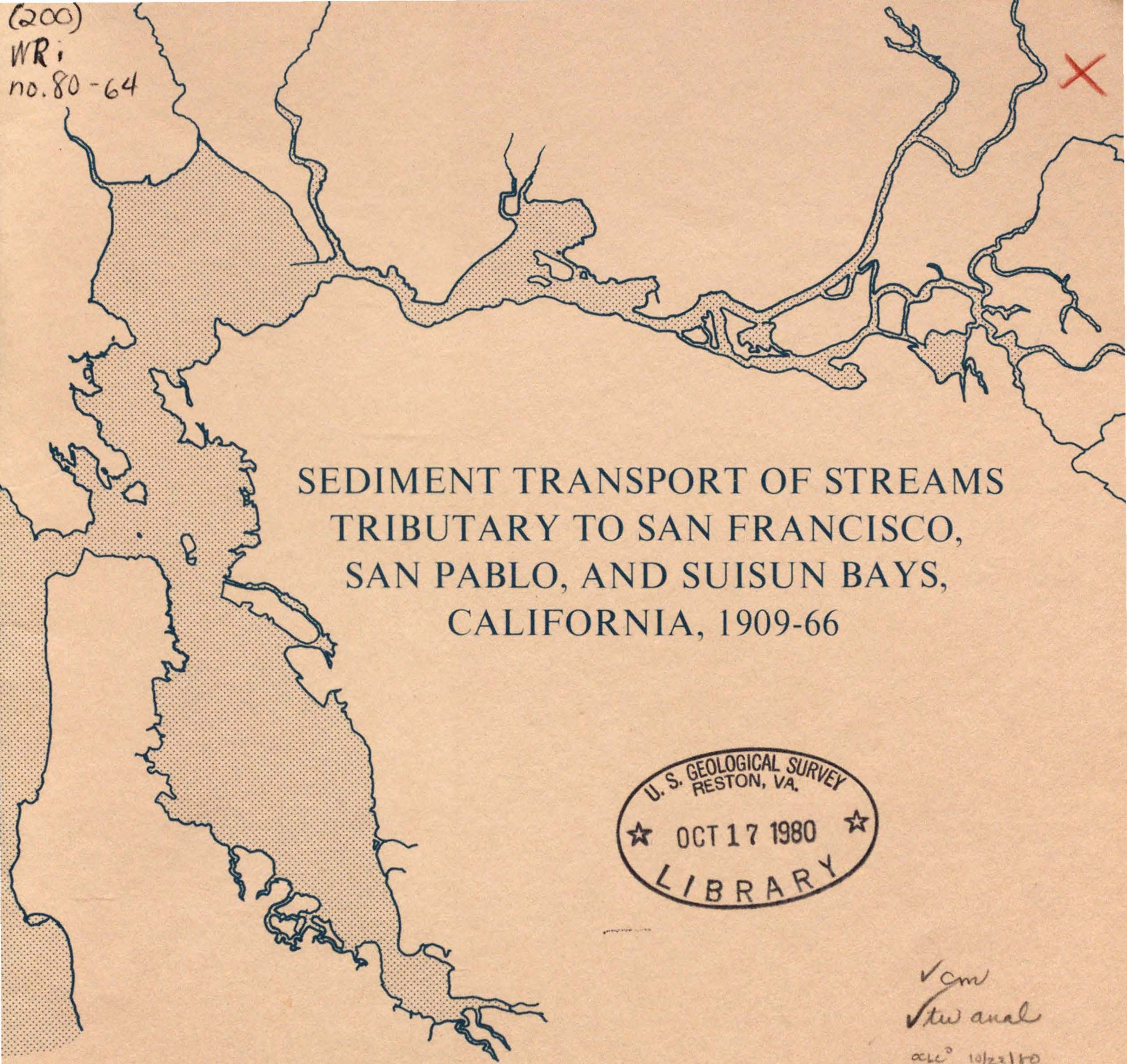

SEDIMENT TRANSPORT OF STREAMS TRIBUTARY TO SAN FRANCISCO, SAN PABLO, AND SUISUN BAYS, CALIFORNIA, 1909-66

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations 80-64

Prepared in cooperation with the
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A review of historical sedimentation data is presented, results of sediment-data collection for water years 1957-59 are summarized, and long-term sediment-discharge estimates from a preliminary report are updated. Comparison of results based on 3 years of data to those for the 10 water years, 1957-66, provides an indication of the adequacy of the data obtained during the short period to define the long-term relation between sediment transport and streamflow. During 1909-66, sediment was transported to the entire San Francisco Bay system at an average rate of 8.6 million cubic yards per year. The Sacramento and San Joaquin River basins provided about 83 percent of the sediment inflow to the system annually during 1957-66 and 86 percent during 1909-66. About 98 percent of this inflow was measured or estimated at sediment measuring sites. Measured sediment inflow directly to the bays comprised only about 40 percent of the total discharged by basins directly tributary to the bays. About 90 percent of the total sediment discharge to the delta and the bays in the San Francisco Bay system thus was determined on the basis of systematic measurements.

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*San Francisco Bay system, Central Valley, Sacramento-San Joaquin Delta

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By George Porterfield, 1915

U.S. GEOLOGICAL SURVEY

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California Department of Water Resources

August 1980

UNITED STATES DEPARTMENT OF THE INTERIOR

CECIL D. ANDRUS, Secretary

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FOREWORD

Sediment discharge to the Sacramento-San Joaquin Delta and the bays downstream during the 51-year period 1909-59 was estimated initially on the basis of data on sediment inflow to the San Francisco Bay system obtained during the 1957-59 water years. The purpose was to satisfy a specific need for information. The estimates have been utilized by concerned agencies in studies relating to San Francisco Bay.

Subsequently the sediment inflow studies and long-term sediment discharge estimates were firmed and extended to 1966 on the basis of additional data to evaluate the validity of the initial estimates. The results indicated a reasonably close relation between the 1957-59 and 1957-66 data, and correspondingly, in estimates of sediment discharge, 1909-59 and 1909-66. The sediment inflow data obtained during 1957-59 fortuitously were reasonably representative of the longer term inflows.

This report was prepared to make the results of these studies generally available. The data, results, and summaries are explained in sufficient detail to identify sediment characteristics, transport, and discharge in units of the San Francisco Bay system, to permit evaluation, to provide a common data base, and to assure consistency in interpretation for use in other studies.

Arvi O. Waananen

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Research Hydrologist
(Retired)

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CONVERSION FACTORS

For use of those readers who may prefer to use metric units rather than inch-pound units, the factors for the terms used in this report are listed below.

Multiply	By	To obtain
acre	0.004047	km^2 (square kilometer)
acre-ft (acre-foot)	0.001233	hm^3 (cubic hectometer)
cfs-days	2447.	m^3 (cubic meter)
ft (foot)	0.3048	m (meter)
ft/s (foot per second)	0.3048	m/s (meter per second)
ft^3/s (cubic foot per second)	0.2832	m^3/s (cubic meter per second)
inch	25.4	mm (millimeter)
mi (mile)	1.609	km (kilometer)
mi^2 (square mile)	2.590	km^2 (square kilometer)
ton (short)	0.9072	Mg (megagram)
ton/d (ton per day)	0.9072	Mg/d (megagram per day)
ton/mi^2 (ton per square mile)	0.3503	Mg/km^2 (megagram per square kilometer)
$(ton/mi^2)/yr$ (ton per square mile per year)	0.3503	$(Mg/km^2)/yr$ (megagram per square kilometer per year)
ton/yr (ton per year)	0.9072	Mg/yr (megagram per year)
yd^3 (cubic yard)	0.7646	m^3 (cubic meter)
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SEDIMENT TRANSPORT OF STREAMS TRIBUTARY TO SAN FRANCISCO, SAN PABLO, AND SUISUN BAYS, CALIFORNIA, 1909-66

By George Porterfield[1]

ABSTRACT

Sediment transported to the Sacramento-San Joaquin Delta and the bays in the San Francisco Bay system in California significantly affects navigation, water quality, construction, and other activities associated with development. Gold mining in the latter half of the nineteenth century, particularly hydraulic mining, caused a tremendous increase in debris discharged to streams over the amount resulting from settlement and agricultural activities. Hydraulic mining ceased in 1884 but the effects on streams continued. In his study of hydraulic-mining debris in the Sierra Nevada in 1917, G. K. Gilbert estimated that sediment transport to the delta averaged about 2 million cubic yards annually prior to the discovery of gold in 1848 and increased to about 18 million cubic yards annually during 1849-1914. Gilbert estimated that hydraulic-mining effects would continue for about 50 years after 1914, with annual sediment transport averaging not less than 8 million cubic yards.

In the present study, sediment transported to the San Francisco Bay system was estimated based on sediment inflow data obtained during 1957-66. During the period 1909-66, sediment was transported to the entire San Francisco Bay system at an average rate of 8.6 million cubic yards per year. About 7.4 million cubic yards, or 86 percent, of this sediment was derived from the Sacramento-San Joaquin River basins upstream from their confluence in the delta region near Antioch.

[1]Deceased

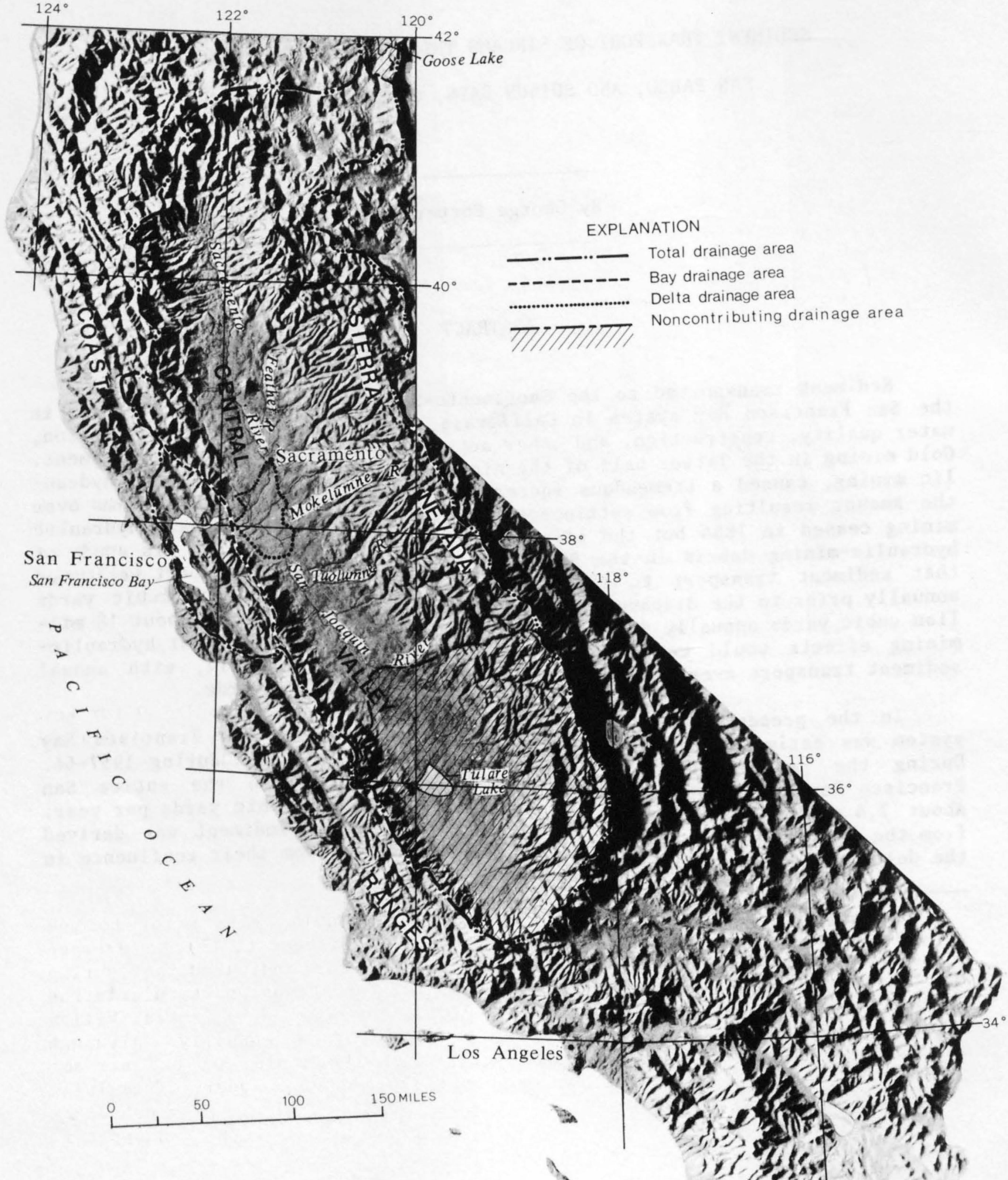

FIGURE 1.--Drainage area tributary to San Francisco Bay.

INTRODUCTION

Sediment transport by streams tributary to San Francisco Bay (fig. 1) is a continuing natural process. The large quantity of sediment eroded from the mountains during recent geologic history is evidenced by the thickness of the post-Eocene deposits in the Sacramento Valley, which ranges from near zero near the margins of the valley to about 3,500 ft beneath the south-central part. Erosion was accelerated by agriculture, construction of roads and trails, overgrazing, and logging when settlers started moving into California in the middle of the nineteenth century. Prior to 1849, the estimated inflow of sediment to the Sacramento-San Joaquin Delta was 2 million cubic yards annually (Gilbert, 1917).

After the discovery of gold in 1848, hydraulic mining was uncontrolled until about 1884, when restrictions and regulations were imposed to decrease debris damage. Gilbert (1917) estimated that during the 1849-1914 period an average of 18.4 million cubic yards of sediment was transported annually by the streams to the bays and ocean. Of this total, 13 million cubic yards was attributed to mining and 5.4 million cubic yards to increase in other human activities and natural degradation. The mining debris buried alluvial farming land, obstructed navigation by shoaling in the Sacramento and Feather Rivers, and raised flood levels of valley streams, thereby increasing the area of periodic inundation. The reclamation of basin lands and delta lands for agriculture by surrounding them with levees also aggravated flood conditions. Flood effects due to mining debris and reclamation were inseparable.

Great quantities of mining debris and other wastes from man's activities during 1849-1914 still remained after 1914 in the basins and channels of streams upstream from the delta. Gilbert (1917) estimated that about 50 years might be required for full discharge of these wastes. In addition, during 1915-57, myriad small projects, great individual projects, and coordinated systems to develop water resources brought many changes. These included facilities for storage and regulation of water for power and irrigation, notably at Lake Almanor on the North Fork Feather River (1924), Millerton Lake on the San Joaquin River (1942), Shasta Lake on the Sacramento River (1943), Folsom Lake on the American River (1955) and Lake Berryessa on Putah Creek (1956), as well as extensive improvements for navigation, flood control, and other purposes. Concurrently, changes occurred in the patterns and extent of land use.

Systematic collection of sediment data began in 1956 at selected locations to determine the quantity of sediment transported by streams tributary to the Sacramento-San Joaquin Delta (areas 11 and 12 in fig. 2) and to the bays in the San Francisco Bay system. Sediment-discharge data for the period 1957-59 were published in a preliminary report (Porterfield and others, 1961) and are summarized in table 1. These data indicated approximately 7.2 million cubic yards (14,200 ton/d) of sediment inflow to the delta and a total of 8.8 million cubic yards (17,300 ton/d) to the San Francisco Bay system annually during 1957-59.

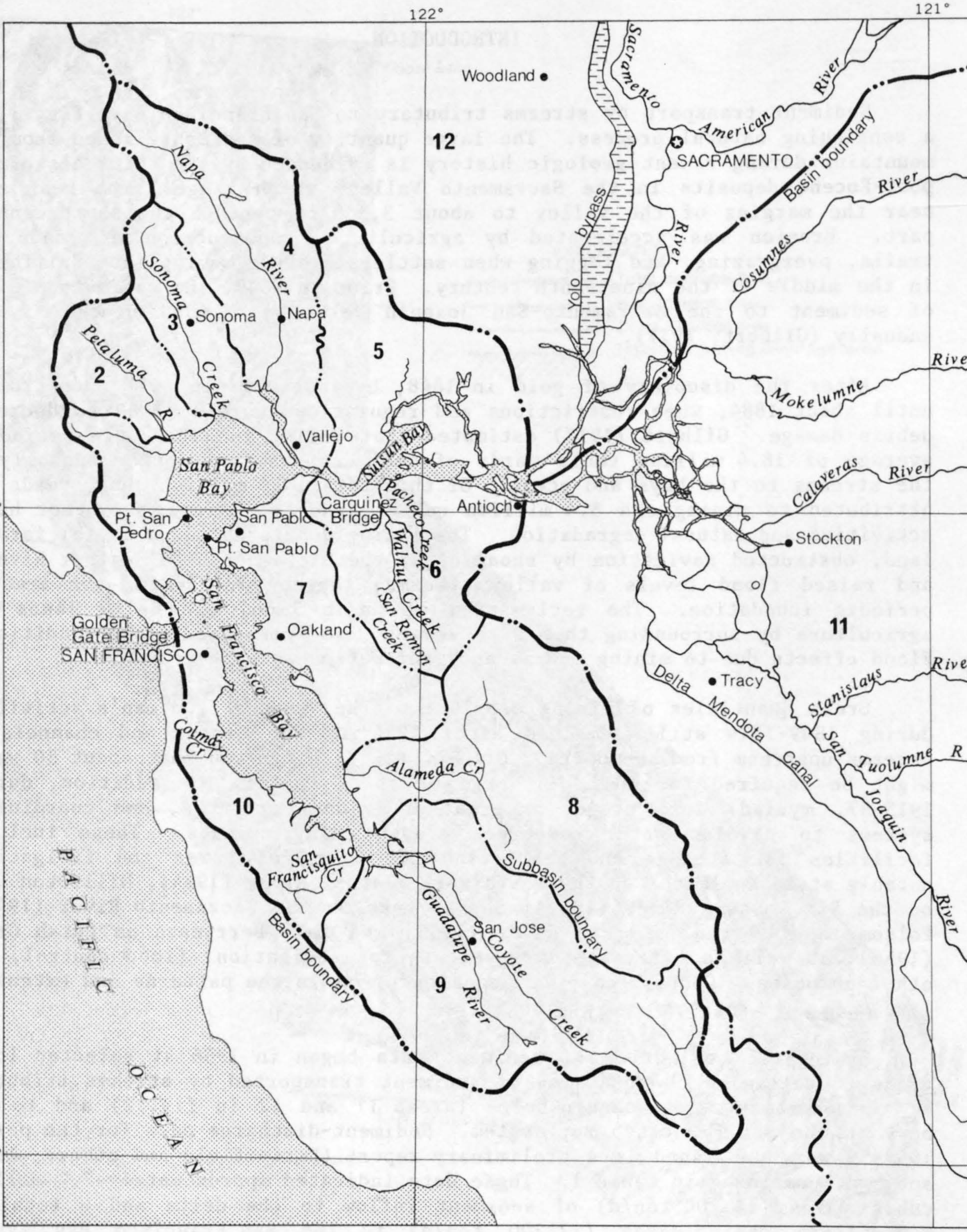

FIGURE 2.--Stream groups tributary to San Francisco Bay. (Numbers correspond to those in table 3.)

Increased use of freshwater in the Central Valley as well as diversions from the valley may change the quantity of sediment transported by valley streams. The competence of the streams to transport available sediment and the quantity transported affect navigation, flood-control projects, fisheries, recreation, water-use projects, and the myriad problems associated with fill, scour, and channelization of rivers. In addition, sediment in rivers has a large absorptive capacity and affects the chemical and biological characteristics of the water.

TABLE 1. - Average daily sediment discharge to San Francisco Bay system

Body of water	1957-59		Estimated 1909-59 discharge[1] (adjusted to 1957-59 conditions)
	Suspended sediment (tons)	Total sediment (tons)	Total sediment (tons)
Sacramento-San Joaquin Delta	12,300	[2]14,200	13,800
Suisun Bay	640	700	500
San Pablo Bay	800	900	1,000
San Francisco Bay	1,390	1,500	800
Total....................	15,130	[3]17,300	16,100

[1]Period 1909-59 selected on basis of available data for unregulated streams.
[2]Approximately 7.2 million cubic yards annually, determined as: 365 × daily sediment (tons) × 2,000 divided by unit weight of sediment × 27 (unit weight of dry sediment, 53.2 lb/ft^3).
[3]Approximately 8.8 million cubic yards annually.

Purpose and Scope

The purpose of this report is to present a review of historical sedimentation data, summarize the results of a sediment-data collection program begun in 1956, and update long-term sediment-discharge estimates presented in a preliminary report in 1961. Comparison of results based on 3 years of data, 1957-59, with those for the 10-year period, 1957-66, provides an indication of the adequacy of the data obtained during the short period to define the long-term relation between sediment transport and streamflow. The results also indicate the magnitude of changes in sediment transport during 1957-66. All periods mentioned in this report refer to water years unless otherwise stated.

The scope of this report is limited to an analysis of sediment data collected on streams tributary to the Sacramento-San Joaquin Delta and to the bays in the San Francisco Bay system downstream from the delta. These data provide a basis for estimating sediment transport to the bay system since the studies reported by Gilbert (1917). The 1957-66 base period is an interval long enough to provide sufficient data for reasonable analysis, and includes the broadest range of extent and availability of sediment data.

Acknowledgments

The writer thanks the U.S. Army Engineer District, San Francisco, Corps of Engineers, the California Department of Water Resources, and San Mateo County for the assistance and cooperation which made this report possible. The Corps of Engineers furnished financial support for the collection of data in the San Francisco Bay area during the 1957-62 period and the California Department of Water Resources cooperated in the collection of data in the Central Valley. The sediment-data program at Colma Creek and Spruce Branch was part of a cooperative program with San Mateo County.

Previous Investigations

Many hydrologic studies have been made of the San Francisco Bay area and its tributaries; however, only the studies made prior to 1957 that consider primarily the sediment problem are described in this section. One of the oldest and most authoritative papers on sedimentation in the San Francisco Bay drainage area is that by Gilbert (1917).

The study by Gilbert was made to determine the extent of the damage caused by mining practices and the degree to which such damage might be reduced by curtailing or stopping these mining practices. His field work was done principally in 1905-08, with additional field work in 1909, 1910, 1913, and 1914. He recognized the need to know and to understand the fundamentals of sediment transport and established a laboratory at the University of California at Berkeley to study the transportation of debris by running water (Gilbert, 1914).

Gilbert's investigations included study of quantities of sand, gravel, and clay excavated by mining, quantity of sediment from sources other than mining, present distribution of sediment, trend of sedimentation, effect of bay area subsidence on the computed quantities of sediment deposited in the bays, quantity of sediment carried out to sea, effect of sediment on tidal volume and the Golden Gate bar, and outlook for hydraulic mining.

In 1930 the U.S. Army Engineer District, San Francisco, Corps of Engineers, made a comprehensive investigation of the effect of sediment on proposed barriers within the bay area (Grimm, 1931). During the investigation, over 400 samples of bottom material were obtained and analyzed. Detailed analyses were made also of tidal prism volumes, tidal currents and their transporting capacities, sediment inflow, flocculation and deposition in the various components of the bay system, sediment flow through the bays, historical deposition in the bays, and historical behavior of the Golden Gate bar. Grimm estimated quantitatively the effect of proposed barriers on sedimentation in the entire bay system.

In 1954, "A Review of Sedimentation" was prepared by the Corps of Engineers in cooperation with the California Department of Water Resources (California Department of Water Resources, 1955a). It describes damaging effects of sediment on the planned barrier system, such as fouling of locks, lock gates, fish ladders, and similar operating equipment, and impediment of upstream transportation by channel deposition in backwater units. These problems establish the need for the best practical determination of the volume and rate of sedimentation in the San Francisco Bay system and the delta area. The Corps computed the present and future sediment inflow rates from sediment yield rates developed by a Soil Conservation Service study (Brown and Thorp, 1947). These sediment rates were modified by estimating the retentive effect of the valley floor and the effects of present and future control of upland and valley streamflow rates.

In 1955, "Sedimentation Appendix G," was prepared by the California Department of Water Resources (1955a) to support the conclusions on sedimentation presented in the comprehensive report on the "Feasibility of Construction by the State of Barriers in the San Francisco Bay System" (California Department of Water Resources, 1955b). The report contains estimates of the effect of barriers on the distribution of sediments based on consideration of the effect of barrier gates and pool operation upon streamflows, salinity, wind and tidal currents, tidal prism volumes, and analysis of present maintenance dredging requirements. "Appendix G" presents two analyses of the present and future sediment inflow rates, with the first based on the relation of streamflow to suspended sediment discharge and bedload and the second on studies of basin yield rates. The latter study was made by the U.S. Army Engineer District, San Francisco, Corps of Engineers.

A summary of sediment inflow to the San Francisco Bay system as derived from these investigations is presented in table 2.

Definition of Terms

Hydrologic terms and abbreviations used generally in this report are defined as follows:

Bed layer is a flow layer, 2-grain diameters thick, immediately above the bed. The thickness of the bed layer varies with the particle size (Einstein, 1950).

Bedload or sediment discharge as bedload is the sediment that is moved along in practically continuous contact with the streambed (Colby and Hembree, 1955), or the bed particles moving in the bed layer (Einstein, 1950). This motion occurs by rolling, sliding, and, sometimes, by jumping.

Bed material is the material of which the streambed is composed.

Bed-material load is sediment transported by a stream that consists of particle sizes large enough to be found in appreciable quantities at the surface of the streambed. Bed material may be transported either as suspended sediment or as bedload.

Measured suspended-sediment discharge is the part of the suspended sediment that can be computed from the total water discharge and mean sediment concentration in the depth actually sampled with the suspended-sediment sampling equipment. This is the part of the suspended sediment that is published annually on a State-boundary basis in U.S. Geological Survey Water-Data Reports and is generally referred to as the suspended sediment or suspended-sediment discharge.

TABLE 2. - Summary of sediment inflow to the San Francisco Bay system from Central Valley streams, from investigations prior to 1957

Investigator	Estimated average annual total sediment inflow, in cubic yards						
	Prior to 1849	1849-1914	Future (adjusted to 1914 conditions)	1931	1954	1955	Future (adjusted to proposed and future controls)
Gilbert (1917)	2,000,000	[1]18,400,000	8,000,000 (minimum)				
Grimm (1931)				5,750,000			
U.S. Army Corps of Engineers (1954)					3,360,000		1,970,000
California Department of Water Resources (1955a, 1955b)						4,000,000	3,000,000

[1]Includes 800,000 yd^3 discharged to the ocean.

Noncontributing area is that part of the natural drainage area of a stream which does not contribute directly to the water or sediment discharge of the stream.

Sediment is fragmental material that originates from weathering of rocks and is transported by, suspended in, or deposited by water or air, or accumulated in beds by other natural agencies (Colby and others, 1953, p. 24)

Sediment concentration is the weight of dry solids divided by the weight of water-sediment mixture and is expressed in milligrams per liter, or parts per million.

Sediment discharge is the rate at which dry weight of sediment passes a section of a stream or is the quantity of sediment, as measured by dry weight or by volume, that is discharged in a given time.

Sediment inflow is synonymous with "sediment discharge" and is used in this report, usually in relation to transport of sediment to areas of reference, as "sediment inflow to the delta."

Sediment load is the sediment moved by a stream, whether in suspension or at the bottom, and is synonymous with "sediment discharge" used in this report.

Sediment-sampling station or sediment station is a particular site on a stream, canal, lake, or reservoir, usually at or near a stream-gaging station, where samples of suspended-sediment concentration are obtained.

Daily stations are those where samples are obtained one or more times daily during medium and high streamflow and one or more times weekly during periods of low, clear flow. Sediment discharge is computed for each day.

Periodic stations are those where too few sediment samples are obtained to permit accurate computation of sediment discharge for each day. Enough samples are obtained, however, to define the relation between instantaneous values of streamflow and sediment discharge for the range of streamflow that occurs at the station.

Sediment-transport curve is the curve that defines the average relation between the rate of sediment discharge and rate of water discharge. Transport curves may be classified according to either the period of the basic data that define the curve or the kind of sediment discharge that a curve represents (Colby, 1956).

