Sediment Transport and Turbidity in the Eel River Basin, California

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1986

Prepared in cooperation with the California Department of Water Resources

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By WILLIAM M. BROWN III *and* JOHN R. RITTER

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SEDIMENT TRANSPORT AND TURBIDITY IN THE EEL RIVER BASIN, CALIFORNIA

By William M. Brown III and John R. Ritter

ABSTRACT

The Eel River has the highest recorded average annual suspended-sediment yield per square mile of drainage area of any river of its size or larger in the United States. This yield, in tons per square mile, is more than 15 times that of the Mississippi River and more than four times that of the Colorado River. The erosion rate in the Eel River basin is a major watershed-management problem.

This study was made by the U.S. Geological Survey to determine the quantity of sediment transported by streams in several areas of the Eel River basin, California. Sediment-discharge data were collected at 22 locations within the basin for various periods between 1955 and 1967. The destruction of some stations by flooding and the establishment of new stations precluded continuous records for all stations for the 12-year period. Other characteristics of the streams and the basin pertinent to sedimentation have been employed to provide complementary information to the sediment records and to aid in the analysis of sedimentation.

The Eel River basin is underlain almost entirely by the sedimentary rocks of the Franciscan Formation. Regional uplifting and faulting of these rocks have produced a rugged topography characterized by steep slopes and narrow canyons which trend northwesterly parallel to the zones of weakness associated with the faulting. Weathering of the Franciscan Formation has produced moderately deep loamy soils which are highly erodible.

The climate of the basin is one of the wettest in the State of California. Throughout the winter months, heavy rains fall during intense storms of moderate duration and produce about 9 percent of the annual runoff in the State, although the basin occupies only 2 percent of the State's land area. The coastal region of the basin is generally cool and foggy, while farther inland, temperatures are more variable and average precipitation is lower. Snow falls in the higher elevations in the eastern part of the basin, but runoff from snowmelt is minor.

The combination of geology, soil types, steep slopes, and heavy precipitation produces slumps and landslides which contribute heavily to the sediment yield of the basin. In the places where landslides are adjacent to the stream channels, sediment production is consistently higher than in other areas. Landslides occur most frequently in the Middle Fork Eel River basin and along the slopes of the main stem of the Eel River in the central part of the basin.

Average annual rainfall in the basin is about 59 inches, and average annual runoff is about 35 inches. Most runoff occurs during and shortly after the late fall and winter storms. Because of the impermeability of the soil and mantle rock, base flow is poorly sustained. Precipitation during winter storms is generally extensive over the entire basin; thus, unit runoff is not extremely variable from point to point in the basin.

During the 10-year period beginning October 1957, the Eel River discharged an average suspended load of more than 31 million tons per year according to measurements made at Eel River at Scotia, the station farthest downstream on the main stem of the Eel River. An additional suspended-sediment discharge averaging more than 1½ million tons per year during the same period was derived from the basin of the Van Duzen River, a tributary which enters the Eel River a few miles downstream from Scotia. All parts of the basin contributed to the suspended-sediment discharge at Scotia, although about two-thirds of the material came from the central one-third of the drainage area. The Eel River above its confluence with the Middle Fork Eel River contributed about 6 percent of the annual suspended load at Scotia, and the Middle Fork drainage added about 13 percent. An additional 13 percent came from the South Fork Eel River drainage. The remaining 68 percent of the annual suspended load was derived from the main stem of the Eel River between the South Fork and Middle Fork tributaries. In this vicinity, which includes the North Fork Eel River drainage, roughly equal portions of the computed load were discharged above and below Fort Seward. Most of the suspended sediment was moved by high flows, which occurred an average of 10 percent or less of the time. With few exceptions, 50 percent or more of the annual suspended load at each station was carried in fewer than 6 days during the water year.

Emphasis is given to catastrophic flooding and record sediment discharges which occurred during the period of data collection. Floods in December 1964 and January 1965 caused a suspended-sediment discharge of 160 million tons in a 30-day period at Eel River at Scotia. This amount was about 51 percent of the suspended load computed for the entire 10-year period at that station. During this same flood period, record suspended-sediment discharges occurred at all sediment stations along the Eel River and its tributaries.

Turbidity and the concentration of suspended sediment at several stations in the Eel River basin follow a linear relation which persists throughout the range of measured values of these two variables. The trend in this relation was similar for each station during each year studied, and this indicated that turbidity may be a useful index for the estimation of sediment concentration at points within the basin.

INTRODUCTION

A Missouri physician, Dr. Josiah Gregg, named the Eel River in 1849 when his exploring party encountered a small group of Indians carrying "eels" (*lampreys*) which they had caught in the river. Settlement and development along the Eel River began within the next decade, and the basin has since become an area of forest-products industry, agriculture, and recreation. The basin, whose population is 50,000, is noted for its natural resources, the most important of which are a vast supply of water and the spectacular California Redwood Forests, within which grow some of the tallest trees in the world.

The Eel River basin is a potentially significant contributor to the water resources of California. Although the basin covers only 2 percent of the land area of the State, the average annual runoff from the basin is about 9 percent of the average annual runoff in the State. However, runoff from the basin is accompanied by a discharge of suspended sediment which is the highest per square mile of drainage basin of any river the size of the Eel River or larger in the United States.

PURPOSE AND SCOPE

The potential importance of the Eel River to the water-resources development of the State of California has led to a number of studies of the Eel River basin by State and Federal agencies. Primary water needs for human consumption, industry, wildlife, and recreation imply certain water-quality requirements, and successful planning for establishing and maintaining a water supply meeting these requirements necessitates reliable information on sediment and turbidity. Part of a study aimed at creating an effective plan of development of the basin is a cooperative venture between the U.S. Geological Survey and the State of California to study sedimentation and the turbidity characteristics of the Eel River and its tributaries. Sediment yield is of great economic importance in the effective design of reservoirs and other construction on rivers, is significant in its relation to the frequent flooding along the Eel River, and has numerous attendant problems of importance to man.

The purposes of this project are to determine the quantity of sediment transported by streams in different areas of the Eel River basin, to compare sediment yields among selected regions of the basin, and to study the relation of turbidity to the concentration of suspended sediment. The data necessary for this project were obtained from sediment stations which were established at several locations in the basin (table 1). Even though many stations were discontinued or relocated as a result of the effects of the December 1964 flood, sufficient complementary records were obtained to provide a representative analysis of sedimentation. Turbidity samples were taken at several stations between 1964 and 1968 with simultaneous sediment samples and water-discharge measurements.

This report presents and interprets the data collected for this project, along with pertinent related information. Methods of analysis of these data are described in conjunction with computations, tables, and graphs.

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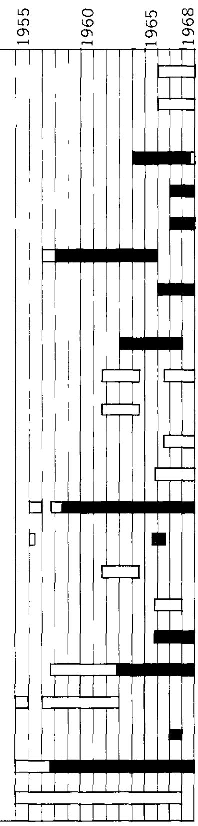
TABLE 1.—*Periods of operation of sediment-sampling stations in the Eel River drainage basin*

Sampled daily ▬ Sampled periodically ▭

Station	Station name
11-4700	Lake Pillsbury near Potter Valley
4705	Eel River below Scott Dam, near Potter Valley
4710	Potter Valley powerhouse tailrace, near Potter Valley
4721.5	Eel River near Dos Rios
4722	Outlet Creek near Longvale
4725	Eel River above Dos Rios
4729	Black Butte River near Covelo
4730	Middle Fork Eel River below Black Butte River, near Covelo
4731	Williams Creek near Covelo
4736	Short Creek near Covelo
4737	Mill Creek near Covelo
4738	Elk Creek near Hearst
4739	Middle Fork Eel River at Dos Rios
4740	Eel River below Dos Rios
4744	Hulls Creek near Covelo
4745	North Fork Eel River near Mina
4750	Eel River at Fort Seward
4755	South Fork Eel River near Branscomb
4765	South Fork Eel River near Miranda
4766	Bull Creek near Weott
4770	Eel River at Scotia
4785	Van Duzen River near Bridgeville

Period of sampling



PREVIOUS INVESTIGATIONS

Studies of erosion and sedimentation in the Eel River basin have been a part of investigations of the northern coastal area of California since July 1958 (California Department of Water Resources, 1966, p. 2). The investigations include many aspects of development, control, and conveyance of water supplies; however, the studies of sediment within the program are more general than detailed. A report by the U.S. Department of Agriculture River Basin Planning Staff, Soil Conservation Service and Forest Service (1970), discusses recent detailed studies of soil types and erosion processes throughout the

Eel River basin. Detailed investigations of sedimentation were begun in 1957 by the U.S. Geological Survey in cooperation with the California Department of Water Resources, and information gained from these investigations has been analyzed as part of a report on the sediment yield of streams in northern coastal California (Hawley and Jones, 1969). A detailed report on many aspects of sedimentation in the Middle Fork Eel River basin is currently being prepared by J. M. Knott of the Geological Survey and will include analysis of sediment data collected since October 1957.

PERSONNEL AND ACKNOWLEDGMENTS

This report was prepared by the U.S. Geological Survey, Water Resources Division, in cooperation with the State of California Department of Water Resources as part of an investigation of the water resources of the State of California. This project was conducted under the general supervision of R. Stanley Lord, district chief in charge of water-resources investigations in California, and under the immediate supervision of L. E. Young, chief of the Menlo Park subdistrict office.

The writers wish to express their gratitude to the following individuals: C. E. Stearns, for consultation and the supply of data on soils and erosion collected by the Soil Conservation Service; G. Porterfield, J. P. Akers, B. L. Jones, and S. G. Heidel, for critical review and constructive commentary; and J. M. Knott, for providing information and computations on sediment transport in the Middle Fork Eel River, and for his review and helpful criticism of this report.

PHYSICAL SETTING

TOPOGRAPHY

The Eel River drains an area of about 3,600 square miles in the Coast Ranges of northern California and empties into the Pacific Ocean some 280 miles north of San Francisco (fig. 1). The basin is about 120 miles long, averages 30 miles in width, and is oriented in a northwesterly direction almost parallel to the Pacific coast. Regional folding and faulting have created a series of northwest-trending ridges and valleys, and a trellis drainage and erosional pattern characterizes the surface features which have formed. Elevations in the generally rugged terrain range from sea level to 7,000 feet, and the Eel River and its tributaries descend rapidly from the higher elevations in narrow, steep-walled canyons. In the coastal region south of Eureka, however, the Eel River near its delta flows in a gently sloping valley about 11 miles long that expands oceanward from 1 to 9 miles in width. Round Valley and Little Lake Valley in the southern part of

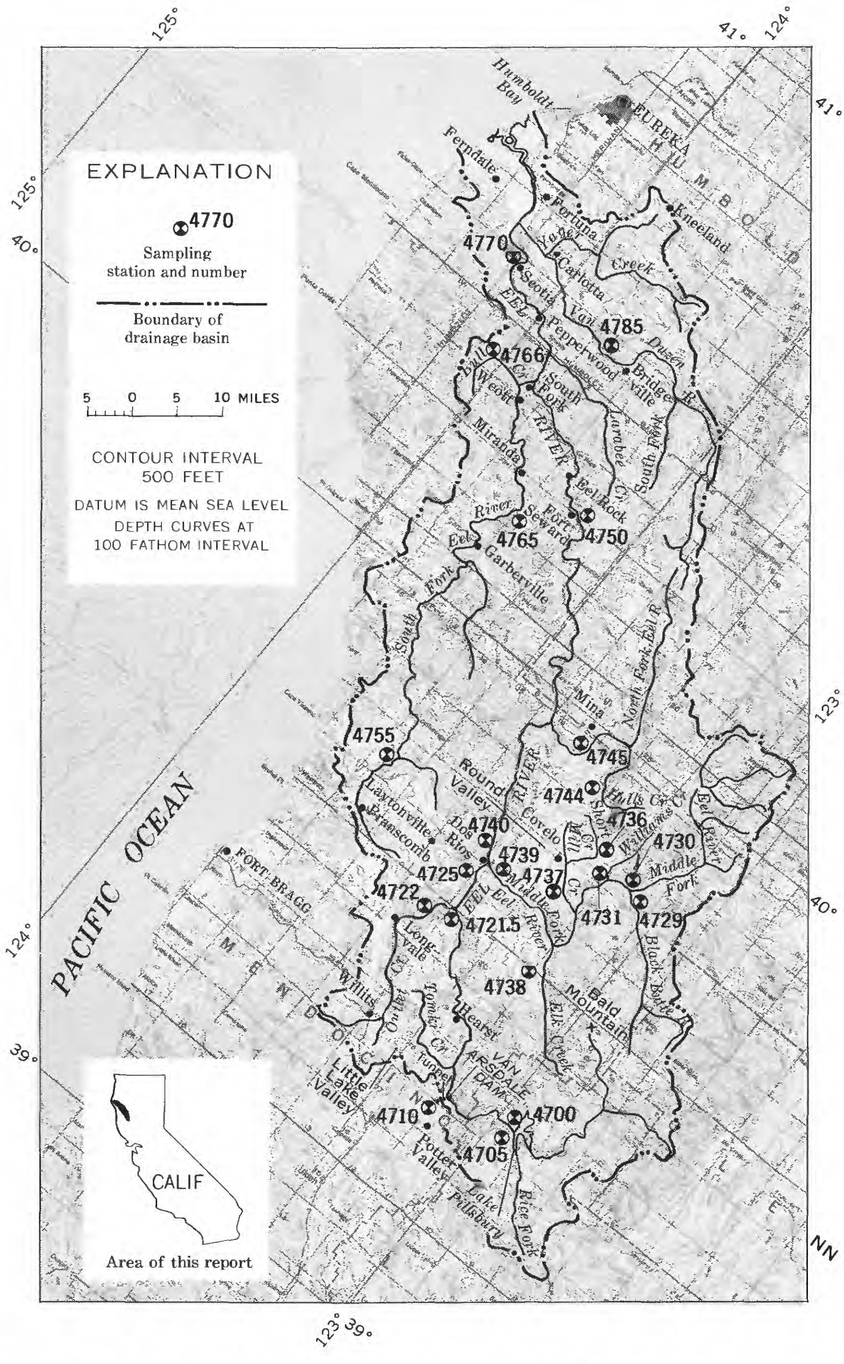


FIGURE 1.—Study area, Eel River basin. Base from U.S. Geological Survey, 1955, scale 1 :500,000.

the basin constitute the only noteworthy areas of regular topography besides the delta area. The only major surface-water features other than the rivers are Lake Pillsbury, a 2,280-acre reservior impounded behind Scott Dam on the Eel River in the southern tip of the basin, and Van Arsdale Reservoir which is just downstream of Lake Pillsbury. Cities and other manmade features constitute but a small part of the basin topography, and along with highways and railroads are confined to the lowlands along the river valleys.

CLIMATE

The climate of the Eel River basin is one of the wettest in the State of California. The average annual precipitation ranges from about 35 inches along the Pacific coast south of Humboldt Bay to more than 110 inches in the mountains southeast of Scotia (fig. 2). This precipitation is generally the result of large storms which move into California from the northwest during the late autumn and winter months. These storms produce brief, intense rains which contribute as much as 80 percent of the annual precipitation in the basin. Snow falls at higher elevations, but its quantity and contribution to runoff are usually insignificant.

The climate of the coastal region of the basin is predominantly influenced by the moist airmass over the ocean which produces onshore winds, cool foggy summers, and mild wet winters. Temperatures near the coast are moderate, ranging from 0.6°C (33°F) to 29°C (85°F) and averaging about 11°C (52°F); rainfall averages about 40 inches per year. Farther inland, the changing topography and increased distance from the ocean bring about wider temperature ranges and increased precipitation. Temperature extremes range from about −18°C (0°F) to about 43°C (110°F), and the mean annual rainfall approaches 80 inches. Because of a decrease in the amount of fog, however, the general climate of the inland part of the basin is less moist than that along the coast.

