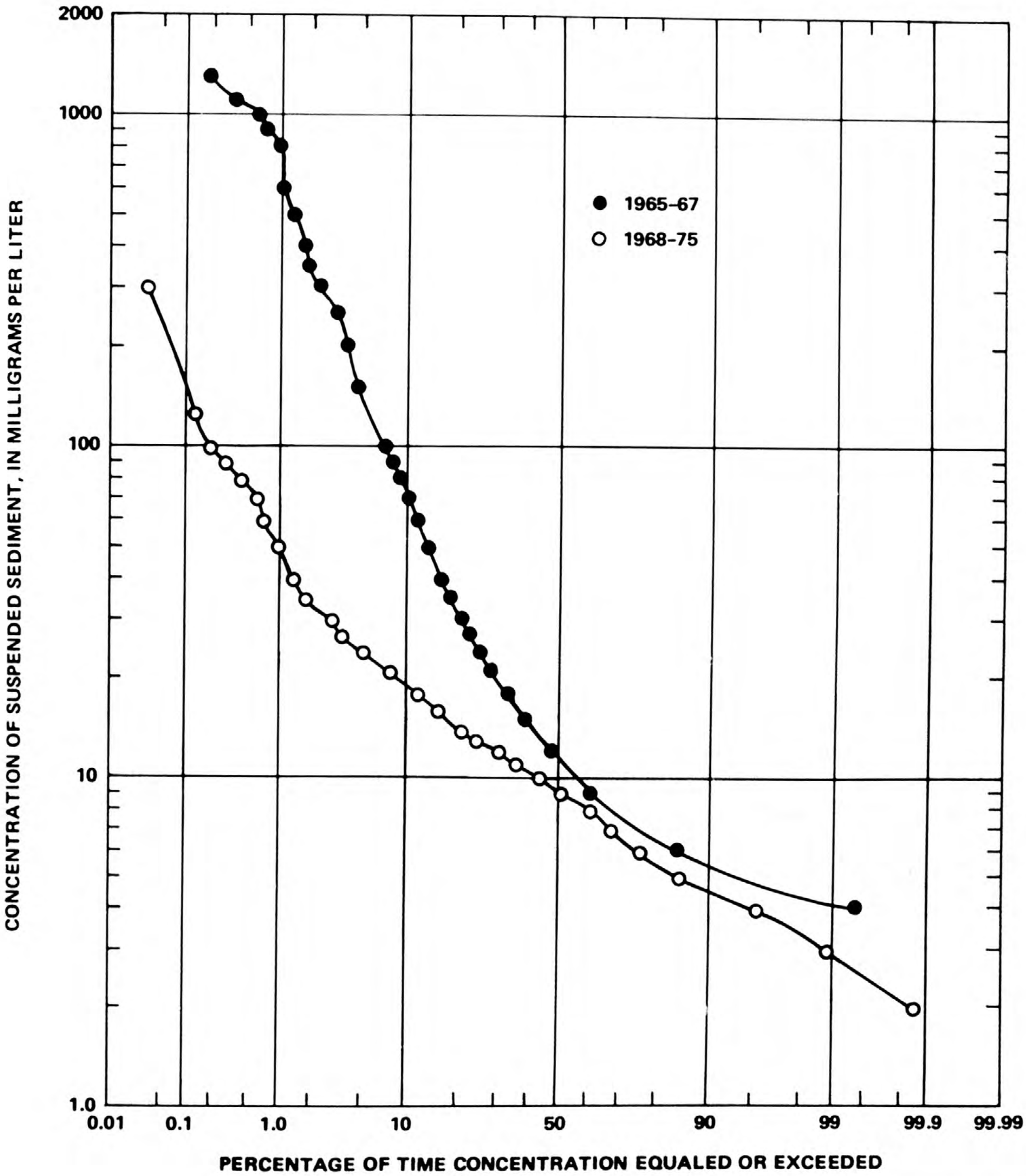


FIGURE 16.--Cumulative suspended-sediment concentration-frequency curves for Feather River near Gridley, 1965-67 and 1968-75 water years.

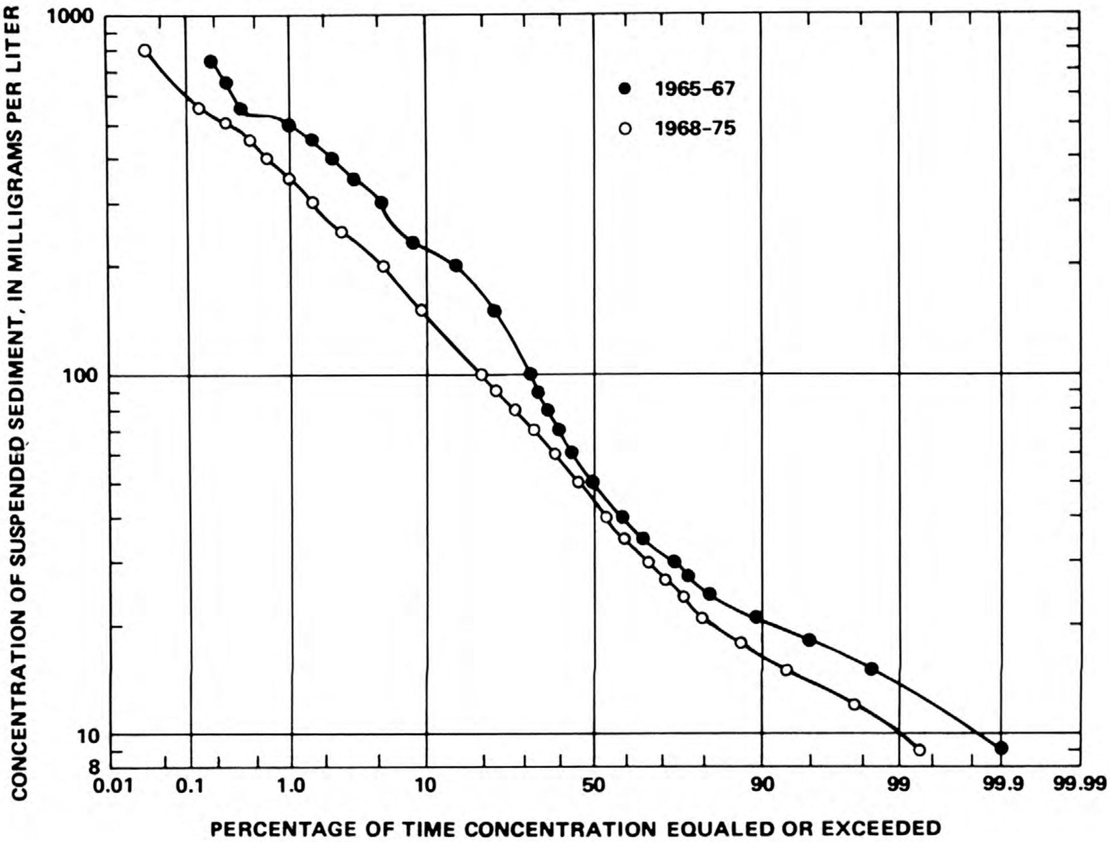


FIGURE 17.--Cumulative suspended-sediment concentration-frequency curves for Feather River at Yuba City, 1965-67 and 1968-75 water years.

Changes in Sediment Transport

The sediment discharge of a stream is the time rate of movement of a volume or weight of the sediment past a point or through a cross section. The concentration of the sediment transported by the stream at any instant can be determined by sampling and, with a continuous record of streamflow and sufficient samples to define a continuous record of concentration, the quantity of sediment transported during the period of record can be calculated.

Daily values of sediment discharge have been computed for Feather River at Oroville, Gridley, and Yuba City for the periods for which observations of sediment concentrations are available. Estimates of sediment discharge during periods when no observations of concentration are available, or extrapolation of sediment records such as the sediment-discharge estimate at Oroville (table 4), are frequently made from a curve showing the relation between water and sediment discharge--referred to as a sediment-transport curve. The construction and use of the curve implies that sediment concentration, hence sediment discharge, is a variable dependent on water discharge; actually the concentration and water discharge can be considered as mutually independent variables, both being dependent on the nature of the drainage basin, seasonal changes, and man's influence. Hence, large differences in concentration can be expected for any given flow rate, and estimates of concentration based on short-term sediment data are no more reliable than estimates of hydrologic data based on a short period of observations.

A plot of daily values of water and suspended-sediment discharge for Feather River at Oroville during the 1958 water year is shown in figure 18. Daily values of concentration may be inferred from the lines of equal concentration for 10 and 100 mg/L. The scatter of points indicates that for a given rate of discharge the suspended-sediment discharge, or concentration, may vary considerably from day to day and season to season. The quantity of silt and clay available for transport is a function of supply and is dependent on natural basin conditions and land use. It is generally much less than the stream is competent to transport. The variable supply of this fine material is responsible for most of the scatter of points in the sediment-transport curve.

The sand-size and larger particles available for transport often equal or exceed the quantity that the stream is competent to transport. The transport of this coarse material is more dependent on measurable hydraulic parameters and can be predicted with some accuracy. Suspended-sediment transport curves for the Feather River are described in two parts, (1) the suspended sediment, which includes both the fine material and sand transported in the sampled zone, and (2) the sand fraction of the suspended-sediment discharge.

The transport curves were constructed by connecting, with a straight line, the points that represent arithmetic averages of water and sediment discharge for small ranges in discharge (fig. 18). Data in figure 18 are also represented by a least-squares regression to compare methods. The curves based on group averages and on least-squares regression (fig. 18), show that the group-averaging technique better defines the relation between water and sediment discharge for the entire range in streamflow. The slope of the least-squares regression is biased by the mass of data in the low discharge range; and the error that results from estimating sediment discharge from the least-squares relation for the three peak-flow values, only, is equal to 12 percent of the annual discharge. Curves representing suspended-sand transport, figures 20 and 21, are based on a least-squares regression because insufficient data were available to define a group-averages curve.