Sediment yield is the quantity of sediment, total or suspended, transported from or produced in a basin or area, and is generally expressed as a quantity, by weight or volume, per unit time and(or) area, as: tons per day per square mile, tons per square mile per year, or annually.

Streamflow is the discharge that occurs in a natural channel (Langbein and Iseri, 1960) and uniquely describes the discharge in a surface stream course. Streamflow may be applied to discharge whether or not it is affected by diversion or regulation. In this report streamflow is used interchangeably with water discharge in both tables and text to avoid any confusion as to whether the term "discharge" refers to water discharge or to sediment discharge.

Streamflow may also be considered to uniquely represent the mixture of water, sediment, and solutes discharged by a natural channel. Water discharge may be considered generally as being that part of streamflow available for domestic and industrial use and it may not include suspended material which may significantly affect the quantity and desirability of the water available.

Suspended sediment is sediment that is moved in suspension in water and is maintained in suspension by the upward components of turbulent currents or by colloidal suspension (Colby and Hembree, 1955).

Tons per day is the unit used in this report to express the quantity of sediment that passes a stream section during a 24-hour period.

Total sediment discharge is the sum of the suspended-sediment discharge and the bedload discharge, as measured by dry weight or volume, that is discharged during a given time (Colby and Hembree, 1955). Total sediment discharge may also be defined as the sum of the sampled and unsampled discharge.

Unsampled sediment discharge or unmeasured sediment discharge is the difference between the total sediment discharge and the sampled suspended-sediment discharge.

Water year is a 12-month period ending September 30 and is designated by the year in which it ends. In this report all periods refer to water years.

DESCRIPTION OF BASIN

Physiography

The drainage area of the streams tributary to the San Francisco Bay system is about 63,000 mi^2, almost 40 percent of the entire area of California (fig. 1).

For convenience in reference, the drainage area is divided into physical units that represent stream groups and major basins. These units and their drainage areas are those used by agencies which participated in a comprehensive survey of San Francisco Bay and tributaries. The use of common physical units provides a uniform approach, and facilitates correlation of results of various studies.

The 12 stream groups tributary to San Francisco Bay are shown in figure 2, and the location and area of each group is given in table 3. Tulare Lake basin in the San Joaquin River basin and Goose Lake basin in the Sacramento River basin are considered to be noncontributing and are not included as part of any stream group.

The Central Valley basin contains 94 percent of the drainage area of the San Francisco Bay system. It is bounded by approximately parallel ranges of mountains--the Sierra Nevada on the east and the Coast Ranges on the west. The valley floor, or Central Valley, which is about one-third of the Central Valley basin, is a gently sloping alluvial plain 400 mi in length and averaging 45 mi in width. The northern part of the Central Valley is drained by the Sacramento River and its tributaries and the southern part by the San Joaquin River and its tributaries. These two streams join in the delta area and discharge into Suisun Bay. Tulare Lake basin in the southern part of the San Joaquin Valley and Goose Lake basin in the northern part of the Sacramento Valley seldom contribute sediment or water to the bay system.

TABLE 3. - Stream groups tributary to San Francisco Bay area

[Values compiled by U.S. Army Engineer District, San Francisco, the State of California, and others]

Number (fig. 2)	Name	Location of drainage area	Drainage area (mi^2)
1	Marin County	Golden Gate Bridge to Petaluma River	133
2	Petaluma River	Petaluma River to Sonoma Creek	146
3	Sonoma Creek	Sonoma Creek to Napa River	165
4	Napa River	Napa River to Carquinez Bridge	417
5	Suisun	Carquinez Bridge to confluence of Sacramento and San Joaquin Rivers (north side of Suisun Bay)	344
6	Mount Diablo	Confluence of Sacramento and San Joaquin Rivers to Carquinez Bridge (south side of Suisun Bay)	251
7	East Bay	Carquinez Bridge to Alameda Creek	319
8	Alameda Creek	Alameda Creek to Coyote Creek	745
9	Coyote and Guadalupe	Coyote Creek to San Francisquito Creek	699
10	Peninsula	San Francisquito Creek to Golden Gate Bridge	246
11	San Joaquin River	Tulare Lake basin north to confluence with Sacramento River	19,096
12	Sacramento	Goose Lake basin south to confluence with San Joaquin River	26,322
	San Francisco Bay	Water surface area of bays including islands at mean high water	463
	Contributing area, total		49,346
	Noncontributing area:		
(1)	Tulare Lake basin	13,625	
(1)	Goose Lake basin	412	
	Total		14,037
	Total area		63,383

[1]Not shown in figure 2.

The floor of the Central Valley is flat. The altitude is generally less than 400 ft and the slope is toward San Francisco Bay from the north, east, and south. Only locally near the valley fringe does it rise to higher altitudes. Considerable areas near the bays are below sea level and are protected from overflow by dikes and natural levees.

The Sacramento River, the largest tributary to the San Francisco Bay system, has a total drainage area of 26,734 mi^2 upstream from the confluence with the San Joaquin River. The river rises near the Oregon border, flows generally south, and near Red Bluff enters the Sacramento Valley, which is the northern division of the Central Valley. It then flows through the valley to the delta where it joins the San Joaquin River and enters Suisun Bay.

Bryan (1923) described the Sacramento Valley as being largely a constructional or aggraded plain, built up with sediment brought by streams from the surrounding mountains. The natural levees of the larger streams and the basins that exist between these levees are significant in the topography (Fenneman, 1931, p. 473) and affected the hydrology of the basin before reclamation of the lowlands and flood control. In the southern part of the Sacramento Valley, the streams have so aggraded their beds that in some places the flood plain declines 10 ft in the first mile laterally from the stream. The downstream reaches of the American River basin and other basins listed below are bounded by the main streams rather than traversed by them. Bryan (1923) describes the river lands as relatively narrow belts that rise 5 to 20 ft above the adjacent land and extend along both sides of the two main streams--the Sacramento and Feather Rivers. They consist of natural levees sloping very gently toward the flood basins or adjacent low plains. They were formed in times of flood by sediment deposited by the overflow of the rivers, and, like the low plains, are the result of processes still in operation.

The flood basins located between the river lands, or natural levees, are broad, shallow troughs, the lowest and flattest parts of the valley. Bryan (1923) listed five principal flood basins--Butte, Colusa, Sutter, American, and Yolo--and two smaller basins, Marysville and Sacramento, and described them in detail as they existed in 1912-14. These basins were dry most of the year and sometimes for entire seasons; however, during floods they filled with water and constituted veritable inland seas. An estimated 60 percent of the valley was subject to overflow before reclamation of lowlands and flood control, which have continued to reduce the amount of land subject to overflow.

Gilbert (1917) reported that in flood times the water regularly overtopped the banks and filled the adjacent flood basins, moving slowly through them and draining gradually back to the main channel as the flood subsided. The detrital load of the flood was spread over the entire inundated tract, including the delta marshes, which acted as a system of settling basins.

The lateral basins affected the character of the channels in important ways. Gilbert (1917) noted that, "They conveyed a large part of the flood discharge and thus left for adjacent portions of the channel only a small part. They acted as reservoirs for the storage of flood waters and fed them gradually to the lower course of the Sacramento, so that the channels in the delta region were only moderately taxed by the floods. The channels in consequence were adjusted for the conveyance of only a fraction of the flood discharge; they were of moderate section and their meanders were of small radius. Between the town of Colusa and the mouth of Feather River the channel of Sacramento River grows gradually smaller downstream until its estimated capacity is only 10 percent of the flood discharge."

West-side tributaries south of Stony Creek still terminate in these flood basins (California Department of Water Resources, 1955a, p. 13). Low flows are lost by evaporation or by percolation to ground water; high flows enter the basins and move laterally south toward the delta. East-side streams generally enter the Sacramento River directly, and during periods of low flows, these streams are confined by the natural levees.

The San Joaquin River drains the southern part of the Central Valley and has a total drainage area of 13,540 mi^2 at Vernalis. The major tributaries of the San Joaquin River, unlike those of the Sacramento River, enter the trunk stream directly. There is no system of flood basins. Under natural conditions, however, there was a system of distributaries in the lower reaches of the river near its confluence with the Sacramento River. Streams descending from the mountains on either side of the river build alluvial fans and the merging of these fans from opposite sides of the valley determines the position of the river. Because streamflow and sediment discharge are greater in the east-side tributaries than in the west, the San Joaquin River has been pushed locally westward to within a few miles of the Coast Ranges. The large fan of the Kings River, near the southern end of the Central Valley, isolated the southern tip of the valley from the rest of the San Joaquin basin and formed a large basin. This is the Tulare Lake basin (fig. 1, drainage area, 13,625 mi^2) which, for all practical purposes, contributes no water or sediment to the bay area.

The San Francisco Bay area, consisting of the water and island areas in the bays downstream from the delta, constitutes a minor part of the total drainage area of the bay system. A detailed description of the various bays in the San Francisco Bay area is given by Hogenson and Wahl (1960).

Climate

Relatively mild winters with low-intensity rainfall and warm, dry summers with an almost complete absence of rainfall characterize the climate of the Central Valley. Annual precipitation in the mountain ranges and foothills bordering the Central Valley is much greater than on the valley floor.

Average annual precipitation varies widely from year to year but generally decreases from north to south. Annual rainfall may range from less than 2 to 11 inches at Bakersfield in the south, from 11 to 43 inches at Red Bluff in the north, and from 28 to more than 100 inches in the Sierra Nevada east of Chico. A substantial part of the precipitation on the higher mountain areas occurs as snow.

The part of the San Francisco Bay drainage area that is adjacent to and drains directly into Suisun, San Pablo, or San Francisco Bay has climatic characteristics that are quite different from those of the Central Valley area. Changes in temperature from summer to winter are modified somewhat by the Pacific Ocean. The long-term average annual precipitation ranges at different points within the area from about 12 to 30 inches. Most of the precipitation occurs during the winter months.

HISTORICAL SEDIMENTATION

In the natural state, the estimated annual sediment inflow to the San Francisco Bay system was about 2 million cubic yards. Gilbert (1917), whose studies provided most of the historical sediment data, reported that the changes in streams brought about by the activities of settlers, primarily after the discovery of gold in 1848, were caused (1) from overloading the streams with detritus and (2) from surrounding parts of the inundated area by levees that restrict the freedom of the valley rivers to expand in time of flood. The overloading was caused chiefly by mining debris, which increased in output until the year 1884, when it was suddenly checked. Agriculture, road building, logging, other industries, and natural degradation that disturbed the soil and exposed it to wash by rain also contributed to overloading.

In the early days the water in the lower course of the Sacramento River was deep and slack. A conspicuous tide extended to Sacramento, 62 mi to the north, and a less notable tide extended to the mouth of the Feather River, 20 mi farther north. Seagoing vessels traveled regularly to Sacramento and occasionally to Marysville on the Feather River (figs. 1 and 3). In times of flooding, water regularly overtopped the riverbanks and filled the adjacent basins, and the detrital load of the flood was spread by the water over the whole inundated tract, including the delta marshes which acted as a system of settling basins. A part of the suspended load was transported past the mouth of the river by the swifter current of the main channel and deposited in the bays beyond, but most of the sediment probably was deposited on the inundated lands. Under natural conditions, there was probably a balance between sediment deposited in the bays and subsidence. Reduction in depth and area of the bays probably began after the start of hydraulic mining.

Prior to hydraulic mining in the Sierra Nevada, only a moderate quantity of earth was moved by the army of miners who worked as laborers with pick, shovel, and rocker. The efficiency of mining methods gradually improved, and, finally, waterpower was substituted for manpower. At the height of hydraulic mining, millions of cubic yards of earth was displaced annually.

Floods moved sand and gravel toward the lowlands, and in 1862, a great flood washed so large a quantity of sediment into the lower reaches of the Sierra Nevada rivers and into the rivers of the Central Valley that the holders of riparian lands became alarmed. The mining-debris problem, then generally recognized for the first time, assumed greater importance in subsequent years and led to protest and litigation that culminated in 1884 in a series of injunctions that restrained miners from dumping mine tailings into streams. The petitioners were valley dwellers concerned about the burial of alluvial farming lands by debris, the obstruction to navigation from shoaling in the Sacramento and Feather Rivers, and the raising of flood levels of valley streams.

In 1880, the State Engineer of California reported on the flow of mining debris. In the same year, the Corps of Engineers, U.S. Army, started an investigation authorized by the U.S. Congress. The result of these and other studies was the establishment by an act of Congress in 1893 of a permanent board, known as the California Debris Commission, with authority to regulate hydraulic mining to protect the navigable waters of the Sacramento and San Joaquin Rivers.

In 1904 a petition from the California Miners' Association to the President of the United States for study of the mining-debris problem resulted in the study by Gilbert (1917). The petition requested recommendation of procedures whereby the mines could continue to operate profitably and yet not interfere with flood control, navigation, and agriculture.

In his study Gilbert estimated the quantity of mining and nonmining debris, the quantity of material deposited in the bays, and the total quantity and distribution of all sediment moved in the San Francisco Bay system drainage basin for the 65 years preceding 1914. A summary of all mining debris for the period 1849-1909 is given in table 4.

TABLE 4. - Summary of mining debris, 1849-1909

[Modified from Gilbert, 1917, table 7, p. 43]

Source of debris	Millions of cubic yards
Hydraulic mining in basin of--	
Upper Feather River	100
Yuba River	684
Bear River	254
American River	257
Streams tributary to lateral basins of Sacramento River	30
Mokelumne River to Tuolumne River, inclusive	230
Ordinary placer mining	60
Quartz mining (one-fourth in Sacramento basin)	50
Drifting (three-fourths in Sacramento basin)	30
Total mining debris from:	
Hydraulic mining	1,555
All mining tributary to Sacramento River	1,390
All mining tributary to Suisun Bay	1,665

A special study of a single district, the Yuba River basin, by Gilbert (1917, p. 43) provided estimates of the nonmining wastes from 1849-1914; the results were extended to other districts by aid of inferences based on evident differences in local conditions. These nonmining wastes are summarized as follows:

	Millions of cubic yards
Agriculture	18
Construction of roads and trails	3.3
Overgrazing	1
Ordinary grazing plus natural waste	10
Total	32.3

The Yuba area study encompassed about 1,000 mi^2. Assuming these estimates to be representative of the mountains and foothills of the Sacramento River basin, the nonmining wastes for the entire basin except valley lands were estimated to be about 360 million cubic yards. The waste from the valley lands was estimated as 60 million cubic yards. The nonmining wastes in the Sacramento River basin thus totaled about 420 million cubic yards during the 65-year period. A similar estimate of nonmining waste in the San Joaquin River basin was 280 million cubic yards. The summary of all waste from the land surface of the Sacramento and San Joaquin River basins, given in table 5, indicates that nearly 30 percent, or 10.8 million cubic yards annually, resulted from "normal" and continuing activities of man.

TABLE 5. - Summary of waste from the land surface of the Sacramento and San Joaquin River basins, from 1850[1] to 1914

	Tributary to Sacramento River (millions of cubic yards)	Tributary to Suisun Bay (millions of cubic yards)
Mining debris[2]	1,400	1,675
Nonmining waste	420	700
Total	1,820	2,375

[1]Estimates by Gilbert refer alternatively to the periods 1849-1914 and 1850-1914. It is assumed that the 1850-1914 period refers to water years, which would include October, November, and December 1849.

[2]In transferring the figure for mining debris from table 4, 10 million cubic yards was added as allowance for the period 1909-1914 (Gilbert, 1917).

The extent and distribution of sediment deposition in the bays were determined from soundings made by the U.S. Coast and Geodetic Survey. Complete surveys of the Suisun Bay were made in 1867-68 and 1887-88, covering a period that included the 16 most active years of hydraulic mining and the succeeding 4 years. A complete survey of San Pablo Bay was made in 1856, a small part was resurveyed in 1887, and the remainder in 1896. The northern part of San Francisco Bay was surveyed in 1855 and again in 1895-1901; its southern part in 1857-58 and in 1895-1899. A summary of sediment deposited in the bays during periods between the surveys and an estimate of total sediment deposited 1849-1914 is given in table 6.

The total quantity of mining debris and nonmining waste from all sources 1849-1914,[1] shown in table 5, was 2,375 million cubic yards, or an average annual rate of 36.5 million cubic yards. Only 50 million cubic yards of this sediment was transported through the bays to the ocean; 1,146 million cubic yards (average of 17.6 million cubic yards annually) was deposited in the bays, and the remainder upstream from the bays (table 7). Gilbert (1917, p. 43) puts the magnitude of hydraulic mining in the Sierra Nevada in perspective by the statement that the volume of earth moved was nearly eight times as great as the volume moved in making the Panama Canal.

In 1914 about one-half of the total quantity of mining debris and nonmining wastes reported in table 7 remained on lands tributary to the San Francisco Bay system. Most of this sediment and debris was involved in the continuing transport process, but a part would be retained on the lands or in inundated areas upstream from the bays. Gilbert (1917, p. 67) estimated the future average discharge to the bay system as not less than 8 million cubic

TABLE 6. - Estimates of the volume of debris deposited in the San Francisco Bay system, 1849-1914

[Modified from Gilbert, 1917, p. 37]

Body of water	Dates of surveys[1]	Volume of debris deposited (millions of cubic yards)	
		Between surveys	1849-1914
Suisun Bay	1867-1888	64	200
Carquinez Strait	1861-1890	40	50
San Pablo Bay	1856-1896	366	570
San Francisco Bay	1855-1901	196	326
Total			1,146

[1]Dates adjusted to correspond with those in text and in Gilbert (1917, p. 32).

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[1]Estimates by Gilbert refer alternatively to the periods 1849-1914 and 1850-1914. It is assumed that the 1850-1914 period refers to water years, which would include October, November, and December 1849.

TABLE 7. - Estimates of the distribution in 1914 of debris moved by mining operations or by rains from lands draining to the San Francisco Bay system during the preceding 65 years

[From Gilbert, 1917, table 9, p. 50]

Location of deposit	Millions of cubic yards
Mountainous areas in the Sierra Nevada	265
Piedmont areas	520
Channels of the valley rivers	100
Inundated lands, including tidal marshes	294
Bays	1,146
Ocean	50
Total	2,375

yards annually, with hydraulic mining debris from gradual removal of the mountain, piedmont, and channel deposits included for as long as 50 years. Future debris and sediment discharge was estimated as continuing at a much greater rate than before settlement of the region. Sediment discharge to the ocean was arbitrarily estimated to be about 5 percent of the sediment transported to the bay system.

In the 1914-66 period, the development of water resources for power, irrigation and other uses, and facilities for navigation improvement, flood control, and other purposes, was extensive. The storage and regulation of water supplies progressed from myriad small projects to great individual projects and coordinated systems. The extent of reservoir storage and flow regulation was significant in relation to the modification of flows and flow frequency and the entrapment of sediment by reservoirs. The growth of storage capability in the Sacramento and San Joaquin River basins from 1920-65 is summarized as follows:

Year	Storage capability (acre-feet)	
	Sacramento River basin	San Joaquin River basin
1920	500,000	300,000
1940	2,100,000	1,900,000
1940	6,700,000	2,400,000
1960	9,400,000	3,300,000
1965	10,900,000	4,000,000

In the Sacramento River basin, storage capability in reservoirs with capacity greater than 20,000 acre-ft increased from about 500,000 acre-ft in 1920 to 10,900,000 acre-ft in 1965. Major projects included Lake Almanor on the North Fork Feather River (1924), Shasta Lake on the Sacramento River (1943), Folsom Lake on the American River (1955), and Lake Berryessa on Putah Creek (1956), all with capacity exceeding 1,000,000 acre-ft. These reservoirs control flow from 9,339 mi^2, or 35 percent of the drainage area of the basin; the total area controlled by reservoirs comprises 50 percent of the basin. Similarly, storage capacity in the San Joaquin River basin increased from 300,000 acre-ft in 1920 to 4,000,000 acre-ft in 1965. Millerton Lake on the San Joaquin River (1924) and the principal reservoirs on the Merced, Tuolumne, Stanislaus, Mokelumne, and Calaveras Rivers, control 32 percent of the total drainage area of the San Joaquin River basin.

The impact of storage on sediment discharge to the San Francisco Bay system is lessened, however, by the great volumes of sediment available from the valley lands and channels, the continuing sediment erosion-transport process, and the effects of overflows and inundation downstream.

METHODS AND PROCEDURES

Data Network

The collection of fluvial-sediment data began in 1956 on six streams tributary to Suisun, San Pablo, and San Francisco Bays; these were the Guadalupe and Napa Rivers, and San Francisquito, Alameda, Sonoma, and Walnut Creeks. Data collection began at about the same time for Central Valley streams as part of a basic-data network to determine sediment transport of California streams. Data from selected Central Valley streams and from the six streams tributary to the bays for the period 1957-59 provided the basis for estimating sediment inflow to the bays during 1909-59 (Porterfield and others, 1961).

Prior to 1956, extensive streamflow data relating to the San Francisco Bay system had been collected and many hydrologic studies had been made, but few data on sediment were obtained. The sediment data were derived principally from samples of bottom material in the bays collected in 1930 (Grimm, 1931), and a few suspended-sediment samples obtained during 1938-47 (Brown and Thorp, 1947) to relate streamflow and suspended-sediment discharge.

Subsequent to 1959, data were obtained also for the Delta-Mendota Canal, which exports water--and sediment--from the delta, and for Colma Creek and Spruce Branch at South San Francisco. Data collection at stations operated primarily as part of the Corps of Engineers comprehensive survey of San Francisco Bay and tributaries was discontinued in July 1962. The Alameda Creek near Niles station was continued as part of a basic-data network. Location of data-collection sites is shown in figure 3, and the records available are shown in table 8.

TABLE 8. - Selected streamflow and sediment stations on streams contributing to San Francisco Bay

Station number	Station number and name (See fig. 3 for location of station)	Drainage area (mi^2)	Streamflow records used in this report	Suspended sediment: Sampling frequency	Suspended sediment: Record available
11162720	Colma Creek at South San Francisco	10.9	1966-67	Daily	1966-67
11162722	Spruce Branch at South San Francisco	1.68	1966-67	Daily	1966-67
11164500	San Francisquito Creek at Stanford University	37.5	1932-40, 1951-66	Periodic	1957-62
11169000	Guadalupe River at San Jose	146	1936-66	Periodic	1957-62
11179000	Alameda Creek near Niles	633	1925-66	Daily	1957-66
11183500	Walnut Creek at Walnut Creek	79.2	1953-66	Periodic	1957-62
11303500	San Joaquin River near Vernalis	13,540	1924-66	Daily	1957-66,
11313010	Delta-Mendota Canal below Tracy Pumping Plant, near Tracy	--	1951-66	Daily	1959-60 1963-66
11323500	Mokelumne River below Camanche Dam near Clements	627	1929-66	Periodic	1957-66
11334500	Cosumnes River near Plymouth	429	1951-60	Periodic	1957-60
11335000	Cosumnes River at Michigan Bar	536	1909-66	Periodic Daily	1957-62 1963-66
11336000	Cosumnes River at McConnell	724	1942-66	Periodic	1957-66
11378500	Sacramento River at Red Bluff	[1]9,022	[1]1892-66	Periodic Daily	1956-57 1958-66
11382000	Thomes Creek at Paskenta	194	1921-66	Daily	1963-66
11407000	Feather River at Oroville[2]	3,624	1901-66	Daily	1957-66
11421000	Yuba River near Marysville	1,339	1944-66	--	--
11426000	Sacramento Weir spill to Yolo Bypass	--	1939-66	--	--
11446500	American River at Fair Oaks	1,888	1904-66	--	--
11447500	Sacramento River at Sacramento	23,530	1949-66	Daily	1957-66
11452500	Cache Creek at Yolo	1,139	1903-66	Periodic Daily	1958,1966, 1959-65
11453000	Yolo Bypass near Woodland	--	1949-66	Periodic	1957-61
11454000	Putah Creek near Winters	574	1930-66	--	--
11456000	Napa River near St. Helena	81.4	1930-66	Daily	1957-62
11458500	Sonoma Creek at Boyes Hot Springs	62.2	1956-66	Periodic	1957-62

[1]Drainage area and water discharge at gaging station Sacramento River near Red Bluff (11378000), excluding Goose Lake basin.

[2]Regulated since November 1967 by Oroville Dam near Oroville.

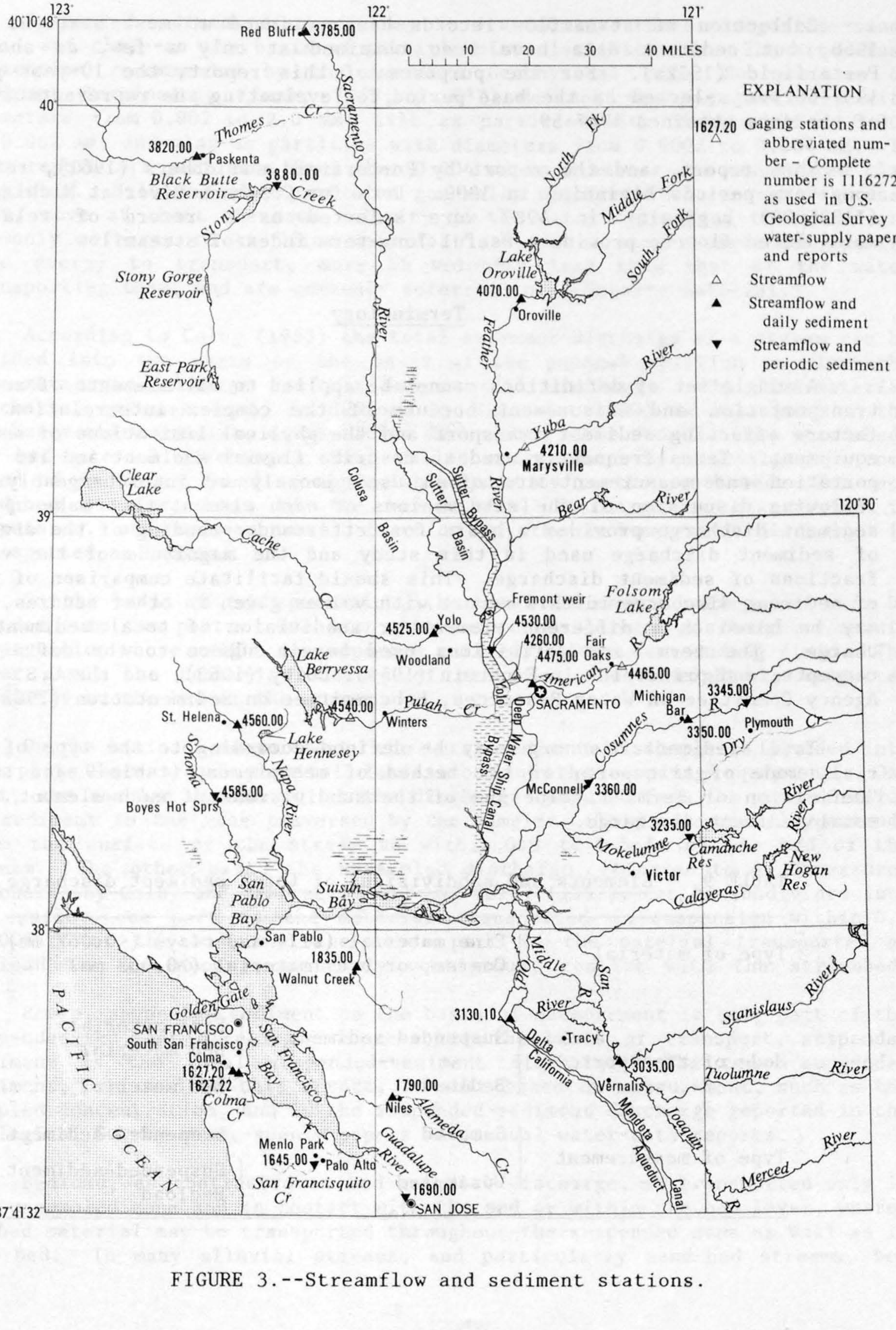

FIGURE 3.--Streamflow and sediment stations.

Collection of streamflow records has continued at most stations since 1966, but sediment data have been obtained at only a few, as shown by Porterfield (1972a). For the purposes of this report, the 10-year period 1957-66 was selected as the base period for evaluating the representativeness of the data obtained 1957-59.