RUNOFF

The average annual runoff in the Eel River basin is approximately 35 inches on the basis of streamflow records and synthesized information for the 60-year period 1900–59 (Rantz, 1964, p. 3). The runoff has been adjusted for evaporation and change in reservoir contents of Lake Pillsbury and for diversion into the Russian River basin at the Van Arsdale Reservoir. Average annual runoff is highest in the western part of the basin and lowest in the central part; however, variations from the average are not great within each of the larger hydrologic units of the basin listed in table 2.

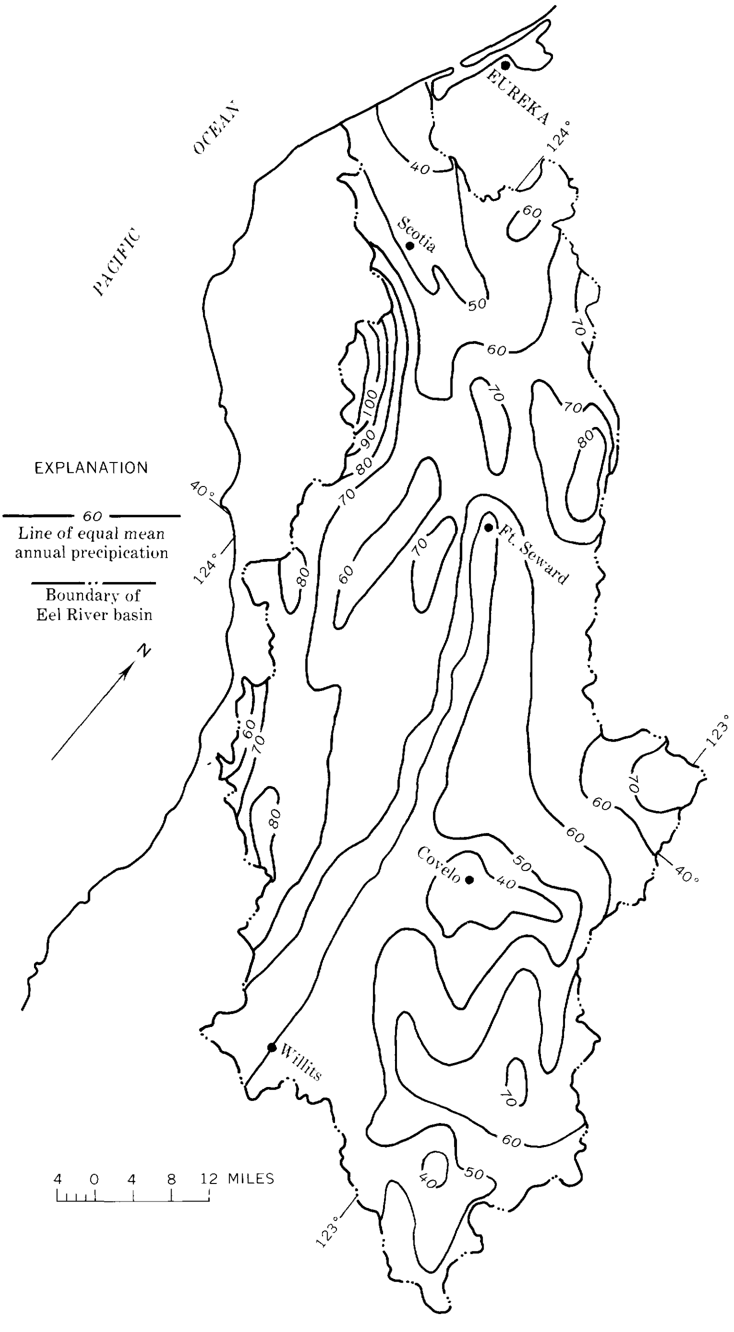


FIGURE 2.—Mean annual precipitation over the Eel River basin, 1900–63. (Rantz, 1968.)

TABLE 2.—*Precipitation and runoff for hydrologic units of the Eel River basin (adjusted to base period 1900–59)*

[From Rantz, 1964, table 1]

Hydrologic unit	Drainage area (sq. mi.)	Average annual precipitation (inches)	Average annual runoff	
			1,000's of acre-feet	Inches
Eel River above Middle Fork	709	52	1,140	30.2
Middle Fork Eel River above mouth	753	54	1,170	29.1
North Fork Eel River above mouth	282	59	425	28.3
South Fork Eel River above mouth	689	71	1,738	47.3
Eel River above Scotia gage	3,113	59	5,720	34.4
Van Duzen River above mouth	429	64	995	43
Eel River above mouth	3,625	59	6,808	35

The runoff throughout the basin is sustained almost entirely by overland runoff and base flow. Although snow does fall in the higher elevations of the eastern part of the basin, the runoff from snowmelt is generally insignificant. Most runoff is the result of large, general storms which affect the entire basin, and the unit frequency distribution of runoff is therefore similar for most individual streams. The ratio of precipitation to runoff varies with each storm depending upon the storm intensity and the amount of antecedent saturation of the soil. High flows diminish quickly in the absence of sustaining rainfall, and discharges drop well below their average annual values during the dry summer months, when there may be more than 200 days without significant precipitation.

Annual runoff extremes for the basin above Scotia during the period of sediment record were 20 inches in the 1964 water year and 67 inches during the 1958 water year. It is noteworthy that neither of these extremes was accompanied by the lowest or highest annual sediment discharge for the same period of record. A detailed study of the relations between runoff and sediment discharge is discussed in a subsequent section of this report (p. 22).

GEOLOGY

The rocks underlying most of the Eel River basin are a part of the Franciscan Formation, which extends over much of the northern Coast Ranges geomorphic province. This formation was described in some detail by Bailey, Irwin, and Jones (1964) and was described in general by Page (1966, p. 258) as a complex assemblage of sedimentary rocks of deep-water origin and mafic marine volcanic material, accompanied locally by masses of serpentine. Sandstone, chiefly graywacke, is the prevalent rock type in the part of the Franciscan assemblage that underlies the Eel River basin.

Upper Cretaceous and Tertiary sedimentary rocks rest on the Franciscan Formation along the western side of the basin, and al-

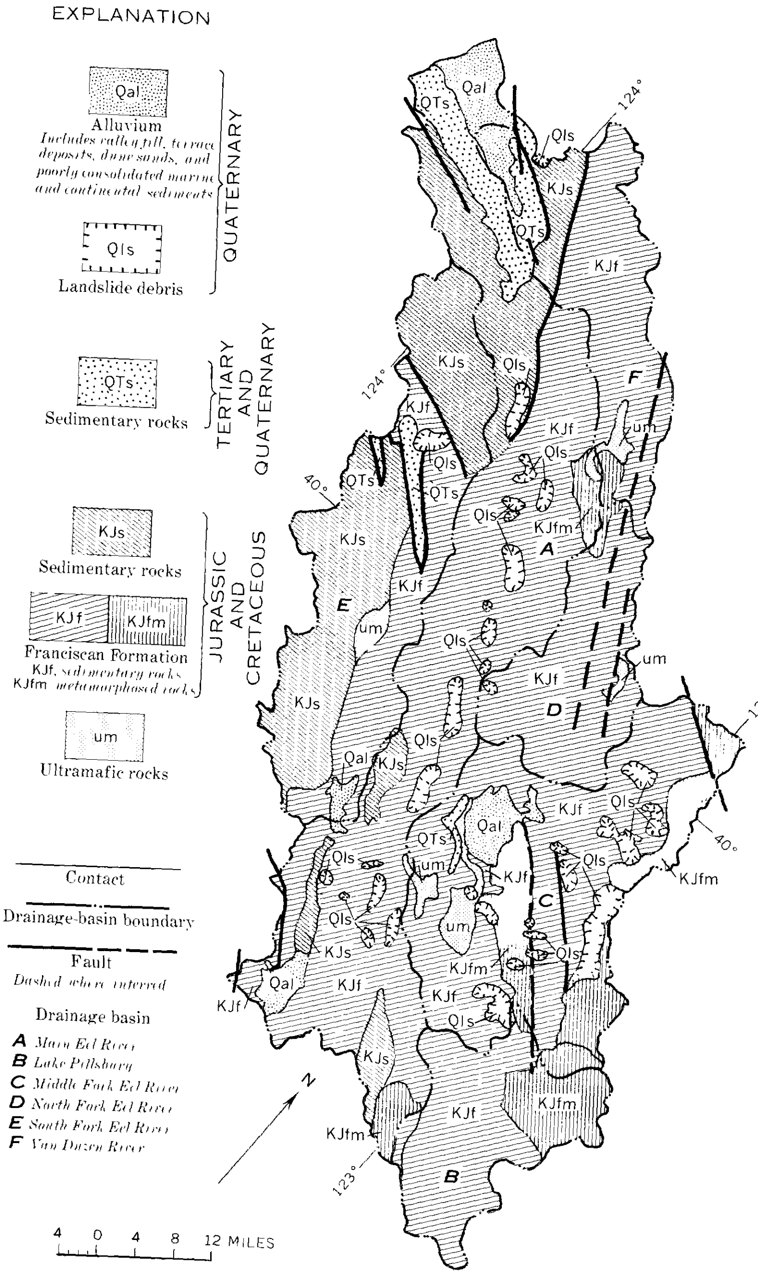


FIGURE 3.—General geology of the Eel River basin. Geology from California Department of Water Resources (1966).

luvial deposits are found in scattered regions of the basin, notably along the main stem of the Eel River (fig. 3).

Major structural features are formed by a complex pattern of strike-slip faulting generally oriented southeast-northwest, and the drainage patterns of the Eel River and its tributaries reflect this orientation. Topographic changes in this region are still in progress as regional uplifting and faulting, which began in the late Miocene period, continue to influence the landforms throughout the northern Coast Ranges.

Widespread areas of the Eel River basin are subject to landslides and earth flows. Combinations of uplifting topography, steep hillslopes, and the saturation of soils by rainfall contribute to mass-movement processes which are commonly augmented by the erosive action of streams along the base of the slopes. Because of their past and potential contributions of large quantities of sediment to stream channels, landslides and earth flows are of special interest in this report. For example, sediment yield is greatest in the central part of the basin along the main stem of the Eel River where large-scale sliding is common along both sides of the river for many miles.

SOILS

Although many soil types are present within the Eel River basin, the general character of soils throughout the basin is similar because the parent rocks are much the same over the entire basin. With minor variations, nearly all the soils are loamy in texture and generally range from 20 to 60 inches in depth (C. E. Stearns, written commun., 1968). These soils are generally stable with good infiltration rates and water-holding capacities, and the natural vegetal cover of the basin helps to reinforce this stability. However, the basin is often subject to a combination of conditions which tends to render these soils unstable. Soils resting on steep slopes become quickly saturated during periods of intense rainfall that follow extended periods of moderate precipitation, and severe erosion may thus occur in a very short period of time. In areas which have been subjected to heavy grazing or to deforestation by fires or lumbering practices, soils may become unstable and erosion may be severe even under normal runoff conditions.

VEGETATION

The vegetal cover of the Eel River basin includes a variety of forms, but the greater part of the basin is moderately to heavily forested with redwood and other conifers. The remaining part is covered by varying proportions of hardwood trees, chaparral, and grass.

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The distribution of these vegetation types forms four roughly defined and discontinuous belts which trend in a northwesterly direction parallel to the long axis of the basin. Along the western side grow forests of California redwoods (*Sequoia sempervirens*), the valuable and spectacular trees which are the basis of the lumber and recreation industries of the basin. The redwoods are concentrated in a large area surrounding the lower reaches of the Van Duzen and Eel Rivers, and they occupy most of the western drainage of the South Fork of the Eel River from Weott to Branscomb. The forest belt directly east of the redwood forests is predominately Douglas Fir but includes grasslands and scattered stands of pine. This belt, extending roughly from Kneeland south through Willits, reflects a change from the coastal climate to one of lower rainfall and less fog. A third zone of vegetation is less readily defined but includes a variety of hardwoods, mixed conifers, and chaparral in the central and southern parts of the basin. A woodland typified by oak, maple, and madrone extends somewhat discontinuously from Fort Seward to Potter Valley. Chaparral covers the drier areas of the southern part of the basin, especially in the vicinity of Lake Pillsbury and along Elk Creek. The fourth forest type, which consists of pines and Douglas Fir, covers the higher elevations of the eastern and southern parts of the basin. It extends over the headwaters of all the eastern drainage and constitutes commercial timberland typical of national forests.

LAND USE

Surveys of land use by the California Department of Water Resources (1965) divide land development within the Eel River basin into four major categories. Irrigated lands compose approximately 14,500 acres and include properties receiving water artificially. Dry-farmed lands are those on which farming practices are dependent upon the natural moisture supplied by ground water and precipitation. These lands cover some 32,000 acres—part concentrated in the delta area of the Eel and the remainder widely scattered throughout the basin. Urban lands compose 11,000 acres, less than 1 percent of the basin area, and are confined generally to the towns along the Eel River valley. Recreational lands make up approximately 28,200 acres of commercial and residential property, campsites, and parks. The remaining 2,272,300 acres of basin area is undeveloped and is used primarily for grazing livestock, various recreational activities, and commercial timber production.

HYDROGRAPHY

PHYSICAL CHARACTERISTICS OF STREAMS

A variety of factors influences the form and processes of natural streams, among which the most significant are precipitation and subsequent channel flow, the composition of the material forming the channel bed and banks, and the topography through which the stream flows. The following discussion describes the general and noteworthy features of the streams in the Eel River basin, and emphasizes those features that significantly affect sedimentation processes.

EEL RIVER ABOVE CONFLUENCE WITH MIDDLE FORK EEL RIVER

The upper Eel River emanates from the slopes of Bald Mountain in western Mendocino County, Calif., and flows in a southerly direction for 23 miles before turning westward and flowing into Lake Pillsbury. In this initial reach, the Eel drops through rugged, forested canyons at an average rate of 200 feet per mile (fig. 4). Several minor tributaries drain the 6,500-foot mountains which form the basin above Lake Pillsbury, and the Rice Fork of the Eel drains the chaparral-covered slopes of the southern tip of the basin, entering Lake Pillsbury from the south.

Soils through which these streams flow are primarily the deep forest soils which tend to be moderately erodible under dense forest vegeta-

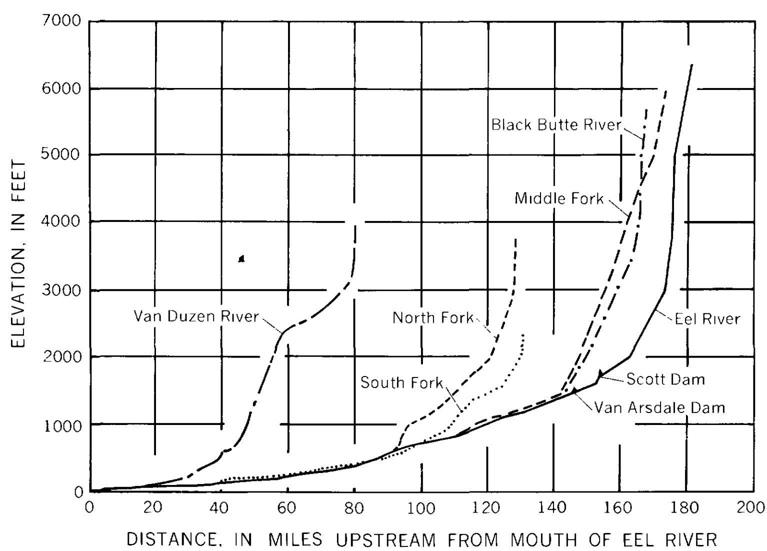

FIGURE 4.—Longitudinal profiles of streams, Eel River basin.

tion. However, a large area of highly erodible material extends south and east of Lake Pillsbury through the Rice Fork basin where the vegetal cover is predominantly chaparral. Below Lake Pillsbury, the water released at Scott Dam continues its westward flow 10 miles to Van Arsdale Reservoir where a portion of it is diverted into the Russian River basin. This diversion is a part of Pacific Gas and Electric's Potter Valley Project to supply water and power for local areas in Lake, Sonoma, and Mendocino Counties. About one-third of the average flow of the Eel River at this point is diverted into Potter Valley. Downstream from Van Arsdale Reservoir, the Eel River turns northwestward, dropping with an average slope of 16 feet per mile to its confluence with the Middle Fork of the Eel River, 55 miles downstream. Landslides and bank slumping are common along this reach, and the slopes adjacent to the river are generally composed of moderately to highly erodible soils.