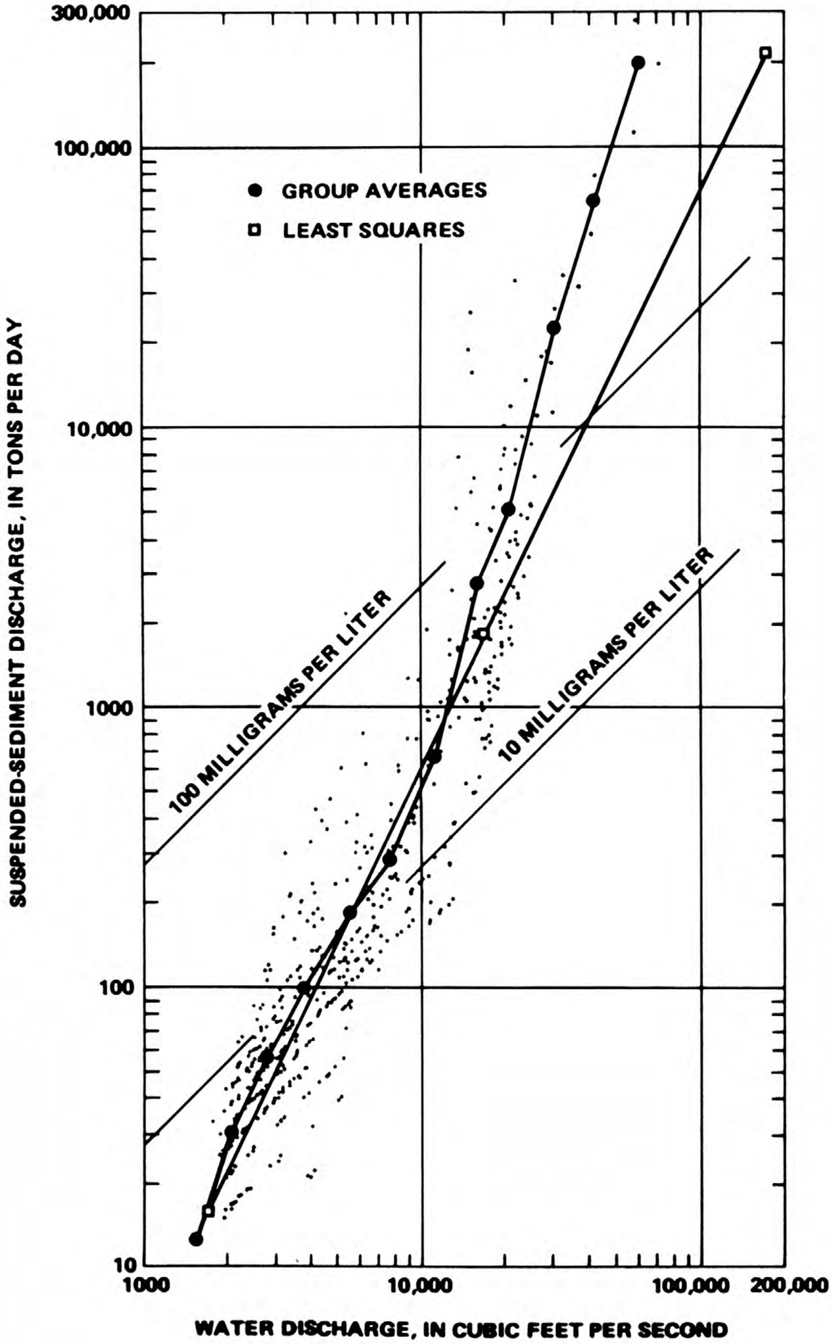


FIGURE 18.--Relation between streamflow and suspended-sediment discharge, Feather River at Oroville, 1958 water year.

Sediment discharge during a specified period is proportional to the summation of the products of the instantaneous water-discharge rates and sediment concentrations that occurred during the period. Sediment discharge may differ for periods of equal average flow if the rates of flow and the frequency of occurrence differ. This difference in sediment discharge can occur with a change in flow frequencies although no change occurs in the relation between water and sediment discharge.

Changes in sediment discharge can result also from changes in concentration at a given rate of water discharge. Concentration changes which result in the normal scatter of data for most streams (fig. 18) can be related to changes in erosional potential associated with generally cyclic variables such as seasonal changes, rainfall patterns and intensity, and antecedent hydrologic conditions. Concentration changes that are permanent or semipermanent result in a change in the transport curve. Such changes may be caused by major floods that rework channels and make available new sources of material for transport by bank cutting and slides, as occurred after the floods in December 1964 in the Coast Ranges of California, or by land reclamation, changes in land use, or major changes in the nature of the basin, such as those caused by construction of a large dam.

Suspended Sediment

Annual variation in sediment transport is demonstrated by the data for Feather River at Oroville 1963-67 (fig. 5). These data indicate a trend toward a decreasing concentration of suspended sediment during the construction period. Construction began in July 1962 and the initial influence can be seen in the increased sediment discharges at flows less than 10,000 ft^3/s during 1963 when the annual flow was greater than average and 1964 when the annual flow was less than average.

The sediment-transport curves for 1957-62, 1965-67, and 1968-75 (fig. 19) show the transition from pre-dam conditions to complete regulation of the Feather River at Oroville. The slope of the 1968-75 transport curve has decreased, and transport is less at flows greater than 6,000 ft^3/s and greater at lower flows than it was during unregulated flow. Except for increased sediment discharge during low flow, very small differences are noted in rates of sediment transport in the construction and preconstruction periods.

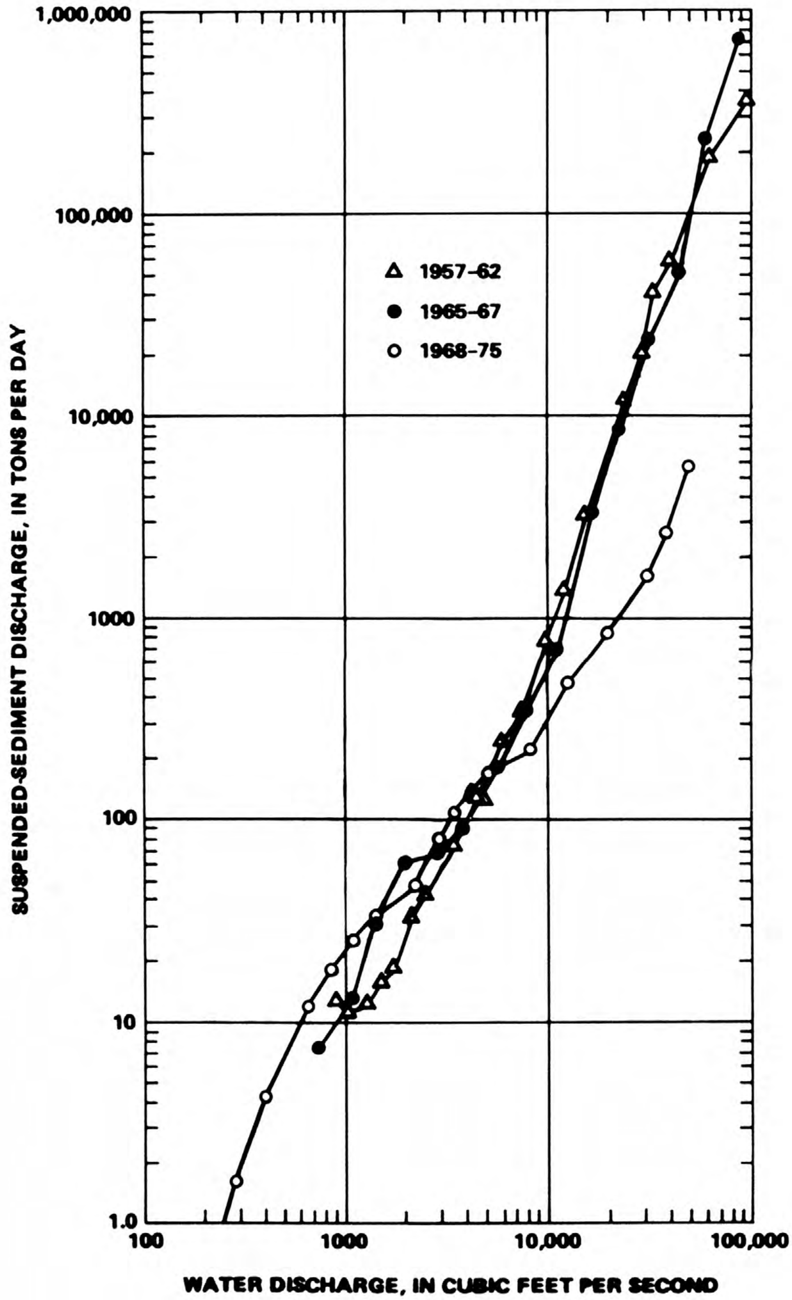


FIGURE 19.--Relation between streamflow and suspended-sediment discharge, Feather River at Oroville, 1957-62, 1965-67, and 1968-75 water years.

Transport curves of suspended-sediment and suspended-sand discharge for Feather River near Gridley for 1965-67 and 1968-75 are given in figure 20. No data are available for Feather River near Gridley nor at Yuba City prior to construction of Oroville Dam; however, the 1965-67 data may be assumed to represent the preconstruction relation between streamflow and sediment discharge because data obtained at Oroville prior to and during the construction period show a similar trend at median or greater flows. Regulation resulted in a decrease in sediment concentrations and discharge for flow rates greater than 2,000 ft^3/s; the reduction in frequency of occurrence of these flow rates (fig. 13) further reduces the sediment discharge at Gridley.

Data obtained in 1974-75, shown in figure 21, indicate a continued decrease in transport of suspended sediment and sand. The slope of the transport curve has decreased to 1.08; thus, mean concentration of suspended sediment increases little with an increase in discharge. A slope of 1.00 would indicate a constant concentration for all flow rates.

Transport curves of suspended-sediment and suspended-sand discharge for Feather River at Yuba City for 1965-67 and 1968-75 are shown in figure 22. These curves reflect not only the influence of regulation but the influence of backwater from Yuba River during flood-stage periods. Backwater from the Yuba River affects the stage-discharge relation at the Feather River gaging station at Yuba City and, thus, the relations among width, depth, and velocity, and it reduces the competence of the river to transport sediment. Because of the backwater effect on the relation of the rate of flow to a given water-surface elevation, the Feather River discharge is determined indirectly from measurements made on the Yuba River and on the Feather River below the confluence with the Yuba. The computed values of daily discharge are subject to error although monthly or annual estimates of flow may be good; instantaneous values of discharge, upon which the transport curves are based, are subject to considerable discrepancies. The concentration records (fig. 17) are good; however, sediment-discharge values (fig. 22) reflect the accuracy of both streamflow and concentration records. These discrepancies may explain most of the irregularities in the Yuba City transport curves. The unusual trend of the 1968-75 curve above 20,000 ft^3/s reflects the backwater effect on the transport competence of the Feather River. This backwater effect was partly negated during 1965-67 by the unusually large flows during the December 1964-January 1965 floods; however, these large flows will occur less frequently because of regulation of flow by Oroville Dam. Conversely, increased regulation of the Yuba River by the New Bullards Bar Reservoir (capacity, 961,300 acre-ft) since 1969 will reduce the backwater effect on Feather River at Yuba City.