This report, and the report by Porterfield and others (1961), refer to long-term periods beginning in 1909. Data for Cosumnes River at Michigan Bar (11335000) beginning in 1909 were selected as a record of relatively unregulated flow to provide a useful long-term index of streamflow.

Terminology

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. Terms frequently used to describe fluvial sediment and its transportation and measurement are often used loosely or interchangeably. The following discussion of the subdivisions of each element that make up total sediment discharge provides a basis for better understanding of the divisions of sediment discharge used in this study and the magnitude of the various fractions of sediment discharge. This should facilitate comparison of values of sediment discharge in this report with values given in other studies, which may be based on a different element or subdivision of total sediment discharge. The terms and definitions used herein adhere to the definitions, concepts, and principles in Einstein (1950), Colby (1963), and the U.S. Inter-Agency Committee on Water Resources, Subcommittee on Sedimentation (1963).

Total sediment discharge may be defined according to the type of material, mode of transport, or the method of measurement (table 9 and section "Definition of Terms"). The sum of the subdivisions of each element is the total sediment discharge.

TABLE 9. - Elements and subdivisions of total sediment discharge

Type of material	Fine material (silt and clay) (<0.062 mm)	
	Coarse, or bed, material (>0.062 mm)	
Mode of transport	Suspended sediment	Fine material
		Bed material
	Bedload	Bed material
Type of measurement	Sampled	Suspended sediment
	Unsampled	Suspended sediment
		Bedload

Suspended-sediment discharge may be divided into three categories--sand, silt, and clay--on the basis of particle-size classification. The size classification recommended by the American Geophysical Union Subcommittee on Sediment Terminology (Lane, 1947, p. 937) defines sand as particles with diameters from 0.062 to 2.0 mm; silt as particles with diameters from 0.004 to 0.062 mm; and clay as particles with diameters from 0.0002 to 0.004 mm. In this report all particles less than 0.004 mm in diameter are considered clay particles. Silt and clay particles generally require little energy to transport, move at about the same velocity as the water supporting them, and are commonly referred to as "fine material." Sand and larger particles require more energy to transport, move at velocity less than that of the water transporting them, and are commonly referred to as "coarse material."

According to Colby (1963) the total sediment discharge of a stream can be divided into two parts on the basis of the general relation to flow--the fine-material discharge and the bed-material discharge. The fine-material discharge, or wash load, is defined by Einstein (1950) as that part of the discharge which consists of particles finer than those found in the streambed. The bed-material discharge, often called coarse-material discharge, is composed of particles found in appreciable quantity in the streambed. For many sand-bed streams, most of the bed-material discharge is transported in suspension, and only a small fraction of the bed-material discharge is transported as bedload.

On the basis of transportation, the total sediment discharge can also be divided into two parts. One part, the suspended-sediment discharge, consists of particles whose weight is supported entirely by the surrounding fluid. The other part, the bedload, consists of particles whose weight is supported primarily by the bed of the stream.

On the basis of measurement, the total sediment discharge is divided into two parts because of physical limitations of the sampling equipment. One part, the sampled discharge, is the discharge computed from the concentration of sediment in the zone traversed by the sampler. This zone normally extends from the surface of the stream to within 0.3 to 0.5 ft of the bed of the stream. The other part, the unsampled discharge, referred to as unmeasured discharge by Colby and Hembree (1955) and Colby (1957), can be subdivided into two parts: one part is the material transported in suspension within 0.3 to 0.5 ft of the bed, and the other part is the material transported as bedload in continuous, or nearly continuous, contact with the streambed.

Hence, suspended sediment on the basis of measurement is only part of the suspended-sediment discharge, whereas, on the basis of transport, suspended sediment is the total suspended-sediment discharge. The term "suspended sediment," as used in this report, is that based on measurement, such as the sampled concentration, and is the suspended-sediment discharge reported in the Geological Survey water-supply papers and annual water-data reports.

Bedload, as contrasted to bed-material discharge, is transported only in the unsampled zone and in contact with the bed or within the bed layer, whereas bed material may be transported throughout the suspended zone as well as in the bed. In many alluvial streams, and particularly sand-bed streams, bed material is transported in the suspended zone and is sampled with the suspended-sediment samplers. Bedload typically constitutes only a small fraction, generally less than 10 and often less than 5 percent, of the total sediment discharge, as determined from bedload equations commonly used.

Sampling Equipment and Methods

Samples of suspended sediment were obtained with depth-integrating samplers and by methods described by the U.S. Inter-Agency Committee on Water Resources, Subcommittee on Sedimentation (1963). The samplers are nozzle type, designed to collect a water-sediment mixture at an intake velocity approximating the stream velocity at the nozzle elevation. The samplers are lowered and raised at a constant rate and collect a depth-integrated sample from the surface of the stream to within 0.3 to 0.5 ft of the streambed. The collected samples have volumes of water-sediment mixture theoretically proportional to the water discharge per unit width at the traversed vertical. The mean sediment concentration in the stream is then obtained by sampling a number of verticals and weighting the mean concentration at each vertical with the corresponding water discharge.

The mean sediment concentration in the sampled zone is representative of the total suspended-sediment concentration for streams transporting predominantly fine material, because fine material normally is uniformly distributed. The mean sediment concentration for streams transporting coarse material is less representative of the total suspended-sediment concentration because coarse material is not uniformly distributed from the streambed to the surface, and the concentration generally increases near the bed. The quantity and particle-size distribution of sediment, therefore, are indicators of the relation of sampled concentration to total suspended-sediment concentration.

Bed-material samples of the upper 1 to 1½ inches of the bed are obtained with a modified clamshell sampler. Samples are taken at several verticals where suspended-sediment samples were collected, and weighted with the water discharge represented by each vertical to obtain the average bed-material size in the stream cross section.

Bedload samplers designed to measure the bedload discharge of a stream were not used during the period covered by this report. Recently such devices have been used or suggested (Hubbell, 1964). Bedload and total sediment discharge for this study were obtained by indirect methods discussed in a following section.

COMPUTATIONS

Suspended-Sediment Discharge

Suspended-sediment discharge is proportional to the product of total water discharge and the mean concentration of sediment in the depth sampled as computed from depth-integrated samples. The number of samples and the frequency of sampling at each station depends on the channel geometry, flow conditions, particle-size distribution of the transported sediment, and the accuracy desired (U.S. Inter-Agency Committee on Water Resources, Subcommittee on Sedimentation, 1963).

Samples were obtained at daily stations (table 8) one or more times daily during periods of high and medium flow, and 1 to 3 times weekly during periods of low or clear flow. These samples were used to define a continuous concentration curve from which daily suspended-sediment discharge was computed.

Samples were obtained at periodic stations (table 8) at sufficient frequency to determine the relation between water and sediment discharge for the range of water discharge. An average curve for this relation is referred to herein as a sediment-transport curve, which is used to compute average sediment discharge from water discharge for periods when sediment samples were not collected (Colby, 1956).

Sediment-Transport Curves

According to Colby (1956), sediment-transport curves may be classified according to either the period of the basic data that defines a curve or the kind of sediment discharge that a curve represents. Sediment-transport curves may be classified as instantaneous, daily, monthly, annual, or flood-period curves. Instantaneous sediment-transport curves are defined by concurrent measurements of sediment discharge and water discharge for periods too short to be substantially affected by changes in flow or concentration during the measurements. Daily, monthly, annual, and flood-period sediment-transport curves are usually defined by and expressed as average sediment and water discharges, and sometimes as total quantities of sediment and water discharges, during the respective lengths of time.

On the basis of the kind of sediment they represent, sediment-transport curves may be classified as suspended-sediment-transport curves, unsampled or unmeasured sediment-transport curves, and total sediment-transport curves. These sediment-transport curves may be further subdivided according to size of particles for which the defining sediment discharges were computed. In this report, suspended-sediment-transport curves have been subdivided, according to particle size, into only two or three parts and identified as sediment-transport curves for particles in the range of sand sizes and for particles in the range of clay and silt sizes.

Total Sediment Discharge

Total sediment discharge is the total quantity, by weight, of all sediment passing a section in a unit time. Samples obtained with samplers currently available for practical field use can be used to compute the discharge of material in the zone traversed by the sampler, that is, the suspended-sediment discharge, but they cannot be used to determine the discharge of material on the bed or in close proximity with the bed (Jordan, 1965, p. 67). Total sediment discharge, therefore, was determined indirectly by one of the several methods described below.

Total sediment discharge for streams with alluvial beds, as defined by Einstein (1950), such as Sacramento River at Sacramento and San Joaquin River near Vernalis, can be computed by the Einstein procedure as modified by Colby and Hembree (1955). Data needed include bed-material particle sizes, suspended-sediment concentration and particle-size distribution of suspended sediment from depth-integrated samples, streamflow, and water temperature. The difference between total sediment discharge determined from the modified Einstein procedure and the measured or sampled suspended-sediment discharge is the unmeasured (Colby and Hembree, 1955) or unsampled discharge. The unsampled discharge per foot of width is generally correlative with mean water velocity (or discharge), and can be used to compute a general relation for adjustment of daily or instantaneous suspended-sediment discharges to total sediment discharge.

Bedload discharge for streams that do not have alluvial beds, defined by Einstein (1950) and Colby and Hembree (1955) as a river section with a sediment bed composed of the same type of sediment as that moving in the stream, may be computed by the Meyer-Peter and Mueller bedload equation. Data needed for this equation are streamflow, average depth and width of the section, slope, roughness factor (Manning's n) for the streambed and banks, and particle-size distribution of bed material. Bedload discharge computed for several increments of discharge may be used to adjust suspended-sediment discharge to total sediment discharge. The sum of the bedload and suspended discharge is assumed to be total discharge if the streambed contains bed material generally too coarse to be transported in suspension, or if the bed material transported in suspension is fine enough to be uniformly distributed from the water surface to the streambed.

Long-Term Sediment Discharge

The relation between sediment discharge and streamflow may vary considerably during short periods and from year to year. Sediment discharges obtained over a period sufficiently long to observe these variations are needed to estimate long-term sediment discharge and rates, and to predict trends in sediment discharge. Average sediment rates are also needed to evaluate the effect of man's activities--diversions, reclamation, land management, navigation, transportation, and industry--on future sediment-transport rates.

Because no sediment data for San Francisco Bay were available except on a short-term basis, an estimate of discharge for the period 1909-59 was made for each location sampled during 1957-59 by the flow-duration, sediment-transport-curve method discussed by Daines (1949), Miller (1951), and Colby (1956). The flow-duration curve, described by Searcy (1959) as a cumulative-frequency curve and the integral of the frequency diagram, represents an average for the period considered rather than the distribution of flow within a single year. If streamflow during the period on which the flow-duration curve is based represents the long-term flow of the stream, the curve may be considered a probability curve and used to estimate the percentage of time that a specified discharge will be equaled or exceeded in the future.

The flow-duration sediment-transport method of computing average sediment discharge is a convenient shortcut to the computation of average sediment discharge from a sediment transport curve and daily water discharges. It does, however, contain the inaccuracies and uncertainties of sediment discharges computed from sediment-transport curves and daily water discharges plus the added small error that results from averaging water discharges and multiplying averages. The method generally is accurate within about the limits of the sediment-rating curve on which it is based. Average sediment discharges computed by this method should be satisfactorily accurate unless the sediment rating curve was incorrectly prepared or was applied to periods for which it did not represent approximately the relation between sediment and water discharges (Colby, 1956).

Sediment values in the report on 1957-59 data (Porterfield and others, 1961) were based on daily values of water discharge and on sediment-transport curves prepared from available instantaneous or daily values of sediment discharge. Theoretically a curve based on one type of data is not interchangeable with a curve based on another type of data; thus a curve based on instantaneous values should not be used to compute sediment discharge from values of daily, weekly, monthly, or annual water discharge. The error caused by interchanging curves generally increases as the length of the average period of water discharge increases. In practice, a transport curve based on instantaneous values usually is similar to a curve based on daily values within limits of accuracy of their definition. An annual curve, however, is not interchangeable with other sediment-transport curves. Estimated daily values for periods during which no samples were collected are subject to large errors because of variation from the average relation between sediment discharge and water discharge. The errors should be generally compensating over a long period of time, and annual totals based on these daily values may approximate the correct values.

Errors may also result if sediment data obtained during the sampled period do not adequately define the extremes, duration of high and low flows, and other variables that affected sediment transport during the longer period 1909-59. The probability that the sediment-transport curve is representative of the longer period is improved if the median discharge, mean discharge, and frequency of occurrence of daily discharges are similar during both periods. This similarity indicates the possibility that the various combinations of events affecting sediment transport were sampled at the same frequency that occurred during the longer period. Fortunately the median and frequency of occurrence of water discharges during the 1957-59 study period for most locations sampled were similar to those for the 51-year period 1909-59 (Porterfield and others, 1961), as shown in figure 4. The tabulated data show similar agreement between the discharge figures for 1957-59 and 1909-59 except for streams contributing to south San Francisco Bay in which greater peak discharges in 1958 produced a greater frequency of occurrence of the high water discharges for 1957-59 than for 1909-59. These higher peak water discharges therefore yielded average sediment discharges for 1957-59 appreciably greater than those estimated for 1909-59.

The flow-duration curves for 1957-59 and 1909-59 for Cosumnes River at Michigan Bar are shown in figure 5. The 1909-59 record is the actual 51-year streamflow record and is indicative of the general relation between flow conditions during the study and long-term periods. Good agreement exists between frequency of occurrence and values greater than median discharge. The sampled period, therefore, may be assumed to be representative of the long-term period. As little sediment is transported when the streamflow is low, divergence of the curves in the low-flow range is not significant. Average streamflow during selected periods through 1959 and 1966 are shown in table 10.

TABLE 10. - Average daily streamflow at selected sites

	Discharge, in cubic feet per second			
Period	11447500 Sacramento River at Sacramento	11335000 Cosumnes River at Michigan Bar	11378000 Sacramento River near Red Bluff	11407000 Feather River at Oroville
1909-59	22,540	494	10,640	5,560
1909-66	22,240	478	10,580	5,400
1949-59	24,420	560	11,890	6,310
1949-66	22,620	483	11,220	5,520
1957-59	23,500	465	13,280	5,850
1957-66	20,900	393	11,410	5,330
Drainage area, in square miles	23,530	536	9,022	3,624

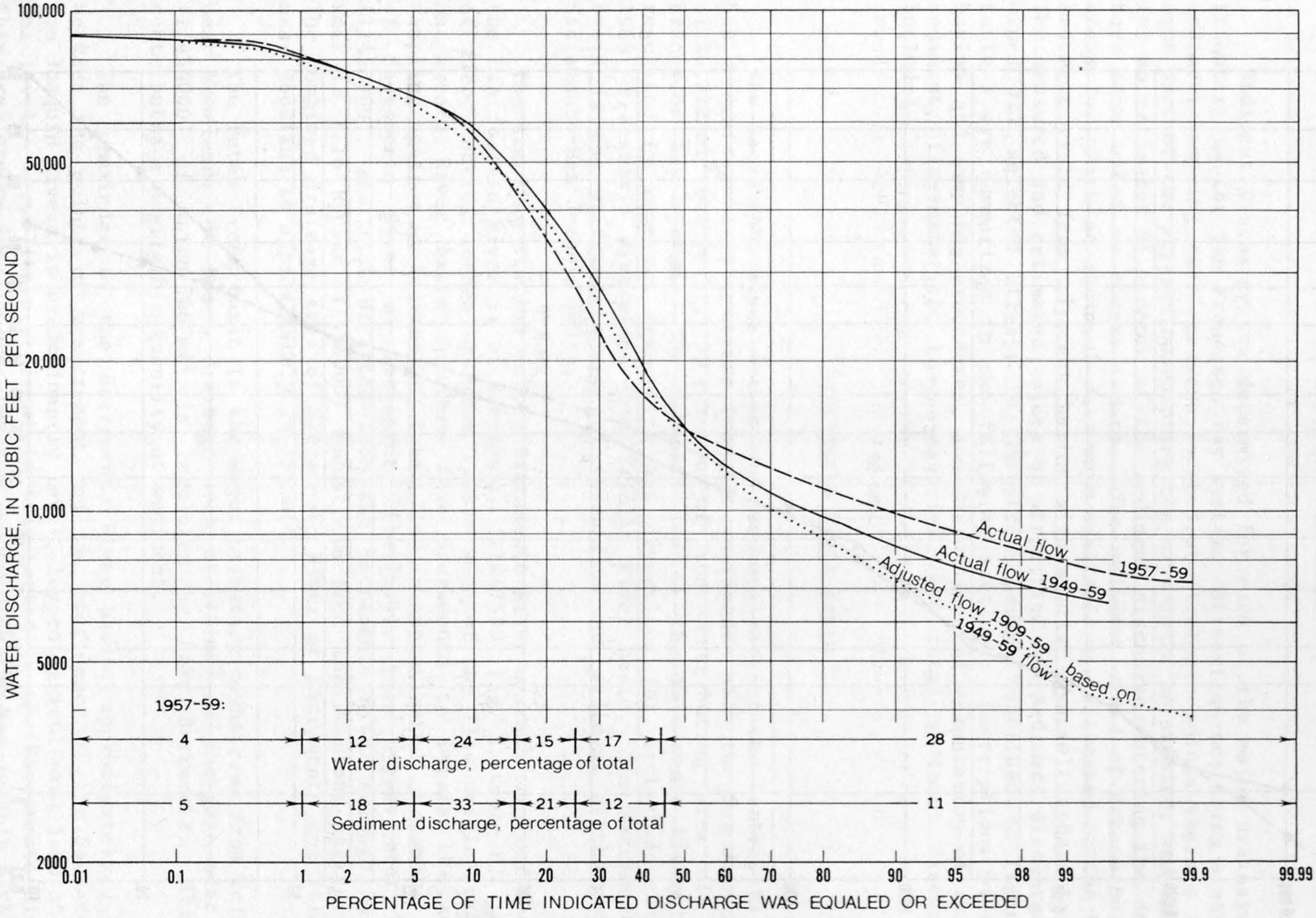

FIGURE 4.--Duration curves of daily streamflow, Sacramento River at Sacramento, 1909-59, 1949-59, and 1957-59.

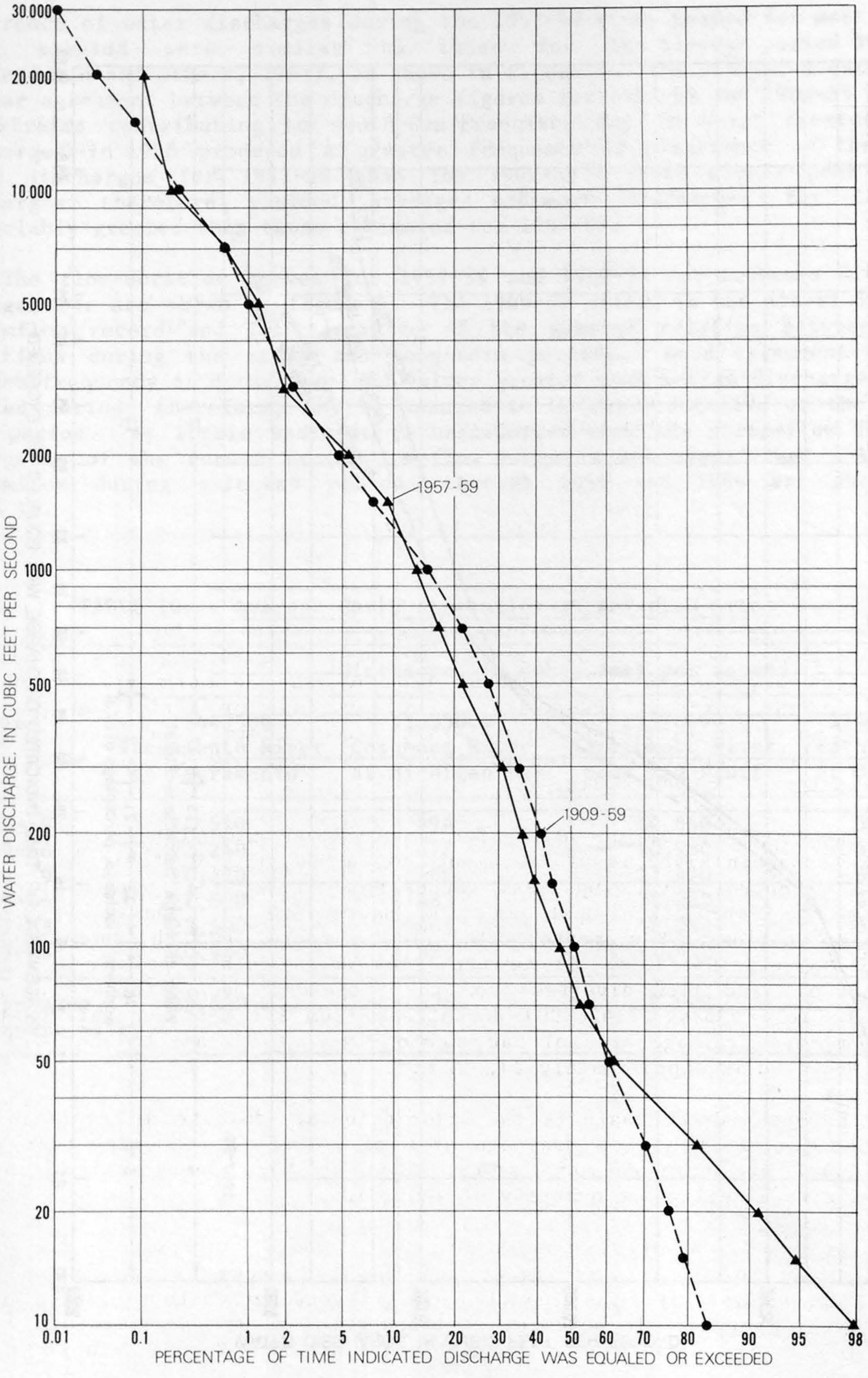

FIGURE 5.--Duration curves of daily streamflow, Cosumnes River at Michigan Bar, 1957-59 and 1909-59.

SEDIMENT DISCHARGE

Sediment discharge was determined for each of the major drainage basins tributary to the San Francisco Bay system. Streamflow-measuring stations and sediment-sampling stations were located at strategic points where a significant part of the streamflow entering the bays could be sampled; and the values for an estimated 91 percent of the sediment discharge entering the delta and bays were based on observed data. The sediment yield of stream basins and areas for which no sediment data were available was estimated on the basis of sediment yield from adjacent basins with similar hydraulic characteristics. The measured and estimated values of streamflow and sediment discharge determined for selected streams in the stream groups described in figure 2 and table 3 are summarized in the following sections. Descriptions of drainage basins and sampling procedures, and discussions of computation of suspended-sediment, fine-material, coarse-material, and total sediment discharge are included.

Sacramento River Basin

The Sacramento River drains the northern part of the Central Valley and has a drainage area upstream from the confluence with the San Joaquin River of 26,322 mi^2 (table 3), 53 percent of the contributing area of the San Francisco Bay system. The natural flow of the Sacramento River basin is regulated by numerous reservoirs and diversions for irrigation, and since 1963, transbasin diversions from Trinity River basin. The Sacramento River basin is the principal source of streamflow and sediment discharged to the Sacramento-San Joaquin Delta.

The sampling station on the Sacramento River nearest the confluence with the San Joaquin River is at Sacramento (11447500, fig. 3, table 8). A system of flood-control levees upstream causes some of the flow originating in the Sacramento River basin upstream from Sacramento to bypass the sediment-sampling station at Sacramento; total flow is approximated by summing the flow of Sacramento River at Sacramento (11447500), Yolo Bypass near Woodland (11453000), and flow diverted from the Sacramento River through Sacramento Weir to Yolo Bypass (11426000) downstream from the Woodland gaging station. The combined drainage area of Sacramento River at Sacramento and Yolo Bypass near Woodland is approximately 24,755 mi^2.

The Putah Creek basin is the major tributary downstream from Yolo Bypass near Woodland. It has a drainage area of 574 mi^2 at the gage near Winters (11454000) of which 566 mi^2 is regulated by Lake Berryessa. This basin contributes a negligible quantity of sediment.

The remainder of the Sacramento River basin, approximately 1,000 mi^2, between the points of measurement and the confluence of the Sacramento and San Joaquin Rivers is predominantly level, leveed agricultural land at or near sea level. Very little sediment is transported to the Sacramento River from this area except locally near the confluence with the San Joaquin River.

Sacramento River at Sacramento

Water discharge

Streamflow records for Sacramento River at Sacramento (station 11447500, fig. 3, table 8) began in 1949, although stage data are available for this vicinity since 1879. The 18-year period, 1949-66, was used to extend streamflow records to the 1909-66 period and to estimate the long-term sediment discharge. The distribution of discharges for the sampled period 1957-66, the period of streamflow record 1949-66, and long-term record 1909-66 are shown in figure 6. The 1909-66 flow-duration curve represents the discharges that would have occurred during the 58-year period under conditions of regulation and land management similar to those existing during the 18-year base period.

The estimated long-term streamflow record for Sacramento River at Sacramento based on the 1949-66 streamflow data is assumed to be representative for the long term because measured mean discharge at two upstream stations--Sacramento River near Red Bluff and Feather River at Oroville--during 1949-66 shows reasonable agreement with the mean discharge during 1909-66 (table 10). Streamflow records for Cosumnes River of Michigan Bar, an unregulated stream in the San Joaquin River basin, also indicate that mean streamflow 1949-66 approximated that for 1909-66.

The accuracy of the extrapolated sediment records depends in part on the assumption that the various combinations of events affecting sediment erosion and transportation during the long-term period occurred at frequencies comparable to those during the sampled period. The flow-duration curves (fig. 6) show the median streamflow during 1909-66, 1949-66, and 1957-66 to be the same, and that the larger streamflows occurred at about the same frequency during the three periods. As the large streamflows transport most of the sediment, the frequency distribution of these water discharges should be comparable if the short record is to be considered representative of the distribution for the longer period. The tabulation in figure 6 shows that in the Sacramento River at Sacramento, 91 percent of the sediment discharge during 1957-66 was transported at streamflows exceeded 50 percent of the time, and 37 percent in 5 percent of the time. The relation between water and sediment discharge during specific time intervals is shown also; for example, 4 percent of the water discharge, and 13 percent of the sediment discharge, occurred in 1 percent of the time.

Suspended-sediment discharge

Daily values of suspended-sediment discharge vary considerably for a given streamflow, as shown in figure 7. This large variation increases the possible error if extrapolated values are based on a short or incomplete sampling period that may not adequately define the sediment-transport curve during the sampled period or represent the occurrence frequency of events during the extrapolated period. A sediment-transport curve, constructed from data similar to that in figure 7, defines the average sediment discharge in each of several ranges of water discharge, as shown in figure 8. The points on the curve represent the average value in each range. This group-averaging technique simplifies delineation of the relation between streamflow and sediment discharge.