Outlet Creek is the major tributary of the Eel above its confluence with Middle Fork Eel River. Outlet Creek has its source in the vicinity of Little Lake Valley and flows into the Eel from the west. Lower elevations, mild slopes, and generally less erodible materials characterize its drainage basin. Tomki Creek provides additional drainage for the steeper, forested area between Van Arsdale Dam and Little Lake Valley.

EEL RIVER BELOW CONFLUENCE WITH MIDDLE FORK EEL RIVER

From Dos Rios to its mouth at the Pacific Ocean, the Eel continues its northwesterly course at a generally regular slope of 8 feet per mile. The Eel River canyon retains its narrow, boxlike proportions throughout most of this reach until the valley begins to widen below Scotia. The North Fork Eel River and the Van Duzen River are the major tributaries entering the Eel from the east along this reach, and the South Fork Eel River provides the principal drainage from the west. The Van Duzen and South Fork Eel Rivers are discussed in separate sections within this report.

The Eel River canyon from Van Arsdale Reservoir north to Eel Rock is characterized by large-scale landsliding, and sediment records indicate that the major part of suspended-sediment discharge from the basin originates in this reach. In addition to the direct contribution of landslides to the main channel, at least 20 short steeply sloping tributaries drain two parallel ridges between which the Eel River flows from Dos Rios to the South Fork, and these streams may be major contributors of fluvial sediment by their combined effects. These smaller streams contribute sediment from side canyons, transport slide material to the main stream, and erode deposits along the channel of the Eel River as it recedes after flooding.

MIDDLE FORK EEL RIVER

The headwaters of the Middle Fork Eel River drain the forested high country of the eastern Eel River basin divide. Stream slopes of these waters are very steep, averaging approximately 140 feet per mile above the mouth of the Black Butte River. Below the Black Butte River to its confluence with the Eel near Dos Rios, the Middle Fork has a more gentle slope of about 21 feet per mile.

The headwater streams of the Middle Fork flow through areas underlain by the metamorphosed sedimentary rocks of the Franciscan Formation, but Elk Creek and the streams in the vicinity of Covelo flow through a complex structure of Quaternary alluvium, marine terrace deposits, and intrusive ultramafic material. Soils formed on the rocks of the central basin lie on gently sloping ground and are more erosion resistant than those in the upper basin. Between the mouth of Elk Creek and Dos Rios, the Middle Fork flows through a narrow canyon where it transects the ridge between adjacent fault-formed valleys.

BLACK BUTTE RIVER

The Black Butte River drains 162 square miles of steep mountain slopes and enters the Middle Fork from the south. The river has a slope of 163 feet per mile along its straight northwesterly course, and the orientation and formation of its valley are probably related to a fault which parallels the river throughout most its length. Deposits of Quaternary landslide material on the slopes along the east side of the river provide a ready source of sediment (fig. 3). The Black Butte River basin is otherwise underlain by the Franciscan sandstones, shales, and conglomerates typical of most of the rest of the Eel River basin.

SOUTH FORK EEL RIVER

The drainage of the South Fork is unique among the tributaries of the Eel, differing in form, climate, vegetation types, and underlying rock. The South Fork has an average slope of 24 feet per mile for its 92-mile length. It flows northwest parallel to the main stem of the Eel through the redwood forests which cover most of its western drainage. Underlying materials are marine sands of Cretaceous age similar to those of the Franciscan Formation but distinctive to the South Fork and lower Eel drainages (fig. 3). The soils that form on this formation are highly erodible, especially along the steeply sloping western side of the basin. The landslide topography found in many areas throughout the Eel River basin does not exist along the South Fork except in a small region north of Garberville.

VAN DUZEN RIVER

The Van Duzen River drains the northern reaches of the Eel River basin and flows out into the flat delta region of the Eel about 11 miles inland from the ocean. The river has an average slope of 59 feet per mile over its 67-mile length. Its headwaters drop quickly from the 4,000-foot elevations near the eastern boundary of the basin at a rate of 110 feet per mile over the first 15 miles, but the stream gradient decreases to less than 30 feet per mile below Bridgeville.

The Van Duzen River and its principal tributary, Yager Creek, flow through moderately sloping grassland in the central part of the drainage basin and through redwood forests in their lower reaches. Many of these grassland areas are underlain by unstable soils and are subject to erosion by gullying. The lower reaches of the basin are underlain by Quaternary terrace deposits and alluvium, and the bedrock of the upper basin contains the sandstone and conglomerate of the Franciscan Formation (fig. 3). Bank cutting and sliding are common along Yager Creek north of Carlotta and along the Van Duzen River between Carlotta and Bridgeville.

HYDRAULIC GEOMETRY

The physical characteristics of streams include the hydraulic geometry of stream channels, which is defined by the relations among certain hydraulic characteristics of the stream (Leopold and Maddock, 1953). At a given cross section, depth, width, velocity, and suspended load vary as power functions of the discharge according to equations of the following form:

$$w=aQ^b \quad (1)$$

$$d=cQ^f \quad (2)$$

$$v=kQ^m \quad (3)$$

$$L=pQ^j \quad (4)$$

where

w=width
d=mean depth=area divided by width
v=mean velocity
L=suspended-sediment load
Q=water discharge
a, c, k, p, b, f, m, and j are numerical constants.

These equations may be determined empirically by plotting data obtained from current-meter and other measurements at river cross sections. When width, depth, velocity, and suspended load are plotted against discharge on logarithmic paper, their relations to discharge are expressed by nearly straight lines.

The graphs of figure 5 illustrate the changes of width, depth, and velocity with discharge of the Eel River at Scotia. The values shown for the exponents b, f, and m are consistent with the nature of the channel. The steep-walled canyon restricts the channel width while the depth and velocity increase rapidly with increasing discharge. The graphs shown are for the period following the December 1964 flood; however, a comparison of these data with preflood data shows that there has been no appreciable change in the hydraulic geometry at Scotia from preflood conditions.

Table 3 lists the parameters of the hydraulic geometry at Scotia and four other stations in the Eel River basin. The data used to de-

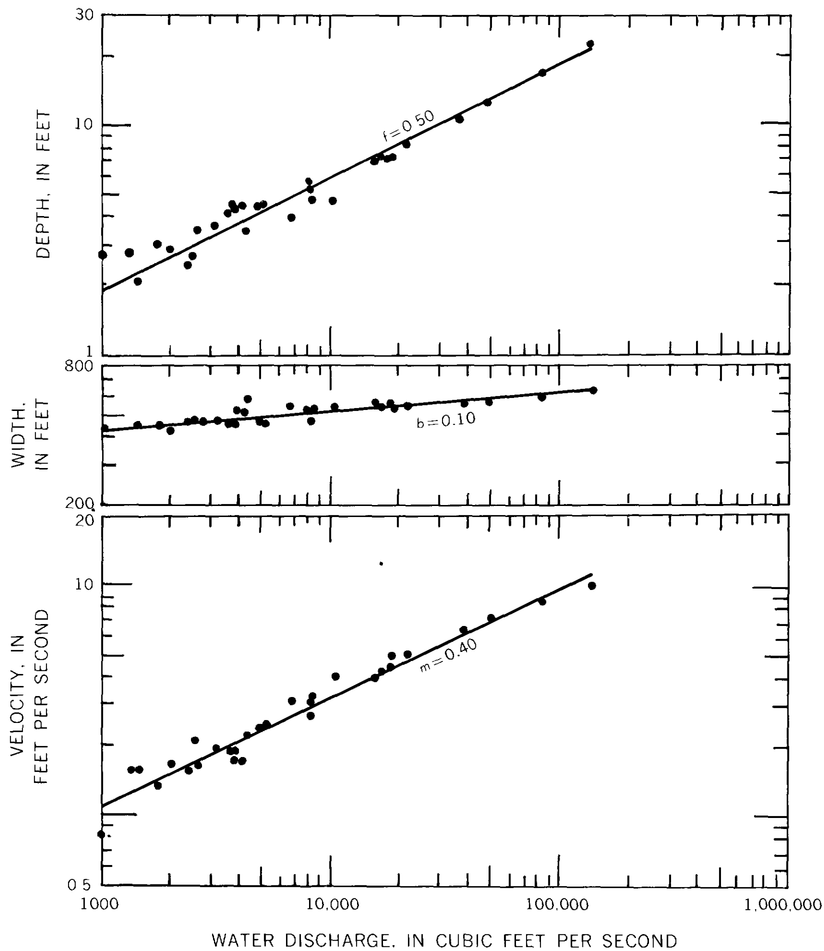

FIGURE 5.—Relation of depth, width, and velocity to discharge, Eel River at Scotia, 1965–68.

rive these parameters were collected during the period 1965–68, and the values shown typify the hydraulic geometry of these stations for this period. Although these values may not provide a visual picture of the channel conditions along the Eel River, they may be used for comparison with those of the other rivers listed.

TABLE 3.—*Rate of increase of width, velocity, and depth with discharge*

[Exponents *b*, *m*, and *f* are defined by equations 1-3 (p. 16)]

Station and location	Rate of increase with discharge (*Q*)			
	b (width)	*m* (velocity)	*f* (depth)	*Q* more than— (cfs)
Black Butte River near Covelo, Calif.	0.06	0.26	0.68	750
Middle Fork Eel River below Black Butte River, near Covelo, Calif.	.10	.32	.58	500
Middle Fork Eel River near Dos Rios, Calif.	.14	.27	.59	1,000
Eel River at Fort Seward, Calif.	.10	.54	.35	1,000
Eel River at Scotia, Calif.	.10	.40	.50	1,000
Rio Grande at San Felipe, N. Mex.[1]	.22	.30	.48	
Rio Grande near Bernalillo, N. Mex.[1]	.03	.51	.46	1,000
Middle Loup River at Arcadia, Nebr.[1]	.13	.35	.52	
Moreau River near Faith, S. Dak.[1]	.10	.34	.56	400
Rio Puerco at Rio Puerco, N. Mex.[1]	.43	.41	.16	
Bighorn River at Thermopolis, Wyo.[1]	.14	.55	.31	
Powder River at Arvada, Wyo.[1]	.10	.31	.59	200
Saline River near Russell, Kans.[1]	.37	.25	.38	

[1] Leopold and Maddock (1953).

At each station on the Eel River, the velocity and depth increase with increasing discharge more rapidly than the width. Velocity increases most rapidly at Eel River at Fort Seward and does so at a rate greater than the rate of increase of the depth. Among the selected stations along the Eel River, this characteristic prevails only at Eel River at Fort Seward, perhaps because the channel is somewhat constricted at that site.

Leopold and Maddock (1953, p. 21) stated that it is typical at a given cross section of an alluvial stream for the suspended-sediment load to increase with increase in discharge, and at a more rapid rate than discharge. That is, the concentration of suspended sediment increases with discharge. At the stations in the Eel River basin, the daily suspended-sediment discharge increases as a power (j, 4) of water discharge ranging from about 1.8 in the upper parts of the sediment-transport curves to about 2.6 in the lower parts (table 4). These values are consistent with those postulated by Leopold and Maddock.

The downstream variation in suspended-sediment discharge at a given frequency of water discharge provides useful information about the nature of sediment transport in the Eel River basin. Concurrent records of suspended-sediment discharge were collected at five stations in downstream order from Black Butte River near Covelo to Eel River at Scotia for the period October 1965–September 1967. After a sediment-transport curve was plotted for each station for this period, the suspended-sediment discharge corresponding to the mean annual water discharge, Q_{mean}, at each station was taken from the curve. These values were used to plot the first graph in figure 6. The second graph in figure 6 was plotted in a similar manner; however, the water discharge used was that discharge equaled or exceeded 1 percent of the time at each station (Q_{01}). It is shown later in this report that Q_{01} produced about 50 percent of the suspended-sediment discharge for the period of record for most stations in the Eel River basin. The graphs indicate that the concentration of suspended sediment increased in a downstream direction at a given frequency of discharge

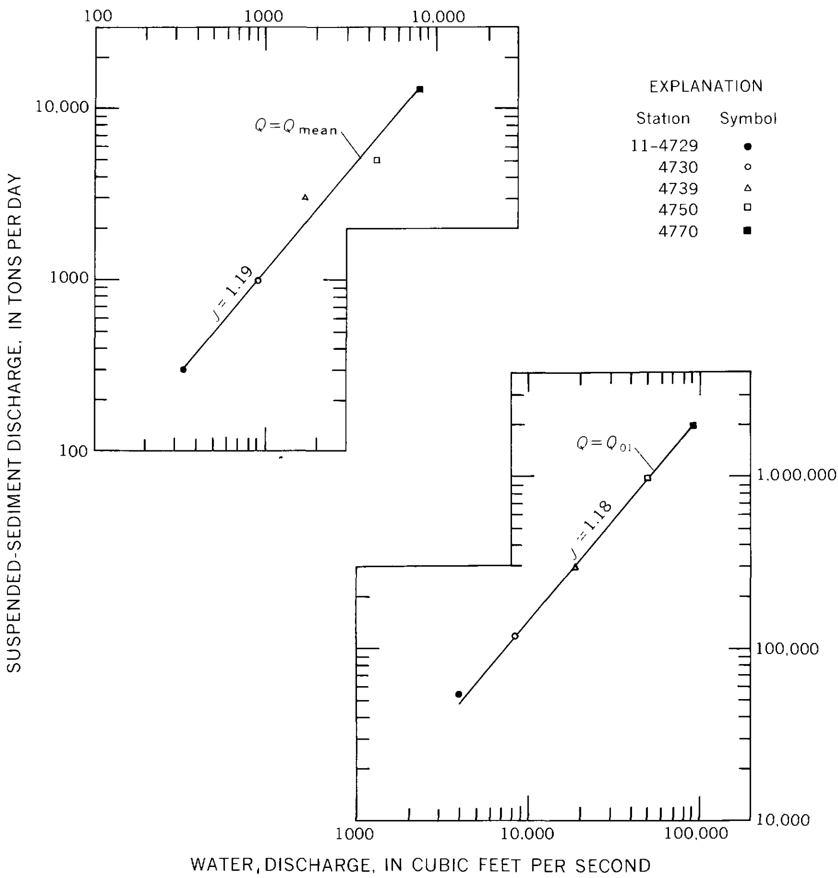

FIGURE 6.—Downstream variations in the relation between water discharge and suspended-sediment discharge in the Eel River basin, October 1965–September 1967. Q_{mean} is the mean annual discharge, and Q_{01} is the discharge equaled or exceeded 1 percent of the time for each station shown. The stations and their corresponding numbers are given in table 5.