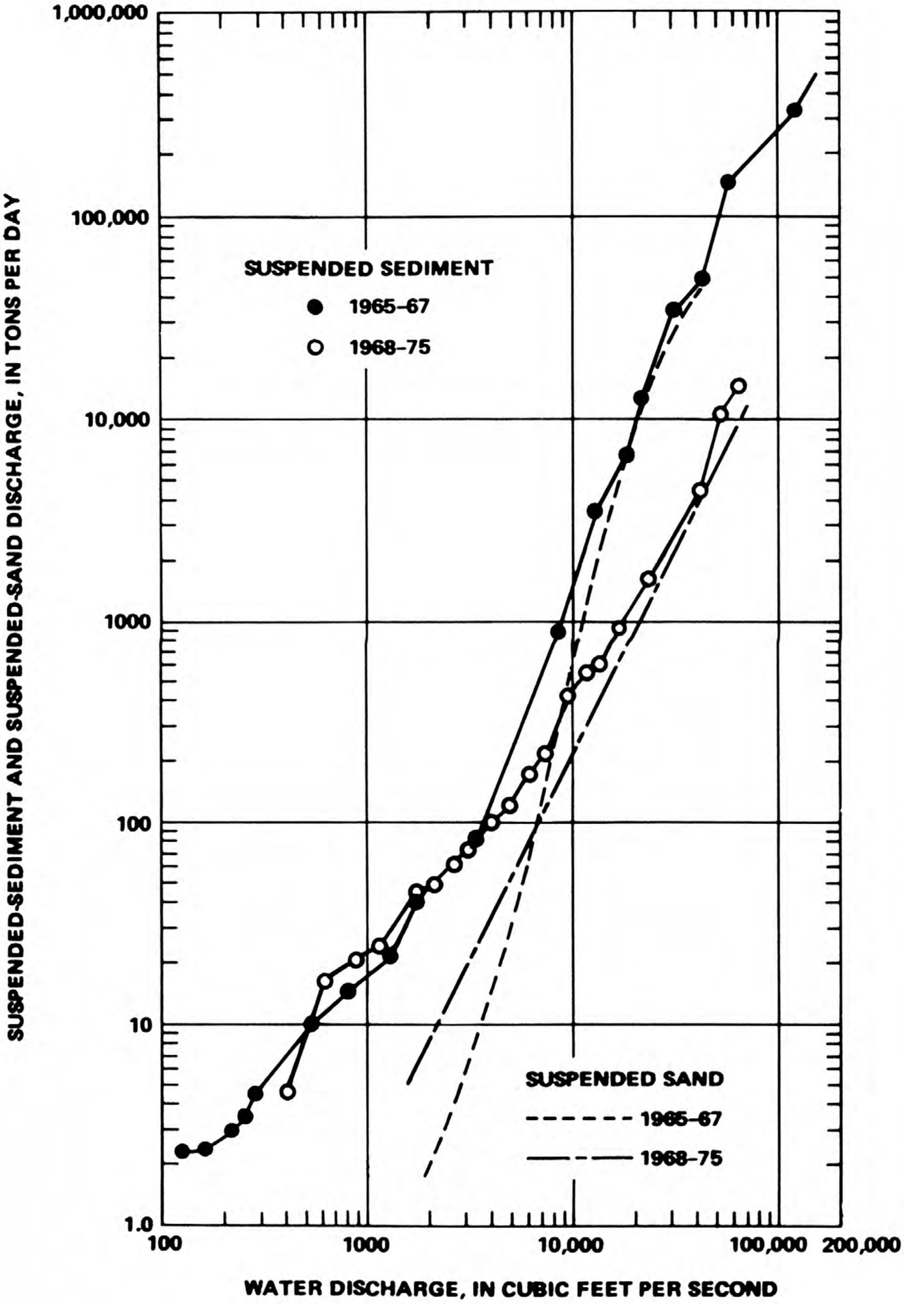


FIGURE 20.--Relation between streamflow and suspended-sediment and suspended-sand discharge, Feather River near Gridley, 1965-67 and 1968-75 water years.

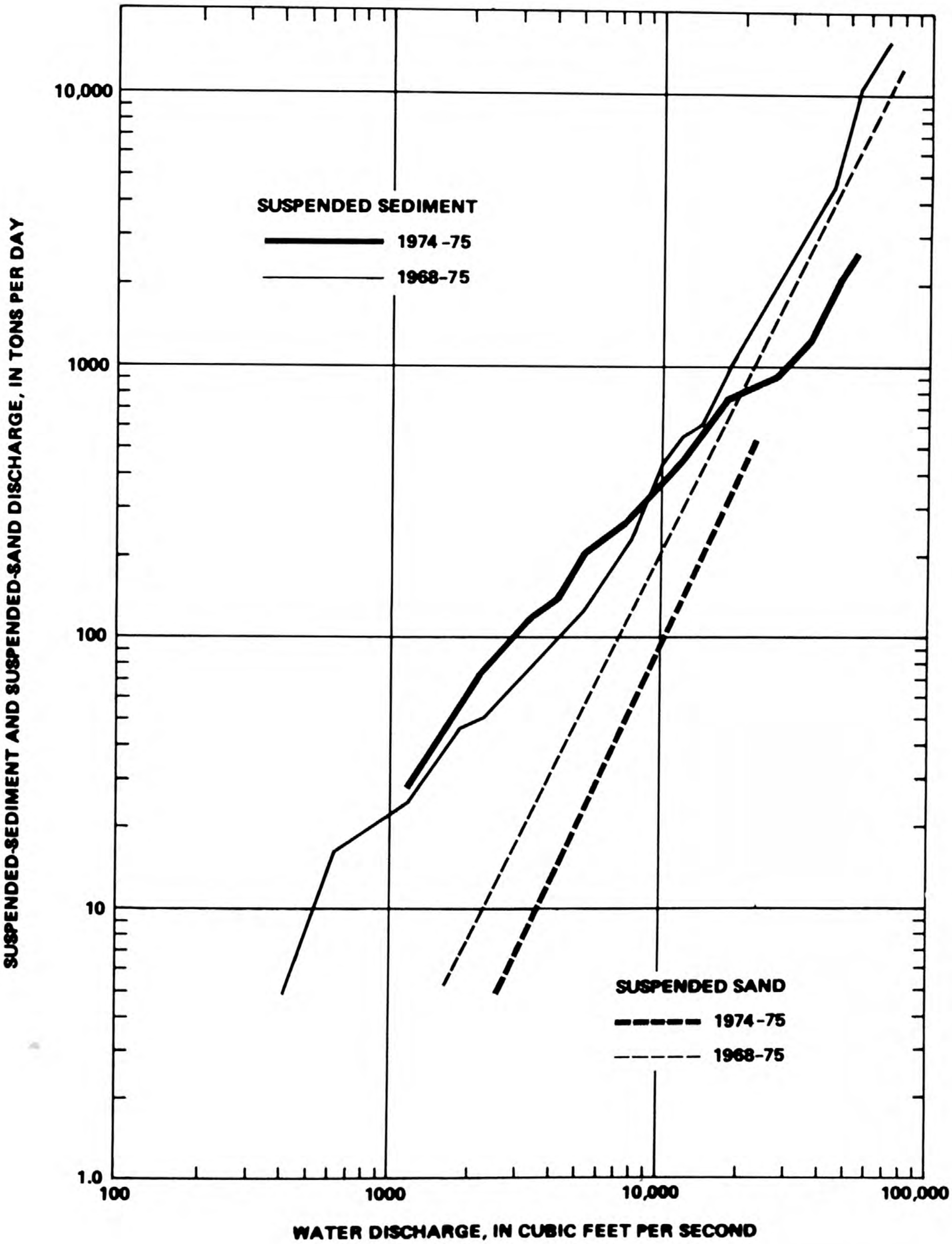


FIGURE 21.--Relation between streamflow and suspended-sediment and suspended-sand discharge, Feather River near Gridley, 1968-75 and 1974-75 water years.

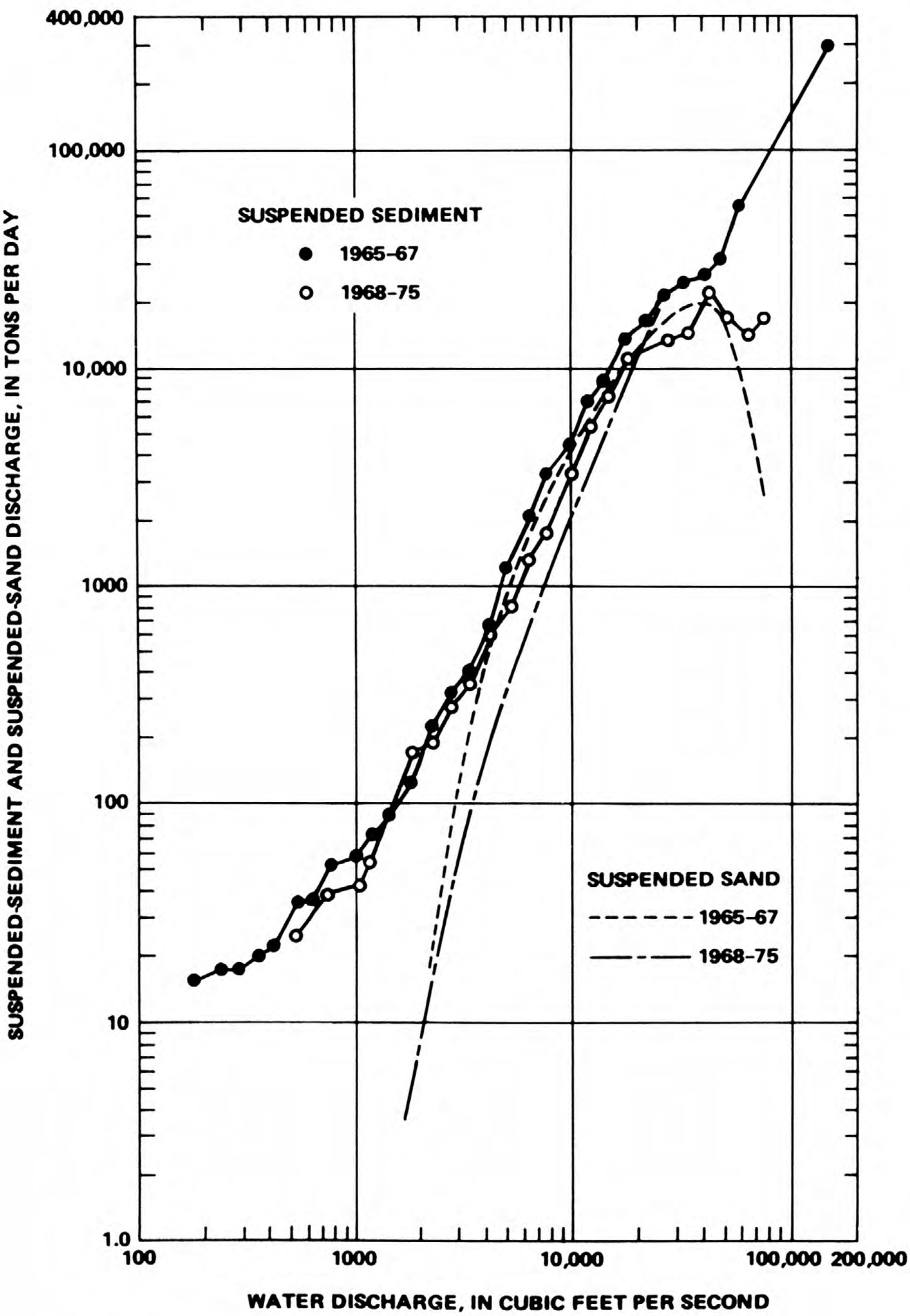


FIGURE 22.--Relation between streamflow and suspended-sediment and suspended-sand discharge, Feather River at Yuba City, 1965-67 and 1968-75 water years.