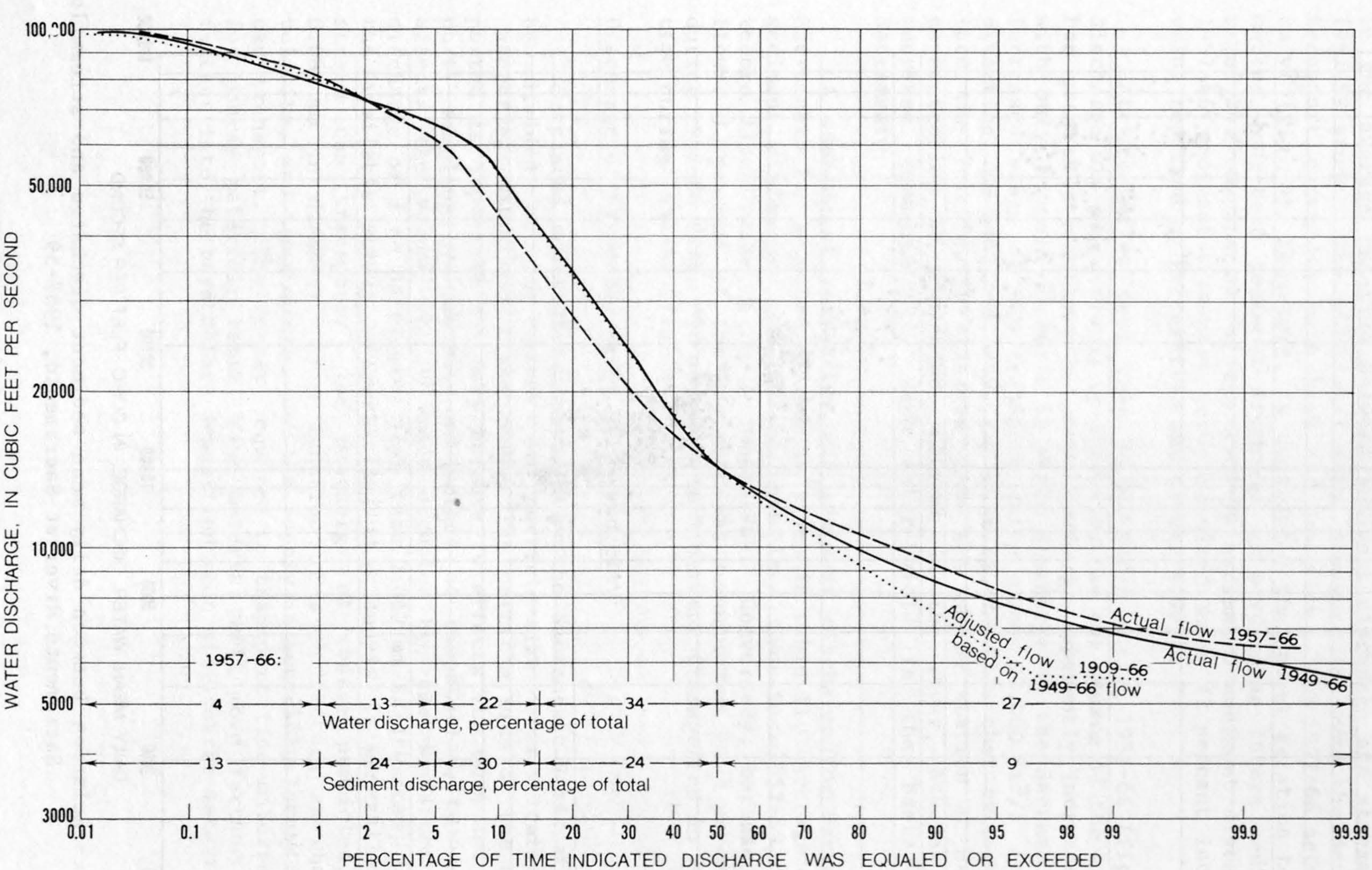

FIGURE 6.--Duration curves of daily streamflow, Sacramento River at Sacramento, 1909-66, 1949-66, and 1957-66.

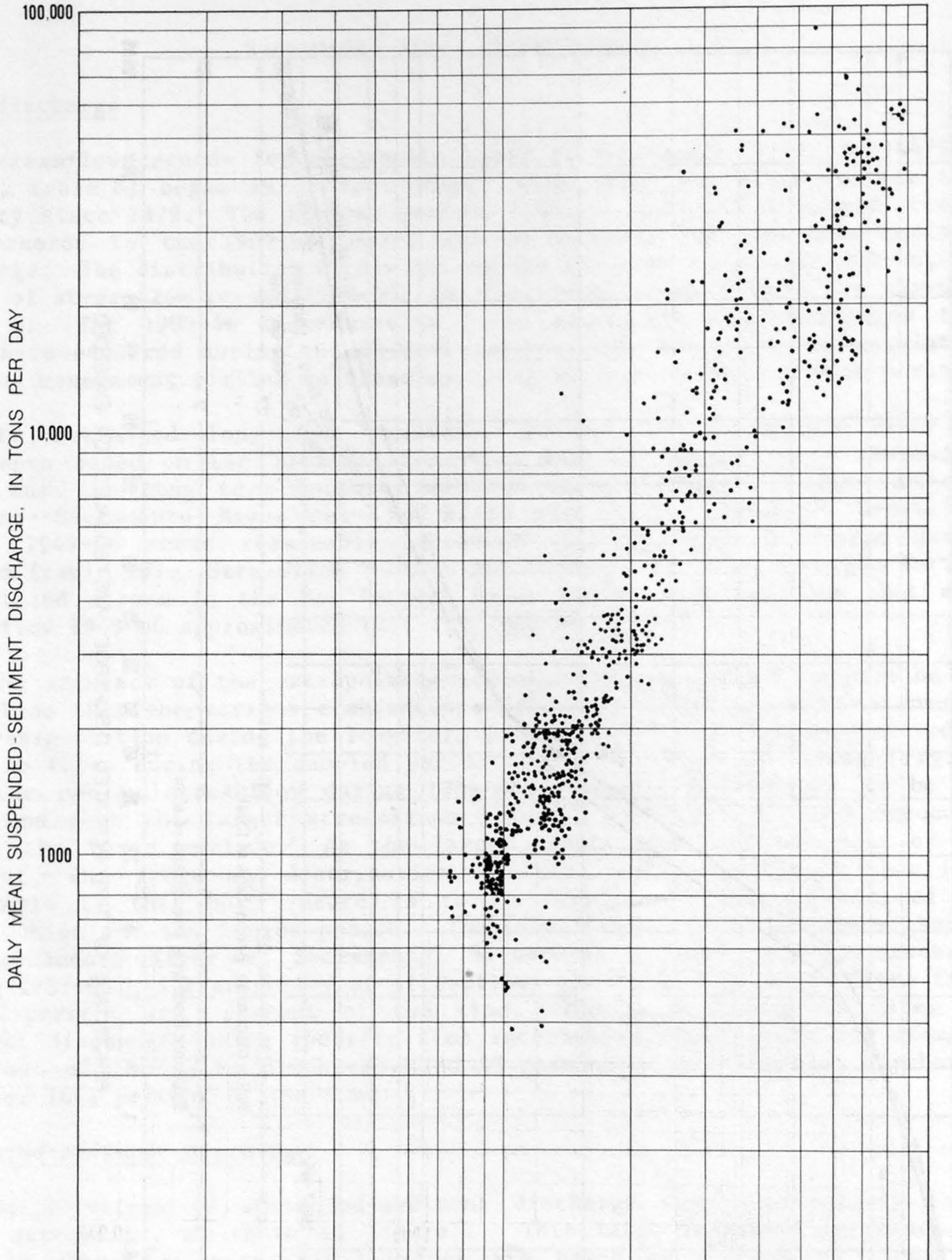

FIGURE 7.--Relation between daily mean sediment discharge and streamflow, Sacramento River at Sacramento, 1957-59.

Sediment data obtained for 1957-66 indicate that little change occurred in the average relation between sediment discharge and streamflow since the 1957-59 study. The additional data, however, improved the definition of the transport curve for both high and low flow. The 1957-66 sediment-transport curve (fig. 8), therefore, is considered the better relation to use for estimating long-term sediment discharge or predicting future sediment-transport rates. Recomputation of the 1909-59 estimated sediment discharge using the 1957-66 sediment-transport curve resulted in a 12 percent increase from the value reported by Porterfield and others (1961).

At streamflow less than 90,000 ft^3/s during 1957-66 (fig. 8), sediment discharge was proportional to approximately the square of the water discharge. For greater streamflows sediment discharge apparently increases considerably with only a small increase in water discharge in the Sacramento River. The increased slope of the transport curve above 90,000 ft^3/s is the result of diverting, in 1963 and 1965, the part of the flow that exceeded 90,000 ft^3/s into the Yolo Bypass upstream from the gaging station at Sacramento. The concentration of suspended sediment in the river, however, continued to increase commensurately with water yield in the basin upstream from Sacramento.

A summary of streamflow and sediment discharge for Sacramento River at Sacramento for selected periods is given in table 11. Average daily water and sediment discharges for 1957-66 were less than for 1957-59, although near-record flows occurred in December 1964. Conversely, because of these large flows, 13 percent of the sediment was transported in 1 percent of the time during 1957-66 (fig. 6), compared to 5 percent transported in 1 percent of the time during 1957-59 (fig. 4).

Discharge of suspended sand, silt, and clay

Suspended sediment transported by the Sacramento River at Sacramento may be divided on the basis of particle-size classification into three categories--sand, silt, and clay. The particle size of the material transported is important not only because it affects the mode and rate of transport, sampling procedures, and method of computation, but also because it affects the volume of, or space occupied by, the deposited material. The discharge of fine particles, less than 0.062 mm in diameter, is controlled by the available supply of particles; this supply is generally less than the stream can transport. The discharge of coarse particles, greater than 0.062 mm in diameter, is a function of such factors as channel geometry, velocity, and temperature, and the supply is generally larger than the stream can transport. The energy required to transport fine material is less than for coarse material; hence, fine material will move farther downstream and farther into the bays before deposition than will coarse material.

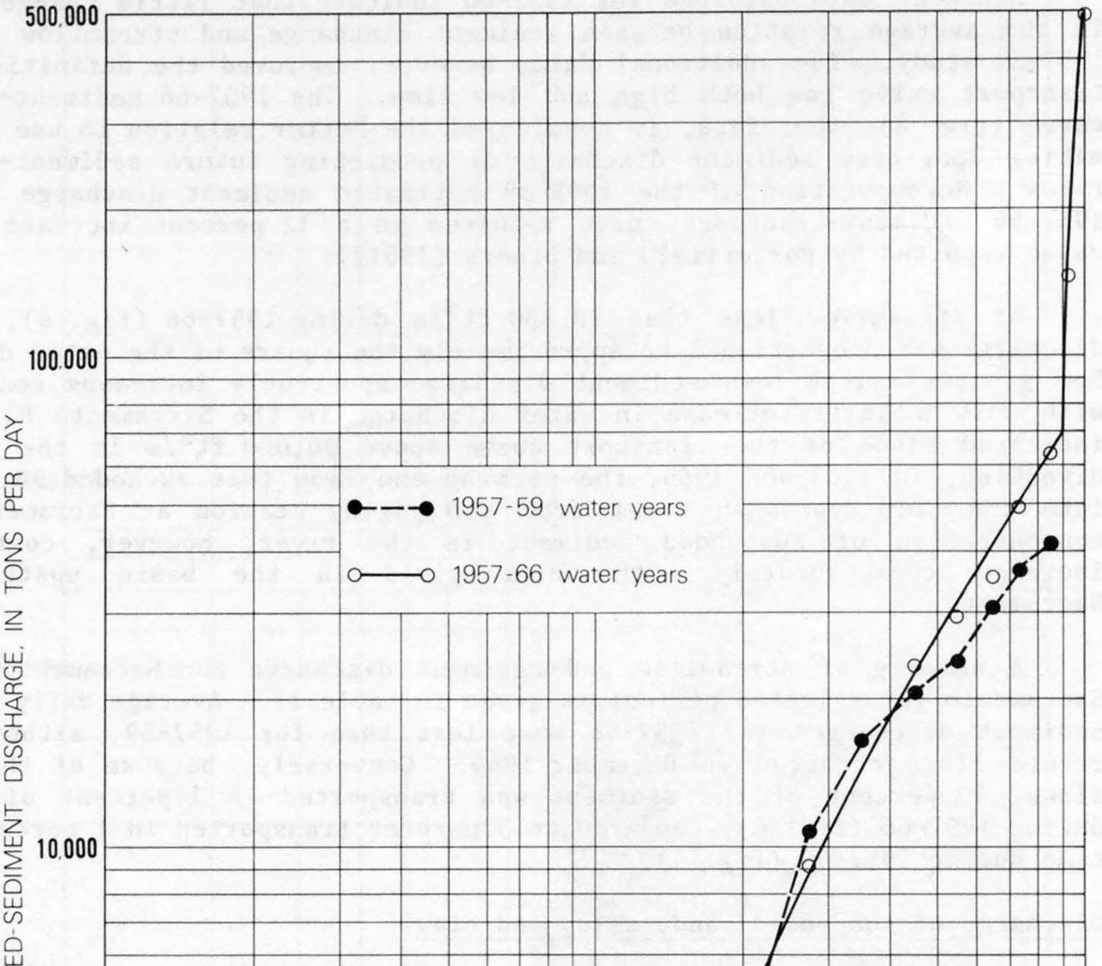

FIGURE 8.--Relation between sediment discharge and streamflow, Sacramento River at Sacramento, 1957-59 and 1957-66.

TABLE 11. - Average daily streamflow and sediment discharge and sediment yield, Sacramento River at Sacramento, 1957-59, 1957-66, 1909-59, 1909-66

Period	Number of years	Water discharge (ft^3/s)	Suspended-sediment discharge: Silt and clay: Tons per day	Suspended-sediment discharge: Silt and clay: Percentage of total	Suspended-sediment discharge: Sand: Tons per day	Suspended-sediment discharge: Sand: Percentage of total	Unsampled-sediment discharge: Sand (0.062-2.0 mm): Tons per day	Unsampled-sediment discharge: Sand (0.062-2.0 mm): Percentage of total	Total sediment discharge: Tons per day	Total sediment discharge: Tons per square mile per year
1957-59	3	23,500	3,850	40	3,950	41	[1]1,850	19	[1]9,650	150
1957-66	10	20,900	4,210	48	3,190	36	1,420	16	8,820	137
1909-59	51	22,540	[1]4,920	46	[1]3,930	37	[1]1,760	17	[1]10,610	165
1909-66	58	22,240	4,640	45	3,830	38	1,730	17	10,200	158

[1]Revised from Porterfield and others, 1961.

Ninety-three samples obtained at Sacramento during the 1957-66 period were analyzed for particle-size distribution. These samples were collected at irregular intervals and were selected to represent flow conditions in the Sacramento River for all seasons and stages. The samples analyzed were collected at water discharges ranging from 7,340 to 98,800 ft^3/s. The sample at 98,800 ft^3/s was collected on December 24, 1964; the sediment discharge for that day was 525,000 tons. The maximum water discharge during 1957-66 was 99,700 ft^3/s on December 25, 1964.

Suspended sand.--The relation between the percentage of suspended-sand discharge and streamflow during 1957-66 for all samples analyzed is shown in figure 9. The correlation is poor partly because percentage of sand is a function of the percentage of fine material which, in turn, is affected by supply rather than by flow conditions. A potential for error exists if the arithmetic, or discharge-weighted, mean percentage of sand is used to estimate the quantity of sand transported by a stream. As sand transport in a sand-bed stream is affected more by the variables affecting streamflow than by supply, a usable relation between the quantity of sand and water discharge, or stream velocity, can be obtained provided an unlimited supply of sand is available in the streambed for transport. The suspended sand-streamflow relation may be shown also by conversion of the percentage values in figure 9 to tons of sand; the resulting relation is given in figure 10.

A sand-transport curve prepared by drawing a smooth curve through the group-average values of sand discharge for small ranges in water discharge is also shown in figure 10. A similar curve for 1957-59 is included for comparison. The average sand discharge during 1957-66 was 3,190 ton/d. Most of the sand is transported during periods of larger flows and velocities. Data in table 12, for example, indicate that 42 percent of the sand was transported in 5 percent of the time by 17 percent of the streamflow.

TABLE 12. - Percentage of streamflow and suspended-sand discharge that occurred during selected time intervals, Sacramento River at Sacramento, 1957-66 and 1909-66

Discharge	Period	Time (percent)			
		1	5	15	50
Water	1957-66	4	17	39	73
	1909-66	4	16	40	78
Suspended sand	1957-66	12	42	78	97
	1909-66	9	35	74	99

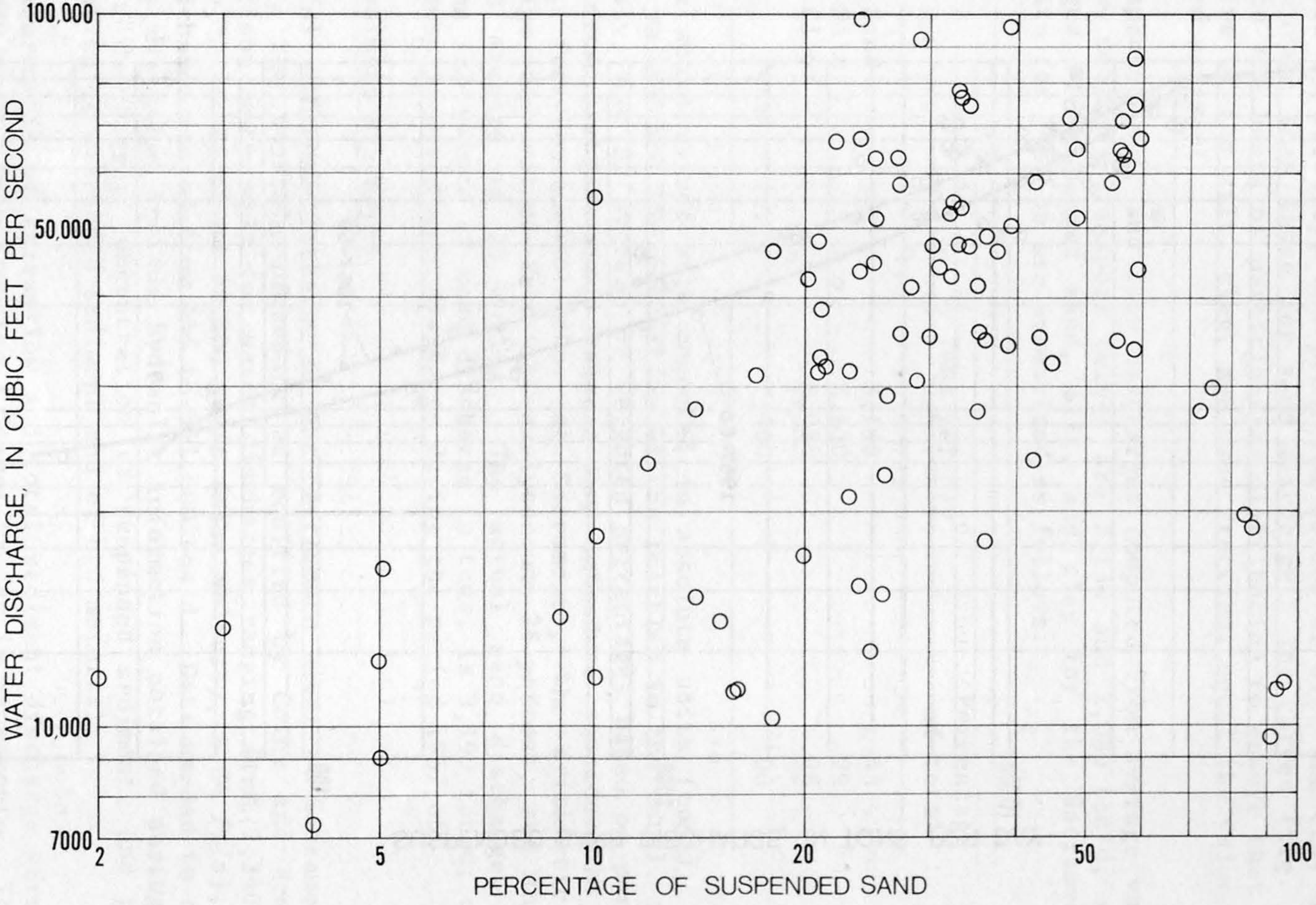

FIGURE 9.--Relation between percentage of sand and streamflow, Sacramento River at Sacramento, 1957-66.

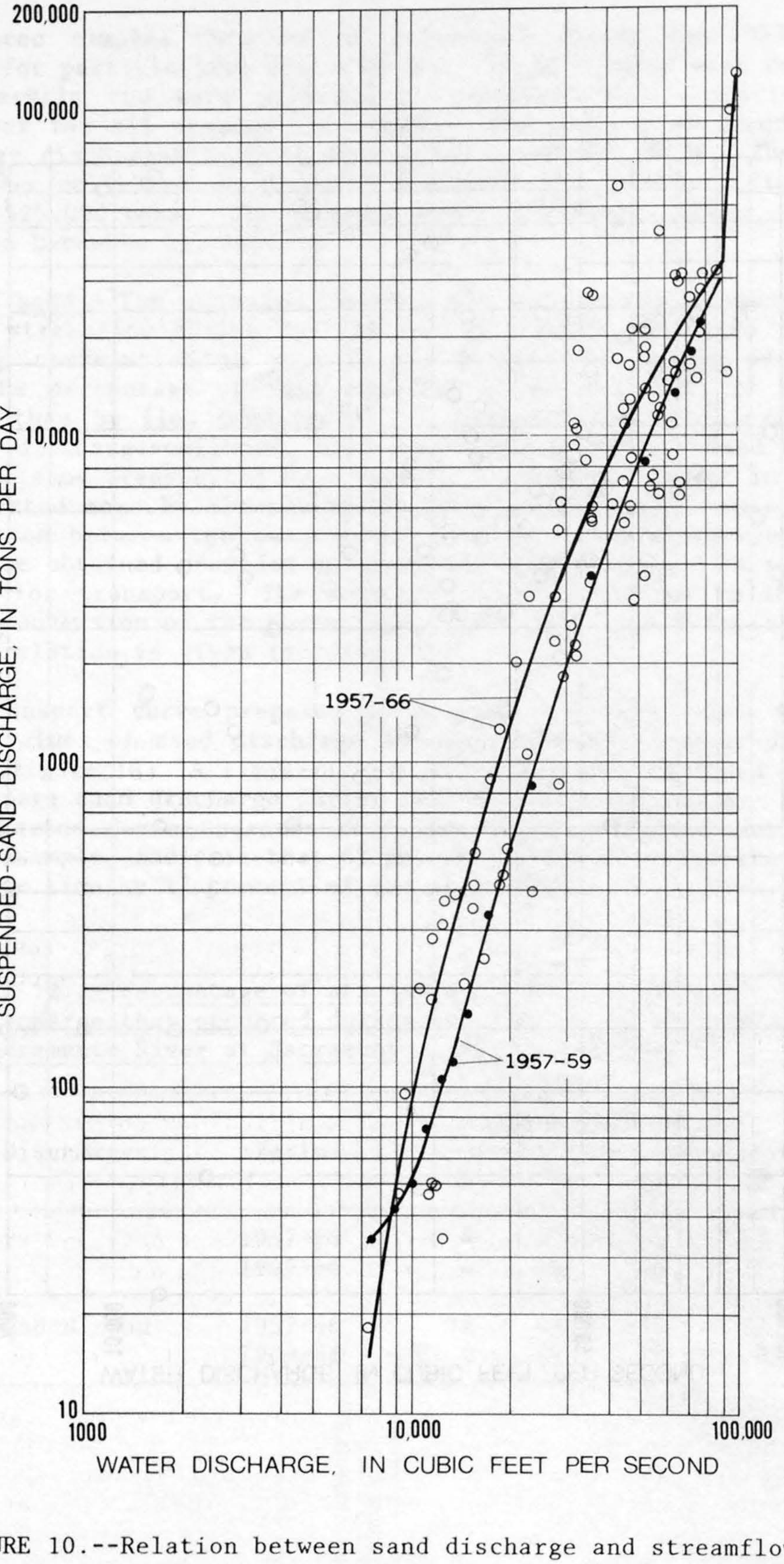

FIGURE 10.--Relation between sand discharge and streamflow, Sacramento River at Sacramento, 1957-66.

Suspended silt and clay.--The average discharge of silt and clay in relation to streamflow for 1957-66 is represented by the curves in figure 11. The quantity of fine material transported is more a function of supply than of flow variables. Thus, silt and clay values often correlate poorly with streamflow or velocity, and predicted values of silt and clay discharge are less accurate than those for sand discharge. The curves (fig. 11) were adjusted on the basis of particle-size distribution to ensure that the combined quantities of the silt, clay, and sand fractions equal the value reported for suspended sediment.

Suspended silt and clay discharges computed from average values defined by these sediment-transport curves are 2,130 and 2,080 ton/d, respectively. Discharges of suspended sand, silt, and clay for the Sacramento River at Sacramento for 1957-66 are summarized as follows:

	Tons per day	Percentage of total
Sand	3,190	43
Silt	2,130	29
Clay	2,080	28
Total...............	7,400	100

The above values were computed in absolute units (tons), and the percentage values are the proportion of the fraction to the total. As mentioned previously, use of average or weighted percentages based on percentages obtained from particle-size analyses may introduce considerable error. For example, for Sacramento River at Sacramento, the arithmetic average of percentage-sand values from all analyses is 28 percent, and the discharge-weighted average is 25 percent. The actual sand discharge, computed by weighting the values of sand discharge in tons, is 3,190 ton/d, or 43 percent of the suspended-sediment discharge during the period 1957-66.

Total sediment discharge

Total sediment discharge of the Sacramento River at Sacramento was computed by the Einstein procedure as modified by Colby and Hembree (1955). Computations were made for water discharges ranging from 7,340 ft^3/s (mean velocity, 1.16 ft/s) to 98,800 ft^3/s (mean velocity, 3.84 ft/s); total sediment discharge ranged from 456 to 551,000 ton/d. Data needed to compute total sediment discharge include hydraulic information obtained during measurement of water discharge, concentration of suspended sediment, and particle-size distribution of suspended sediment and of bed material.

Measurements of streamflow and total sediment discharge were made at the gage 1,000 ft upstream from the I Street bridge in Sacramento. The channel at the gage is leveed and the banks are stabilized with rocks or vegetation. Flow of the Sacramento River at Sacramento is affected during flood periods by upstream weirs that divert water into the Yolo Bypass, and during low-flow periods below about 30,000 ft^3/s, by tides. Tidal action affects the stage-

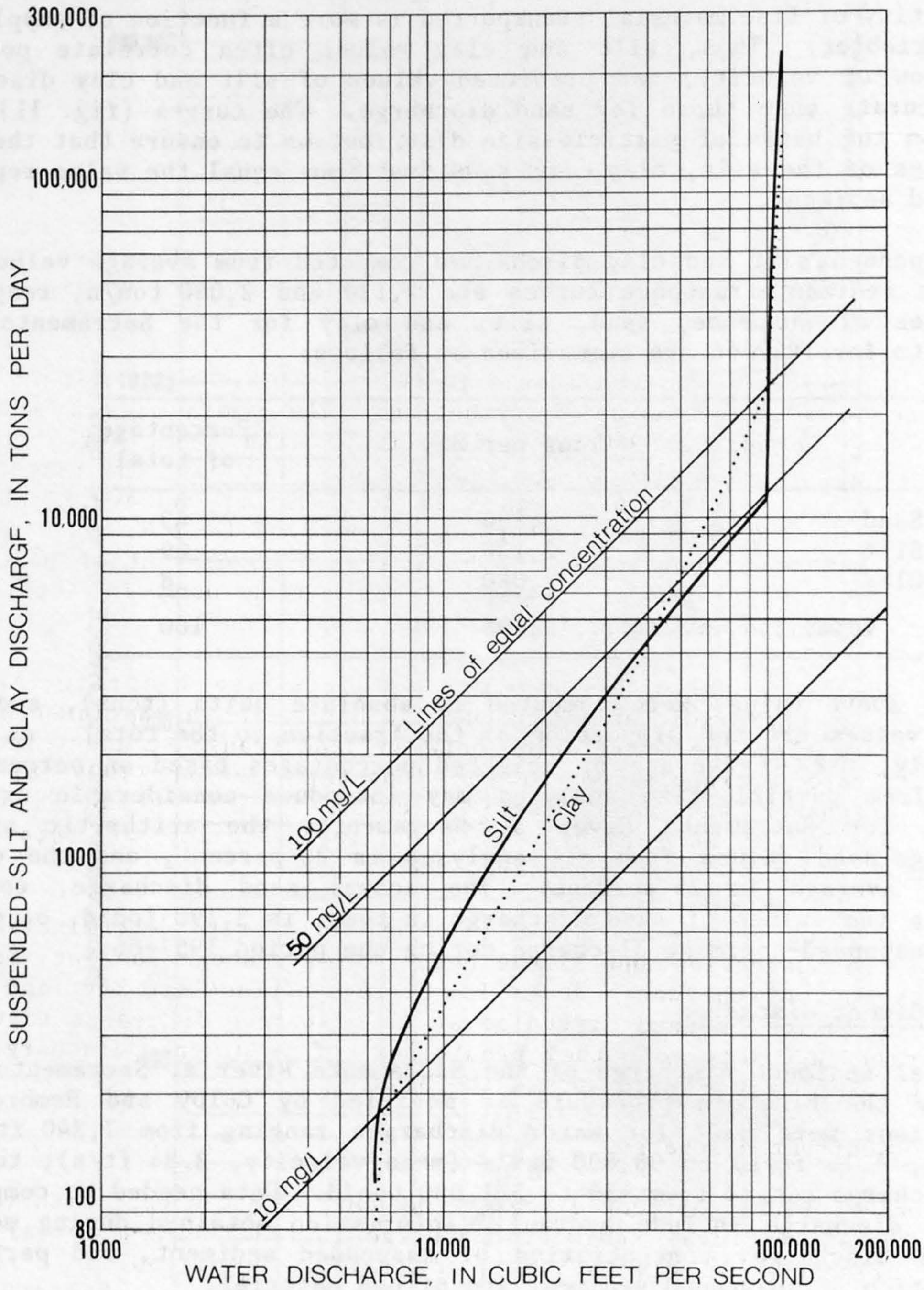

FIGURE 11.--Relation between silt and clay discharge and streamflow, Sacramento River at Sacramento, 1957-66.

discharge relation at the gage but no reversal of flow occurs; when flows exceed about 30,000 ft^3/s, the tidal effect on the relation of width, depth, and velocity to water discharge is generally negligible.