TABLE 4.—*Rate of increase of suspended-sediment discharge with water discharge at selected stations in the Eel River basin*

Station and period of record (water years)	Range of water discharge (cfs)	Approximate value of *j* in equation 4
Black Butte River near Covelo, 1966–67	100– 1,000	2.6
Middle Fork Eel River below Black Butte River near Covelo, 1963–67	1,000– 10,000	2.2
Middle Fork Eel River near Dos Rios 1958–67	500– 5,000	2.2
	5,000– 50,000	1.8
Eel River at Fort Seward 1966–67	1,000– 10,000	2.5
	10,000–100,000	2.0
Eel River at Scotia, 1958–67	4,000– 40,000	2.3
	40,000–700,000	2.4
South Fork Eel River near Branscomb, 1963–67	200– 2,000	2.5
	2,000– 20,000	1.8

and that concentrations increased at about the same rate for discharges between Q_{mean} and Q_{01}. (The latter observation was tested, and there was no appreciable change in j for other values of Q between Q_{mean} and Q_{01}.) These phenomena are supported by the observation that the average annual yield of suspended sediment per square mile of drainage area increased with increasing drainage area (table 5). Although these empirical observations show conditions atypical of other rivers (Leopold and Maddock, 1953, p. 22), they give some insight into the unusually high capacity for sediment transport of the Eel River and its tributaries. These observations help to verify that there was less sediment-free inflow, such as ground-water inflow, than sediment-producing runoff as the drainage area increased downstream. It is possible that the erodibility of the basin changes in a downstream direction because of changing geology below Fort Seward (fig. 3), although data are insufficient to support this contention adequately.

TABLE 5.—*Downstream variations in sediment yield and hydraulic geometry, Eel River basin*

[Upper values, at Q_{mean}; lower values, at Q_{01}]

Station and No.	Average sediment yield, 1966–67 (tons per sq mi) [1]	Average sediment yield, 1963–67 (tons per sq mi) [1]	Variation in hydraulic geometry at Q_{mean} and Q_{01} (1966–67)					
			Q (cfs)	W (feet)	d (feet)	V (ft per sec)	L (tons per day)	Concentration (mg/l)
Black Butte River, near Covelo 11-4729.	4,330		338		1.0	4.0	300	330
			4,050	160	3.3	7.6	55,000	5,040
Middle Fork Eel River, below Black Butte River, near Covelo, 11–4730.	4,210	8,127	914		1.1	4.2	1,000	400
			8,500	250	3.9	8.6	120,000	5,220
Middle Fork Eel River near Dos Rios, 11–4739.	6,181	12,027	1,726		1.8	4.6	3,000	640
			19,100	275	7.7	8.8	300,000	5,810
Eel River at Fort Seward, 11–4750.	6,932		4,472		7.2	2.4	5,000	410
			50,000	350	18	8.8	1,000,000	7,410
Eel River at Scotia, 11–4770.	8,311	15,829	7,853		5.5	2.8	13,000	610
			93,400	600	18	9.0	2,000,000	7,930

[1] Values computed from data shown in table 8.

The Eel River accommodated high sediment-producing discharges in 1966 and 1967 principally by a downstream increase in depth of flow (fig. 7). At Q_{01}, depth of flow increased downstream at about twice the rate of increase in width, while the downstream rate of increase in velocity was almost negligible.

Further analysis of the hydraulic geometry of the Eel River basin is somewhat hampered by insufficient data and is generally beyond the scope of this report. However, the material presented in this section when viewed in connection with other information presented in this report and with other findings (Carlston, 1969) may be useful in future and more detailed studies of the Eel and similar rivers.

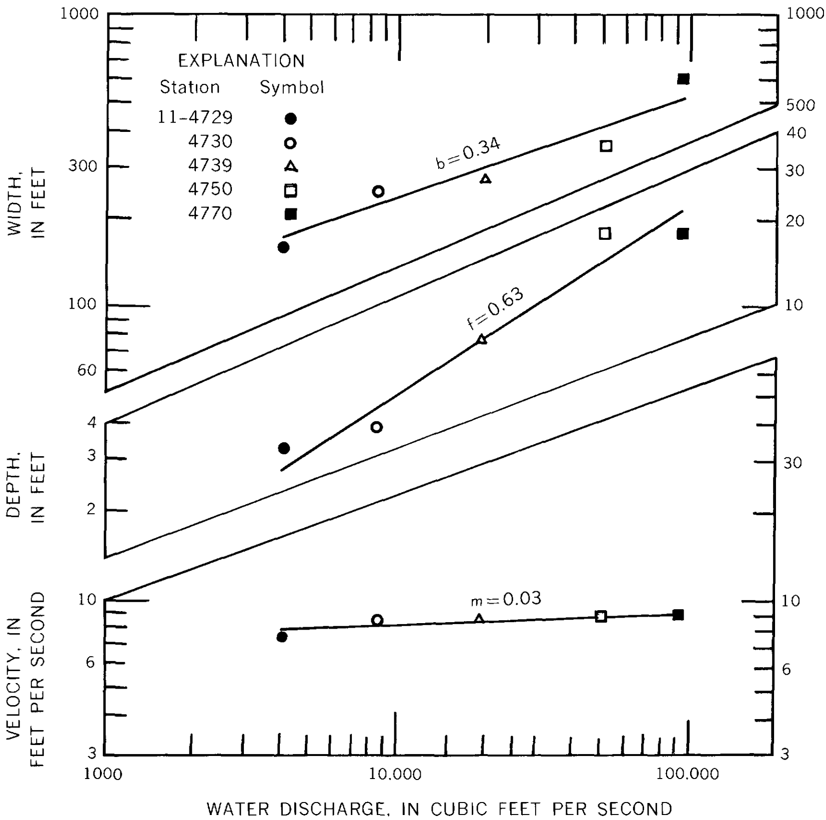

FIGURE 7.—Relation of width, depth, and velocity to discharge, showing downstream variations in the hydraulic geometry of the Eel River, October 1965–September 1967. The discharge from which the points are plotted is that discharge, Q_{01}, equaled or exceeded 1 percent of the time for each station shown.

FLUVIAL SEDIMENT

DEFINITION OF TERMS

Many terms relating to fluvial sediment are not completely standardized; the terminology used in this report is based on the following definitions:

Fluvial sediment or **sediment** is fragmental material that originates from weathering of rocks and is transported by, suspended in, or deposited by streams.

Suspended sediment or **suspended load** is sediment that moves in suspension in water and is maintained in suspension by the upward components of turbulent currents or by colloidal suspension.

Bedload or **sediment discharged as bedload** includes both the sediment that moves along in continuous contact with the streambed (contact load) and the material that bounces along the bed in short skips or leaps (saltation load).

Sediment sample is a quantity of water-sediment mixture that is collected to determine the concentration of suspended sediment, the size distribution of suspended or deposited sediment, or the specific weight of deposited sediment.

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

Sediment-transport curve is a curve of relation between water discharge and sediment discharge. Usually the relation is between water discharge and suspended-sediment discharge, but it can be between water discharge and bedload discharge or between water discharge and total sediment discharge (sum of sediment discharge in suspension and as bedload).

Water discharge or **discharge** is the amount of water flowing in a channel expressed as volume per unit of time. The water contains both dissolved solids and suspended sediment.

The general principles of sediment-discharged measurement as well as the practical aspects of selecting sampling points and determining the frequency of sampling are discussed in several reports. A suitable reference on methods of measurement and analysis of sediment loads is Report 14 of the U.S. Inter-Agency Committee on Water Resources (1963). The procedure for the measurement of water discharge was described in detail in Corbett and others (1943).

METHODS OF COMPUTATION

Basic data which were interpreted for use in graphs and tables in this report were prepared according to standard procedures of the U.S. Geological Survey, Water Resources Division, California District. However, it is instructive to comment further on certain of these procedures and the methods of data interpretation in this report because of the record values of some of the sediment-discharge data.

The sediment yield of the Eel River basin and its subunits is determined in this report primarily from measured, computed, and estimated rates of transport of suspended sediment. These rates correspond to certain significant time periods within the years during which sediment samples were taken, and the rates can be extrapolated to other periods of time, given certain complementary information (Miller, 1951). However, an extreme flood event which occurred during the period of sediment record produced sediment-transport rates of such magnitude that their correspondence to time periods other than the period during and after the flood is somewhat obscure. Thus, the analyses here are presented on the basis of preflood and postflood sediment transport rates, with the emphasis that the characteristics of these rates are probably dissimilar. Extrapolation is performed using both preflood rates and rates for the entire period of record so that the bias of the flood effects is apparent.

Sediment-transport curves shown in this report were plotted from suspended-sediment data according to standard procedures with the following exception: The coordinates of each of the points used to define the curves represent an average value for a selected interval of water discharge and the corresponding average sediment discharge computed for that interval. These computations were performed as a part of a computer program written for this purpose, and a sample of the output of this program is shown in table 6. The data show that the upper end of the curve is defined by only a few points, and the water and sediment discharges defining some of these points are estimated or computed rather than measured directly. However, the value used to define the upper ends of curves shown in this report have not been revised to fit an assumed pattern. Only values previously computed and published have been used to maintain consistency in reports on this subject and to allow for the fact that some sediment-discharge values are affected by unusual hydrologic events. Obviously, there are limitations on the accuracy of the sediment-transport curves and the accuracy of extreme values estimated from these curves. However, the adequacy of these values cannot be intelligently evaluated until additional information is obtained on the probable accuracy of measured sediment discharge (Colby, 1956, p. 167). It should be sufficient to say that interpolation of the curves and use of the extreme values presented in this report should be done with caution and with the previous comments in mind. Extrapolation of curves shown in this report, especially at the upper end, is too likely to be in error to be useful because there are too few measured values, and many of the estimated values were the result of an extremely infrequent flood event (Helley and LaMarche, 1968).

TABLE 6.—*Sample of computer output of program designed to compute an average relation between water discharge and suspended-sediment discharge*

[A plot of Q_w versus Q_s may accompany this output at the option of the user]

11-4770. Eel River at Scotia, Calif.

[Period of daily record: October 1957-September 1967]

Range of water discharge, Q_w, in cubic feet per second	Average of discharges within range listed in column 1, in cubic feet per second	Average suspended-sediment discharge, Q_s, in tons per day, corresponding to value of Q_w in column 2	Number of days during period of record when Q_w within range listed in column 1	Percent of time Q_w equaled or exceeded
0. 0- 10. 0			0	100. 00
10. 0- 100. 0	78. 2	0. 52	104	100. 00
100. 0- 200. 0	146. 0	0. 94	759	97. 15
200. 0- 300. 0	243. 5	2. 14	243	76. 37
300. 0- 500. 0	378. 2	5. 82	192	69. 72
500. 0- 750. 0	622. 4	11. 23	141	64. 46
750. 0- 1000. 0	861. 6	35. 95	102	60. 60
1000. 0- 1500. 0	1256. 3	54. 25	187	57. 80
1500. 0- 2000. 0	1718. 7	111. 60	164	52. 68
2000. 0- 3000. 0	2511. 5	241. 29	282	48. 19
3000. 0- 4000. 0	3464. 2	793. 04	200	40. 47
4000. 0- 5000. 0	4478. 9	1621. 74	174	34. 99
5000. 0- 6000. 0	5478. 2	2772. 40	121	30. 23
6000. 0- 7000. 0	6507. 4	4969. 24	92	26. 92
7000. 0- 8000. 0	7486. 9	5855. 47	95	24. 40
8000. 0- 9000. 0	8490. 5	8170. 84	59	21. 80
9000. 0- 10000. 0	9496. 3	14156. 20	71	20. 18
10000. 0- 11000. 0	10452. 6	14736. 31	38	18. 24
11000. 0- 12000. 0	11461. 5	20726. 73	52	17. 20
12000. 0- 13000. 0	12360. 6	25039. 09	33	15. 77
13000. 0- 14000. 0	13380. 0	26781. 66	30	14. 87
14000. 0- 15000. 0	14346. 4	32095. 36	28	14. 05
15000. 0- 20000. 0	17406. 7	51303. 33	120	13. 28
20000. 0- 25000. 0	22135. 1	80425. 62	74	9. 99
25000. 0- 30000. 0	26837. 2	126637. 19	43	7. 97
30000. 0- 40000. 0	34716. 2	199858. 06	74	6. 79
40000. 0- 50000. 0	43915. 2	295276. 06	46	4. 76
50000. 0- 60000. 0	54757. 1	447514. 25	35	3. 50
60000. 0- 70000. 0	65317. 4	495434. 75	23	2. 55
70000. 0- 80000. 0	72438. 4	615384. 56	13	1. 92
80000. 0- 90000. 0	83707. 1	906428. 56	14	1. 56
90000. 0- 100000. 0	94130. 8	1273538. 00	13	1. 18
100000. 0- 150000. 0	119473. 6	1904052. 00	19	0. 82
150000. 0- 200000. 0	184250. 0	6262500. 00	4	0. 30
200000. 0- 250000. 0	206500. 0	3540000. 00	2	0. 19
250000. 0- 300000. 0	261000. 0	5995000. 00	2	0. 14
300000. 0- 400000. 0	311000. 0	19000000. 00	1	0. 08
400000. 0- 500000. 0			0	0. 05
500000. 0- 600000. 0	521000. 0	40000000. 00	1	0. 05
600000. 0- 700000. 0	648000. 0	57000000. 00	1	0. 03
700000. 0- 800000. 0			0	0. 0
800000. 0- 900000. 0			0	0. 0
900000. 0-1000000. 0			0	0. 0
Total			3, 652	

FLOOD OF DECEMBER 1964

In December 1964, rainfall of historically unprecedented intensity coupled with conditions favorable for heavy runoff produced record flooding in the Eel River basin, as well as in a large area of the Western United States (Rantz and Moore, 1965). Rainfall which in places exceeded 20 inches in a 48-hour period produced runoff that sent river stages 5–15 feet above previous record stages and caused severe damage in river valleys in all parts of the Eel River basin. High-velocity flow and high stages accelerated erosional processes so much that an enormous volume of soil and rock was stripped from the land and deposited downstream or carried to the sea.

Bank slumping, landslides, and channel scouring in upstream reaches contributed a record sediment load to streams throughout the basin, and the downstream deposition of this material added to the damage caused by the rampaging waters. Sediment and debris clogged bridges and culverts, forcing floodwater to overtop the structures or to seek alternative channels. In the flood plains and other areas of the lower valleys where the flow velocity decreased, sediment commonly was deposited to depths of several feet. Houses, stores, and automobiles abandoned before the rising waters were left filled with sediment and debris when the water receded (figs. 8 and 9).

The quantity and distribution of material transported during the course of the flood are best determined from the suspended-sediment discharge measurements made at gaging stations at that time. That ideal could not be realized at various stations during the 1964 flood. At every station for which sediment records were available or could be calculated, the volume of suspended sediment and the rate at which it moved exceeded all previous records. For example, a suspended-sediment discharge of 116 million tons was computed for Eel River at Scotia for a 3-day period beginning December 22, 1964. The total suspended-sediment load at this station for the previous 8 years amounted to 94 million tons.

Erosion was most severe in the eastern section of the Eel River basin where the North and Middle Forks of the Eel River were fed by runoff from the steep westward-facing slopes. These slopes, saturated by antecedent precipitation and somewhat unstable even under normal conditions, were badly eroded by landslides, slumps, and gullying in areas of sparse vegetal cover. Material derived from this type of erosion, added to the contributions from banks and channels, provided the sediment load for the steeply sloping tributaries of these two rivers.

Farther downstream in the vicinity of the confluence of the Middle Fork Eel and Black Butte Rivers, enough sediment was deposited

FIGURE 8.—Remains of the devasted town of Pepperwood on the Eel River upstream from Scotia, Feb. 5, 1965. Pepperwood was destroyed by flooding during December 1955. It was subsequently rebuilt, only to be destroyed again by the flood of December 1964.

FIGURE 9.—House engulfed by landslide associated with the December 1964 flood near the South Fork Eel River about 15 miles downstream from Garberville. A small stream is flowing over the top of a fence which once bridged the stream near where the man is standing.

as a result of the flood to raise the streambeds 6–8 feet (Hickey, 1968, p. E8). Hickey noted that in this area, channel fill continued during the following water year, probably as a result of continued erosion of material brought into upstream reaches during the 1964 flood period.