The transport curve, 1968-75, for Yuba City indicates values of concentration approaching those during the 1965-67 period for flows less than about 4,000 ft^3/s and decreasing at larger flows; hence, based on the similarity of the 1965-67 Oroville data to preconstruction data, the concentration has not yet been reduced significantly by the regulation by Oroville Dam. Sediment transport will be reduced, however, because of reduced occurrence of flow rates greater than 4,000 ft^3/s. The 1974-75 data for Yuba City, unlike those for Gridley, indicate no change from the 1968-75 average relation between streamflow and sediment discharge.

Suspended Sand

Transport curves showing the relation of streamflow to suspended-sand discharge in the sampled zone are based on particle-size analyses of suspended samples. The number of analyses each year is small because of economic and physical limitations, and sufficient samples to define the average particle-size distribution of the sediment discharge usually are obtained only after many years of routine sampling. The sand curve for Feather River at Oroville for the period 1957-62 (fig. 4) is well defined and provides the basis for a reliable estimate of sand transport prior to regulation. Sand transport at Oroville was almost eliminated by construction of Oroville Dam and Thermalito diversion dam. Coarse material is trapped by Lake Oroville and the diversion pool, and little or no sand-size material is available for erosion and entrainment in the bed and banks of the stream between the diversion dam and the Oroville gaging station.

Sand-transport curves for Feather River near Gridley and Yuba City (figs. 20 and 22) are based on limited data which have considerable scatter for a given flow rate. The curves represent the best estimate based on available data and are shown to reflect possible trends. Data for Gridley indicate a definite decrease in sand discharge at flow rates greater than 7,000 ft^3/s, which occur about 12 percent of the time, and an increase in sand discharge at the lesser flows. The 1974-75 data (fig. 21) indicate a continued change in the rate of suspended-sand transport.

Sand-transport data for Feather River at Yuba City indicate a decrease in sand transport at flow rates from 2,000 to 20,000 ft^3/s, which occur about 65 percent of the time. The sand data also indicate a definite backwater effect, and the sand discharge decreases more rapidly at peak flows than does the suspended-sediment discharge.

Flow rates and sediment concentration in 1968-75 decreased at Yuba City over those in 1965-67, although these rates may not be much reduced over preconstruction rates. The decrease was less than at the Gridley station because tributary inflow contributed some sediment and because of the availability of material in the bed and banks of the channel for erosion and transport.

Changes in Basin Sediment Yield

Streamflow and sediment concentration are variables dependent on the character of the drainage basin and are affected although not to the same degree, by some common factors. The number of these factors and degree of influence may vary from period to period, and the variance explains to a large degree the large range of concentration values that occur for a specific flow rate. Factors affecting erosion, sediment transport, and runoff include quantity and type of vegetation, changes in vegetation due to fire, floods, and drought, and changes in land management, construction, urbanization, road building, channelization, reclamation, and conservation.

The effects of changes on runoff and sediment concentration are shown to some degree by double-mass curves (fig. 23) showing the relation between accumulated annual streamflow and sediment discharge. The slope of the line between points representing data for one year or combination of years indicates the value of the discharge-weighted mean suspended-sediment concentration for that period. Changes in slope for successive periods graphically show changes in concentration and the magnitude and frequency of these changes. Differences in mean concentrations generally result because of the infinite possibilities available from the interrelation of the many factors affecting sediment transport and streamflow. Frequency of occurrence and magnitude of flow rates are the usual causes of the variation in mean annual sediment discharge with streamflow, and changes in slope do not necessarily imply a change in the average relation between instantaneous or daily values of streamflow and sediment discharge or that a change has occurred in basin yield. For example, the maximum annual sediment discharge frequently occurs during a year of below-average streamflow that may include several large storms but for which the annual precipitation and runoff are deficient; the large flow rates transport most sediment and the below-normal antecedent precipitation creates conditions favorable to erosion. Conversely, a year of greater-than-average runoff that has no large peak flows may have less than average sediment discharge, because the generally moist conditions favor vegetation and reduce the erosion potential. If the sampling period is of sufficient length to represent most possible combinations of events, the slope of the cumulative streamflow-sediment-discharge curve for that period represents the long-term concentration yield of the basin, and the trend shown by magnitude and frequencies of annual changes in concentration depicts the probable occurrence of these events.[1] A permanent change in the sediment yield of a basin and its influence on the relation between water discharge and sediment discharge may be noted by the shift of the sediment-transport curves at Oroville for 1957-62 to 1968-75 (fig. 19).

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[1]A regression equation based on cumulative values of streamflow, except under special conditions, should not be used to compute or extrapolate sediment discharge.

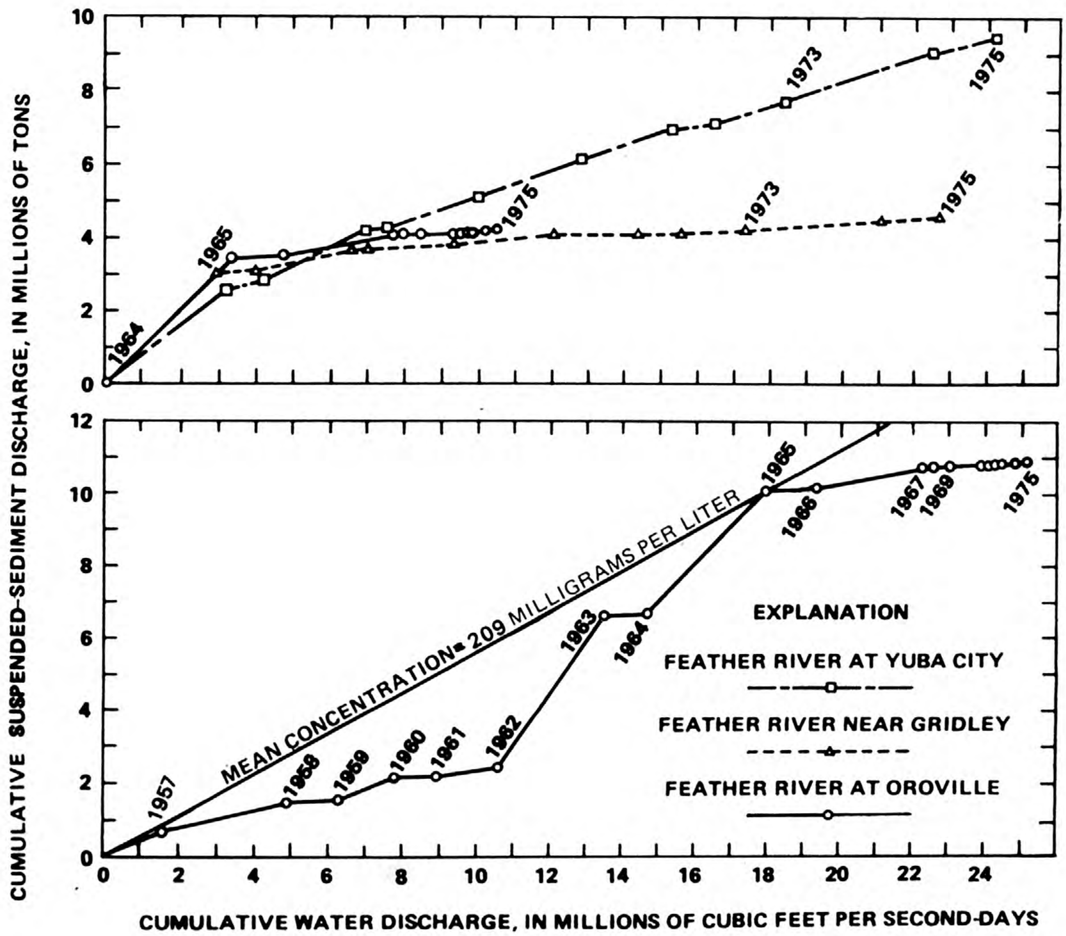

FIGURE 23.--Relation between cumulative streamflow and suspended-sediment discharge, Feather River at Oroville, 1957-75 water years, and Feather River near Gridley and at Yuba City, 1965-75 water years.

A stream draining a basin of stable or uniform runoff and erosional characteristics will be characterized by a double-mass curve that shows little variation in slope such as the 1957-62 (fig. 23) data for Feather River at Oroville. Streams that drain basins of widely varying basin conditions and potential storm patterns may be characterized by curves with large slope variations such as those during 1957-65 for Oroville.

Sufficient data were not obtained prior to the beginning of construction of the Oroville Dam in July 1962 to adequately define the historical relation between streamflow and sediment discharge at the Oroville gaging station. An analysis of streamflow data suggests that the trend indicated by the 1957-62 data may represent most periods that had normal or below normal flow rates. Although the 1958 water year runoff was above average, the maximum daily discharge for 1958 was exceeded in 21 of the years from 1902-57, and the mean sediment concentration was less than that for the 1957 and 1960 water years which had less flow. Maximum daily discharges that occurred in 1963 and 1965 were equaled or exceeded in about 6 of the years prior to 1963.

Suspended-sediment concentrations during the 1963 water year, although affected to some extent by construction, may be representative of water years that have above-normal flow rates. The large difference between sediment discharge in 1958 and 1963 illustrates that the magnitude and frequency of flows influence the annual sediment discharge more than average flow or total annual flow. The annual flows for the 1958 and 1963 water years rank 9th and 15th during the 1902-65 period; however, owing to the larger daily flows that occurred during the 1963 water year, the 1963 sediment discharge was more than five times that of 1958. Differences shown by the 1958 and 1963 transport curves (fig. 24) and by the change in slope in the double-mass curves (fig. 23) are indicative of annual differences that occurred routinely during the long term and are not indicative of permanent changes in basin yield.

On the assumption that the 1957-62 data, with a mean suspended-sediment concentration of 86 mg/L, are representative of 45 years of the 1902-62 period, and the 1963 data, with a mean concentration of 539 mg/L, are representative of the 16 years that have peak-flow values exceeding those of 1958, the weighted mean concentration for the full period would be 205 mg/L. This estimate is in agreement with the concentration of 209 mg/L determined from the duration data in table 4. Thus, the average slope of the curve shown by the accumulated sediment discharge for the 1957-65 period (fig. 23) apparently approximates the historical relation for 1902-62.

The change in slope of the double-mass curve for Oroville since total regulation began in 1967 results from change in the relation between streamflow and sediment discharge (fig. 19) and in the frequency of occurrence and magnitude of flow rates (fig. 12). The trend indicated by 15 mg/L for 1968-75 should continue unless interrupted by some unusual natural occurrence or by a drastic change in reservoir operation.