Bed-material samples were obtained during 1960-67 at streamflows ranging from 7,340 to more than 70,000 ft^3/s, and each sample contained material from three to eight locations laterally in the stream cross section. The bed of the Sacramento River is composed of sand and fits ideally the definition of an alluvial channel; that is, there is an unlimited supply in the bed of sand sizes transported in suspension by the stream. Material from the bed, bed-material discharge, is the largest fraction of material transported by the Sacramento River at Sacramento (sum of suspended-sand and unsampled-sediment discharge in table 11).

The bed material was considered to be well sorted with respect to median grain size and particle-size distribution. The median grain size of bed material sampled during 1960-67 varied little with time, streamflow, known depth of scour, or laterally in the stream cross section. The range of median diameter (D_{50}) for all samples was 0.29 to 0.39 mm; the average D_{35} ranged from 0.26 to 0.34 mm and the average D_{65} from 0.33 to 0.45 mm. D_{35} and D_{65} are the diameters of particles of which 35 and 65 percent of particles are finer, respectively, and are important parameters used in total sediment discharge computation by the modified Einstein procedure.

The generally unlimited supply of uniform-size bed material and the uniform, generally predictable, channel geometry of the Sacramento River at Sacramento improves the correlation between sand transport and velocity; they also facilitate extrapolation to the long-term period (1909-66) of total sediment discharge and sand discharge computed from the occasional total sediment discharge measurements. Hence, the accuracy of total sediment discharge determinations is considered good.

The opportunity afforded at Sacramento for accurate determination of sand discharge, in suspension and in the bed, is fortunate. The Sacramento River transports most of the water and sediment to San Francisco Bay, and the accurate determination of sand discharge at this station increases significantly the overall accuracy of the prediction of sediment discharge to the Sacramento-San Joaquin Delta and to the bays.

Unsampled sediment discharge

Values of total sediment discharge do not correlate well with velocity or streamflow because total sediment discharge includes fine-material discharge that is influenced by many variables not readily predictable. Direct computation of daily total sediment discharge would require a total sediment discharge determination each time a suspended-sediment sample is obtained. As frequent measurements of total sediment discharge are not economically feasible, an indirect method for determining total sediment discharge was substituted. The method used for the Sacramento River requires an accurate record of sampled suspended sediment and a reasonably adequate correlation of unsampled sediment discharge to some predictable variable, which in this instance is stream velocity.

Unsampled discharge is the sediment transported in the zone from the streambed to 0.3-0.5 ft above the streambed, and is the material referred to by Colby (1957) as unmeasured load. The unsampled discharge includes the material, generally sand-size particles (>0.062 mm) for the Sacramento River at Sacramento, transported in suspension in this zone plus the material transported generally in contact with the streambed (bedload). Material smaller than sand size is not included in the unsampled discharge at Sacramento because this material is uniformly distributed from the streambed to the surface and hence is included in the computation of sampled suspended-sediment discharge.

Values of unsampled sediment discharge from each determination of total sediment discharge plus values of average suspended-sediment discharge, from figure 8, provide the basis for development of the relation between total sediment discharge and streamflow shown in figure 12. Average daily values of total sediment discharge are given in table 11.

Total sand discharge.--Sand is a significant part of the sediment transported by the Sacramento River. The quantity of sand discharge therefore is an important factor when evaluating the effect of sediment on delta development, computing the quantity of sediment deposited in the delta or moving into the bays, and determining the average unit weight, and hence the volume, of the deposited sediment in the delta and bays.

Because most of the sand transported, as suspended sediment as well as bedload, is derived from the bed, and because a large quantity of bed material is available for transport from the channel and the basin upstream, the rate of sand discharge should continue undiminished for a considerable period. Transport of sand is a function of streamflow; therefore, the quantity of sand transported at various flow rates imposed by regulation after 1966 can readily be calculated from the relations shown in figures 10 and 12. Total sand discharge for 1957-66 averaged 4,610 ton/d, the sum of suspended sand and unsampled discharge, 52 percent of the total sediment discharge of the Sacramento River at Sacramento (table 11).

Bedload.--The bedload, or that part of the discharge that moves in almost continuous contact with the bed, was estimated by tractive force equations to be 120 ton/d, only 1.4 percent of the total sediment discharge. Bedload therefore is an insignificant part of the sediment discharge of the Sacramento River, although unsampled discharge and bed-material discharge, which are derived from the bed, are a significant part of total sediment discharge.

Yolo Bypass near Woodland

Part of the floodflows from the Sacramento River are diverted to the Yolo Bypass through the Fremont Weir upstream from the confluence of the Sacramento and Feather Rivers. Some flow originating on the west side of the Sacramento Valley enters the bypass directly and does not reach the gaging station at Sacramento. The quantity of this flow is determined at the gaging station on Yolo Bypass near Woodland (11453000, fig. 3, table 8).

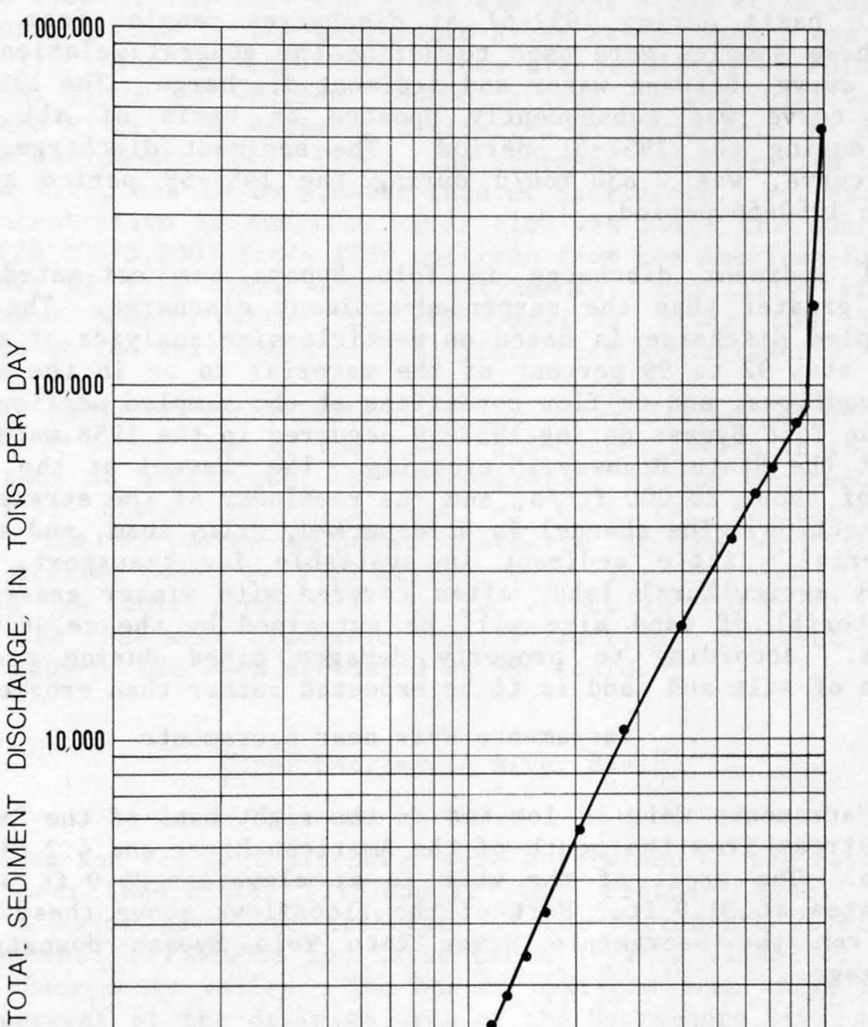

FIGURE 12.--Relation between total sediment discharge and streamflow, Sacramento River at Sacramento, 1957-66.

Samples of suspended sediment were collected at the gage near Woodland on a periodic basis during 1957-61 at discharges ranging from 360 to 124,000 ft^3/s. These samples were used to define the general relation, or sediment-transport curve, between water and sediment discharge. The 1957-59 sediment-transport curve was subsequently updated on basis of all sediment data obtained during the 1957-61 period. The sediment discharge, based on the adjusted curve, was 2,830 ton/d during the 1957-59 period and 1,230 ton/d during the 1960-66 period.

Total sediment discharge in Yolo Bypass was estimated to be about 2 percent greater than the suspended-sediment discharge. The low value for the unsampled discharge is based on particle-size analyses of suspended sediment that show 92 to 99 percent of the material to be in the silt-clay range during floodflows, and on flow conditions at the sampled section. Most of the flow in the Yolo Bypass during 1957-59 occurred in the 1958 water year and was sampled at the State Highway 16 crossing. The channel at the crossing has a capacity of about 20,000 ft^3/s, and the remainder of the streamflow is in the overflow section. The channel is hard-packed, silty loam, and except for some fine material, little sediment is available for transport. The overflow section is agricultural land, often covered with winter grasses, and little coarse material of sand size will be entrained by the relatively low water velocities. According to property damages cited during previous floods, deposition of silt and sand is to be expected rather than erosion.

Sacramento Weir near Sacramento

The Sacramento Weir is located on the right bank of the Sacramento River 3.2 mi upstream from the mouth of the American River and 4.2 mi upstream from Sacramento. The crest of the weir is at elevation 25.0 ft and the top of movable gates at 31.0 ft. Part of the floodflows above these elevations are spilled from the Sacramento River into Yolo Bypass downstream from the Woodland gage.

The suspended-sediment discharge diverted over Sacramento Weir during 1957-66 was estimated to be 1.64 million tons, assuming daily concentrations at the weir numerically equal to those at Sacramento. The estimated diversion in December 1964 was 1.3 million tons. The concentration of suspended material bypassed, however, differs from that at Sacramento because flow siphoned over the weir into the bypass is from the top part of the flow, perpendicular to the flow of the river. In addition, Sacramento River flow downstream is diluted by American River flow, which enters the Sacramento River between the weir and the gage at Sacramento.

The relation of concentration in the upper 20 ft of flow to concentration in the entire flow was determined frequently at Sacramento during 1960-64 for flows deeper than 20 ft. The average annual ratio of the concentration of samples integrated through the upper 20 ft of flow to those from the full depth of flow ranged from 0.76 to 0.90, and the ratio of concentration for depths of flow greater than 30 ft averaged about 0.72. Because the depth of flow at Sacramento is greater than 30 ft during spills to the bypass, the sediment concentration in the water siphoned from the Sacramento River to the bypass is assumed to be about 70 percent of that in river water.

Average flow of the American River was about 3,200 ft^3/s during 1957-66. The corresponding flow in the Sacramento River at Sacramento was 20,900 ft^3/s (tables 10, 11). The American River flows are regulated by Folsom Lake, and during floods, flows and sediment concentrations are low relative to those of the Sacramento River. As sediment discharged at Sacramento is derived principally from Sacramento River flows, the sediment concentration upstream from the American River has to be greater than at Sacramento. For example, if the sediment concentration in American River flow was zero, the concentration in the 17,700 (20,900-3,200) ft^3/s flow upstream from the American River would be 20,900/17,700, or 1.18 times that at Sacramento. Similarly, if the average daily sediment concentration in the American River was 50 mg/L, the concentration at the weir would be 1.11 times that at Sacramento.

Assuming sediment concentration of the water discharged over Sacramento Weir to be 0.70 times that of the river, and concentration in the river to be 1.11 times that at Sacramento, the concentration of the bypassed water would be 0.70×1.11 times, or 78 percent of that for Sacramento River at Sacramento. The estimated sediment discharge at the weir then would be 0.78×1.64 million tons, or 1.28 million tons, for 1957-66. This value has been adopted for this report; it is equivalent to 350 ton/d, as shown in table 30 in the "Sediment Discharge Summary" section. Sediment discharge for 1909-59 and 1909-66 has been estimated as 330 ton/d.

Upper Sacramento River Basin

Streamflow and sediment discharge were determined on the main stem of the Sacramento near Red Bluff (11378500), the Feather River at Oroville (11407000), a major east-side tributary of the Sacramento River, and Thomes Creek at Paskenta (11382000) and Cache Creek at Yolo (1145200), on the west side of the Sacramento Valley. The basins upstream from these stations constitute 51 percent of the drainage area of the Sacramento River basin. Sediment data were not obtained on the Yuba River and the American River, both major tributaries on the east side of the Sacramento Valley. The drainage areas, streamflow, and sediment discharge at selected stations in the upper Sacramento River basin are summarized in table 13.

Sediment sampling began at Thomes Creek in October 1962. During the period 1963-66, a total of over 12,000,000 tons of sediment was discharged from the 194-square-mile basin. This is an average daily discharge of 8,300 tons or 15,600 $(ton/mi^2)/yr$. The rate is high because streamflow during 1965 was considerably greater than the long-term average and unduly influenced the 4-year average. During 1965 the sediment discharge was almost 11,000,000 tons, or 56,000 ton/mi^2, of which over 5,000,000 tons moved in 1 day, December 22, 1964. The long-term average based on water-discharge values for the period 1921-64 and sediment values for the period 1963-64 is 1,660 ton/d or 3,120 $(ton/mi^2)/yr$.

TABLE 13. - Summary of average daily streamflow and sediment discharge and drainage areas at selected stations, upper Sacramento River basin, 1957-66

Station	Drainage area		Water discharge		Suspended sediment	
	Square miles	Percentage of total	Cubic feet per second	Percentage of total	Tons per day	Percentage of total
11378500 Sacramento River at Red Bluff	9,022	36.4	11,413	47.4	4,100	43.4
11382000 Thomes Creek at Paskenta	194	.8	264	1.1	[1]1,660	17.6
11407000 Feather River at Oroville	3,624	14.6	5,325	22.1	2,790	29.5
11421000 Yuba River near Marysville	1,339	5.4	2,500	10.4	--	--
11426000 Sacramento Weir spill to Yolo Bypass	--	--	171	--	350	--
11446500 American River at Fair Oaks	1,888	7.6	3,200	13.3	--	--
11447500 Sacramento River at Sacramento	23,530	95.1	20,902	--	7,400	--
11452500 Cache Creek at Yolo	[2]611	2.5	[3]566	2.4	[1]1,570	16.6
11453000 Yolo Bypass near Woodland	1,225	--	3,002	--	1,700	--
Total, Sacramento River basin	24,755	100	24,075	100	9,450	100

[1]1921-64 (adjusted).

[2]Contributing area. Does not include 528 mi^2 upstream from Cache Creek near Lower Lake

[3]1960-63.

Cache Creek, which enters Yolo Bypass upstream from the Woodland gage, is partly regulated by Clear Lake. Lustig and Busch (1967) reported the suspended-sediment discharge at Cache Creek at Yolo for the 4-year period 1960-63 to be 2,132,000 tons (1,460 ton/d). Before flowing into the bypass, flow from Cache Creek at Yolo enters a settling basin where an estimated 50-60 percent of the total sediment is deposited.

Major tributaries on the east side of the Sacramento Valley are the Yuba River and the American River. Sediment data are not available for these two streams. The Yuba River is regulated by several reservoirs and has many diversions of water for power and irrigation. The drainage area at the station near Marysville (11421000) is 1,339 mi^2, about 6 percent of that for Sacramento River at Sacramento; 1,108 mi^2 of this basin is upstream from Englebright Dam and yields little sediment to the Sacramento River.

The American River has a drainage area of 1,943 mi^2 at Sacramento, 8 percent of that for the Sacramento River basin; but 1,888 mi^2 of the basin is regulated by Folsom and Nimbus Reservoirs and does not contribute a significant quantity of sediment to the delta.

The data in table 13 for Sacramento River at Red Bluff, Thomes Creek at Paskenta, Feather River at Oroville, and Cache Creek at Yolo indicate that the combined water discharge is about 73 percent and the combined sediment discharge about 107 percent of the water and sediment discharged downstream in the Sacramento River at Sacramento (11447500), in Yolo Bypass (11453000), and over Sacramento Weir (11426000). The total quantities of sediment transported to the valley lands and channels thus may exceed substantially the quantities discharged downstream. It might be inferred, therefore, that the area downstream from Red Bluff and Oroville to Sacramento probably still is an aggrading area. The factors affecting sediment transport and deposition, described in the "Physiography" section, although modified by flood control and reclamation works, still exert considerable influence on transportation and deposition of sediment in the Sacramento Valley.

San Joaquin River Basin

The San Joaquin River drains the southern part of the Central Valley. The drainage area upstream from the confluence with the Sacramento River is 19,096 mi^2, or 39 percent of the contributing area of the San Francisco Bay system (table 3). Together, the Sacramento and San Joaquin basins comprise about 92 percent of the San Francisco Bay drainage area.

Streamflow in the San Joaquin River basin is regulated by numerous lakes, storage reservoirs, power developments, ground-water withdrawals, and diversions for irrigation; low flow consists mainly of return flow from irrigated areas. Flow of each of the major tributaries on the east side of the San Joaquin Valley is regulated by one or more dams in the foothills and mountains; flow in the valley is regulated by a complex system of irrigation dams and ditches. A major diversion, the Delta-Mendota Canal, transports water from the delta near Tracy to the Mendota Pool on the San Joaquin River to replace water previously diverted from the river. The California Aqueduct, a major feature of the California State Water Project, diverts larger quantities of water from the delta than does the Delta-Mendota Canal. Some of the water diverted by the aqueduct will remain in the San Joaquin River basin; however, large quantities of water will be diverted from the basin.

Sediment samples were obtained on the San Joaquin River near Vernalis, (drainage area, 13,540 mi^2), and on two major tributaries that join the San Joaquin River downstream from Vernalis, the Mokelumne River near Clements, (drainage area, 627 mi^2), and Cosumnes River at McConnell (drainage area, 724 mi^2). The combined drainage area of the three sampling stations is 14,891 mi^2, 78 percent of that for the San Joaquin River basin. The quantity of sediment diverted from the delta through the Delta-Mendota Canal was determined during 1959-60 and 1963-66.

San Joaquin River near Vernalis

Suspended-sediment discharge

The sampling station San Joaquin River near Vernalis (11303500, fig. 3, table 8) is located approximately 70 river miles upstream from the confluence of the San Joaquin and Sacramento Rivers. Daily values of suspended sediment since 1957 are available for this location, and streamflow records are available for 1924 and 1929-66.

The sediment-transport curve based on 1957-66 data and points representing average values of daily sediment discharge for each of several small ranges of daily streamflow are shown in figure 13. Because daily values of sediment discharge varied considerably with streamflow, data obtained during 1957-59 were insufficient for adequate definition of a sediment-transport curve. For example, on the 6 days of the greatest streamflow during 1957-59, the discharges ranged from 38,400 to 40,900 ft^3/s, but the sediment discharge during these days ranged from 6,640 to 28,500 ton/d. The points (fig. 13) representing average values of sediment discharge indicate that the data obtained during the longer period, 1957-66, provide better definition of the average long-term relation between streamflow and sediment discharge than is shown by the 1957-59 data. The 1957-66 relation therefore is considered the better relation for use in estimating long-term sediment discharge or predicting future rates. Recomputation of the estimated sediment discharge for 1909-59 resulted in a 20 percent decrease from the value reported by Porterfield and others (1961).

The average streamflow at San Joaquin River near Vernalis during 1957-66 was significantly lower than previously reported average streamflow (1924, 1929-59), resulting in lower sediment discharge and, also, a smaller adjusted long-term flow.

The decrease in discharge, at least during the period of sediment observations, is shown by the following average discharges:

31 years (1924, 1929-59)	4,781 ft^3/s	38 years (1924, 1929-66)	4,333 ft^3/s
3 years (1957-59)	4,025 ft^3/s	10 years (1957-66)	2,850 ft^3/s

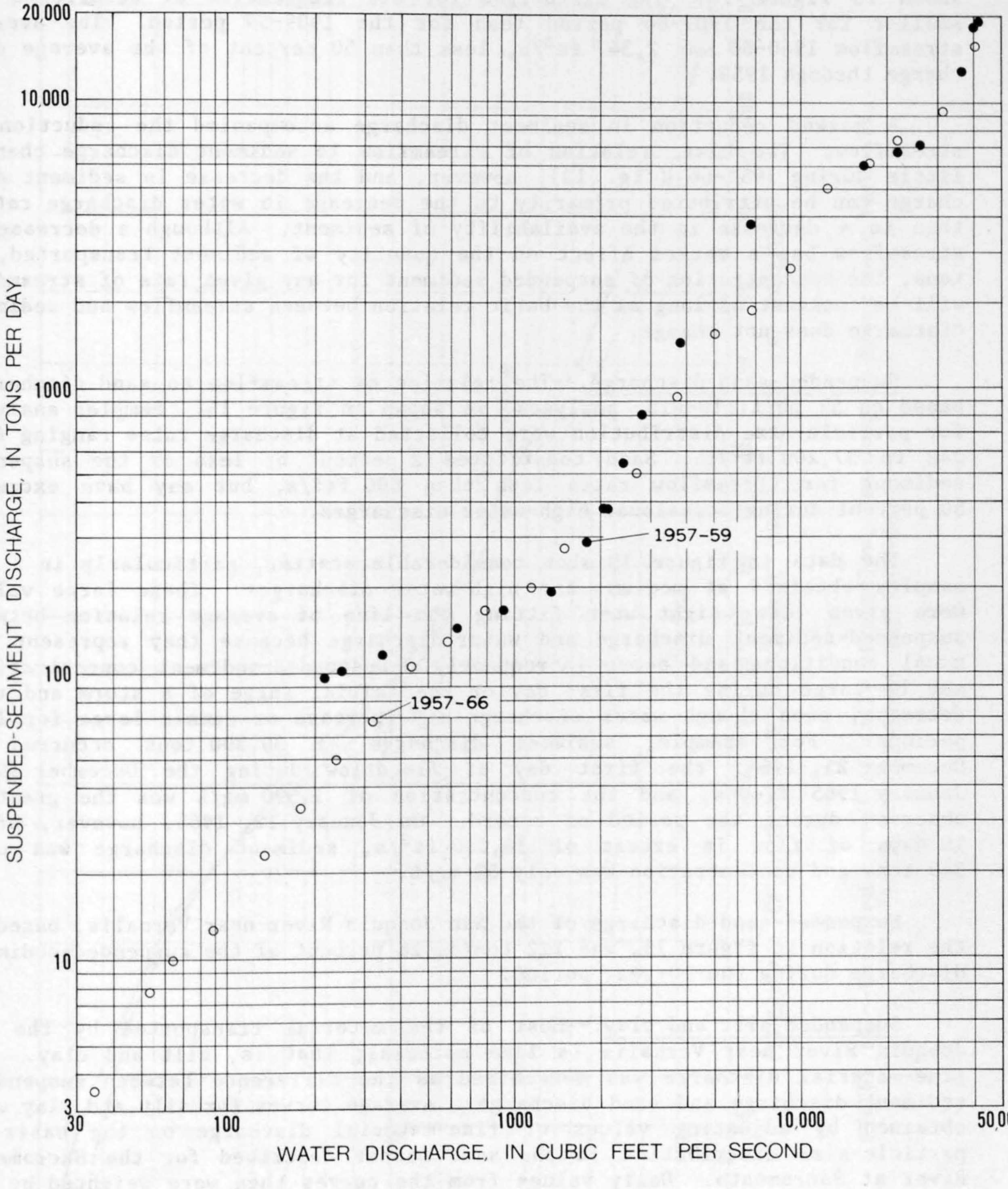

FIGURE 13.--Relation between sediment discharge and streamflow, San Joaquin River near Vernalis, 1957-59 and 1957-66.

Flow-duration curves for the adjusted periods 1909-59 and 1909-66 are shown in figure 14. The discharges for all frequencies of occurrence are smaller for the 1909-66 period than for the 1909-59 period. The average streamflow 1960-66 was 2,347 ft^3/s, less than 50 percent of the average discharge through 1959.

A marked reduction in sediment discharge accompanied the reduction in streamflow. The basic relation of streamflow to sediment discharge changed little during 1957-66 (fig. 13), however, and the decrease in sediment discharge can be attributed primarily to the decrease in water discharge rather than to a decrease in the availability of sediment. Although a decrease in streamflow has a marked effect on the quantity of sediment transported, in tons, the concentration of suspended sediment for any given rate of streamflow will be constant as long as the basic relation between streamflow and sediment discharge does not change.

Suspended-sand discharge.--The relation of streamflow to sand discharge, based on 57 particle-size analyses, is shown in figure 15. Samples analyzed for particle-size distribution were collected at discharge rates ranging from 242 to 37,200 ft^3/s. Sand constituted 2 percent or less of the suspended sediment for streamflow rates less than 500 ft^3/s, but may have exceeded 50 percent during occasional high-water discharges.

The data in figure 15 show considerable scatter, particularly in a few samples obtained at medium- and high-water discharges. These large values were given less weight when fitting the line of average relation between suspended-sediment discharge and water discharge because they represent unusual conditions and occur infrequently. Suspended-sediment concentrations may be large during the first day or the initial surge of a storm and then decrease, even though water discharge may increase or remain large for long periods. For example, sediment discharge of 30,300 tons occurred on December 25, 1964, the first day of floodflow during the December 1964-January 1965 floods, and the concentration of 1,590 mg/L was the greatest observed during the period of record. On January 12, 1965, however, after 19 days of flow in excess of 14,000 ft^3/s, sediment discharge was only 349 tons and concentration was only 68 mg/L.

Suspended-sand discharge of the San Joaquin River near Vernalis, based on the relation in figure 15, was 222 ton/d, 28 percent of the suspended-sediment discharge during the 10-year period.

Suspended silt and clay.--Most of the material transported by the San Joaquin River near Vernalis is fine material; that is, silt and clay. The fine-material discharge was determined as the difference between suspended-sediment discharge and sand discharge. Average curves for silt and clay were obtained by adjusting values of fine-material discharge on the basis of particle-size distribution in the same manner described for the Sacramento River at Sacramento. Daily values from the curves then were weighted by the frequency of occurrence by using the duration-curve method to obtain daily mean values.