On the upper main stem of the Eel, 2 feet of sediment was deposited just above the confluence with the Middle Fork. Sediment transport and deposition from this point upstream is partly influenced by the operations of Lake Pillsbury and Van Arsdale Reservoir.

During the period December 21–30, 1964, the suspended-sediment discharge computed for Eel River at Scotia was about 145 million tons. A suspended-sediment load of about 7½ million tons was computed during this same period at Eel River above Dos Rios compared with a load of approximately 8½ million tons at Middle Fork Eel River near Dos Rios. Although measurements of sediment discharge for the flood period are not available for points along the Eel River between Dos Rios and Scotia, the difference between sediment discharges computed at these two points equals the suspended-sediment yield for the central part of the basin less material deposited along the channel. If the sediment discharge of the South Fork is taken to be approximately 19 million tons, the computed value for the sediment load derived from the central part of the basin and the North Fork

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drainage is 110 million tons, or 76 percent of the sediment load at Scotia. The sediment load estimated for the South Fork Eel River was taken as 13 percent of the load computed at Scotia on the basis of relations between past records at the two stations; however, the accuracy of this value is of minor significance in this particular example. The large sediment yield between Dos Rios and Scotia emphasizes the need for additional sediment data from along this reach.

EEL RIVER AT SCOTIA

Sediment studies began at Eel River at Scotia in September 1955. Periodic observations were made during the 1956 and 1957 water years, and a program of daily sampling was begun in October 1957. Suspended-sediment measurements are made from the bridge on U.S. Highway 101, 0.5 mile north of Scotia and 6 miles upstream from the mouth of the Van Duzen River. The Eel River channel along this reach is straight for a distance of 1,000 feet above and 1,000 feet below the bridge and has steep wooded banks which are not subject to overflow. The channel is fairly stable and the annual changes in streambed elevation are minor. The streambed is a shallow layer of gravel resting on bedrock, and the bottom topography generally consists of shifting gravel bars and exposed bedrock. Bank slumping occurs at higher stages of flow (fig. 10).

FIGURE 10.—Two views (above and facing page) of the left bank of the Eel River just upstream from the Scotia gage, Feb. 5, 1965. A fallen tree, undermined by erosion during the December 1964 flood, rests on a shelf at the transition from alluvial material to bedrock. Flow in picture above is from left to right.

During the 10-year period of daily sediment record, large variations in both runoff and sediment discharge occurred at the Scotia station. Precipitation and runoff were greatest during the 1958 water year when the total runoff was the highest for the 55-year period of record for the station. A large number of rainy days resulted from storms occurring during each month from October through April, and days of high sediment transport were more evenly distributed than in the following 9 years. Runoff was lowest in the 1964 water year, and high flows occurred only in November and January. Annual discharges within 15 percent of the mean annual flow at Scotia were measured during 3 of the 10 years of sediment record.

Suspended-sediment discharge of Eel River at Scotia was 313,900,000 tons from October 1957 through September 1967. Maximum yearly discharge was 167,800,000 tons for the 1965 water year, and the minimum yearly discharge was 4,758,000 tons during the 1962 water year. The monthly maximum suspended-sediment load was 145,700,000 tons in December 1964, and the minimum was 12.3 tons in October 1958. The maximum daily load was an estimated 57 million tons on December 23, 1964, and minimum discharge of less than 0.5 ton per day was measured nearly every year during September and October.

The relation between water discharge and suspended-sediment discharge for Eel River at Scotia is shown in figure 11. This curve represents the 10-year period of sediment record at this station and is biased by the record sediment discharges observed during the 1965 water year. The points through which the curve is drawn are plotted from the data shown in table 6.

To demonstrate the effect of the December 1964 flood on the relation between water discharge and suspended-sediment discharge at Scotia, similar computations were made for the preflood and postflood data, an the resulting curves are shown in figure 12. These data must be supplemented by additional data from the years following 1967 in order that apparent trends may be established as conclusive; however, the curves of figure 12 indicate at least a temporary change in trend. A similar change may have been associated with the large-scale flooding of 1955; however, this cannot be substantiated. Sufficient information is not available to determine the duration of these effects; thus, it is not known if the 1965–67 trend will persist for more than a short period.

The seasonal variability of sediment yield for the Eel River at Scotia and other stations is illustrated by figure 13. In every year, increased sediment yield is an immediate result of winter storms, and the greater part of the total annual load is moved during the days of maximum runoff in these storm periods. The effects of snowmelt,

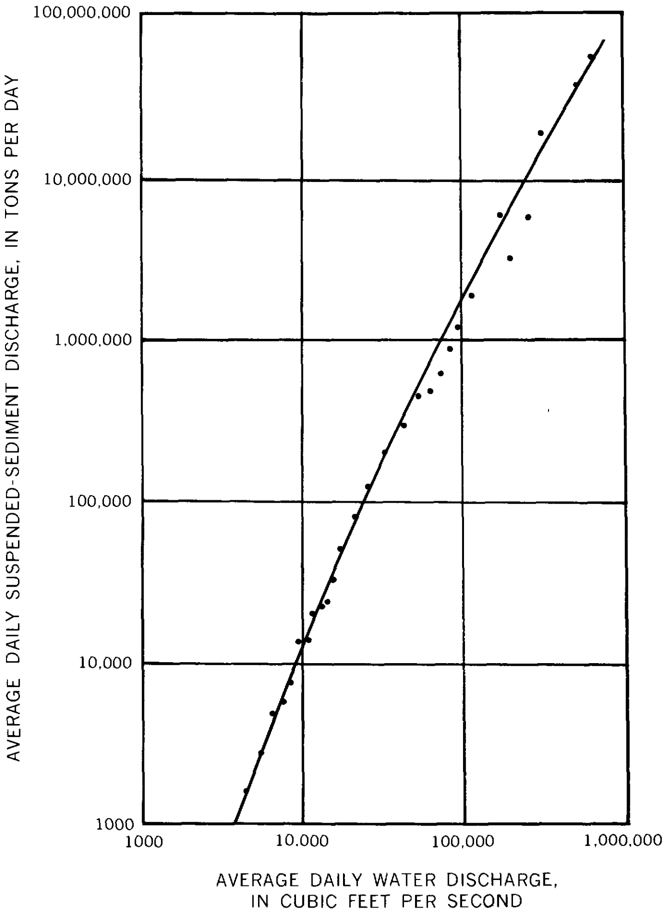

Figure 11.—Sediment-transport curve for Eel River at Scotia, October 1957–September 1967.

frozen ground, and runoff from ground-water inflow are usually insignificant in the movement of sediment during periods between storms. Sediment transport during the summer months is negligible.

Figure 14 indicates an approximate relation between yearly water discharge and sediment load. Because the relation between sediment discharge and streamflow is not constant throughout the year, the use of this curve for estimating periods shorter than a year would be misleading. The data are so scattered that even the estimation of annual sediment discharges is questionable, and several additional data points will be needed to define a more usable curve. Estimates or interpolation of sediment discharge may be done more accurately on a daily basis using the curves of figure 12.

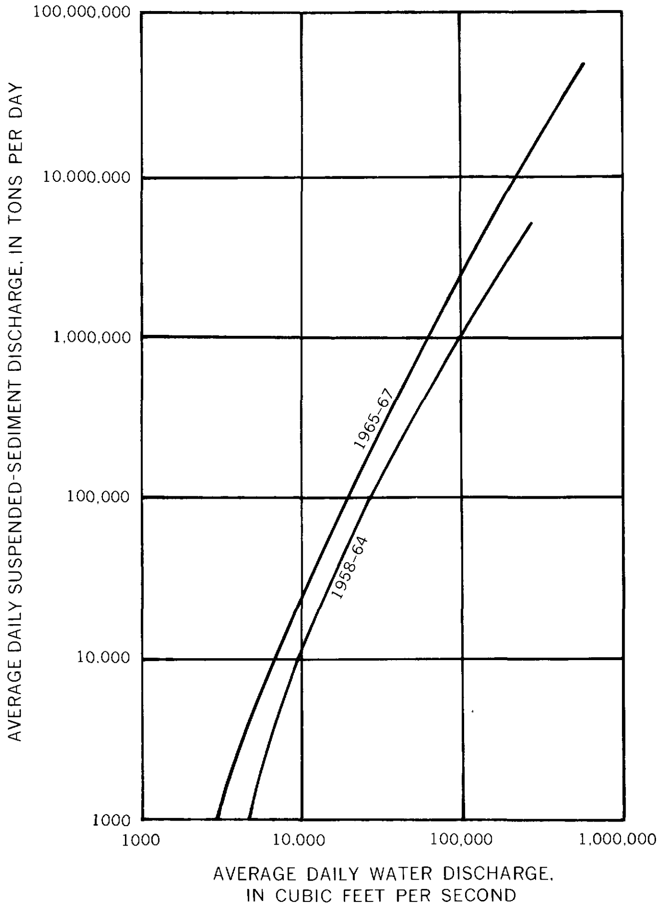

FIGURE 12.—Sediment-transport curves for Eel River at Scotia, showing the change in sediment-transport characteristics after the December 1964 flood.

The variation in particle-size distribution with water discharge for sediment carried as suspended load is shown in figure 15. The scatter of the data points renders the graph somewhat inconclusive; however, certain properties of the relations shown are noteworthy. The most obvious characteristic of the graph is the change in the amount of coarser material transported before and after the December 1964 flood at discharges above 40,000 cfs. Apparently, about 10 percent more sand and silt was carried in suspension in the period after the flood than in the period preceding it. The graph also shows that as much as 50 percent of the suspended load has been of sand size, a size

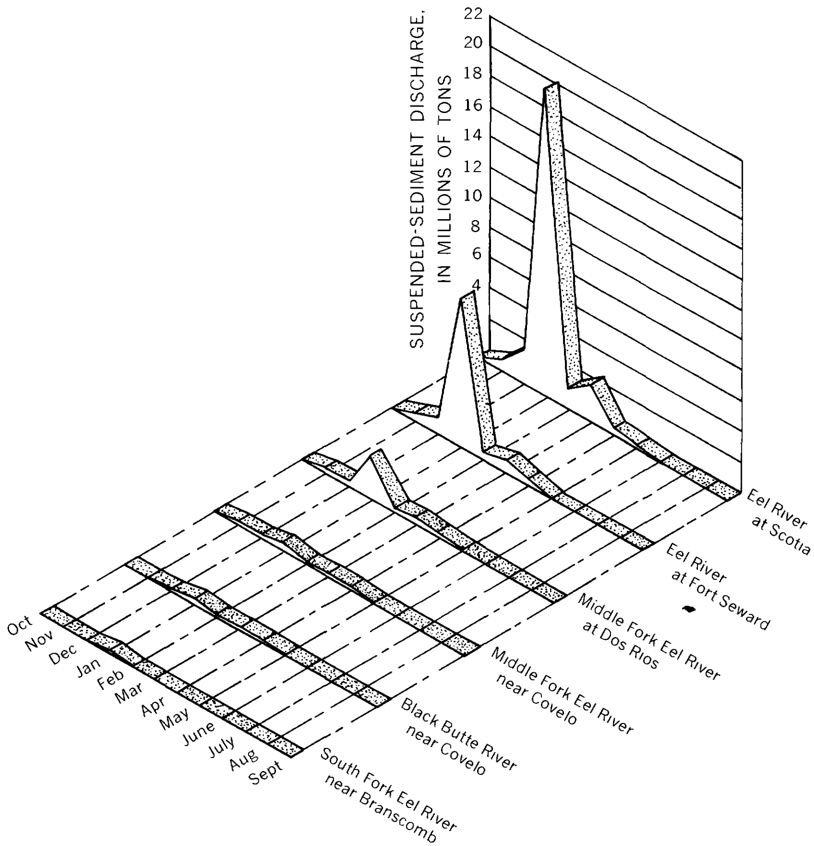

FIGURE 13.—Comparison of suspended-sediment loads of six streams in the Eel River basin, showing typical seasonal variation in sediment discharge, October 1966–September 1967.

that is usually a part of the bed material. Coarse material transported is primarily a function of flow and the availability of coarse material. Hence, the curves indicate that the quantity of coarse material available for transport increased during and after the 1965 water year.

Long-term average suspended-sediment discharges at Scotia were computed by combining the flow-duration characteristics of the water discharge for a long period of streamflow record with sediment-discharge figures taken from appropriate sediment-transport curves, according to procedures discussed by Colby (1956, p. 24). Using the curve of figure 11, the computed average suspended-sediment discharge was 23 million tons per year for the period of streamflow record 1911–14 and 1917–67 water years. Using the

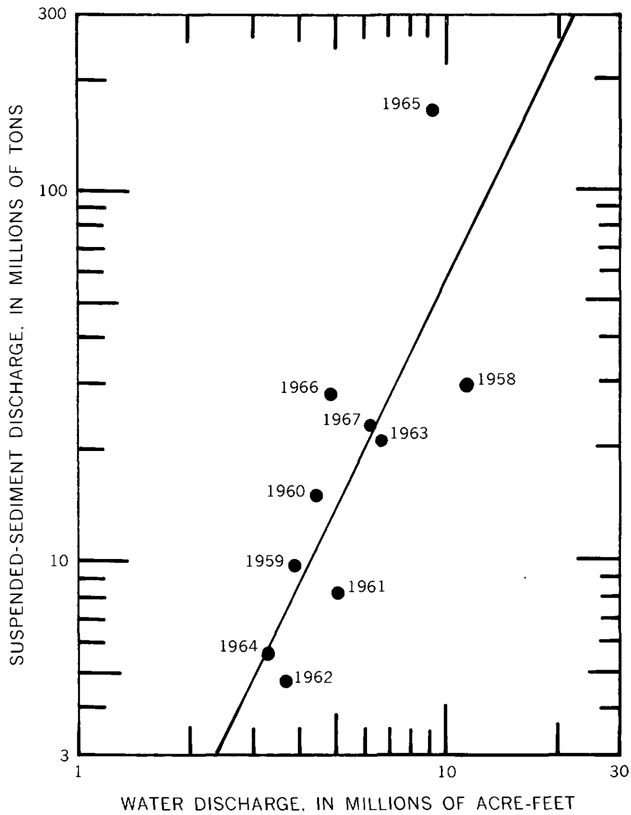

FIGURE 14.—Relation of streamflow to suspended-sediment discharge by water years, Eel River at Scotia.

sediment-transport curve shown in figure 12 for the preflood period, an average suspended-sediment discharge of 13 million tons per year was computed for the 1911–14 and 1917–64 water years.

Suspended-sediment yield for the basin above Scotia was 10,080 tons per square mile per year for the 1958–67 water years, and the yield for the preflood period, 1958–64, was 4,330 tons per square mile per year. The lower figure very nearly represents the long-term yield, which is based on preflood sediment records, and is highly significant even though it is considerably less than the flood-affected higher value. It must be emphasized that preflood sediment discharges and yields were many times greater than those for similar basins throughout the United States (Judson and Ritter, 1964). The flood effects only increased formerly excessive values.[1]

[1] Preflood yields for other stations where data are available may be computed from figures given in table 8.