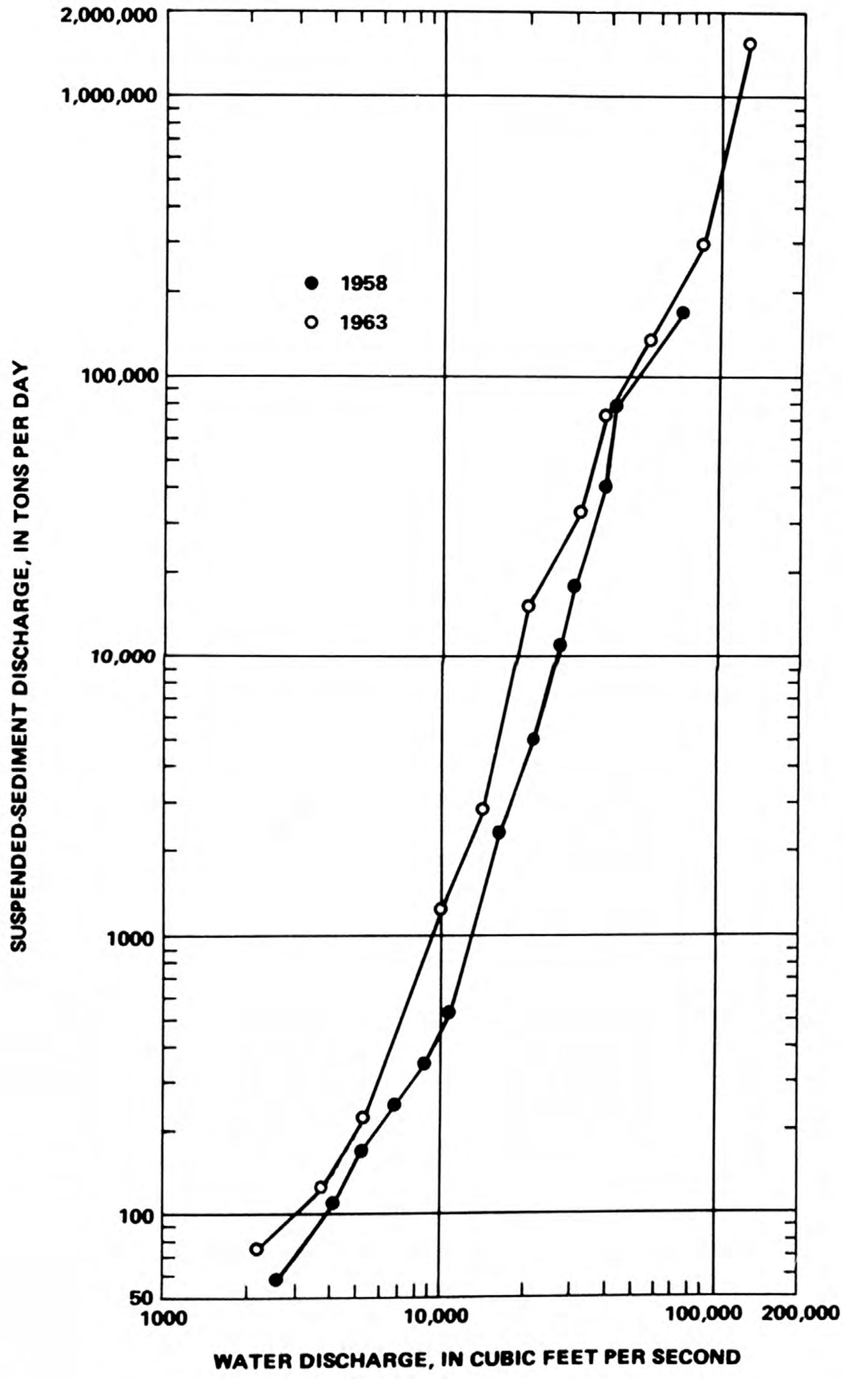

FIGURE 24.--Relation between streamflow and suspended-sediment discharge, Feather River at Oroville, 1958 and 1963 water years.

Data available are insufficient to define trends in suspended-sediment concentration for Feather River near Gridley and at Yuba City prior to regulation of Feather River by Oroville Dam. However, the similarities in sediment transport and flow-duration data during 1965-67 at Oroville, Gridley, and Yuba City indicate continuity of flow downstream. The average concentration at Gridley and Yuba City may follow the same trend of increasing concentration downstream during 1902-62 as during 1965-67 (table 3). The slopes of the lines representing mean concentration of suspended sediment, 1902-62, for Gridley and Yuba City are therefore probably progressively larger than that shown (209 mg/L) for Oroville in figure 23.

Prior to construction of Oroville Dam, the mean sediment concentration at Gridley was a little greater than that at Oroville; and the mean concentration since regulation, 1967-75, continues to be a little greater than the concentration at Oroville. The decrease in the slope (mean concentration) of the curve of cumulative water and sediment discharge for Gridley is due to the decrease in availability of sediment for erosion and transport (fig. 17) and to the reduction of flow rates greater than 3,000 ft^3/s to transport sediment.

The mean concentration of suspended sediment in Feather River at Yuba City was probably greater than the mean concentration at Oroville and Gridley, 1902-62. The decrease in slope after regulation is due to a small change in the relation of streamflow to sediment discharge (fig. 22) and in the frequency and magnitude of flow rates (fig. 14). The 1967-75 trend is uniform at about 114 mg/L; however, the period is too short to conclude that the trend will continue at this level indefinitely. Adjustment to a lower level of concentration will probably be delayed because of the large quantity of material available for erosion and transport in the bed and banks of the stream, the new material brought into the river by tributary inflow, and the effect of the Yuba River on sediment transport and deposition at Yuba City. Data obtained during 1974-75 indicate a continued trend of mean concentration at 114 mg/L, and the effects of the regulation already apparent at Gridley have not yet affected the relation between sediment transport and streamflow at Yuba City.

Changes in Hydraulic Geometry

Hydraulic characteristics of stream channels such as the width, depth, velocity, and suspended-sediment discharge and their relation to streamflow were termed "hydraulic geometry" by Leopold and Maddock (1953). They developed an empirical quantitative relation among average measurements of these variables that shows that the width and depth, as well as velocity, are functions of the sediment transported in the channel. These characteristics are important determinants of the shape of the cross section of a channel and progressive changes in its shape downstream. The empirical relation between hydraulic characteristics of the channel and suspended-sediment discharge provides, in semiquantitative terms, a logical explanation of the observed channel shape.

The width, depth, and velocity of a stream are measured each time a measurement is made of the streamflow rate--water discharge--or of the total-sediment discharge of the stream. Streamflow is computed as the product of width, depth, and velocity of the stream, and any change in discharge results in adjustment of one or more of these parameters. The competence of the stream to transport sediment is also proportional to these parameters, and the transport of sand (bed material) in both the sampled and unsampled zones increases exponentially with velocity. The sand discharge (fig. 4) increases by about the third power of water discharge, and the unsampled discharge at Gridley (fig. 8) increases with about the 5.4 power of the velocity from 1.5 to 5.0 ft/s.

Water discharge is not always measured at the same site; the site chosen usually is that where the hydrologist can obtain the best measurement. Thus, some of the scatter in data used to obtain the average relation between streamflow and width, depth, and velocity may be attributed to the differences in the measuring section rather than to differences caused by seasonal variation in geometry, or to changes that reflect long-term trends. To prevent bias caused by differences in measuring sections, the values of width, depth, and velocity were taken from measurements made about the same distance from the streamflow-gaging station. The average relations between streamflow and mean width, depth, and velocity for Feather River near Gridley for 1965, 1965-67, 1968-75, and 1974-75 water years, and at Yuba City for 1964-66 and 1968-70 water years are shown in figures 25 and 26. The sum of the slopes of the lines representing width, depth, and velocity for each period equals unity (Leopold and Maddock, 1953, p. 8).

Flow rates for an equal frequency of occurrence increased downstream from Gridley to Yuba City during 1965-67 and 1968-75 (figs. 13 and 14), and the product of width, depth, and velocity must follow the same trend. A summary of average values of width, depth, and velocity from figures 25 and 26 for selected flow rates of 10, 50, and 90 percent frequency of occurrence and corresponding ratios of width to depth (w/d) and velocity to depth (v/d), and the Froude number (F), are listed in table 10. The Froude number is a dimensionless combination of velocity, density, specific weight, and length ($F = v/\sqrt{gd}$) that is commonly associated with competence of a stream to transport bed material.

Width and velocity increase and depth decreases from Gridley downstream to Yuba City for flow rates of equal magnitude and of equal frequency of occurrence, both for the period prior to and for that following regulation. The other parameters listed in table 10 also show an increase in the downstream direction. Because of the large variation in rate of change of depth and velocity with streamflow from 1964-66 to 1968-70, a shift in trend occurred in the velocity-to-depth ratio in 1968-70, and currently the v/d ratio decreases with increasing flow rates whereas this ratio increased with increasing flow during 1964-66. A summary of changes in parameters (table 10) resulting from increasing flow rates, or occurring with time at constant flow rates or with constant and equal flow-frequency rates, downstream from Gridley to Yuba City for periods prior to and following regulation is given in table 11.