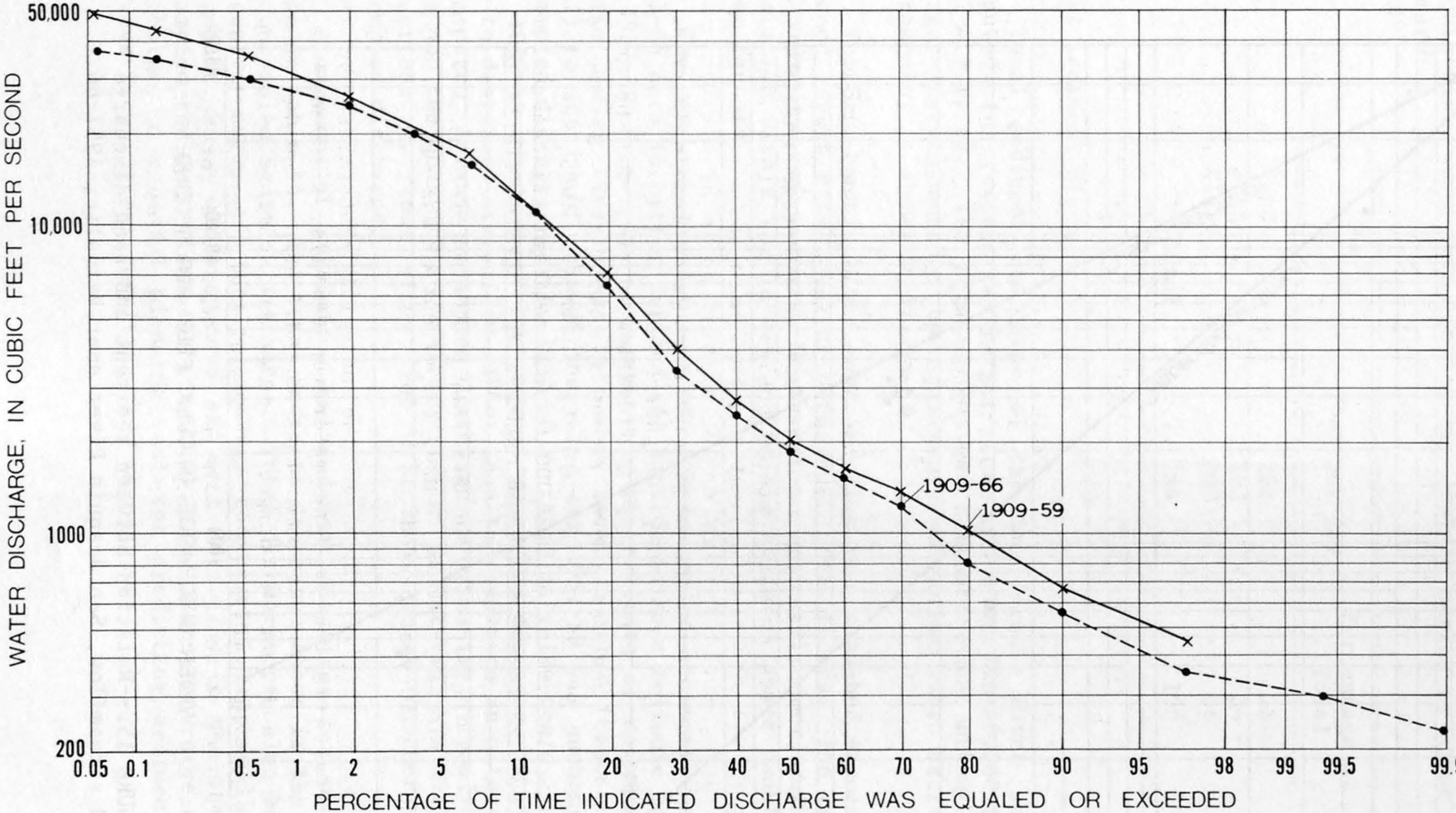

FIGURE 14.--Duration curves of daily streamflow, San Joaquin River near Vernalis, 1909-59 and 1909-66.

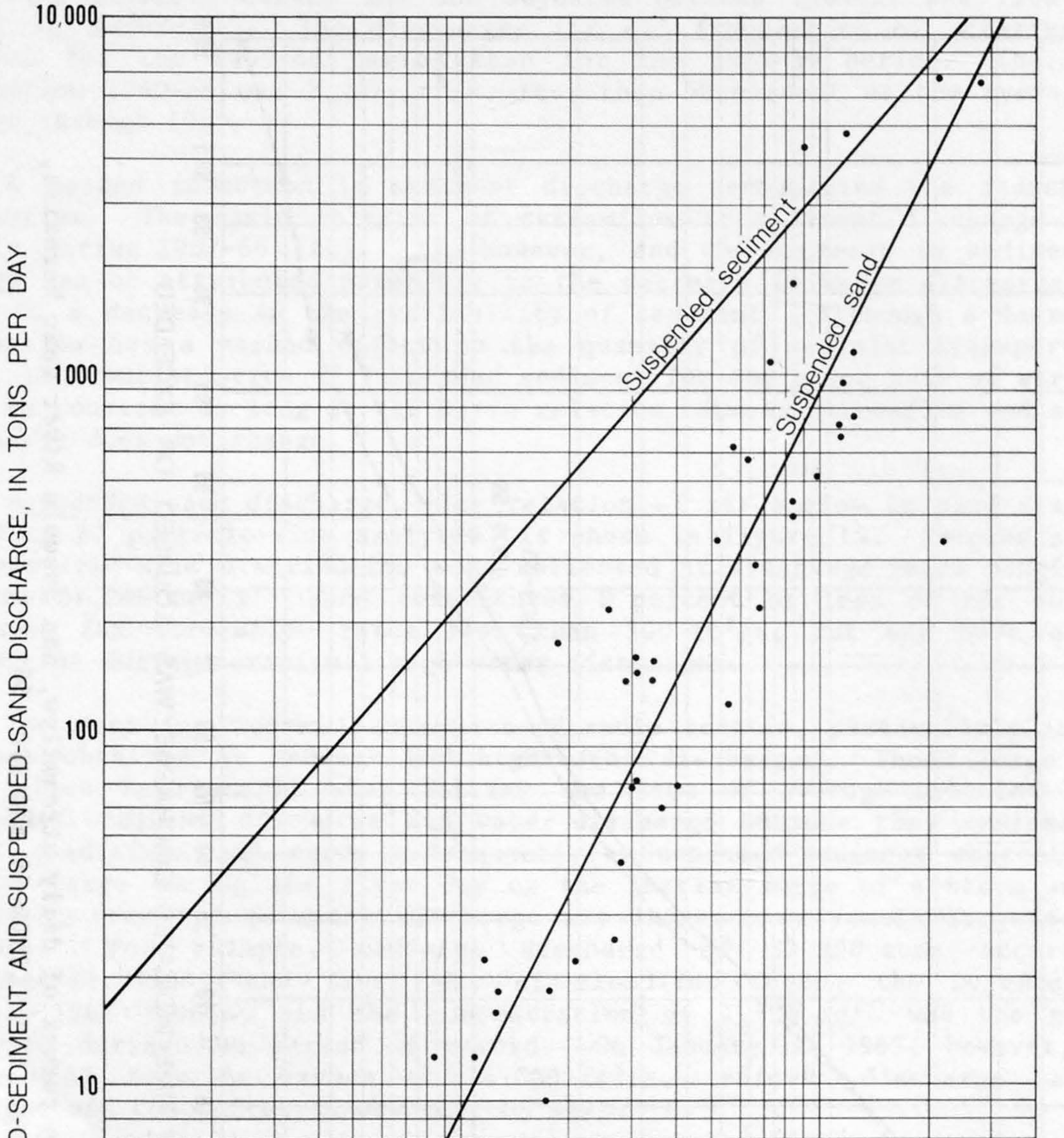

FIGURE 15.--Relation between sediment and sand discharge and streamflow, San Joaquin River near Vernalis, 1957-66.

The distribution of suspended sand, silt, and clay discharge for San Joaquin River near Vernalis for the 1957-66 period is shown by the following summary:

	Tons per day	Percentage of Total
Sand	222	28
Silt	263	34
Clay	299	38
Total..........	784	100

Total sediment discharge

Total sediment discharge of the San Joaquin River near Vernalis was computed for water discharges ranging from 290-40,000 ft^3/s (velocity, 0.82-4.7 ft/s). The relation between streamflow and unsampled sediment discharge, determined by the procedure described for Sacramento River at Sacramento, is shown in figure 16.

The San Joaquin River near Vernalis is a sand-bed stream and is confined between levees except during occasional great floods. The relations of average velocity and width to discharge are generally poor, and are affected by vegetation within the levees and on the terraces above bankful stage, and by other factors.

The revised transport curve for unsampled sediment discharge based on 1957-66 data is better defined and considered more reliable than the one based on 1957-59 data. On recomputation, the estimate of unsampled sediment discharge during 1909-59 was increased from 213 ton/d (Porterfield and others, 1961) to 266 ton/d, though the value for 1957-59 was unchanged at 204 ton/d. Unsampled discharge during 1957-66 averaged only 104 ton/d, less than one-half the 1957-59 discharge. The reduced unsampled discharge is attributed primarily to decreased streamflow rather than to reduction in material available for transport. Because unsampled discharge is primarily a function of flow variables and the quantity and characteristics of material available for transport, reductions in flows after 1966 will have caused further decreases in the unsampled discharge.

A summary of streamflow and sediment discharge for selected periods is shown in table 14. The total sediment discharge shown is the sum of suspended and unsampled sediment discharge. Total discharge can also be computed from a transport curve of total discharge constructed graphically by adding the transport curve for suspended sediment (fig. 13) to the transport curve for unsampled sediment discharge (fig. 16). The transport curve of total sediment discharge is a useful planning tool for predicting sediment discharges for various flow regimes resulting from regulation.

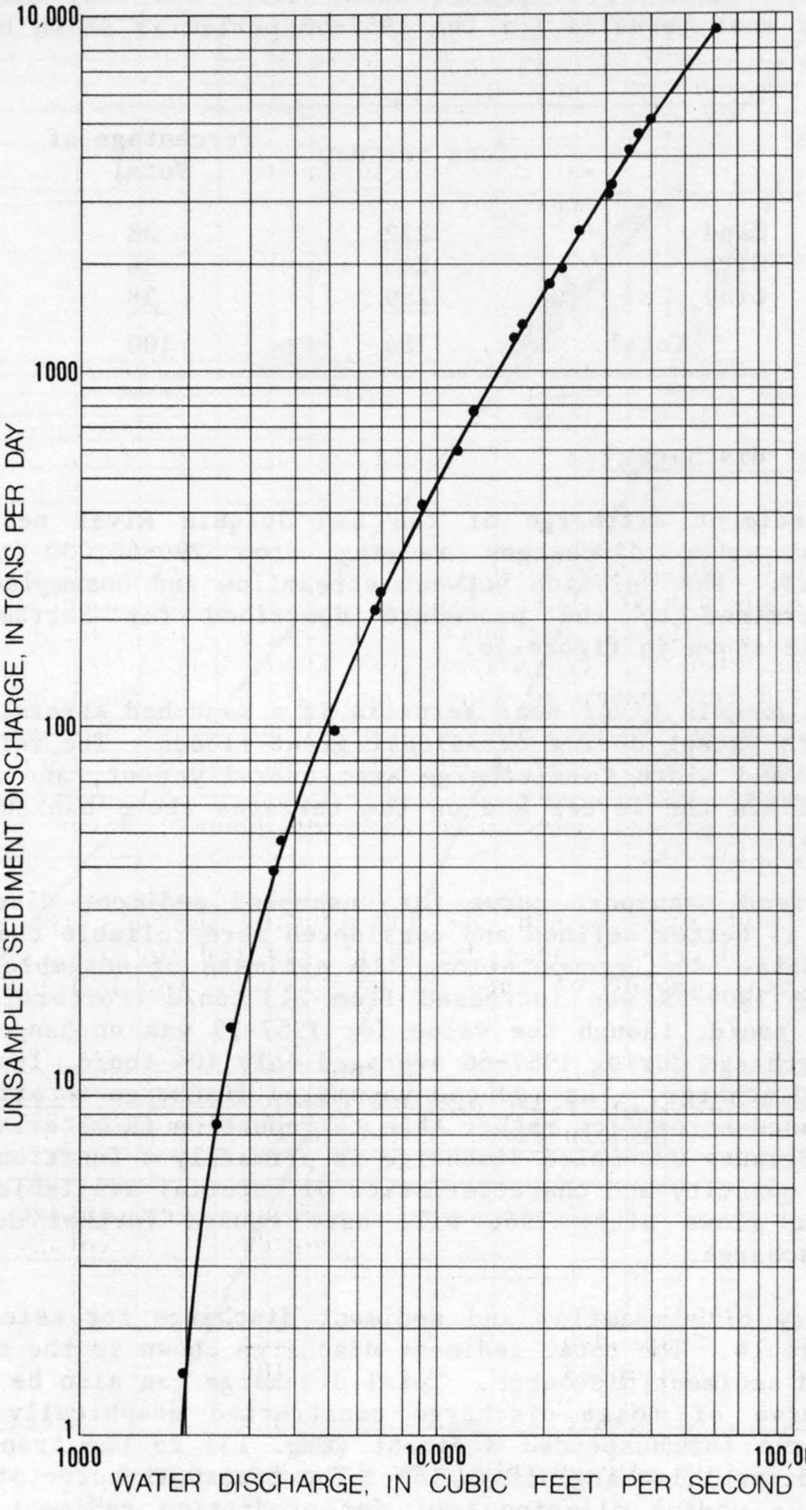

FIGURE 16.--Relation between unsampled sediment discharge and streamflow, San Joaquin River near Vernalis, 1957-66.

TABLE 14. - Summary of average daily streamflow and total sediment discharge, San Joaquin River near Vernalis, 1957-59, 1957-66, 1909-59, and 1909-66

Period	Water discharge (ft^3/s)	Sediment discharge (ton/d)		
		Suspended	Unsampled	Total
1957-59	4,025	1,230	204	1,430
1957-66	2,850	784	104	888
1909-59	4,870	[1]1,460	[1]266	1,730
1909-66	4,450	1,310	230	1,540

[1]Revised from Porterfield and others (1961).

Total sand discharge.--Sand is a minor fraction of material transported by the San Joaquin River near Vernalis. Very little sand is transported in suspension at streamflows less than 200 ft^3/s, and only about 1 percent of the material transported at streamflows less than 1,300 ft^3/s is sand. The suspended sand and the unsampled sand discharge is transported primarily during high water discharge; 69 percent is transported during discharges greater than 11,000 ft^3/s in about 5 percent of the time; and 48 percent is transported during discharges greater than 20,000 ft^3/s in about 2 percent of the time. The average daily sand discharge for San Joaquin River near Vernalis is summarized in table 15.

Because most of the sand is transported during high discharges, any regulation that decreases peak discharge and reduces average flow will also reduce the total amount of sand transported by the San Joaquin River near Vernalis.

TABLE 15. - Average daily sand discharge, San Joaquin River near Vernalis, 1957-66

	Tons per day	Percentage of total
Sand:		
Suspended	222	25
Unsampled	104	12
Total.................	326	37
Total suspended-sediment discharge.................	888	100

Cosumnes River Basin

The Cosumnes River, a tributary of the San Joaquin River, originates in the Sierra Nevada at an elevation of about 7,600 ft, flows westward to the delta, and joins the San Joaquin River about 20 mi upstream from the confluence of the San Joaquin and Sacramento Rivers.

The Cosumnes River is partly regulated by a small reservoir in the mountains (capacity, 40,570 acre-ft) and by small diversions for irrigation and domestic supply. The basin has no major storage reservoirs or regulation such as those on other major east-side tributaries of the San Joaquin River. Values of sediment yield determined for the Cosumnes River basin thus approximate the yields from east-side basins of the San Joaquin Valley prior to extensive regulation.

Sediment samples were collected on the Cosumnes River near Plymouth, at Michigan Bar, and at McConnell. The Plymouth sampling station (11334500, drainage area, 429 mi^2) is located in the foothills of the Sierra Nevada at an elevation of 580 ft, about 45 mi west of the headwaters of the Cosumnes River. The station on Cosumnes River at Michigan Bar (11335000, drainage area, 536 mi^2) is located about 10 mi west of Plymouth at an elevation of 168 ft. The station on Cosumnes River at McConnell (11336000, drainage area, 724 mi^2) is located about 19 mi southwest of Michigan Bar at an elevation of about 30 ft.

Water discharge

Average daily streamflow in the Cosumnes River basin was less during 1957-66 than during the period 1909-66. The values at Michigan Bar for several selected periods are shown in table 16. Average streamflow and the frequency of occurrence of floods during the 1957-59 sampling period more nearly agree with the long-term average streamflow and flood frequency than do those during the 1957-66 period. Estimates of long-term sediment discharge based on 1957-59 streamflow records therefore are considered satisfactory.

TABLE 16. - Average daily streamflow during selected periods, Cosumnes River at Michigan Bar

Period	Water discharge (ft^3/s)
1909-56	495
1909-59	494
1909-66	478
1957-59	465
1957-66	393
1960-66	362

Suspended-sediment discharge

Sediment samples were collected in the Cosumnes River basin during 1957-59 on an intermittent basis, and sediment discharge was computed by the flow-duration sediment-transport method. A summary of these data is shown in table 17. Sufficient samples were obtained at Cosumnes River at McConnell to define the relation between streamflow and sediment concentration for the range of water discharge that occurred during this period; subsequent samples have verified this relation. Sediment discharge for Cosumnes River at McConnell therefore was not revised from the value originally reported (Porterfield and others, 1961). Data for Cosumnes River at Michigan Bar, however, did not adequately define the relation between streamflow and sediment discharge during 1957-59, and a new transport curve based on subsequent data was prepared for Michigan Bar. Data obtained at Cosumnes River near Plymouth, although not as complete as the data obtained at McConnell, are considered fair and provide an indication of the sediment yield from the Sierra Nevada.

Sediment yield increases downstream in the Cosumnes River basin although runoff decreases. The sediment yield of the basin above Plymouth, in the steeper forested slopes of the Sierra Nevada is 143 $(ton/mi^2)/yr$. The yield of the 97 mi^2 intervening area in the foothills between Plymouth and Michigan Bar is 342 $(ton/mi^2)/yr$, or 2.4 times the sediment yield upstream from Plymouth; and the yield downstream in the basin between Michigan Bar and McConnell is over 3 times the yield in the basin upstream from Cosumnes River near Plymouth (table 17).

Cosumnes River at Michigan Bar

Streamflow records at Michigan Bar began in 1907; sediment data collection began in 1957. Because of the long-term streamflow record, data collected at this site provide a valuable base for determining historical sediment yield and estimating the impact of future changes in streamflow on sediment transport. A summary of data for Cosumnes River at Michigan Bar for selected periods is given in tables 17 and 18.

Most of the suspended sediment was transported by large flows that occur infrequently. About 35 percent of the sediment transported during 1957-66 and 31 percent transported during 1909-66 was sand. Minor quantities of sand were transported at streamflows less than 1,200 ft^3/s. Table 19 shows the water and sediment discharge that occurred during selected time intervals; 35 percent of the suspended sediment was transported by floodflows that occurred in only 0.1 percent of the time during 1909-66, and 99 percent of the suspended sediment and all the suspended sand were transported in 15 percent of the time. Percentages of streamflow and sediment discharge during 1909-66 (table 19) are reasonably comparable with those occurring during both 1909-59 and 1957-59 (Porterfield and others, 1961).

TABLE 17. - Streamflow and sediment data, Cosumnes River basin, 1957-59 and 1909-59

Station	Drainage area (mi^2)	Elevation (ft)	Water discharge average daily (ft^3/s)		Suspended sediment: Concentration (mg/L)	Suspended sediment: Average daily (ton/d)		Suspended sediment: Annual yield (ton/mi^2)	
			1957-59	1909-59	1957-59	1957-59	[1]1909-59	1957-59	1909-59
Cosumnes River near Plymouth	439	580	428	[1]431	149	172	171	143	142
Intervening area	97	--	37	--	911	91	--	342	--
Cosumnes River at Michigan Bar	536	168	465	494	209	[2]263	[2]273	179	186
Intervening area	188	--	64	--	1,300	224	--	437	--
Cosumnes River at McConnell	724	30	529	[1]532	341	487	439	246	221

[1]Adjusted.

[2]Revised from Porterfield and others (1961) on basis of 1957-66 data that includes daily values during 1963-66.

TABLE 18. - Summary of average daily streamflow and sediment discharge and sediment yield at selected sites in Cosumnes River basin, 1957-59, 1957-66, 1909-59, and 1909-66

Period	Water discharge (ft^3/s)	Sediment discharge (ton/d)		Annual suspended-sediment yield (ton/mi^2)	Suspended sand		Total sand	
		Suspended	Total		Tons per day	Percentage of suspended-sediment discharge	Tons per day	Percentage of total sediment discharge
Cosumnes River at Michigan Bar								
1957-66	393	307		209	107	35		
1909-66	478	256		174	80	31		
Cosumnes River at McConnell								
1957-59	529	487	606	246	252	52	371	61
1957-66	411	376	463	190	184	49	271	59
1909-59	532	439	546	221	241	55	348	44
1909-66	512	412	519	208	215	52	322	62

TABLE 19. - Percentage of streamflow and sediment discharge that occurred during selected time intervals at selected sites in Cosumnes River basin, 1957-66 and 1909-66

Discharge	Period	Time (percent)			
		0.1	1.0	5.0	15
Cosumnes River at Michigan Bar					
Water	1957-66	7	23	46	72
	1909-66	4	18	40	67
Suspended sediment	1957-66	53	93	98	99
	1909-66	35	87	96	99
Suspended sand	1957-66	62	97	100	--
	1909-66	46	93	99	100
Cosumnes River at McConnell					
Water	1957-66	5	25	52	78
	1909-66	4	20	44	70
Suspended sediment	1957-66	19	57	85	96
	1909-66	15	51	75	91
Suspended sand	1957-66	19	61	85	96
	1909-66	15	52	77	92
Unmeasured sediment	1957-66	5	44	90	96
	1909-66	4	37	82	97
Total sediment	1957-66	16	55	86	97
	1909-66	13	48	77	92

The periodic data used to determine the 1957-59 sediment discharge values were not defined above 6,300 ft^3/s. Daily values available for 1963-66 improved the definition of the high end of the streamflow-sediment relation curve. Recomputation of the 1957-59 sediment discharge resulted in increase in average daily sediment discharge from 75 to 263 ton/d (table 17), and an increase in corresponding values for 1909-59 from 77 to 273 ton/d.

Cosumnes River at McConnell

Suspended-sediment samples were obtained at Cosumnes River at McConnell on an infrequent basis during 1957-66. Sediment discharge was computed by the sediment-transport, flow-duration curve method. The transport curve is well defined and is based on samples collected at flows ranging from 2 to 32,000 ft^3/s. A summary of streamflow and sediment data is given in table 18.

As at Michigan Bar, average streamflow of Cosumnes River at McConnell was less during 1957-66 than during 1957-59. Sediment discharge, however, was greater upstream at Michigan Bar during 1957-66 than 1957-59. The increase in sediment discharge during a period of lesser streamflow at Michigan Bar is attributable to the distribution and duration of floodflow and to the transport of suspended sediment in the Cosumnes River basin, principally during the peak discharges. In April 1958, the peak discharge and daily mean water discharges were greater at McConnell than at Michigan Bar; but in December 1964, greater flows occurred at Michigan Bar. The decrease in sediment discharge downstream was partly due to attenuation of flood peaks downstream from Michigan Bar. Flood peaks were reduced because of channel overflow between Michigan Bar and McConnell. Floodwater inundated about 17,600 acres below Michigan Bar station to depths as great as 20 ft in low areas and remained on the land for periods ranging from 1 to 30 days (U.S. Army Corps of Engineers, 1965, p. A-79). Deposition of sediment in the flooded areas reduced sediment discharge downstream. The change in sediment transport characteristics in the downstream direction is illustrated by data for Michigan Bar and McConnell (table 19), which indicate that during 1957-66, 93 percent of the suspended sediment was transported in 1 percent of the time at Michigan Bar as compared to 57 percent at McConnell.

The quantity of sediment transported by floodflows at Cosumnes River at McConnell is given in table 18. Table 19 shows that for 1957-66, 57 percent of the suspended sediment was transported by 25 percent of the water in 1 percent of the time, and 97 percent of all sediment was transported by flows that occur only 15 percent of the time.

Sediment data obtained in the Cosumnes River basin do not indicate any significant change from 1957-59 in the water-sediment discharge relation during 1957-66. Changes in sediment transport therefore are attributed primarily to changes in magnitude, duration, and frequency of floodflows. Any change in reclamation, flood control, diversions, and land use that affects the duration, magnitude, and frequency of floodflows therefore could alter the quantity of sediment transported by the Cosumnes River. As an example, the annual discharges at Michigan Bar in 1958 and 1964 were nearly equal; but, owing to the greater momentary and daily mean discharge in December 1964 than in April 1958, sediment discharge in 1964 was more than 1.5 times that in 1958.

Total sediment discharge.--Total sediment transport was computed for Cosumnes River at McConnell by techniques similar to those described for the Sacramento and San Joaquin rivers. The relation developed during the 1957-59 study (Porterfield and others, 1961) between total sediment discharge and streamflow was not revised and was used to compute the total sediment discharge for the 1957-66 period.

The ratio of total discharge to suspended discharge at McConnell is greater than that for Sacramento River at Sacramento or San Joaquin River near Vernalis. The greater percentage of unsampled discharge may be due to the channel condition at the gage. The river is confined most of the time to a narrow, sand-bed channel about 100 ft wide. Overflow sections at the gage, however, are stable and covered with grass, and contribute little if any sediment to the stream. Because of reduced flow velocities in the overflow section, the proportion of sand transported in suspension or in the unsampled zone is probably less in the overflow section than in the main channel.

Sand comprises 49 percent of the suspended material transported by the Cosumnes River at McConnell, 59 percent of the total discharge during the period 1957-66, and about 62 percent of the material transported during 1909-66 (table 18). Because most sand is transported during periods of high flow, any reduction in quantity, duration, or frequency of peak discharges will reduce the quantity of sand transported to the delta.

Delta-Mendota Canal

The Delta-Mendota Canal, part of the Central Valley Project, conveys water into the Mendota Pool on the San Joaquin River. Water is diverted into Delta-Mendota Canal from the Sacramento-San Joaquin Delta by way of Old River and a dredged channel to Tracy pumping plant where it is lifted about 200 ft into the canal.

The discharge of the canal, computed from records of pump operation, averaged 1,592 ft^3/s for the period of record June 1951-September 1966. The maximum daily discharge was 4,934 ft^3/s, and no flow occurred many days most years. The annual streamflow and sediment discharge during the 5 years that sediment samples were collected are shown in table 20. The numerical averages of the percentage of sand, silt, and clay fraction for particle-size analyses, and the annual sand discharge are also shown in table 20. Sand transported in the canal is very fine and amounts to only about 6 percent of the total sediment discharge. Most of the material transported, about 60 percent, is in the clay size range; the remainder is silt-size material.

TABLE 20. - Streamflow and suspended-sediment data, Delta-Mendota Canal below Tracy pumping plant near Tracy, 1959-60 and 1963-66

Period	Water discharge (cfs-days)	Suspended sediment discharge (tons)	Particle-size distribution (percentage of size indicated in millimeters)			Sand discharge (tons)
			<0.004	0.004-0.062	>0.062	
July 1959-June 1960	693,354	161,556	63	36	1	3,700
1963	677,389	172,281	--	--	3	9,200
1964	830,421	198,758	63	31	6	15,500
1965	741,926	208,960	--	--	12	11,500
1966	806,369	194,067	--	--	4	16,100
Total	3,749,459	935,622	--	--	--	56,000
Average daily	2,052	512	--	--	--	------

During the period of record (table 20), 1,237,316 tons of suspended sediment were transported to the delta by the San Joaquin River near Vernalis. During the same period, 935,622 tons of sediment, about 76 percent of the amount at Vernalis, were pumped from the delta. Some of this material settles and is dredged from the canal, and some is returned to the San Joaquin River basin.

Mokelumne River Basin

The Mokelumne River rises in the Sierra Nevada and flows westward to the delta where it joins the San Joaquin River. Natural flow of the Mokelumne River has been regulated by Salt Springs Reservoir (drainage area, 169 mi^2) since 1931; Pardee Reservoir (drainage area, 578 mi^2) since 1929; Camanche Reservoir (drainage area, 621 mi^2), since December 1963, and by several smaller reservoirs, diversions, and powerplants.

Sediment samples were collected from 1957 to 1966 at the gage at Mokelumne River below Camanche Dam (11323500, fig. 3, table 8), 1.0 mi downstream from the Camanche Dam site. The streamflow-sediment discharge relation is affected by reservoir storage and regulation and was modified further on completion of Camanche Dam in 1963. Most of the sediment eroded from the basin upstream from the large reservoirs is deposited in the reservoirs. Data on streamflow and suspended-sediment discharge for selected periods are given in table 21. Construction work at Camanche Dam affected the relation of streamflow and sediment concentration. Sediment discharge for a given water discharge was generally higher during the construction period than prior to construction. Since completion of Camanche Dam, average sediment concentrations for a given discharge were less than those prior to 1961.