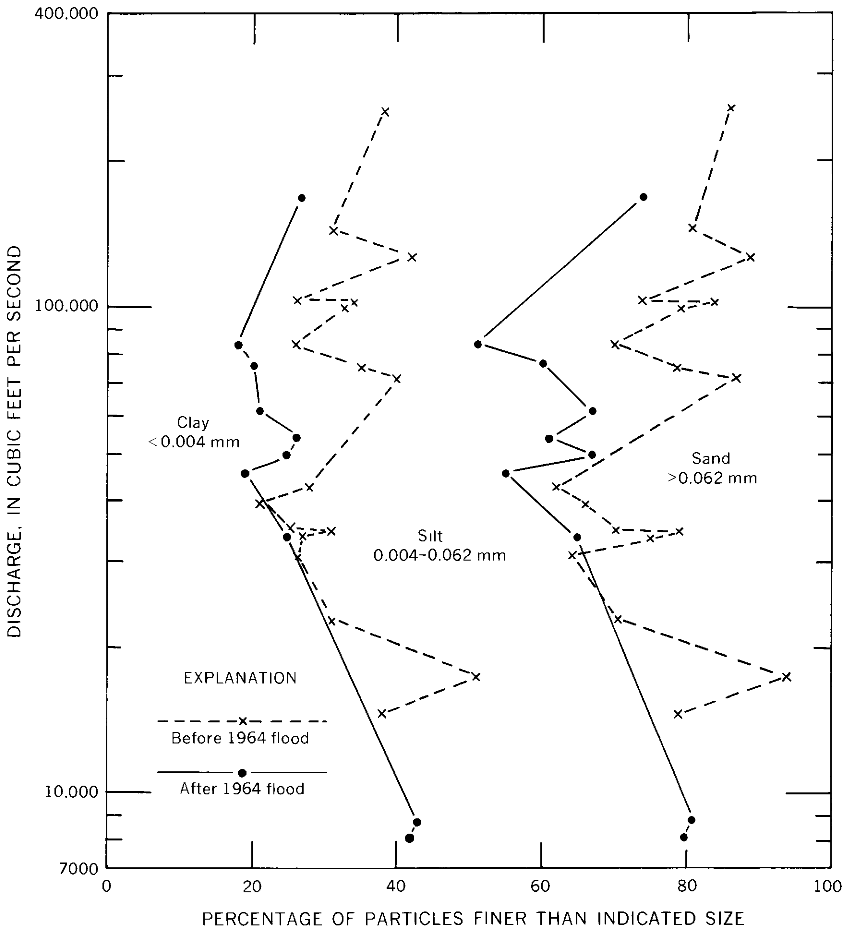

Figure 15.—Particle size versus water discharge, Eel River at Scotia, 1963–66.

A comparison of the sediment yield of the Eel River with other rivers of the world is shown in table 7. The figure of 10,000 tons per square mile per year for the Eel River is computed only for the period of sediment record at Eel River at Scotia. The validity of this comparison is somewhat questionable because of short periods of record and differences in methods of sampling; however, the general magnitude of the average annual suspended load figures is indicative of the extremely high sediment production of the Eel River basin.

TABLE 7.—*Suspended-sediment yields of selected rivers of the world*

[Holeman (1968)]

River and location	Drainage area (sq mi)	Average annual suspended load (tons per sq mi)	Average water discharge at mouth (10^3 cfs)	Period of sediment record
Ching—Changchiashan, China	22,000	20,500	2	1932–45
Semani—Urae Kucit, Albania	2,040	11,844		1961–63
Eel—California, U.S.A	3,113	[1] 10,000	7	[1] 1957–67
Yellow—Shenhsien, China	276,000	7,545	53	1934–42
Ganges delta—East Pakistan	409,200	4,000	498	1874–79
Colorado—Arizona, U.S.A	137,800	1,082	5.5	1925–57
Brazos—Texas, U.S.A	34,800	1,000	5.2	1924–50
Arno—San Giovanni Alla Vena, Italy	3,160	770		1936–42 1954–64
Pecos—New Mexico, U.S.A	3,970	685	.6	1948–57
Mississippi—Louisiana, U.S.A	1,244,000	277	630	1951–65
Nile—Egypt	1,150,000	100	100	1958–64

[1] Figures from this report; not shown by Holeman (1968).

MIDDLE FORK EEL RIVER NEAR DOS RIOS

Sediment studies began at Middle Fork Eel River near Dos Rios in January 1956 with periodic sampling which continued through September 1957. Daily sampling was started in October of the 1958 water year and has been continued since that time.

Sediment samples are taken at the highway bridge approximately 0.5 mile upstream from the mouth of the Middle Fork. The stream channel at this point has steep rocky banks and a gravel bed. The channel curves slightly just upstream from the bridge, and is straight for about 1,500 feet downstream of that point. The stream flows in one channel at most stages, and the steep banks are not subject to overflow. Streamflow at higher stages is characterized by high velocities and standing waves. The channel is somewhat contracted in the vicinity of the bridge, and flood stages are so high that streambed elevation changes are small relative to the depth of water. High water during the December 1964 flood reached the base of the bridge, about 68 feet above the streambed at that time. The streambed material that moves past the sediment-sampling site ranges from sand to cobbles with varying types of flow. Bank slumping is minimal in the vicinity of the bridge, and the channel geometry has remained basically unchanged over the past several years.

Runoff of the Middle Fork near Dos Rios prior to the 1966 water year was computed as the difference in runoff between stations on the Eel River downstream and upstream of the mouth of the Middle Fork. However, a streamflow gaging station was established on the Middle Fork in August 1965, and the runoff has been determined at the gage since that time. Total runoff since sediment studies began in

1957 has been about 13,620,000 acre-feet with a corresponding suspended-sediment load of 42,450,000 tons. Both the maximum annual water discharge and the maximum annual suspended-sediment discharge occurred in the 1965 water year when a load of 18,700,000 tons was moved past the gaging site by a flow of 2,768,000 acre-feet.

A sediment-transport curve for Middle Fork Eel River near Dos Rios is shown in figure 16. The curve represents 10 years of sediment data, and restrictions on its application are similar to those discussed for Eel River at Scotia. The data used to define this curve are taken from unpublished records of the U.S. Geological Survey. Figure 17 illustrates the change in the sediment-transport relation at the station due to the effects of the December 1964 flood.

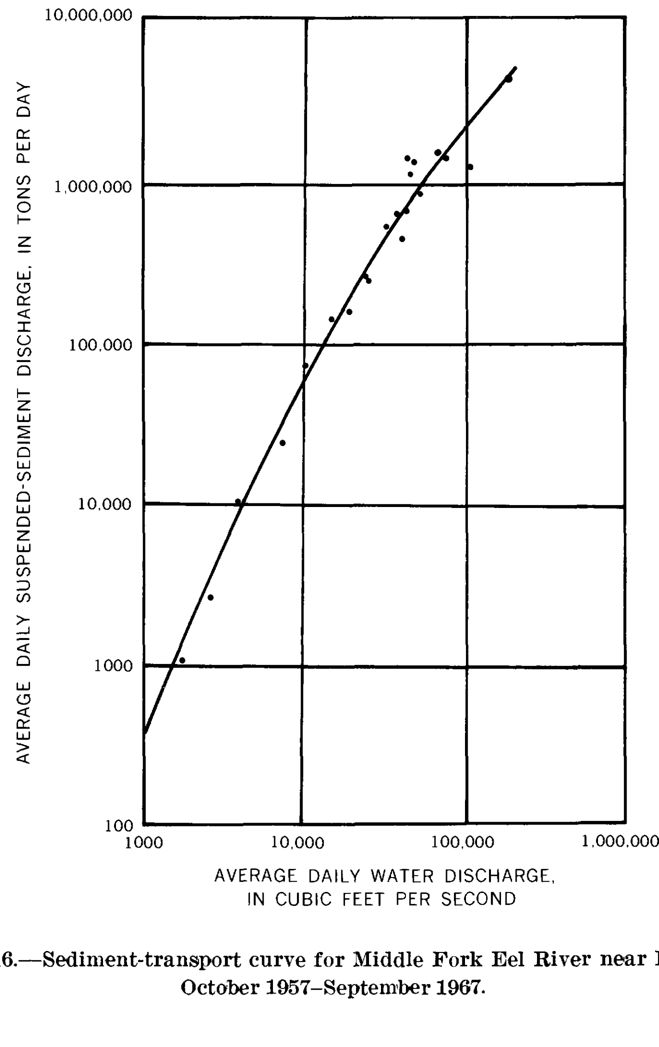

FIGURE 16.—Sediment-transport curve for Middle Fork Eel River near Dos Rios, October 1957–September 1967.

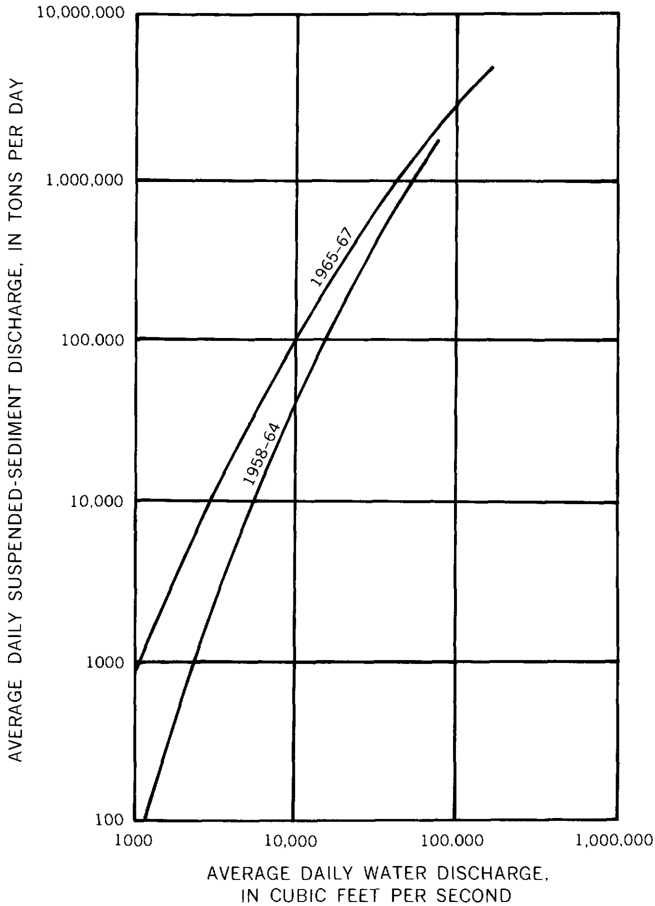

FIGURE 17.—Sediment-transport curves for Middle Fork Eel River near Dos Rios, showing the change in sediment-transport characteristics after the December 1964 flood.

Results of particle-size analyses of samples taken at Middle Fork Eel River near Dos Rios are plotted in figure 18. Two points are plotted for each sample taken to show the breakdown of percentages of sand, silt, and clay carried in suspension at different discharges, The two points chosen define the break in each sample between sand and silt and between silt and clay. The lines on this and subsequent particle-size plots in this report serve only to define general boundaries and indicate possible trends. At Middle Fork Eel River near Dos Rios, the particle-size distribution is similar for most values of water discharge, and there was no apparent change in the distribution after the flood of December 1964.

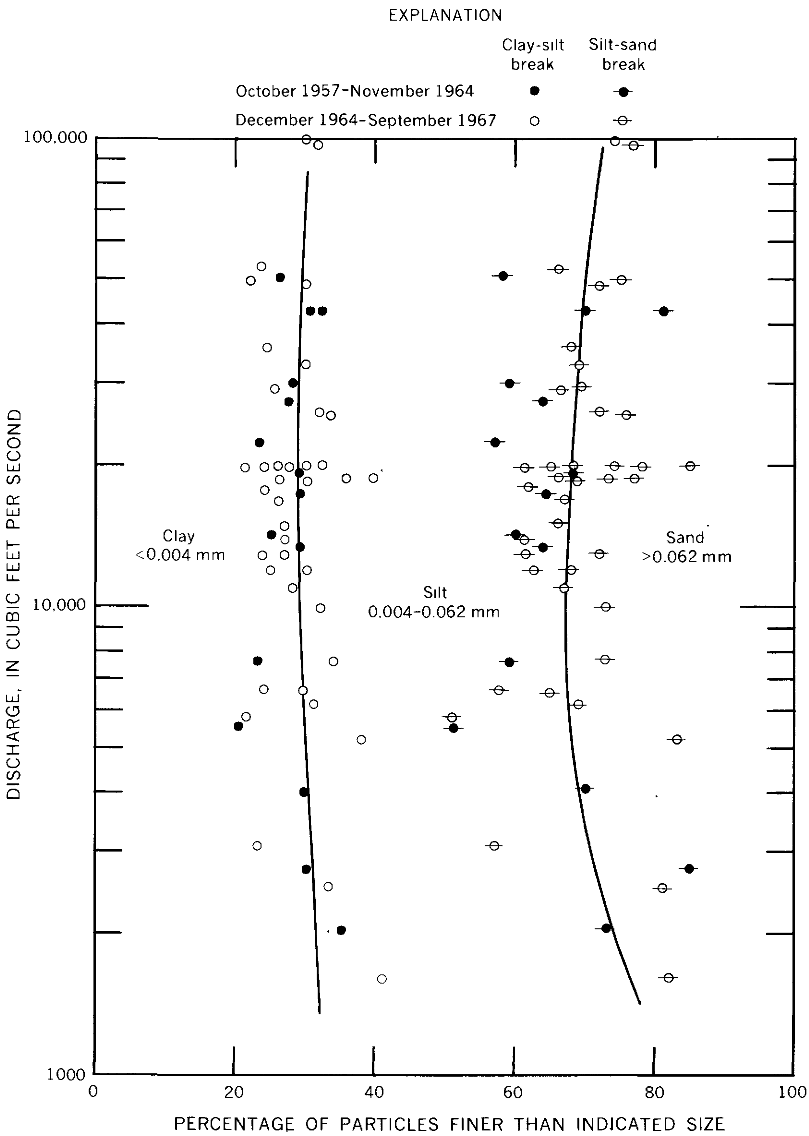

FIGURE 18.—Particle size versus water discharge, Middle Fork Eel River near Dos Rios, 1958–67. Prior to October 1965 the water discharge was estimated by the method described on page 36.

MIDDLE FORK EEL RIVER BELOW BLACK BUTTE RIVER

Upstream from Middle Fork Eel River near Dos Rios, daily sediment sampling was carried on for a 5-year period just below the confluence of the Middle Fork Eel and Black Butte Rivers. Sampling was begun in October 1962 and discontinued on September 30, 1967. The station was destroyed in the December 1964 flood, then replaced, and again destroyed by a flood in January 1967. No suitable site was found to replace the station below the Black Butte River after the 1967 event, and the station was relocated above the Black Butte River. The nature of records obtained at the new station after relocation is, of course, not equivalent to the nature of records from the previous location. Although the available data do not cover an extensive time period, they are of high value when viewed in connection with the general runoff patterns of the Middle Fork basin and the data obtained from studies near Dos Rios.

The stream channel of the Middle Fork below the Black Butte River has a shifting gravel bed and steep banks lined with boulders and brush. The stream has one channel at high stages and two at low stages. At high stages, standing waves form in the swift flow. Low-water streambed elevations remained fairly constant for the 10 years preceding the December 1964 flood, but considerable deposition has taken place since that time (figs. 19 and 20).

Extreme flows of 89,100 and 132,000 cfs occurred in December 1955 and December 1964, respectively. Daily suspended-sediment loads ranged from negligible traces on many days throughout the period of record to an estimated maximum of 2½ million tons on December 22, 1964. The smallest and largest annual loads were recorded in consecutive years. In the 1964 water year 105,300 tons of suspended sediment was discharged, whereas 10,100,000 tons was discharged during the 1965 water year.

Sediment discharge per square mile of drainage area is higher at this station than at any other station in the Eel River basin except Eel River at Scotia. An average rate of more than 8,000 tons per square mile of suspended-sediment discharge has been computed for the upper Middle Fork Eel River drainage basin for the 5-year period beginning October 1963. Storm runoff transports most of this load; 50 percent of the suspended load is transported during an average of 4 days per year. The sediment-transport curve for Middle Fork Eel River below Black Butte River is shown in figure 21, and the relation between particle size and water discharge is shown in figure 22.