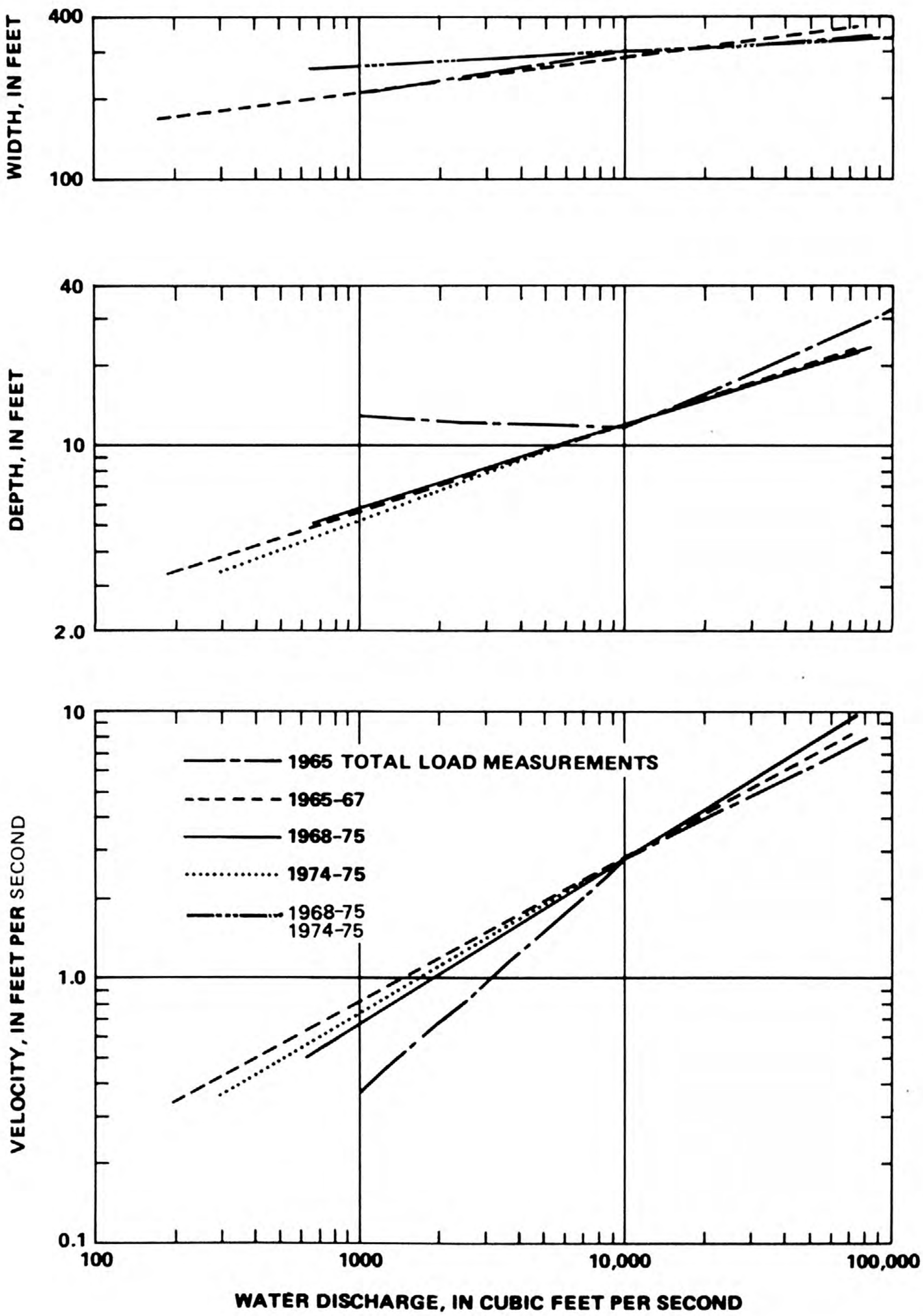

FIGURE 25.--Relation between streamflow and the width, depth, and velocity for Feather River near Gridley, 1965, 1965-67, 1968-75, and 1974-75 water years.

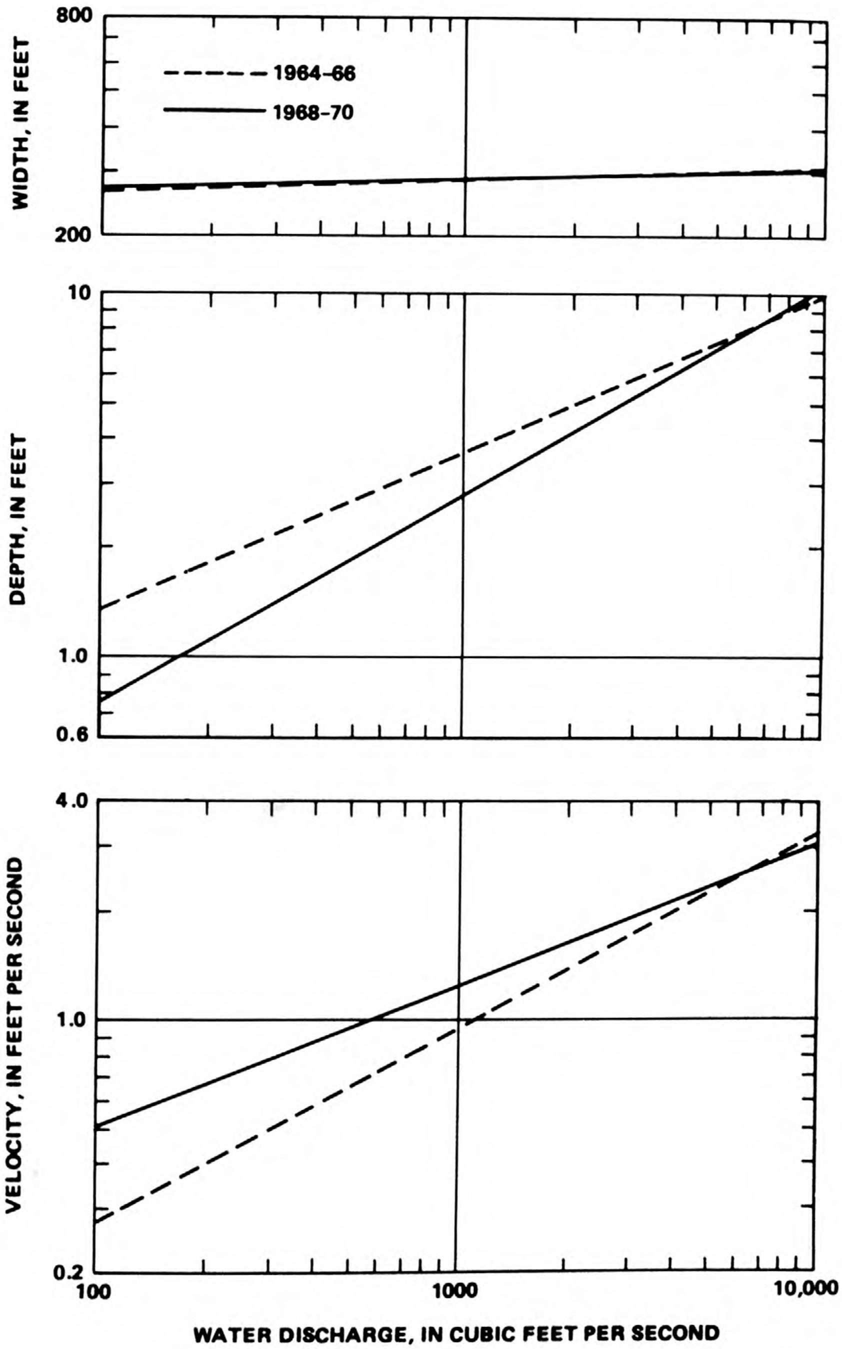

FIGURE 26.--Relation between streamflow and the width, depth, and velocity for Feather River at Yuba City, 1964-66 and 1968-70 water years.

TABLE 10.--*Selected hydraulic variables for Feather River near Gridley, 1965-67 and 1968-75 water years, and Feather River at Yuba City, 1964-66 and 1968-70 water years*

	Discharge, Q (ft^3/s)	Frequency of occurrence, in percent	Width, w (ft)	Depth, d (ft)	Velocity, v (ft)	w/d	v/d	Froude number, F	Sediment discharge (ton/d)		Concentration, c (mg/L)
									Suspended, s	Sand, s_d	
Feather River near Gridley											
1965-67											
	11,800	10	292	12.8	3.16	22.8	0.25	0.16	2,700	1,300	85
	3,500	50	250	8.6	1.63	29.1	.19	.10	96	10	10
	670	90	203	5.0	.66	40.6	.13	.05	13	--	7
1968-75											
	11,800	9	300	12.7	3.09	23.6	.24	.15	560	290	18
	3,500	49	281	8.6	1.45	32.7	.17	.09	85	25	9
	670	98	258	5.0	.52	51.6	.10	.04	18	--	10
Feather River at Yuba City											
1964-66											
	11,800	13	314	10.7	3.51	29.3	.33	.19	7,000	5,800	220
	3,500	50	300	6.3	1.85	47.6	.29	.13	460	270	49
	670	91	285	3.0	.78	95.0	.26	.08	40	--	22
	13,000	10	314	11.2	3.73	28.0	.33	.20	8,000	6,700	228
	3,500	50	300	6.3	1.85	47.6	.29	.13	460	270	49
	710	90	286	3.1	.80	92.3	.26	.08	46	--	24
1968-70											
	11,800	9	307	11.6	3.30	26.5	.28	.17	5,200	4,000	163
	3,500	45	296	5.8	2.04	51.0	.35	.15	380	65	40
	670	98	275	2.3	1.08	12.0	.46	.12	30	--	17
	13,000	7	308	12.3	3.43	25.0	.28	.17	6,700	5,000	191
	3,500	43	296	5.8	2.04	51.0	.35	.15	380	65	40
	710	98	286	2.3	1.08	12.4	.47	.13	35	--	18

TABLE 11.--*Summary of changes in hydraulic geometry and related variables shown in table 10*

[Column-heading symbols are those in table 10. +, increase in value; -, decrease in value; N, no change]

Station	Discharge (ft³/s) Q	1965-67[1]									1968-75[1]								
		w	d	v	w/d	v/d	F	s	s_d	c	w	d	v	w/d	v/d	F	s	s_d	c
Changes with increase in discharge:																			
Feather River near Gridley	670-11,800	+	+	+	-	+	+	+	+	+	+	+	+	-	+	+	+	+	+
Feather River at Yuba City	670-11,800	+	+	+	-	+	+	+	+	+	+	+	+	-	-	+	+	+	+
	710-13,000	+	+	+	-	+	+	+	+	+	+	+	+	-	-	+	+	+	+
Changes from 1965-67 to 1968-75[1]																			
Feather River near Gridley	11,800										+	-	-	+	-	-	-	-	-
	3,500										+	N	-	+	-	-	-	+	-
	670										+	N	-	+	-	-	-		-
Feather River at Yuba City	11,800										-	+	-	-	-	-	-	-	-
	3,500										-	-	+	+	+	+	-	-	-
	670										-	-	+	+	+	+	-		-
Changes downstream from Gridley to Yuba City:																			
At constant discharge	11,800-11,800	+	-	+	+	+	+	+	+	+	+	-	+	+	+	+	+	+	+
	3,500-3,500	+	-	+	+	+	+	+	+	+	+	-	+	+	+	+	+	+	+
	670-670	+	-	+	+	+	+	+		+	+	-	+	+	+	+	+		+
At constant frequency discharge	11,800-13,000	+	-	+	+	+	+	+	+	+	+	-	+	+	+	+	+	+	+
	3,500-3,500	+	-	+	+	+	+	+	+	+	+	-	+	+	+	+	+	+	+
	670-710	+	-	+	+	+	+	+		+	+	-	+	+	+	+	+		+

[1]Feather River at Yuba City, 1964-66 and 1968-70.

Changes in geometry (with time) at a station, owing to the regulation by Oroville Dam, are more complex. At Feather River near Gridley, between 1965-67 and 1968-75 the width increased and velocity decreased for all flow rates listed in table 11, and depth changed little at the lower flows and decreased at larger flows, the ratio of width to depth increased, and the ratio of velocity to depth and Froude number decreased. Measurements during 1974-75 water years indicated only a small change in width over the 1968-75 mean values; however, significant change occurred in depth and velocity, indicating a trend toward a decrease in depth and an increase in velocity (fig. 25).

Leopold and Maddock (1953, p. 24) stated "a wide river having a particular velocity is observed to carry a smaller suspended load than a narrow river having the same velocity and discharge." They also stated that for a given discharge rate and width, an increase in suspended sediment requires an increase in velocity and a reduction in depth. A wide, shallow channel is associated with a decrease in suspended-sediment discharge and an increase in bedload. Thus, a larger percentage of the sediment load at Gridley at the larger flow rates may now be transported as bedload rather than as suspended load. The decreases, however, in velocity and the velocity-to-depth ratio indicate a general decrease in the competence of the stream to transport sediment, a trend that was apparently reversed in 1974-75 water years.