Samples obtained during 1957-61 are representative of the sediment yield of the unregulated area (49 mi^2) between Pardee Reservoir and the gage, plus sediment passed through the reservoir, and sediment eroded from the banks and bed of the stream by water released from Pardee Reservoir. If all sediment transported by Mokelumne River at Clements during 1957-61 is assumed to have come from the basin downstream from Pardee Reservoir, the sediment yield of the unregulated basin would be 260 $(ton/mi^2)/yr$ (table 21). This value, equivalent to an average daily suspended-sediment discharge of 35 tons, was reported for the 1957-59 period (Porterfield and others, 1961).

Samples obtained during construction of Camanche Dam are not representative of past or future conditions and were not included in the updated sediment-transport curve. Samples obtained during 1964-66 reflect the trend of the future transport downstream from Camanche Dam. The transport curve based on these data is poor because of insufficient data and the poor relation between regulated flow and sediment concentration. The data indicate reduced sediment concentrations since completion of the dam; 10 mg/L for 1964-66 compared to 17 mg/L for 1957-59. Sediment discharge averaged 18 ton/d, about half of that during the period prior to regulation by Camanche Dam. If all sediment transported by Mokelumne River below Camanche Dam during 1964-66 is assumed to have come from the basin downstream from Camanche Dam, the sediment yield of the unregulated basin would be 1,100 $(ton\ mi^2)/yr$ (table 21).

TABLE 21. - Sediment and streamflow data for selected periods, Mokelumne River below Camanche Dam

Period	Drainage area, unregulated (mi^2)	Water discharges, average daily (ft^3/s)	Suspended sediment		
			Average concentration (mg/L)	Daily mean (ton/d)	Annual yield (ton/mi^2)
1957-59	49	772	17	35	260
1960-61	49	240	5	3.4	25
1962	49	536	91	131	973
1963	49	979	183	484	3,604
1964-66	6	680	10	18	1,100
1957-66	--	604	48	78	[1]862
1909-59	49	[2]821	19	43	320
1909-66	--	826	22	49	[1]417
After construction of Camanche Dam	6	826	[3]12	[3]27	--

[1]Weighted mean.
[2]Adjusted on basis of 1929-59 flow record.
[3]1909-66 flow adjusted to 1964-66 sediment transport.

The possible effect of future regulation on streamflow and sediment discharge in the Cosumnes River basin is illustrated by comparing water and sediment yield of similar foothill areas in the Cosumnes and Mokelumne River basins. Mean concentration of suspended sediment is higher, although streamflow is less, in the intermediate basin between Cosumnes River near Plymouth and at Michigan Bar than in the Mokelumne River downstream from Camanche Dam. Regulation affects sediment transport by attenuating peak flows which erode and transport most sediment and by trapping sediment in the reservoirs. Attenuation of Mokelumne River peak flows is illustrated in the flow-duration curves (fig. 17) for three periods of flow; unregulated (1905-28), regulated by Pardee Reservoir (1929-59), and almost completely regulated by Camanche Dam (since 1964). Peak flows were greater and occurred over a greater percentage of time during 1905-28 than during the periods regulated by Pardee and Camanche Reservoirs. The maximum discharge during 1964-66 did not exceed 3,000 ft^3/s, compared to 23,000 ft^3/s that occurred in 1929-59; yet the mean and median flows were 84 and 79 percent, respectively, of those during 1929-59.

Sediment discharge and concentration of suspended sediment in the Mokelumne River are less since regulation began (table 21). If, however, the sediment discharge at the gage is assumed to come from the 6-square-mile basin between Camanche Dam and the gage, then the rate for this basin would be 1,100 (ton/mi^2)/yr, a greater yield from the basin downstream from Camanche Dam than from the 49-square-mile basin downstream from Pardee Reservoir. Part of this larger yield may be attributed to material eroded from the bed and banks of the channel by water released from the reservoir. Erosion downstream from the dam should decrease as the channel reaches equilibrium with the flow regime imposed by regulation.

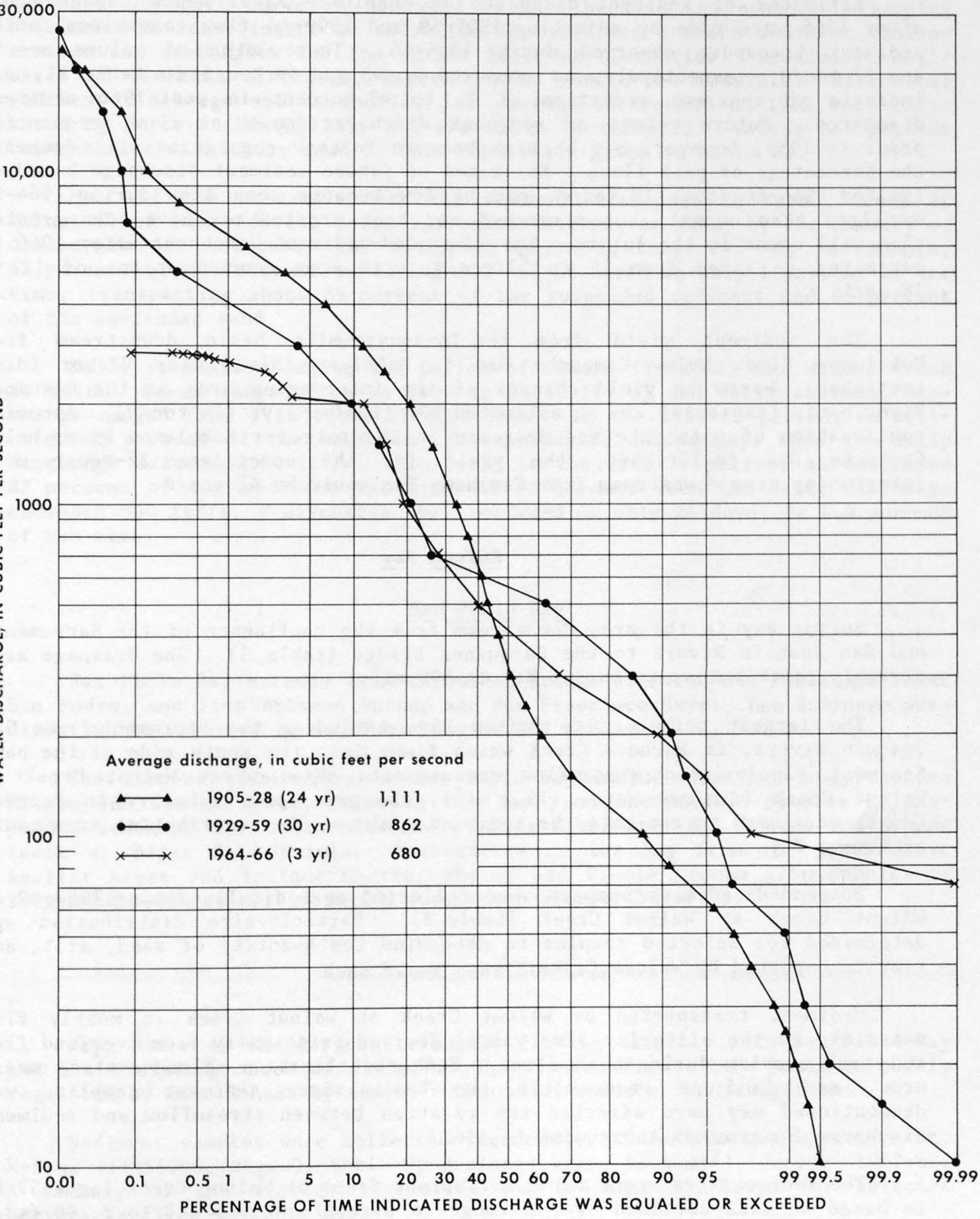

FIGURE 17.--Duration curves of daily streamflow, Mokelumne River below Camanche Dam, 1905-28, 1929-59, and 1964-66.

Estimates of sediment discharge at Mokelumne River below Camanche Dam after 1966 were made by adjusting 1909-59 and 1909-66 flow conditions to the sediment transport observed during 1964-66. These adjusted values are 28 and 27 ton/d, respectively, as compared to 43 and 49 ton/d in table 21, and indicate an apparent reduction of 35 to 45 percent in post-1966 sediment discharge. Future values of sediment discharge based on flow frequencies prior to 1959, however, may be high because further regulation will decrease the percentage of peak flows. Estimates of future sediment discharge based on limited 1964-66 data, 18 ton/d, may be low because mean flow during 1964-66 was less than normal, but streambed and bank erosion may have been greater than will occur in the future. The suspended-sediment discharge after 1966 is estimated to range from 18 to 27 ton/d, with mean concentrations of 12 to 18 mg/L.

The sediment yield from the 16-square-mile basin downstream from Mokelumne River below Camanche Dam to Mokelumne River near Victor (discontinued), based on yield changes of the intervening area in the Cosumnes River basin (table 17), is an estimated 320 (ton/mi^2)/yr (14 ton/d). Assuming continuation of this rate and decrease in the rate for Mokelumne River below Camanche Dam to 27 ton/d, the yield for the unregulated 22-square-mile intervening area downstream from Camanche Dam would be 41 ton/d.

Suisun Bay

Suisun Bay is the area downstream from the confluence of the Sacramento and San Joaquin Rivers to the Carquinez bridge (table 3). The drainage area directly contributory to Suisun Bay is 595 mi^2.

The largest tributary to Suisun Bay, excluding the Sacramento and San Joaquin Rivers, is Pacheco Creek which flows into the south side of the bay. Sediment samples and streamflow measurements obtained at Walnut Creek at Walnut Creek (drainage area, 79.2 mi^2), the principal tributary to Pacheco Creek, were used to estimate the sediment yield of the contributing area south of Suisun Bay.

Suspended-sediment samples were collected periodically during 1957-62 at Walnut Creek at Walnut Creek (table 8). Particle-size distribution was determined for selected samples to determine the quantity of sand, silt, and clay transported by Walnut Creek.

Sediment transported by Walnut Creek at Walnut Creek is mostly fine material, in the silt-clay size range, derived principally from overland flow and bank erosion during high flows. Bank stabilization, flood-control measures, and land-use changes in the basin since sediment sampling was discontinued may have affected the relation between streamflow and sediment discharge for periods subsequent to 1962.

The sediment-transport curve for Walnut Creek at Walnut Creek for 1957-62 is based on data obtained over a range in streamflow from 1.0 to 2,180 ft^3/s and represents a sediment-discharge range from 0.02 to 48,000 ton/d. The sediment-transport curve is not well defined because the number of samples obtained was insufficient to establish the relation between sediment concentration and streamflow for the entire range of streamflow. Reasonable estimates of sediment discharge, however, were considered feasible. Historical sediment discharge and streamflow for periods subsequent to 1962 were estimated by Porterfield (1972b), and are shown in table 22. Values for periods commensurate with those used in this report are given in table 23.

Most of the streamflow and the sediment transport in Walnut Creek at Walnut Creek occur during large infrequent storms, as shown by the summary of discharges for selected time intervals given in table 24. As an example, 47 percent of the streamflow during 1957-62 occurred in only 1 percent of the time, transporting about 89 percent of the suspended sediment and 96 percent of the suspended sand.

Daily streamflow during the period of record (1953-68) for Walnut Creek at Walnut Creek ranged from no flow to 5,510 ft^3/s, and daily sediment discharge ranged from 0 to about 220,000 tons. In the 1909-62 period, an estimated 85 percent of the sediment was transported during days when the daily discharge exceeded 560 ft^3/s. Similarly in the 1966-70 period, an estimated 82 percent of the sediment was transported on days when the daily discharge exceeded 560 ft^3/s, a discharge that occurred on only 24 days, or 1.4 percent of the time.

San Pablo Bay

San Pablo Bay extends from Carquinez Bridge to Point San Pablo and Point San Pedro, and lies between Suisun and San Francisco Bays. The drainage area directly contributory to San Pablo Bay is 962 mi^2.

The largest tributaries to San Pablo Bay include the Napa and Petaluma Rivers and Sonoma Creek, entering the bay from the north. Samples of suspended sediment have been obtained at Napa River near St. Helena and Sonoma Creek at Boyes Hot Springs. Tributaries to the bay from the south drain smaller areas and include Castro, Rheim, and Pinole Creeks. No samples of suspended sediment were obtained from south-side tributaries.

Napa River near St. Helena

Napa River is the largest tributary flowing directly into San Pablo Bay and has a drainage area of 333 mi^2. The natural flow of the basin is partly regulated by Lake Hennessey and by numerous diversions for irrigation.

Sediment samples were collected frequently at the station Napa near St. Helena (11456000, fig. 3, table 8; drainage area, 81.4 mi^2), during 1957-62. A summary of the average streamflow and sediment discharge for selected periods is given in table 25.

TABLE 22. - Streamflow and suspended-sediment discharge for selected periods, Walnut Creek at Walnut Creek

[From Porterfield (1972b)]

Period	Water discharge		Suspended-sediment discharge						
			Clay		Silt		Sand		Total
	Average daily (ft^3/s)	Average annual (acre-ft)	Tons per year	Percent	Tons per year	Percent	Tons per year	Percent	Tons per year
1957-62	24.5	17,750	37,300	45	22,800	27	23,100	28	83,200
1909-62	31.9	23,090	40,300	46	26,000	30	21,000	24	87,300
1963-65	36.1	26,170	[1]58,000	43	37,000	28	39,000	29	134,000
1966	16.2	11,750	--	--	--	--	653	8	8,540
1967	63.3	45,830	--	--	--	--	73,700	32	232,700
1968	16.4	11,920	--	--	--	--	2,250	16	13,800
1969	58	[1]42,220	--	--	--	--	21,400	18	120,900
1970	53	[1]38,060	--	--	--	--	44,900	25	177,000
1966-70	41	29,960	49,900	45	32,100	29	28,600	26	110,600

[1]Estimated from streamflow records Walnut Creek at Concord.

TABLE 23. - Average daily streamflow and sediment discharge and sediment yield, Walnut Creek at Walnut Creek, 1957-59, 1957-66, 1909-59, and 1909-66

Period	Water discharge (ft^3/s)	Sediment discharge (ton/d) Suspended	Sand	Annual suspended-sediment yield (ton/mi^2)
1957-59	37	406	118	1,870
1957-66	27	249	70	1,150
1909-59	31	250	60	1,150
1909-66	32	242	59	1,110

TABLE 24. - Percentage of streamflow and sediment discharge that occurred during selected time intervals, Walnut Creek at Walnut Creek, 1957-62

Discharge	Time (percent) 0.1	1.0	5.0	15
Water	--	47	76	89
Suspended sediment	--	89	99	99.9
Suspended sand	--	96	100	100

TABLE 25. - Average daily streamflow and sediment discharge and sediment yield for selected streams tributary to San Pablo Bay, 1957-59, 1957-66, 1909-59, and 1909-66

Period	Water discharge (ft^3/s)	Suspended sand (ton/d)	Suspended sediment (ton/d)	Total sediment (ton/d)	Annual suspended-sediment yield (ton/mi^2)
Napa River near St. Helena					
1957-59	91	42	131	140	587
1957-66	81	43	178	190	798
1909-59	86	42	164	174	735
1909-66	85	42	168	178	753
Sonoma Creek at Boyes Hot Springs					
1957-59	66	47	[1]85		497
1957-66	57	38	83		490
1909-59	63	41	[1]87		509
1909-66	61	40	86		506

[1]Revised from Porterfield and others (1961).

Analysis of the sediment data indicates that little change in the basic relation between streamflow and sediment discharge occurred during the sampled period, but definition of the relation was improved by data obtained subsequent to 1959. Average values of streamflow and sediment discharge for small ranges in streamflow for both the 1957-59 period, used originally to estimate the historical 1909-59 sediment discharge, and the 1957-62 period are shown in figure 18; the transport curve represents all data obtained 1957-62. Sediment discharge for 1909-59, recomputed on the basis of 1959-62 data, was 164 ton/d, or 6 percent less than the original estimate by Porterfield and others (1961).

Peak discharges that transport most of the sediment were more frequent during 1909-59 than during 1957-59. Sediment discharge was therefore larger although streamflow was less during the longer period. The relation was reversed during the 1957-66 period as a result of the high peak discharges in 1963 and 1965. Table 26 shows the percentage of streamflow, suspended sediment, and suspended sand that occurred during selected time intervals.

TABLE 26. - Percentage of streamflow and sediment discharge that occurred during selected time intervals in selected streams tributary to San Pablo Bay, 1957-59, 1957-66, and 1909-59

Discharge	Period	Time (percent) 0.1	1.0	5.0	15
		Napa River near St. Helena			
Water	1957-59	5	26	65	88
	1909-59	7	30	64	87
Suspended sediment	1957-59	17	61	95	99.5
	1909-59	34	78	96	99.7
Suspended sand	1957-59	13	59	96	99.8
	1909-59	21	72	97	99.9
		Sonoma Creek at Boyes Hot Springs			
Water	1957-59	4	28	67	91
	1957-66	7	34	66	88
	1909-59	6	30	66	87
Suspended sediment	1957-59	15	65	95	99.8
	1957-66	32	82	97	99.8
	1909-59	29	77	97	99.7
Suspended sand	1957-59	11	65	99.8	--
	1957-66	21	83	100	--
	1909-59	17	74	100	--

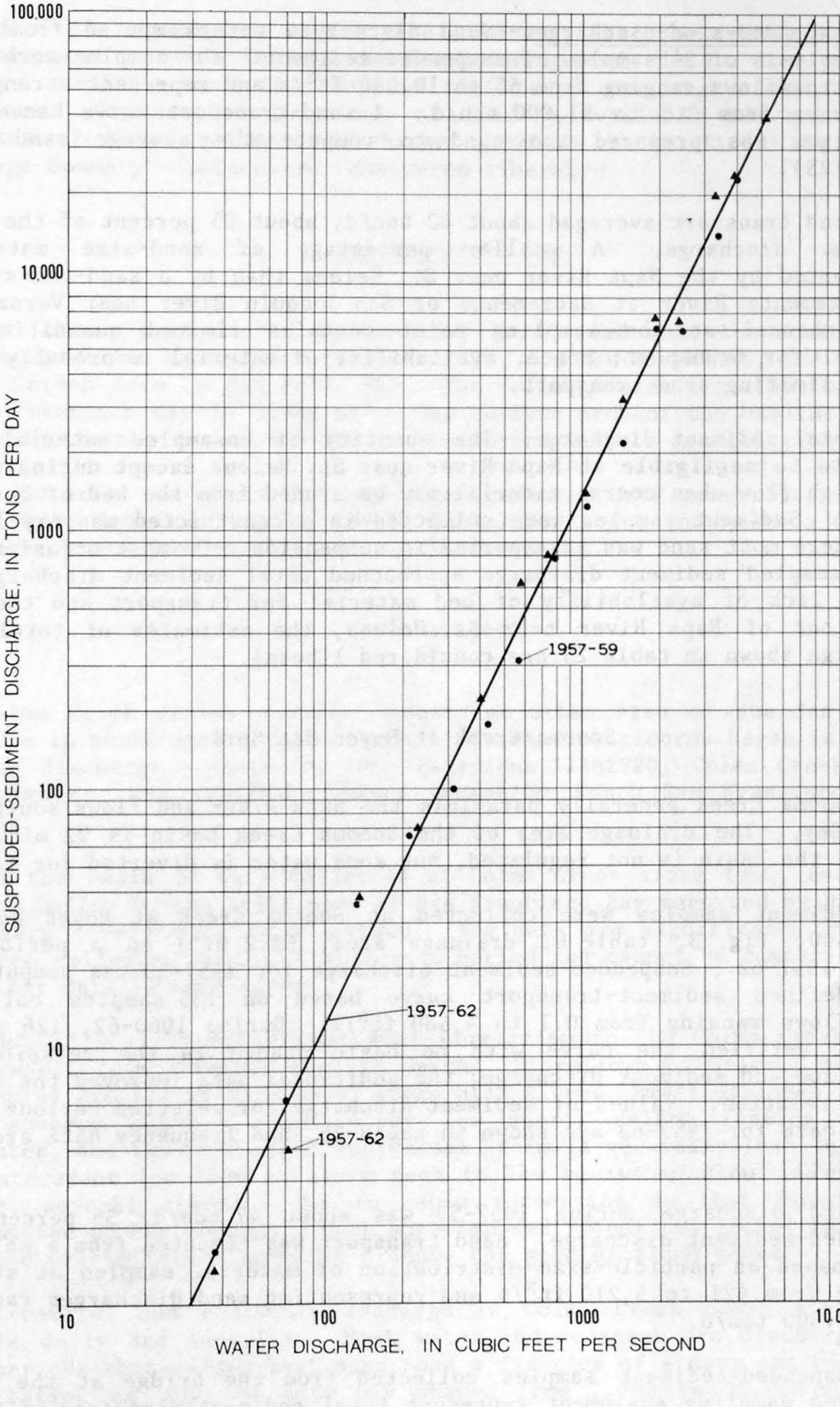

FIGURE 18.--Relation between suspended-sediment discharge and streamflow, Napa River near St. Helena, 1957-59 and 1957-62.

Suspended-sand discharge.--Sand discharges were computed from particle-size analysis of 34 samples of suspended sediment. The samples were collected from streamflows ranging from 55 to 10,000 ft^3/s and represent a range of sand discharges from 0.5 to 21,000 ton/d. A sand-transport curve based on these discharges was prepared and used to compute the average sand transport (table 25).

Sand transport averaged about 42 ton/d, about 25 percent of the suspended-sediment discharge. A smaller percentage of sand-size material was transported by the Napa River near St. Helena than by a sand-bed stream such as Sacramento River at Sacramento or San Joaquin River near Vernalis. The river channel at the sampling point contains limited quantities of bed material for transport; hence, availability of material is probably the major factor limiting sand transport.

Total sediment discharge.--The quantity of unsampled material is estimated to be negligible at Napa River near St. Helena except during periods of very high flow when coarse material may be eroded from the bed or banks of the stream. Sediment samples were collected in a constricted masonry-lined section where most sand was transported in suspension. On most occasions, therefore, sampled sediment discharge approached total sediment discharge. Owing to the lack of availability of bed material for transport and the sampling conditions of Napa River near St. Helena, the estimates of total sediment discharge shown in table 25 are considered liberal.

Sonoma Creek at Boyes Hot Springs

Sonoma Creek generally parallels the Napa River and flows south into San Pablo Bay. The drainage area of the Sonoma Creek basin is 92 mi^2. Natural flow of the basin is not regulated, but some water is diverted for irrigation.

Sediment samples were collected at Sonoma Creek at Boyes Hot Springs (11458500, fig. 3, table 8; drainage area, 62.2 mi^2) on a periodic basis during 1957-62. Suspended-sediment discharge for 1957-59 was computed from a well defined sediment-transport curve based on 135 samples collected at streamflows ranging from 0.1 to 4,580 ft^3/s. During 1960-62, 126 additional samples verified the curve with no basic change in the relation between streamflow and sediment discharge; the additional data improved the definition of the relation. Values of sediment discharge for selected periods and based on all data for 1957-62 are shown in table 25, and frequency data are shown in table 26.

Sand discharge during 1957-59 was about 47 ton/d, 55 percent of the suspended-sediment discharge. Sand transport was computed from a well-defined curve based on particle-size distribution of material sampled at streamflows ranging from 421 to 5,210 ft^3/s and representing sand discharges ranging from 6 to 11,300 ton/d.

Suspended-sediment samples collected from the bridge at the gage with suspended sampling equipment represent total sediment discharge of the stream for material transported in suspension which includes sand, silt, and clay.

The bed of the stream has very little sand available for transport, and most available sand is moved through the reach during each flood. Some gravels and sand are available from the banks of the stream when high streamflows erode the banks. Because of the lack of readily available bed material, the estimates of total sediment discharge shown in table 30 in the "Sediment Discharge Summary" section are considered liberal.

San Francisco Bay

For this report, San Francisco Bay is divided into the south bay, the part south of the Golden Gate (fig. 2 or 3), and the north bay, the part north of the Golden Gate to San Pablo Bay. The drainage area contributing directly to San Francisco Bay is 1,908 mi^2. The surface area of the bay including the islands in the bay is 463 mi^2 and is considered to be a non-contributing area.

Tributaries to the south bay where sediment data were obtained include Colma Creek, San Francisquito Creek, Guadalupe River, and Alameda Creek. No data were obtained on tributaries to the north bay.

Colma Creek

Colma Creek drains a small industrial urban area of the San Francisco Peninsula in northern San Mateo County. Streamflow records began in 1964, and sediment discharge records in 1966 (stations 11162720, Colma Creek at South San Francisco, and 11162722, Spruce Branch at South San Francisco, fig. 3, table 8).

On the basis of data collected at Colma Creek since 1966, estimates of sediment inflow to the south part of San Francisco Bay reported by Porterfield and others (1961) have been revised. The data are significant, even though they were collected during a different period and cannot be compared directly with other data in this report.

Knott (1969) reported that most streamflow in the Colma Creek basin is storm runoff from November through March. Stormflows of Colma Creek and its tributaries are flashy because of steep hill slopes, small drainage areas, and large sewered areas. Flood peaks are short, seldom lasting more than 15 minutes, and the life of an individual storm is generally less than 6 hours from antecedent low flow to storm peak to low recession flow. Occasionally, however, several storms occur in rapid succession so that floodflows are superimposed on one another. Such superimposed floodflows rather than intense sustained precipitation commonly produce the greater flood peaks.

Streamflow and sediment discharge in Colma Creek basin are extremely variable daily and annually. Most water and sediment are discharged during storm periods that seldom last more than a fraction of a day; and the sediment concentration at any one site may change from 1,000 to 25,000 mg/L within 30 minutes and back to 1,000 mg/L an hour later.

Sediment yield of Colma Creek during 1966-69 was affected considerably by urbanization. Native vegetation and topsoil were removed from large areas during construction of residential and roadway projects, and the highly erosible parent material was exposed to winter rains. Erosion in such areas was many times greater than the erosion of the original landscape. The measured sediment yield was, however, reduced considerably by several debris basins constructed downstream from principal erosion areas. Sediment yield during 1966-70 (Knott, 1973) is given in table 27. During 1966-69, the total basin discharge of suspended sediment was 230 ton/d or 6,730 (ton/mi^2)/yr.

The sediment discharges determined for Colma Creek and Spruce Branch gaging stations are suspended-sediment discharge and do not include bedload. Bedload, however, probably constitutes only a small part of the total sediment discharge, as stream velocities and turbulence during medium and high flows are sufficient to keep most of the transported sediment in suspension.

Sediment yields of the Colma Creek basin after 1969 will undoubtedly be lower than yields observed during 1966-69 when construction activity was high. After complete urbanization (65 percent urban and 35 percent open space), the sediment yields for the entire basin probably will range from 9,700 tons in a year of average rainfall to 25,000 tons in a year of extremely high rainfall (27 to 68 ton/d, respectively). Sediment yields for average or extremely high rainfall periods, for conditions short of complete urbanization, can be estimated from equations given by Knott (1973) and based on sediment-yield indexes for various types of land use and the percentage of land use.

Sand discharge for Colma Creek and Spruce Branch for 1966 and 1967 was 80,400 tons, or 3,220 (ton/mi^2)/yr; sand constituted 48 percent of the sediment discharge in 1966-67. Part of the sand from Colma Creek basin does not enter the bay but is deposited in the lower reaches of the channel and is removed periodically by dredge.

San Francisquito Creek at Stanford University

San Francisquito Creek drains a small basin on the west side of South San Francisco Bay about 28 mi south of San Francisco. The basin above the station San Francisquito Creek at Stanford University (11164500, fig. 3, table 8) is predominantly in the natural state, and has a drainage area of 37.5 mi^2. Natural flow of the basin is regulated by Searsville Lake, 5 mi upstream from the gage, and by diversion of about 800 acre-ft annually for irrigation. The drainage area between the gage and Searsville Lake is approximately 23 mi^2.

Sediment samples were collected at San Francisquito Creek at Stanford University during 1957-62 on a periodic basis. A summary of streamflow and suspended-sediment discharge for selected periods is presented in table 28. The percentages of streamflow, suspended sediment, and suspended sand occurring during selected time intervals are shown in table 29.

Sediment discharge was higher per unit streamflow during low and medium flow when computed from samples obtained during 1960-62 than from 1957-59 data. No additional samples were obtained at high flows comparable with those from 1958.