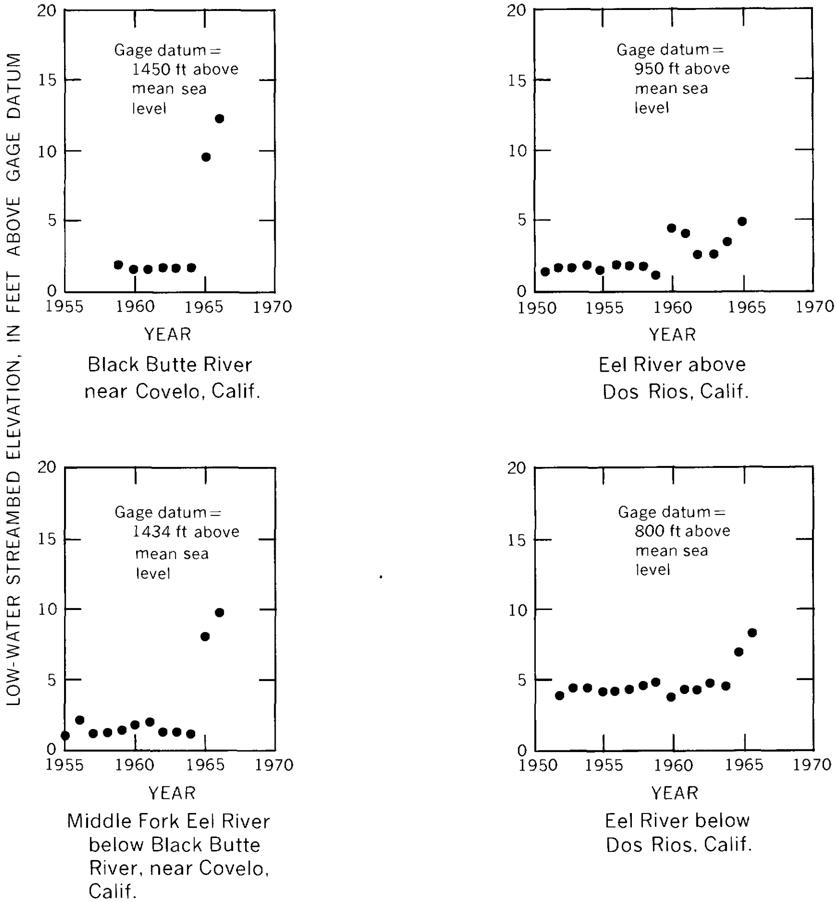

FIGURE 19.—Changes in low-water streambed elevation, by year, at four stations in the Eel River basin. From Hickey (1968).

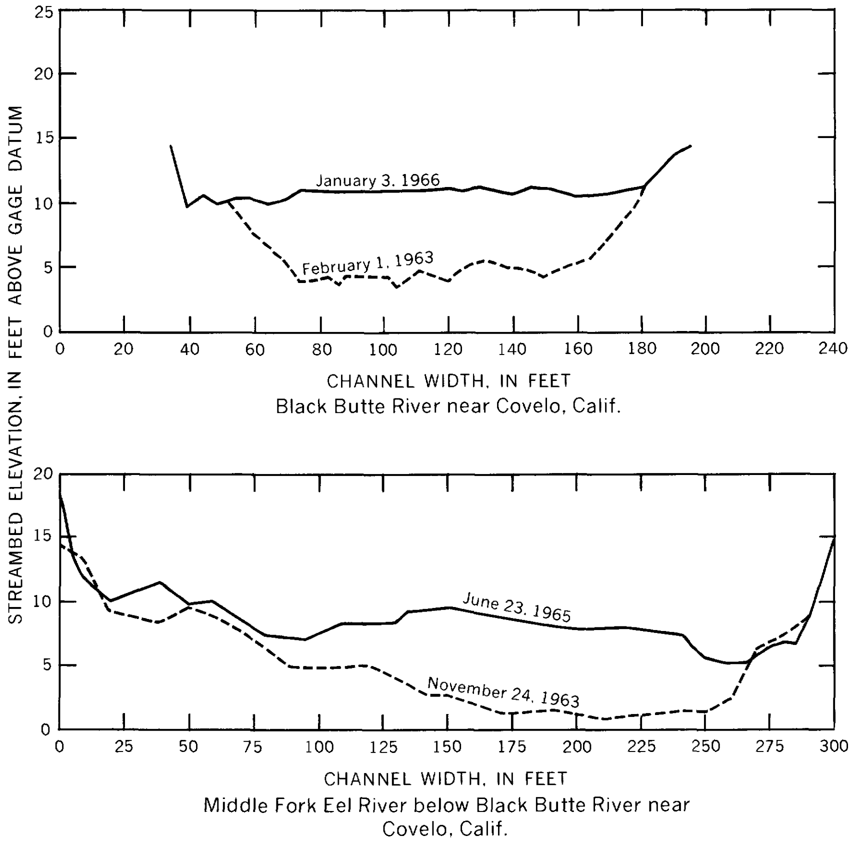

FIGURE 20.—Cross sections at selected gaging stations in the Eel River basin, showing changes attributable to record-high flows during the 1965 water year. From Hickey (1968).

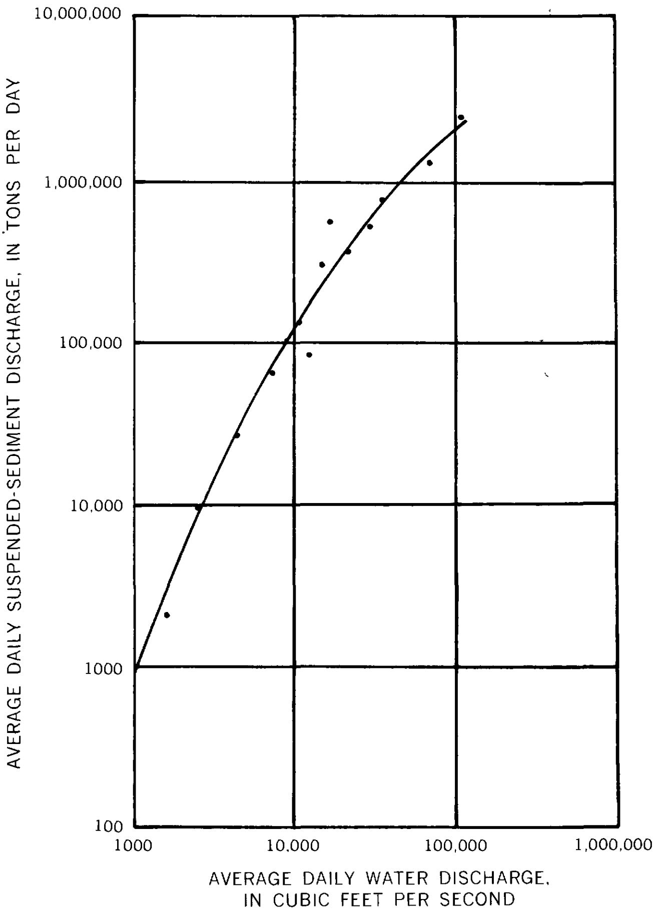

FIGURE 21.—Sediment-transport curve for Middle Fork Eel River below Black Butte River, near Covelo, 1963–67 water years.

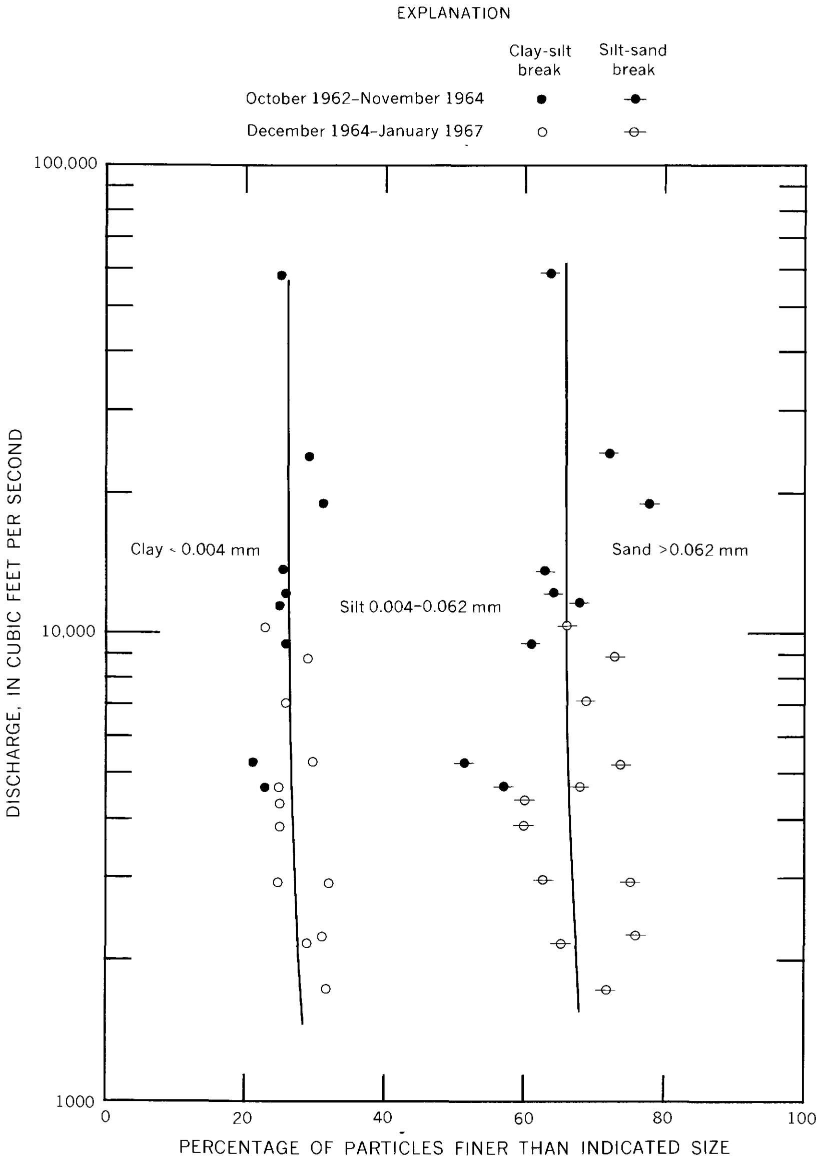

Figure 22.—Particle size versus water discharge, Middle Fork Eel River below Black Butte River, near Covelo, 1963–67 water years.

BLACK BUTTE RIVER

Sediment studies in the Black Butte River basin are based on suspended-sediment samples collected daily from November to April of the 1966 water year and December to September of the 1967 water year. During these periods, daily measurements of suspended load were made at the gaging station 0.5 mile upstream from the confluence of the Black Butte and Middle Fork Eel Rivers. Because of the short sampling period, only a limited amount of information is available from which to evaluate fluvial sediment characteristics. However, information from other sources, together with interstation correlation and field observations, offers alternatives in evaluating the basin sediment yield.

The channel of the Black Butte River in the vicinity of the gaging station is straight, and has steep sparsely wooded banks and a gravel bed. For the 2-year period of suspended-sediment observations, sediment deposition has occurred in this section. During the December 1964 flood, the channel bed aggraded approximately 8 feet (fig. 19), and deposition occurred subsequently as material deposited upstream in 1964 was transported downstream by high water in the 1966 and 1967 water years (Hickey, 1968). Deposition of this type is not likely to continue indefinitely; however, the time necessary for the stream to readjust itself to a configuration consistent with the changes which resulted from the flood is unknown.

The general relation between water discharge and suspended-sediment discharge is shown in figure 23 and can be considered representative only of the short term from which the data are taken. Extension of these data over past or projected flows presents many uncertainties because of the presently changing channel conditions. The relation between particle size and water discharge (fig. 24) shows a pattern similar to other stations in the Middle Fork Eel River basin; however, the number of samples is insufficient to show more than a comparison with other stations.

Runoff in the Black Butte River basin ranged from a minimum of 1.2 cfs in September 1959 to a maximum of 29,000 cfs in December 1964, during a 9-year period of record beginning in October 1956. Total runoff for the period of sediment record was 473,800 acre-feet, and the corresponding sediment discharge was calculated to be 1,405,000 tons. Maximum monthly suspended-sediment discharge was 496,200 tons in January 1967, and the maximum daily suspended-sediment discharge was 143,000 tons on January 4, 1966. Minimum loads of less than 0.1 ton were measured for many days during the summer months in 1967.

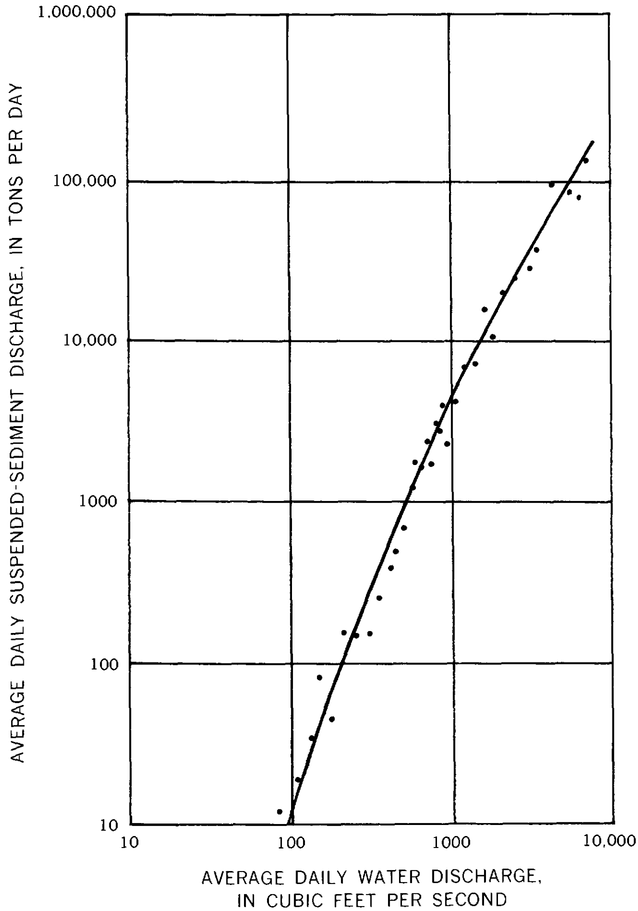

FIGURE 23.—Sediment-transport curve for Black Butte River near Covelo, November 1965–April 1966 and December 1966–September 1967.

Fluvial sediment in the Black Butte River basin is derived primarily from a large area of landslides covering the eastern slopes of the basin (fig. 3). Although the sediment removed from this slide region is not measured directly, observations of the mechanisms by which it moves show that large volumes of soil and rock will enter the stream channel under the influence of bank cutting by the stream. The already precarious stability of an earthflow is readily disturbed as the lower supporting material is removed, and residual uphill material becomes immediately susceptible to downslope movement (fig. 25).

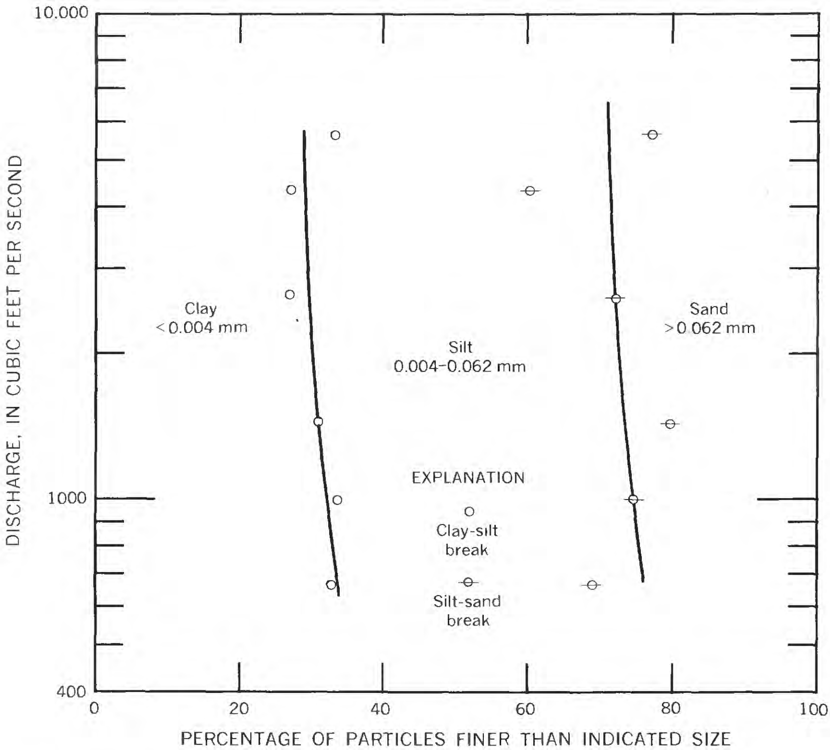

FIGURE 24.—Particle size versus water discharge, Black Butte River near Covelo, December 1966–September 1967.