Changes in the hydraulic geometry (with time) at Yuba City, owing to regulation, do not follow the same trends as those at Gridley. The mean width and depth of flow decrease and velocity increases at flow rates less than 7,000 ft^3/s; the reverse is true for depth and velocity at larger flows. The velocity-to-depth ratio and Froude number also increase at flow rates less than 7,000 ft^3/s--a flow that now occurs 80 percent of the time. Leopold and Maddock (1953) have shown that for a given width and discharge, an increase in suspended sediment requires an increase in velocity and a reduction in depth. They concluded, from observations of channel adjustments during floods, that the observed changes in the streambed resulted from changes in the sediment load brought into the measuring reach upstream. Colby (1961) has shown that mean velocity is the major factor determining the discharge of bed material. Thus, changes in hydraulic geometry at Feather River at Yuba City, 1968-70, indicate an increase in the competence of the Feather River to transport sediment.

Trends in Suspended-Sediment Concentration

Changes in sediment concentration will occur downstream when streamflow is regulated by a large dam such as Oroville Dam. A change in concentration will occur with the beginning of regulation because most of the sediment originating upstream from the dam is trapped by the reservoir. Additional changes in sediment concentration will occur downstream from the reservoir because of changes in bank and channel erosion effected by the new flow rates imposed on the channel by regulation. The initial change in concentration owing to reduction in basin area and trapping of sediment by the reservoir will be abrupt and readily discerned; however, other changes, or trends, in concentration during the period of channel adjustment to the new flow rates may be gradual, and considerable time may be required before quasi-equilibrium again occurs in the sediment supply and sediment transport.

The abrupt change in concentration for a given flow rate, caused by trapping sediment in the reservoir, is apparent in the change of the average relations between streamflow and suspended-sediment discharge as shown by the sediment-transport curves in figures 19 and 20. The physical changes in channel geometry are indicated by changes in width, depth, and velocity, as shown in figures 25 and 26. Long-term trends in concentration, however, are not readily apparent in average transport curves based on a short period of record, because the large seasonal and annual variations in concentration for a given flow rate disguise small changes in concentration. Thus, a rank correlation method (Kendall, 1948) that results in a numerical coefficient and a level of significance was used to determine the trend of sediment concentration with time. The coefficient of correlation is denoted by ρ (rho).

The data ranked to compute the coefficient of correlation were the departure ratios of the observed daily sediment discharge from the average sediment discharge for 1968-75 (figs. 19, 20, 22). Guy (1957) demonstrated that departure ratios of storm events from unadjusted sediment-transport curves are useful parameters for evaluating the trend of concentration with time. He noted also that values obtained from a sediment-transport curve adjusted for factors known to affect sediment erosion and transport, such as rainfall intensity and season, do not appreciably alter the ranking of sediment yield with time compared to the ranking of values obtained from an unadjusted transport curve.

Departure ratios of suspended-sediment discharge were computed and ranked for streamflow values greater than 13,000 ft^3/s near Gridley and for streamflow values ranging from 2,000 to 24,000 ft^3/s at Yuba City. The use of storm-runoff values only to evaluate trends eliminated the effect of base-flow characteristics on the analysis and provided a more realistic parameter to describe the basin effect on sediment transport. As the departure ratio of sediment discharge for a given streamflow rate is equal numerically to the ratio of sediment concentration, the ranking effectively shows trends in concentration of suspended sediment. Streamflow values greater than 24,000 ft^3/s were not used in the ranking for Yuba City because of suspected bias owing to backwater effect on the Feather River by the Yuba River during periods of storm runoff.

Departure ratios of sediment discharge were ranked chronologically and in decreasing order of magnitude. The coefficient of correlation, denoted by ρ, is defined as follows:

$$\rho = 1 - \frac{6 \Sigma (d^2)}{n^3 - n}$$

where d is the difference between the two ranks and n is the number of items ranked. If the two rankings of the departure ratios are identical and in decreasing order with time, all differences (d) are zero and $\rho = +1$, indicating a decrease in sediment concentration with time. If one ranking is the reverse of the other, then $\rho = -1$, indicating an increase in sediment concentration with time. A random order of the two rankings relative to each other indicates there is no discernible trend as the coefficient ρ approaches 0.

An edited list of observed sand discharges and an illustration of the determination of the coefficient of rank correlation is shown in table 12. The list does not contain values of sand discharge for streamflow rates greater than 24,000 ft^3/s because of the backwater effect. For a given flow rate, backwater reduces the mean stream velocity and increases depth of flow, thereby decreasing the competence of the stream to transport sediment and inducing deposition. Some of the large differences, or discrepancies, in sand discharge for a given flow rate may be attributed to backwater effect; however, a considerable number of the discrepancies are probably due to inaccuracies in determination of the instantaneous flow rate at the time of sampling and to sampling errors. The computed values of sand discharge are based on the sand-transport curve (fig. 22) that approximates the average of the observed sand-discharge values. The accuracy of the coefficient of correlation for the sand discharge is reduced because of the small number of sand samples available, discrepancies in streamflow, and sampling errors.

The value of the rank correlation coefficient at Yuba City, determined from data in table 12, is -0.273. The level of significance, determined from figure 27, of this coefficient based on 44 samples is 0.07. A significant level of 0.05 is generally the upper limit used to ensure that the two rankings are independent of each other and that the correlation is significant. These data indicate, at a 93-percent level of confidence, a trend towards increased concentration of sand.

TABLE 12.--*Trend analysis of suspended-sand discharge, Feather River at Yuba City, 1968-75 water years*

[Values of sand discharge for streamflow rates greater than 24,000 ft^3/s not used]

Date	Water discharge (ft^3/s)	Suspended-sand discharge (ton/d)		Ratio y_o/y_c	Chrono-logical rank	Magnitude		(Difference in rank)^2 (d^2)
		Observed (y_o)	Computed (y_c)			Order	Rank	
01-30-68	2,300	59	16	3.69	1	6.05	42	1,681
02-14-68	4,370	45	240	.19	2	4.81	18	256
02-20-68	4,100	17	190	.09	3	3.69	1	4
03-20-68	1,900	2.5	66	.04	4	3.15	23	361
05-04-68	4,470	392	250	1.57	5	2.37	37	1,024
05-09-68	3,000	23	57	.40	6	2.27	33	729
01-13-69	8,900	363	1,660	.22	7	1.79	22	225
01-14-69	16,000	7,930	6,900	1.15	8	1.68	43	1,225
01-21-69	9,800	54	2,100	.03	9	1.57	5	16
03-25-70	2,930	38	52	.73	10	1.54	34	576
04-16-70	2,590	23	41	.56	11	1.47	40	841
01-25-71	10,900	1,990	2,700	.74	12	1.29	28	256
04-22-71	9,380	1,050	1,900	.55	13	1.27	29	256
06-08-71	8,900	938	1,660	.57	14	1.15	8	36
12-30-71	5,620	223	480	.46	15	1.13	27	144
10-12-72	3,230	46	76	.61	16	1.01	39	529
11-22-72	2,250	10	15	.67	17	.99	35	324
01-10-73	10,600	12,500	2,600	4.81	18	.97	36	324
02-16-73	12,300	2,840	3,800	.75	19	.84	24	25
03-02-73	19,000	1,780	10,100	.18	20	.75	19	1
03-12-73	8,370	429	1,400	.31	21	.75	25	16
04-02-73	1,590	3.4	1.9	1.79	22	.74	12	100
11-12-73	19,000	31,800	10,100	3.15	23	.73	10	169
11-15-73	17,500	7,270	8,700	.84	24	.67	17	49
11-20-73	22,200	11,200	15,000	.75	25	.61	16	81
11-26-73	19,700	5,190	11,000	.47	26	.57	14	144
11-29-73	13,600	5,300	4,700	1.13	27	.57	32	25
12-13-73	10,900	3,490	2,700	1.29	28	.56	11	289
12-19-73	7,560	1,400	1,100	1.27	29	.55	13	256
01-15-74	20,000	1,920	11,300	.17	30	.47	26	16
03-28-74	16,500	1,960	7,500	.26	31	.46	15	256
04-26-74	9,410	1,080	1,900	.57	32	.40	6	676
06-27-74	2,660	75	33	2.27	33	.31	21	144
11-15-74	7,470	1,590	1,030	1.54	34	.28	44	100
12-19-74	3,530	79	80	.99	35	.26	31	16

TABLE 12.--*Trend analysis of suspended-sand discharge, Feather River at Yuba City, 1968-75 water years*--Continued

Date	Water discharge (ft^3/s)	Suspended-sand discharge (ton/d)		Ratio y_o/y_c	Chronological rank	Magnitude		(Difference in rank)^2 (d^2)
		Observed (y_o)	Computed (y_c)			Order	Rank	
01-23-75	3,040	57	59	.97	36	.22	7	841
02-03-75	4,350	546	230	2.37	37	.20	41	16
02-10-75	4,050	29.5	190	.16	38	.19	2	1,296
02-13-75	15,800	6,660	6,600	1.01	39	.18	20	361
02-14-75	4,170	294	200	1.47	40	.17	30	100
02-27-75	1,850	1.1	5.6	.20	41	.16	38	9
04-04-75	1,590	11.5	1.9	6.05	42	.09	3	1,521
04-30-75	8,150	2,218	1,320	1.68	43	.04	4	1,521
07-01-75	2,510	7.3	26	.28	44	.03	9	1,225

$n = 44$

$\Sigma(d^2) = 18,060$

$$\rho = 1 - \frac{6\ \Sigma(d^2)}{n^3 - n} = 1 - \frac{6 \times 18,060}{85,184 - 44} = 1 - 1.273 = -0.273$$

Level of significance = 0.07

The rank correlation coefficient, ρ, and the level of significance of the coefficient for selected periods for Feather River at Oroville, Gridley, and Yuba City are listed in table 13. The coefficients for Feather River at Oroville prior to construction of the Oroville Dam, 1957-62, are too small and the level of significance is too large to indicate that the ratios occur naturally in decreasing magnitude with time. Apparently the Feather River at Oroville was in quasi-equilibrium prior to construction of the dam.

During the construction period, 1965-67, coefficients for the Feather River stations at Oroville, Gridley, and Yuba City indicate a high level of confidence, greater than 99 percent, in the significance of a decreasing trend in the concentration of suspended sediment. A decreasing trend in the concentration of suspended sand, which is a fraction of the suspended sediment, is indicated for the Feather River at Oroville and Yuba City. A decrease in concentration of suspended sand with time is not indicated for Gridley; thus, the decrease in suspended-sediment concentration at Gridley may be due solely to a decrease in the silt and clay fractions of the suspended sediment.