TABLE 27. - Streamflow and sediment discharge of Colma Creek and Spruce Branch at South San Francisco, 1966-70

Streamflow and sediment station	Drainage area (mi^2)	Year	Water discharge: Annual (cfs-d)	Water discharge: Maximum daily (ft^3/s)	Suspended sediment, Total: Discharge (tons)	Suspended sediment, Total: Mean concentration (mg/L)	Suspended sediment, Sand: Discharge (tons)	Suspended sediment, Sand: Mean concentration (mg/L)	Suspended sediment, Maximum daily (tons): Total	Suspended sediment, Maximum daily (tons): Sand
Colma Creek at South San Francisco	10.8	1966	1,700	160	32,100	6,990	[1]11,800	2,570	5,790	[1]2,480
		1967	3,640	462	122,000	12,400	[1]60,800	6,190	27,000	[1]14,800
		1968	1,920	198	35,700	6,890	18,800	3,630	7,890	4,810
		1969	3,890	162	65,100	6,200	34,200	3,260	4,290	2,610
		1970	2,900	205	24,900	3,180	14,300	1,830	5,560	3,590
Spruce Branch at South San Francisco	1.68	1966	416	43	4,760	4,240	2,220	1,980	854	523
		1967	740	113	9,800	4,900	5,580	2,790	2,200	1,400
		1968	364	60	[3]39,300	[3]40,000	--	--	--	--
	[2].70	1969	304	13	[3]27,000	[3]32,000	--	--	--	--

[1]Revised from Knott (1969).
[2]Drainage area reduced by upstream diversion.
[3]Result of highway construction, real estate development, and ineffective debris basin.

TABLE 28. - Average daily streamflow and sediment discharge and sediment yield for selected streams tributary to San Francisco Bay, 1957-59, 1957-66, 1909-59, and 1909-66

Period	Water discharge (ft^3/s)	Sediment discharge: Sand (ton/d)	Sediment discharge: Suspended (ton/d)	Sediment discharge: Total (ton/d)	Annual yield (ton/mi^2)
San Francisquito Creek at Stanford University					
1957-59	20	14	[1]45		[2]438
1957-66	12	--	23		224
1909-59	15	11	[1]34		331
1909-66	14	--	31		302
Guadalupe River at San Jose					
1957-59	37	94	[1]223	239	557
1957-66	24	55	118	128	295
1909-59	29	58	[1]129	141	323
1909-66	28	56	122	134	305
Alameda Creek near Niles					
1957-59	123	208	[1]793	870	457
1957-66	71	62	336	360	194
1909-59	[3]86	56	[1]308	330	178
1909-66	[3]81	51	288	310	166

[1]Revised from Porterfield and others (1961).

[2]Annual yield adjusted for regulation by Searsville Lake is 714 ton/mi^2.

[3]Adjusted for regulation.

On the basis of data obtained during 1957-62, an updated sediment-transport curve was prepared and used to revise the estimates for 1957-59 and 1909-59 reported by Porterfield and others (1961). Values from the revised curve are considered more representative of the average relation between streamflow and suspended-sediment discharge for San Francisquito Creek. Sediment discharge for 1957-59 was revised from 46 to 45 ton/d; and the discharge for 1909-59 was reduced 11 percent, from 38 to 34 ton/d.

Sand discharge was determined from a sand-transport curve based on 14 particle-size analyses of samples collected from streamflows ranging from about 20 to over 20,000 ft^3/s. Sand discharge was 14 ton/d or about 31 percent of the suspended-sediment discharge for 1957-59. Sediment samples during high flows were obtained at a small concrete dam below the gage where most of the sand was in suspension and was sampled with suspended-sampling equipment; the suspended-sediment discharge is therefore assumed to be nearly equal to the total sediment discharge of the stream.

TABLE 29. - Percentage of streamflow and sediment discharge that occurred during selected time intervals in selected streams tributary to San Francisco Bay, 1957-59, 1957-66, and 1909-59

Discharge	Period	Time (percent)			
		0.1	1.0	5.0	15
San Francisquito Creek at Stanford University					
Water	1957-59	8	40	82	99
Suspended sediment	1957-59	27	78	98	99.9
Suspended sand	1957-59	35	91	99.9	100
Guadalupe Creek at San Jose					
Water	1957-59	14	58	94	99.7
	1957-66	18	56	91	98.7
	1909-59	13	54	91	99.8
Suspended sediment	1957-59	35	87	99.6	100
	1957-66	47	78	99.3	100
	1909-59	32	84	99	100
Alameda Creek near Niles					
Water	1957-59	15	56	88	98
	1909-59	12	45	77	93
Suspended sediment	1957-59	36	92	99.7	99.9
	1909-59	37	81	97	99.8

Suspended-sediment yield during 1957-59 was 438 (ton/mi^2)/yr, based on the drainage area (37.5 mi^2) for the station. After adjustment for regulation by Searsville Lake, the yield for the intervening area between the lake and the station was 714 (ton/mi^2)/yr.

Guadalupe River at San Jose

Guadalupe River drains an area southeast of south San Francisco Bay and flows through San Jose to enter the south end of the bay. The station, Guadalupe River at San Jose (11169000, fig. 3, table 8), has a drainage area of 146 mi^2. Records of streamflow have been collected since 1929, and sediment discharge was recorded for 1957-62. A summary of streamflow and sediment discharge for selected periods is presented in table 28.

The natural flow of the river has been regulated by several reservoirs since 1936 and by additional reservoirs and diversions since 1951. The relation between streamflow and sediment discharge at the station was poor owing to the effects of regulation, agriculture, and urbanization.

Suspended-sediment discharge.--On the basis of a revised sediment-transport curve that reflects additional data obtained during 1960-62, sediment discharge for 1957-59 (Porterfield and others, 1961) was revised from an average of 115 to 223 ton/d, and values for 1909-59 were revised from an average of 77 to 129 ton/d.

Peak flows at San Jose transport most of the sediment. Thus sediment samples during floodflows and proper interpretation of data are necessary to provide reliable results from the infrequent samples. All flow during 1957-59 occurred in less than 25 percent of the time, and the peak flows that transported 99 percent of the sediment occurred in only 5 percent of the time (table 29).

During 1957-66, daily flows larger than 900 ft^3/s occurred only 18 times: 10 times in 1958 and 8 times in 1963. The estimated total sediment discharge on these 18 days was 336,000 tons, about 87 percent of the sediment discharge during the period; during the 10-year period, most of the sediment was transported during two storm periods and in only 18 days.

Suspended-sand discharge.--Suspended-sand discharge was computed for 19 samples analyzed for particle-size distribution. The samples were collected at streamflows ranging from 13 to 1,680 ft^3/s and represented sand discharge from 0 to 5,180 ton/d. The relation between sand discharge and streamflow in Guadalupe River at San Jose was poor, and no samples were collected during the large flows that transport most of the sand. As about 80 percent of the sand is transported at flows greater than 1,680 ft^3/s (1957-59), and 100 percent is transported at flows that occur less than 10 percent of the time, the computed sand discharge of 94 ton/d for 1957-59 (table 28) should be considered only as a reasonable estimate.

Total sediment discharge.--Total sediment discharge for Guadalupe River at San Jose was computed by the modified Einstein procedure for a range of streamflows. The relation between unsampled sediment discharge and streamflow developed from these computations was used to determine a discharge-weighted mean total sediment discharge.

Total sediment discharge for 1957-66 averaged 128 ton/d or 1.08 times the suspended-sediment discharge. The percentage of unsampled sediment discharge for Guadalupe River at San Jose, where the median diameter of the bed material is about 5 mm, is considerably less than that for Sacramento River at Sacramento or San Joaquin River near Vernalis, both sand-bed streams in which the median diameter of the bed material is about 0.3 mm. Because of turbulence, most sand-size particles available for transport are transported in suspension, and are sampled with the suspended-sediment sampling equipment. The unsampled sediment in Guadalupe River, therefore, consists primarily of material too coarse to be transported in suspension by the available streamflow.

Alameda Creek near Niles

Alameda Creek is an east-side tributary of south San Francisco Bay. The station Alameda Creek near Niles (11179000, fig. 3, table 8) has a drainage area of 633 mi^2. Alameda Creek has been partly regulated by Calaveras Reservoir since 1916, although the dam was not completed until 1925, and by San Antonio Reservoir since 1965. Natural flow is also affected by diversions for irrigation and, since 1962, by water imported from Delta-Mendota Canal.

Streamflow records for Alameda Creek started in 1891. Discharges used in this report for 1909-59, however, were adjusted on the basis of flow during 1925-59 and should be representative of flow conditions since 1909 assuming regulation by Calaveras Reservoir. Records of daily sediment discharge have been compiled since 1957. A summary of water and sediment discharge for selected periods is shown in table 28.

Suspended-sediment discharge for the 51-year period 1909-59, estimated by Porterfield and others (1961), was 308 ton/d, or 39 percent of 793 ton/d, the average during 1957-59. The difference in sediment discharge between the 3- and 51-year periods was the greatest reported for any stream in the 1959 study. The difference may be attributable to the greater frequency during 1957-59 than during 1909-59 of greater streamflows that transported most of the suspended sediment in the Alameda Creek basin. Nearly all the sediment was transported by streamflows that occur about 15 percent of the time (table 29).

Sediment data obtained after 1959 indicate that little, if any, change occurred in the relation between water and sediment discharge determined for 1957-59. Decreases in sediment discharge therefore can be attributed primarily to decreases in the magnitude and duration of peak flows. Average daily water discharge during 1957-66 was 71 ft^3/s and suspended-sediment discharge was 336 ton/d.

The historical sediment discharge for 1909-59 was revised from 330 to 308 ton/d on the basis of the 1957-66 sediment-transport curve (fig. 19). The revised value provides a better estimate, because the original 3 years of data were not sufficient for definition of the average values of sediment discharge for the entire range of streamflow.

Suspended-sand discharge.--The discharge of sediment in the sand range was computed from a relation of water to sand discharge based on analysis of 57 samples for particle-size distribution. The samples were collected at streamflows ranging from 8 to 7,550 ft^3/s.

Sand is the minor fraction of material transported by Alameda Creek. The average sand discharge during 1957-66 was 62 ton/d, 18 percent of the suspended-sediment discharge. Most sand was transported when the water discharge was greater than 200 ft^3/s, although some sand was found in suspension at discharges of only 8 ft^3/s. Paradoxically, some discharges as great as 980 ft^3/s did not transport any sand. About 47 percent of the sand was tranported by discharges occurring 0.03 percent of the time and 99 percent by discharges occurring 0.8 percent of the time.

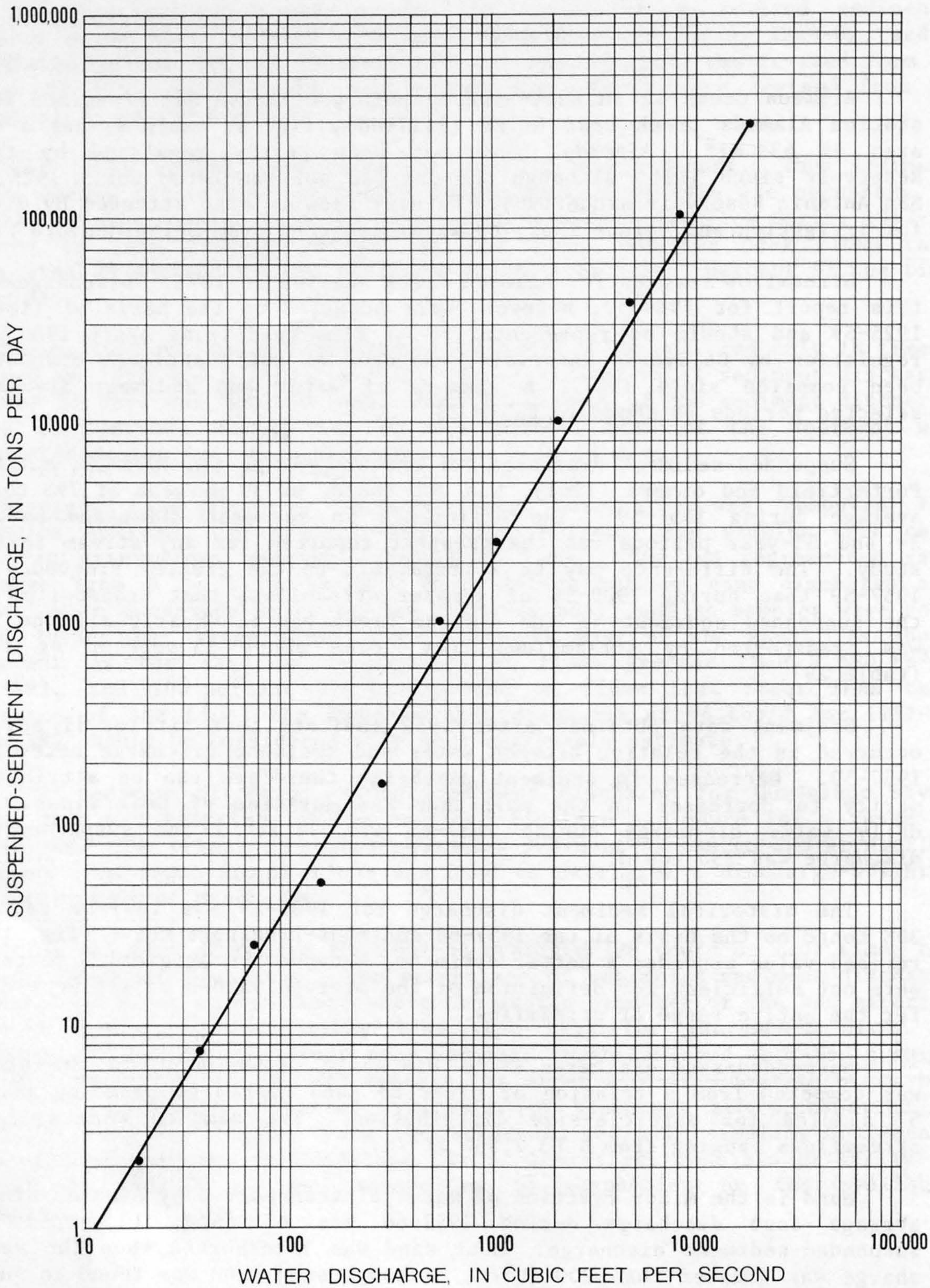

FIGURE 19.--Relation between suspended-sediment discharge and streamflow, Alameda Creek near Niles, 1957-66.

Alameda Creek sediment samples were obtained at or near a concrete weir where most sediment in the sand range was in suspension, and all the sediment could be sampled with suspended-sediment sampling equipment. Estimates of total sediment discharge are included in table 28.

Sediment Discharge Summary

A summary of sediment discharge to the Sacramento-San Joaquin Delta and to the bays from all basins in the San Francisco Bay system for the periods 1957-59, 1957-66, 1909-59, and 1909-66 is presented in table 30. The summary includes the results of determinations at key sediment measurement sites, as reported herein, and estimates for unmeasured areas and basins based on sediment yield rates indicated by known data from nearby or similar areas. The detailed computations for estimated discharges have not been presented. Table 30 shows suspended-sediment and total sediment discharge, as well as sediment yield expressed in tons per square mile per year. The latter value is useful for purposes of comparison of basin yields and application to unmeasured areas.

The Sacramento and San Joaquin River basins provided about 83 percent of the sediment inflow to the San Francisco Bay system during 1957-66 and 86 percent during 1909-66. About 98 percent of this inflow was measured or estimated at sediment measurement sites. Measured sediment inflow directly to the bays comprised only about 40 percent of the total discharged by basins directly tributary to the bays. About 90 percent of the total sediment discharge to the delta and the bays in the San Francisco Bay system thus was determined on basis of systematic measurements.

Comparison of the values of daily sediment discharge in table 30 for key segments of the San Francisco Bay system with those in table 1 provides an index of the adequacy of the initial estimates (Porterfield and others, 1961), and the areas of significant change.

SUMMARY AND CONCLUSIONS

Sediment transported to the Sacramento-San Joaquin Delta prior to the discovery of gold in 1848 had been estimated by Gilbert (1917) to average about 2 million cubic yards annually. Gilbert's studies indicated that during the period 1849-1910, as a result of gold mining operations, particularly the increased use of hydraulic mining, the sediment transported by Central Valley streams increased to an average of 18 million cubic yards annually. Although hydraulic mining ceased in 1884, the effects of the mining on the streams continued. Gilbert estimated that a period of about 50 years (from 1914) would be required for termination of the effect of hydraulic mining debris on the rivers. He further estimated future average annual sediment transport of not less than 8 million cubic yards.

TABLE 30 - Summary of suspended- and total-sediment discharge, in tons per day, of drainage

Drainage basin or hydrologic unit	Drainage area, in square miles	1957-59		
		Suspended sediment in tons per day	Total sediment	
			Tons per day	Tons per square mile per year
Sacramento River at Sacramento	23,530	7,800	[1]9,650	150
Sacramento Weir bypass	--	18	18	--
Yolo Bypass near Woodland	1,225	[1]2,830	2,880	858
Other Sacramento River basin streams	1,567	--	--	--
Sacramento River basin	26,322	10,648	12,548	174
San Joaquin River near Vernalis	13,540	1,230	1,430	39
Cosumnes River at McConnell	724	487	606	306
Mokelumne River below Camanche Dam	627	35	38	[2]283
Intermediate basin, Mokelumne River below Camanche Dam near Victor (discontinued)	16	15	16	365
Dry Creek	329	154	190	211
Calaveras River	393	22	24	[5]280
Area of negligible contribution	3,467	--	--	--
San Joaquin River basin	19,096	1,943	2,304	44
Total, Sacramento-San Joaquin Delta	45,418	12,591	14,852	119
Pacheco Creek basins:				
Walnut Creek at Walnut Creek	79.2	406	430	1,980
Remainder, contributing	39.31	200	210	1,950
Remainder, noncontributing	19.93	--	--	--
Remainder of stream group 6	43	150	160	1,360
Stream group 5	114	100	105	336
Area of negligible contribution	300	--	--	--
Total, Suisun Bay	595	856	905	555
Napa River near St. Helena	81.4	131	140	628
Other Napa drainage	252	246	270	391
Sonoma Creek at Boyes Hot Springs	62.2	85	96	563
Other Sonoma drainage	31.4	18	20	232
Petaluma Creek	41	42	45	400
Part of stream group 1	60	55	60	365
Part of stream group 7	82	120	130	579
Area of negligible contribution	352	--	--	--
Total, San Pablo Bay	962	697	761	289

[1]See footnotes at end of table.

basins tributary to the San Francisco Bay system, 1957-59, 1957-66, 1909-59, and 1909-66

1957-66			1909-59			1909-66		
Suspended sediment, in tons per day	Total sediment		Suspended sediment, in tons per day	Total sediment		Suspended sediment, in tons per day	Total sediment	
	Tons per day	Tons per square mile per year		Tons per day	Tons per square mile per year		Tons per day	Tons per square mile per year
7,400	8,820	137	8,850	[1]10,610	165	8,470	10,200	158
350	350	--	330	330	--	330	330	--
1,700	1,740	519	[1]1,690	1,720	513	1,630	1,660	495
--	--	--	--	--	--	--	--	--
9,450	10,910	151	10,870	12,660	176	10,430	12,190	169
784	888	24	1,460	1,730	47	1,310	1,540	42
376	463	234	439	546	275	412	519	259
78	85	[3]940	43	47	350	[4]49	53	[3]451
10	12	--	14	15	342	14	15	342
125	145	161	168	208	230	158	196	217
26	28	329	27	30	353	25	28	330
--	--	--	--	--	--	--	--	--
1,370	1,621	31	[1]2,151	2,576	49	1,968	2,351	45
10,820	12,531	101	[1]13,021	[1]15,236	122	12,398	14,541	117
249	265	1,220	250	265	1,220	242	255	1,180
120	127	1,180	120	127	1,180	120	125	1,160
--	--	--	--	--	--	--	--	--
92	98	832	92	98	832	89	96	815
136	144	461	125	135	433	130	137	439
--	--	--	--	--	--	--	--	--
597	634	389	587	625	384	581	613	376
178	190	852	164	174	780	168	178	798
340	366	530	302	330	478	320	338	490
83	94	552	87	98	575	86	98	575
18	20	233	22	24	279	22	24	279
41	44	392	53	58	517	53	58	517
54	59	360	60	65	396	61	66	400
74	80	357	65	70	312	64	69	307
--	--	--	--	--	--	--	--	--
788	853	324	753	819	311	774	831	316

TABLE 30 - Summary of suspended- and total-sediment discharge, in tons per day, of drainage basins

Drainage basin or hydrologic unit	Drainage area, in square miles	1957-59		
		Suspended sediment in tons per day	Total sediment	
			Tons per day	Tons per square mile per year
North Bay: Part of stream group 1	45	40	45	365
Area of negligible contribution	14	--	--	--
South Bay: Alameda Creek near Niles	633	793	870	502
Guadalupe River at San Jose (9)	146	223	239	598
Remainder of stream group 9	519	440	470	331
San Francisquito Creek	37.6	45	50	[6]487
Colma Creek	12.48	--	--	--
Remainder of stream group 10	56.72	83	90	579
Part of stream group 7	81	120	130	586
Area of negligible contribution	363.3	--	--	--
Total, San Francisco Bay	1,908	1,744	1,894	362
Total water surface of San Francisco Bay system	463	--	--	--
Total, San Francisco Bay system	49,346	15,888	18,412	136

[1]Revised from Porterfield and others (1961).
[2]Unregulated basin drainage area in 49 mi^2.
[3]Weighted average. Sediment discharge and effective drainage area changed because of construction of Camanche Dam.
[4]Post-1966 rate because of regulation should range from 18-27 ton/d.
[5]Unregulated basin drainage area since 1930 is 31 mi^2.
[6]Excluding drainage area above Searsville Lake.
[7]1966-69. Predicted post-1969 rates range from 27-68 ton/d. (Not included in total).

tributary to the San Francisco Bay system, 1957-59, 1957-66, 1909-59, and 1909-66--Continued

1957-66			1909-59			1909-66		
	Total sediment			Total sediment			Total sediment	
Suspended sediment, in tons per day	Tons per day	Tons per square mile per year	Suspended sediment, in tons per day	Tons per day	Tons per square mile per year	Suspended sediment, in tons per day	Tons per day	Tons per square mile per year
39	44	360	44	50	406	43	49	398
--	--	--	--	--	--	--	--	--
336	360	208	308	330	190	288	310	179
118	128	320	129	141	353	122	134	335
235	250	176	310	330	232	290	310	218
23	26	253	34	37	360	31	34	330
230	230	[7]6,726	--	[7]40	--	--	[7]40	--
42	46	296	66	72	464	61	66	425
50	54	244	65	70	316	60	65	293
--	--	--	--	--	--	--	--	--
1,073	1,138	174	956	1,070	197	895	1,008	185
--	--	--	--	--	--	--	--	--
13,278	15,156	110	[1]15,317	[1]17,750	131	14,648	16,993	125

Several studies of sedimentation in the San Francisco Bay system, made between 1914 and 1956 in relation to sediment effects on proposed barriers and for other purposes, produced sediment inflow estimates ranging from 3.4 to 5.8 million cubic yards. But no systematic sediment-discharge data were obtained during the period.

In response to the need for reliable estimates of sediment discharge, systematic collection of sediment records was started in 1957. Data obtained during 1957-59 provided a basis for initial estimates of sediment inflow to the delta and the bays. Sediment transport to the delta during 1909-59 was estimated, on basis of these data, to be 7.2 million cubic yards (14,200 ton/d) annually (Porterfield and others, 1961).

Data obtained during 1959-66 permitted the firming and extension of the initial evaluations of sediment inflow, including better definition of streamflow-sediment discharge relations. The 1957-66 period was used to provide 10 years of record, even though many sediment records were available only for 1957-62. The results corroborated the 1957-59 estimates, appeared reasonable, and the study was not extended beyond 1966. The accuracy of the sediment-discharge values reported in table 30 is considered good. About 75 percent of the sediment discharge was estimated on the basis of daily sampling and 16 percent from periodic sampling. Only 9 percent of the sediment discharge was estimated on the basis of known sediment yields from nearby or comparable basins.

A brief summary of sediment discharge for selected periods for major segments of the San Francisco Bay system, expressed in volume, is given in table 31. Annual sediment discharge volumes in cubic yards may be approximated from the daily values in tons in table 30 by using estimated unit weights for dry sediment ranging from 51-54 lb/ft^3. The volumes may be determined as:

$$\text{Annual volume} = 365 \times \frac{\text{sediment in tons} \times 2000}{\text{unit weight of sediment} \times 27}$$

and, for the Sacramento-San Joaquin Delta during 1957-66 would be:

$$\text{Annual volume} = 365 \times \frac{12531 \times 2000}{53.2 \times 27} = 6{,}368{,}000 \text{ yd}^3$$

The 1957-66 sediment inflow to the delta averaged 6.4 million cubic yards annually (17,438 yd^3/d). The long-term inflow for the period 1909-66, assuming the controls and regulation existing during 1957-66, was estimated to be 7.4 million cubic yards annually (20,131 yd^3/d). The total volume of sediment from all sources transported to the full San Francisco Bay system during 1909-66 was estimated to be 8.6 million cubic yards annually. These long-term estimates provide a corroboration of Gilbert's (1917) estimate of future average annual sediment transport of not less than 8 million cubic yards.

TABLE 31. - Summary of total sediment discharge, in cubic yards per day, of selected hydrologic units tributary to the San Francisco Bay system, 1957-59, 1957-66, 1909-59, and 1909-66

Hydrologic unit	Period				
	1957-59	1957-66	1909-59	1909-66	
	Cubic yards per day	Cubic yards per day	Cubic yards per day	Cubic yards per day	Percentage of total
Sacramento River	17,338	15,202	17,577	16,900	71.6
San Joaquin River	3,176	2,236	3,570	3,231	13.7
Sacramento-San Joaquin Delta.........	20,514	17,438	21,147	20,131	85.3
Suisun Bay	1,308	915	901	887	3.8
San Pablo Bay	1,085	1,221	1,170	1,194	5.0
San Francisco Bay	2,707	1,302	1,477	1,386	5.9
Total..................	25,614	20,876	24,695	23,598	100
[1]Annual total, in cubic yards.....	9,349,000	7,620,000	9,013,000	8,631,000	

[1]365 days.

A small part of the sediment transported to the San Francisco Bay system is discharged to the ocean. Gilbert (1917) had estimated this discharge as about 50 million cubic yards of the 1,196 million cubic yards transported into the bay system during 1849-1914 (table 7), or about 4 percent of the total, and future discharge as about 5 percent. On this basis about 0.4 million cubic yards of the estimated average of 8.6 million cubic yards of sediment transported annually to the San Francisco Bay system during 1909-66 may have been discharged to the ocean.

Reservoir storage and regulation developed since 1914 in upstream reaches of Central Valley streams has modified flows reaching the valley floor and the proportion of high flows downstream that transport most of the sediment. Levees, dikes, and channels now provide some control also. This control may offset some of the storage effects by accelerating discharge downstream. Under natural conditions, flood runoff in the downstream reaches of the streams had been attenuated and delayed through overflow and detention of floodflows on the valley floor. The detention of major floodflows still occurs.

The 1909-66 sediment transport rate may be projected as the possible future rate, assuming continuation of the controls and regulation existing in 1966. Some change is occurring, of course, owing to increased controls on streamflow and frequency distribution of flow rates. Records for 1957-66 indicated a 9-percent decrease in sediment discharge from the 1957-59 rate for Sacramento River at Sacramento and 18 percent for the total San Francisco Bay system. Part of the decrease may be attributable to reduced streamflow and part to changes in flow frequency. The flow rates for Sacramento River at Sacramento, for example, were greater than median discharge during 1957-66 except during the 1964-65 flood period. Higher flows occurred less frequently, however, during 1959-66 than during 1957-59 or the estimated period 1909-66, thus resulting in reduced sediment discharge. Should future flow rates approach those for 1957-66, the average sediment discharge to the delta may decline from the projected 1909-66 values to those determined for 1957-66.

In the light of the extensive development of the water resources of the region and concomitant reduction and control of floods, the estimates of sediment discharge to the delta and the San Francisco Bay system reported herein may be conservative.

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