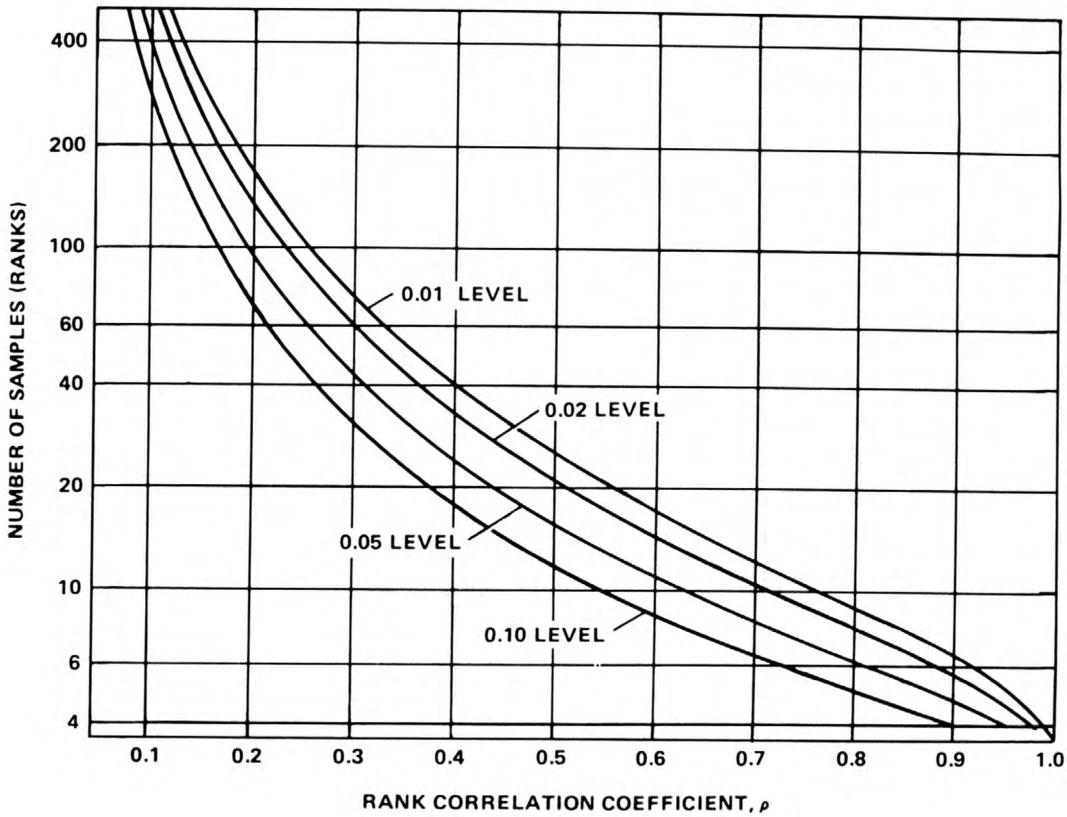

FIGURE 27.--Lower limit of rank correlation coefficient, ρ, for given number of samples and level of significance.

The period following completion of Oroville Dam, 1968-75, indicates the effect of total regulation on the channel at Oroville. Because of the highly skewed distribution of flows (fig. 12) since regulation began, rank correlation coefficients were determined for flow rates that are equal to or greater than 18,000 ft^3/s and occur 1.3 percent of the time (n = 27) and for flow rates that are equal to or greater than 500 ft^3/s and occur 10 percent of the time (n = 213). The coefficient based on the larger flows does not indicate that a decreasing trend in suspended-sediment concentration exists and that the concentration in the reach of the channel at the gage is in approximate equilibrium with flow rates imposed by regulation. Because of the proximity of the Thermalito diversion dam, 0.4 mi upstream and the fish barrier dam 300 ft downstream from the Oroville gage, this equilibrium for larger flows probably occurred rapidly. The reach is short, the bed and banks are stable, and very little sediment inflow will occur. Conversely, the rank correlation coefficient for values greater than 500 ft^3/s indicates a good probability of a decreasing trend in concentration values. Thus, concentration values for flow rates ranging from 500 to 18,000 ft^3/s, although small, may decline a small amount from their current value. This decline will reduce the slope of the 1968-75 concentration curve (fig. 15) for concentration values that occur from about 0.1 to 10 percent of the time. The effect of this additional decrease in sediment concentration on the channel at Oroville should be insignificant.

TABLE 13.--*Rank correlation coefficients and level of significance for selected periods*

Station	1957-62						1965-67						1968-75					
	Suspended sediment			Suspended sand			Suspended sediment			Suspended sand			Suspended sediment			Suspended sand		
	Number of samples	Correlation coefficient	Level of significance	Number of samples	Correlation coefficient	Level of significance	Number of samples	Correlation coefficient	Level of significance	Number of samples	Correlation coefficient	Level of significance	Number of samples	Correlation coefficient	Level of significance	Number of samples	Correlation coefficient	Level of significance
Feather River at Oroville	153	0.062	>0.10	16	0.147	>0.10	108	0.722	<0.01	18	0.480	0.04	[1]213 [2]27	0.181 .268	<0.01 >.10	6	0.143	>0.10
Feather River near Gridley	--	--	--	--	--	--	74	.767	<.01	13	-.055	>.10	238	.533	<.01	24	.748	<.01
Feather River at Yuba City	--	--	--	--	--	--	754	.213	<.01	18	.585	.01	1,831	-.028	<.01	44	-.273	.07

[1]Base discharge = 500 ft^3/s.
[2]Base discharge = 18,000 ft^3/s.

Rank correlation coefficients of suspended sediment and of suspended sand near Gridley, 1968-75, indicate the probability is small that the rankings of these ratios are independent of each other and the probability is large that the ratios occur naturally in decreasing magnitude with time; thus, a decreasing concentration of suspended-sediment concentration with time is indicated. Conversely, the concentrations of suspended sediment and sand at Yuba City did not decrease with time during 1968-75, or at least at the flow rates existing during this period. Because of the supply of sand available for erosion and transport in the river channel between Gridley and Yuba City, and the sediment brought into the river by tributary inflow, a considerable period of time may be required before the channel at Yuba City approaches equilibrium with the new flow regime. The length of this time period depends to a great extent on an unknown factor--the quantity of material made available to the channel by tributary inflow.

SUMMARY AND CONCLUSIONS

Characteristics of channel shape, such as width, depth, and slope, as well as stream velocity, are the result of the quantity and distribution of historical streamflow and the sediment transported in the channel.

Regulation of the Feather River since 1968 by Oroville Dam has changed the flow frequencies, attenuated peak flows, and reduced the concentration of suspended sediment in the channel downstream from the dam. Sediment transported by the Feather River is now mostly deposited in Lake Oroville, and water released to the downstream channel is clear water, which has a greater competence to erode and transport sediment than does silt-laden water.

Suspended-sediment discharge to the Lake Oroville damsite average about 2.5 million tons or 136 (tons/mi^2)/yr during 1957-62. The estimated suspended-sediment discharge 1902-62 was 72.3 million tons or 395 (tons/mi^2)/yr. Total sediment is an estimated 454 (tons/mi^2)/yr. At this rate the average future inflow of sediment to Lake Oroville is 800 acre-ft/yr, and about 4,000 years will be required to fill the reservoir. Because the usable storage capacity of the reservoir is less than the total capacity and because initial sediment deposits deplete the volume of the operating pool and power pool in the upper part of the reservoir, the useful life may be less than 4,000 years.

Data on streamflow and suspended-sediment discharge obtained at gaging-station sites on the Feather River at Oroville, Gridley, and Yuba City provide a basis for evaluating changes caused by Oroville Dam and Reservoir. These show that the average streamflow and the frequency of occurrence of the larger flows decreased at all sites, with the impact decreasing in a downstream direction. A significant change occurred at Feather River at Oroville because some flow is diverted around the gaging site. The median discharge decreased from 2,900 ft^3/s to 410 ft^3/s and the average discharge decreased from 5,830 ft^3/s to 1,060 ft^3/s. The flow at Oroville, 1968-75, is less than 380 ft^3/s 5 percent of the time and 430 ft^3/s 82 percent of the time; flow exceeded 2,000 ft^3/s only 5 percent of the time. No change in median flow was noted in the Feather River near Gridley or Yuba City, although the average flow decreased; flows greater than median flow decreased and those less than median increased.

A decrease in the average, median and maximum suspended-sediment concentrations resulted from regulation by Oroville Dam, although average and median concentrations continued to increase downstream. Maximum concentrations, 1965-67, partly affected by construction of the dam, decreased downstream. A summary of changes in suspended-sediment concentrations is given in table 14.

TABLE 14.--*Average, median, and maximum suspended-sediment concentrations, in milligrams per liter*

	1957-62	1965-67	1968-75
Feather River at Oroville			
Average	86	196	15
Median	6	11	4
Maximum	1,500	4,000	80
Feather River near Gridley			
Average	--	208	19
Median	--	11	9
Maximum	--	1,300	300
Feather River at Yuba City			
Average	--	223	114
Median	--	50	45
Maximum	--	750	800

Trends in the concentration of suspended-sediment and suspended sand following regulation indicate a declining trend in suspended-sediment concentration for Feather River near Gridley, but no trend is indicated for suspended sand. Sand transport is apparently approaching equilibrium with the new flow regime. Trends in concentration data for Feather River at Yuba City downstream do not indicate a declining trend in suspended sediment or suspended sand.

Sediment transport also decreased because of regulation; however, the influence of regulation decreased downstream. Sediment transport was affected not only by the reduced streamflow but also because the mean concentration of suspended sediment decreased for the larger flows. Transport at Feather River at Oroville decreased at flows greater than 6,000 ft^3/s and increased at lesser flows, and at Feather River near Gridley transport decreased at flows greater than 2,000 ft^3/s and increased at lesser flows. Data obtained during 1974-75 indicate a continued and significant change relative to the 1968-75 transport. No significant change has occurred at Yuba City at flows less than 4,000 ft^3/s, and minor decreases occurred at larger flows.

Surveys of the river channel at selected cross sections 7.6, 26.1, and 30.6 mi downstream from Oroville Dam show an increase in width and depth since 1909-11 and an increase in the rate of scour 1965-70. The largest increase occurred at 26.1 mi from the dam. Analyses of data obtained from streamflow measurements at Gridley, 1965-74, and Yuba City, 1964-70, show changes in channel geometry since completion of Oroville Dam. At Feather River near Gridley the width increased and the velocity decreased for flows less than 10,000 ft^3/s, with the converse true at greater flows, and mean depth of flow changed little. At Feather River at Yuba City the depth decreased and velocity increased for flows less than 7,000 ft^3/s, with the converse true at greater flows, and mean width of flow changed little. The changes at Gridley signify a general decrease in the competence of the stream to transport sediment; the changes at Yuba City, however, indicate an increase in the competence of the Feather River to transport sediment. The increase in competence at Yuba City results in an increased sediment-discharge yield in the basin downstream from Gridley to Yuba City.

Changes in streamflow, sediment transport, and hydraulic geometry attributable to regulation by Oroville Dam decrease downstream from the dam. As of 1975, channel adjustments to compensate for the new flow regime are apparently complete at Feather River at Oroville and are still in process at Feather River near Gridley and Feather River at Yuba City.

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