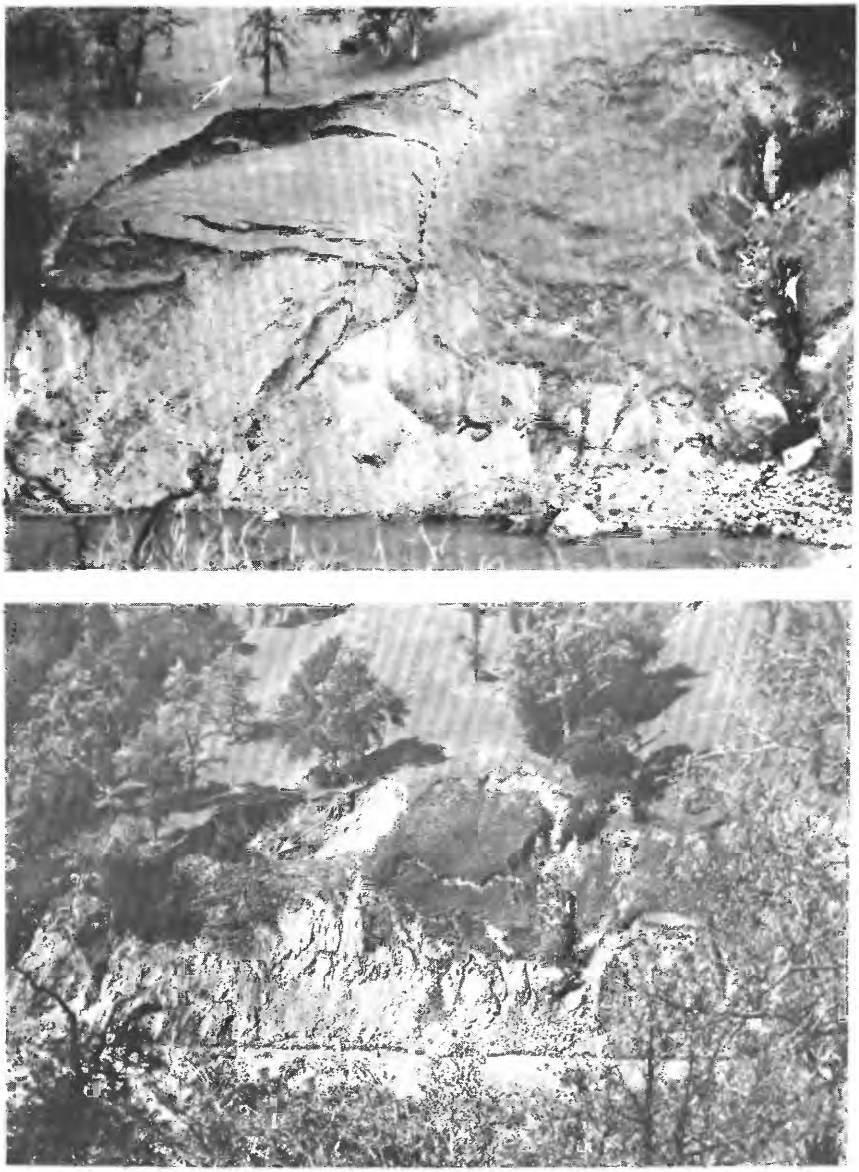

FIGURE 25.—Mass wasting adjacent to stream, typical of many locations in the Eel River basin. Comparative photographs show slide activity along the Middle Fork Eel River. *Top*, Photograph taken Apr. 23, 1968. Recent and older landsliding along the Middle Fork Eel River above the mouth of the Black Butte River. Note gullying along the older slide (at right) and the seeps at the bases of both slides. *Bottom*, Photograph taken Apr. 30, 1969. Slide in left of picture has moved several feet, toppling a tree (indicated by arrow in each photograph) which was undisturbed the previous year. Note the crack in the older slide which does not appear in the earlier picture.

EEL RIVER AT FORT SEWARD

A sediment station was established on the Eel River at Fort Seward in October 1965. Sediment samples have been collected daily at the highway bridge about 0.25 mile east of Fort Seward since that time. Information about the nature of fluvial sediment at this station is minimal because of the short period of sampling; however, sediment studies at this station do give some indication of the contribution of sediment of that part of the basin between Dos Rios and Scotia. Because of the magnitude of the sediment yield in this area, future sediment programs should emphasize the reach of the Eel River between Dos Rios and Scotia.

Varying proportions of sand and gravel make up the streambed at the gaging site. The river banks are steep and rocky and not subject to overflow. The flow is in one channel at all stages, and at higher stages the flow is swift and turbulent. At a gage height of approximately 30 feet, the flow begins to override a sharp bend in the river about 600 feet upstream of the gage and approaches the bridge at a slight angle.

Suspended-sediment discharge was 29,210,000 tons during the 2-year period of record at Fort Seward, and this discharge was about 56 percent of that recorded during the same period at Scotia. The South Fork Eel River annually contributes about 13 percent of the sediment discharge at Scotia (table 9); thus, the South Fork and the Eel River above Fort Seward had a combined suspended-sediment discharge which was about 69 percent of that at Scotia. The remaining drainage area below Fort Seward and above Scotia excluding the South Fork apparently contributed about 31 percent of the discharge at Scotia during the 2-year period, or about 17,000 tons per square mile per year from a 35-mile stretch of river draining 469 square miles. Similarly, the suspended-sediment yield between Dos Rios and Fort Seward, a reach draining 657 square miles, was about 15,000 tons per square mile per year. These yields are about twice the yield of the entire basin above Scotia during this period. This again emphasizes the importance of sediment studies in the drainage area between Dos Rios and Scotia, which includes the North Fork Eel River and Larabee Creek drainages.

A sediment-transport curve for a 2-year period of sediment record at Eel River at Fort Seward is shown in figure 26. The variation in particle-size distribution with flow is shown by figure 27.

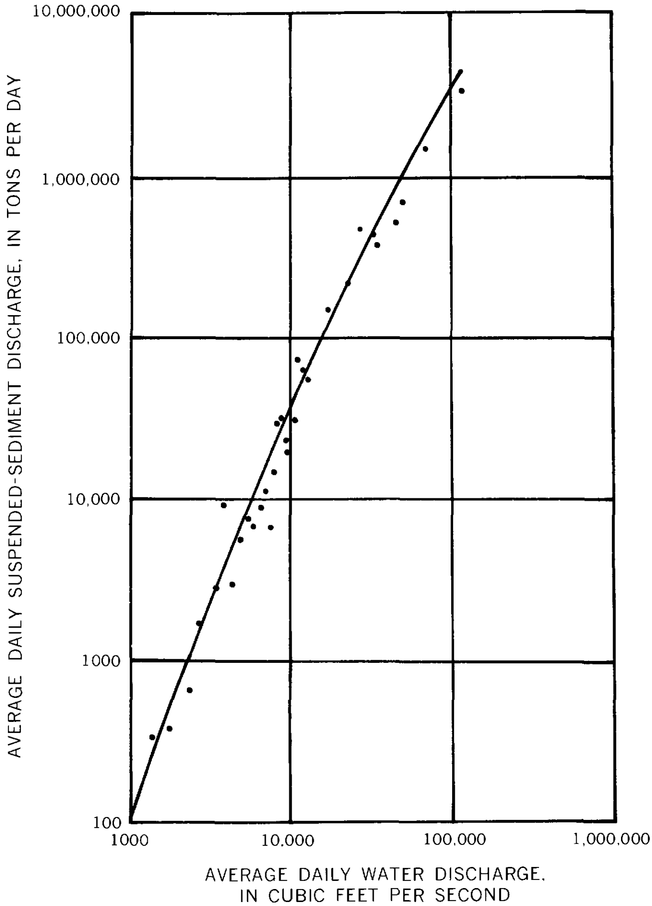

FIGURE 26.—Sediment-transport curve for Eel River at Fort Seward, 1966–67 water years.

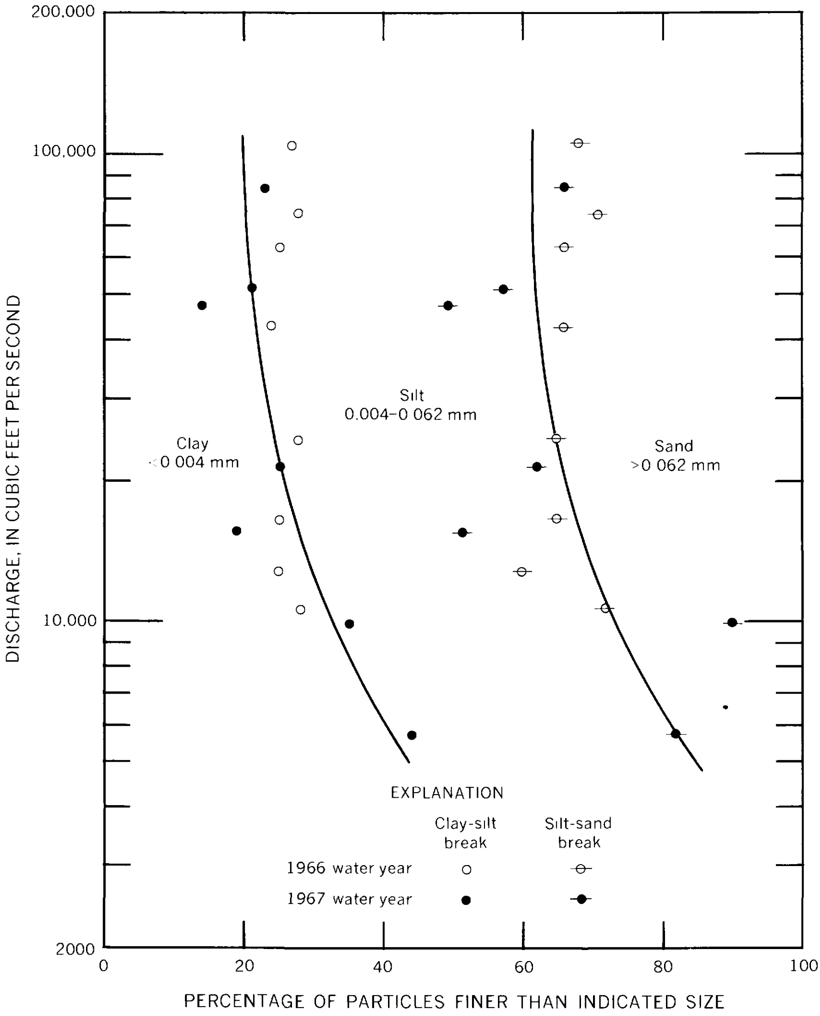

Figure 27.—Particle size versus water discharge, Eel River at Fork Seward. 1966–67 water years.

SOUTH FORK EEL RIVER

Sediment studies along the South Fork Eel River are based primarily on data collected at samplings stations near Branscomb and Miranda. Periodic sediment sampling was begun at South Fork Eel River near Miranda in October 1955 and continued through September 1962. South Fork Eel River near Branscomb was sampled periodically from August 1957 until a daily sampling program began in October 1962. Daily sediment sampling has been continuous at the Branscomb station since that time.

The channel bed at South Fork Eel River near Miranda is composed of gravel. The left bank of the river is wooded, and is fairly stable at all stages. The right bank is sandy up to medium stages and wooded at high stages, and the river overflows the right bank at a gage height of about 30 feet. The channel is straight for a distance of 600 feet upstream and 600 feet downstream from the measuring cableway, and flow in the channel is swift at high stages.

Computations by Hawley and Jones (1969, p. 13) from the periodic records collected at the Miranda station indicate that sediment discharge from October 1957 through September 1962 was 8,870,000 tons, or about 13 percent of the suspended-sediment discharge measured downstream at Scotia during the same period. The maximum annual load was 3,900,000 tons, which accompanied a water discharge of 2,444,000 acre-feet in the 1958 water year. Sediment data are not available subsequent to September 1962; thus, the effect of the December 1964 flood on the sediment transport at the Miranda station is unmeasured.

Upstream, at South Fork Eel River near Branscomb, the streambed consists of gravel and bedrock, and the channel has steep banks covered with undergrowth. The flow is confined to one channel at all stages.

Hawley and Jones (1969, p. 13) computed a sediment discharge of 446,000 tons at the Branscomb station for the 5-year period beginning October 1957. Suspended-sediment discharge from October 1962 through September 1967 was 800,700 tons, of which 502,800 tons was measured during the 1965 water year. Average runoff over the 10-year period was 125,200 acre-feet per year, and the maximum annual runoff was 219,200 acre-feet in the 1958 water year. The patterns of runoff and sediment discharge at the Branscomb station are similar to the patterns observed elsewhere in the basin. Maximum annual suspended-sediment discharge did not accompany the maximum annual water discharge which occurred in 1958, and the 1966 and 1967 water years exhibited comparatively high sediment discharges because of continuing adjustments of the stream to the December 1964 flood effects.

The sediment-transport curve for South Fork Eel River near Branscomb is shown in figure 28. The data from which the plot is derived are representative of the 1963–67 period and do not include the periodic data collected before October 1962. Plots of particle size versus water discharge for South Fork Eel River near Miranda and South Fork Eel River near Branscomb are shown in figures 29 and 30.

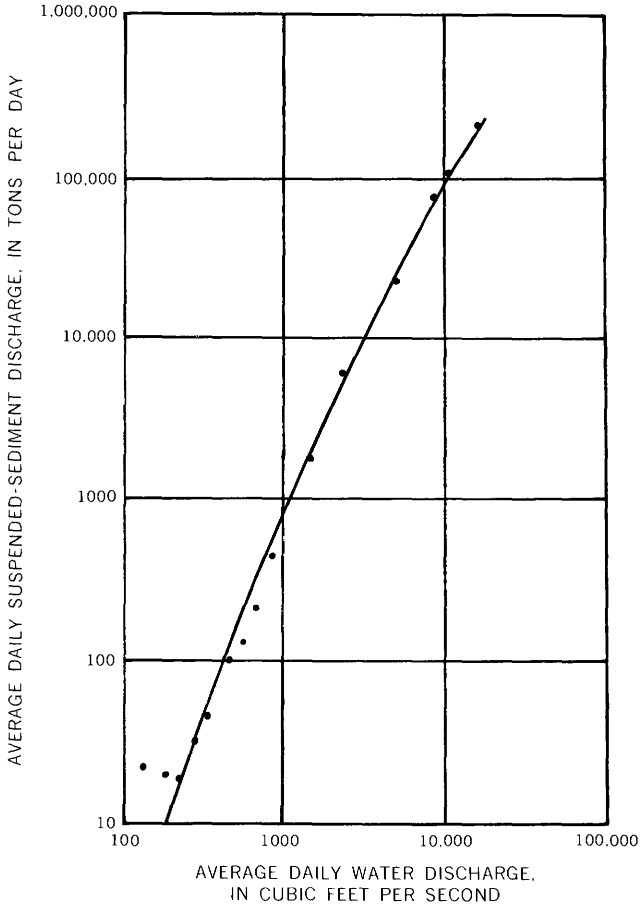

FIGURE 28.—Sediment-transport curve for South Fork Eel River near Branscomb, 1963–67 water years.

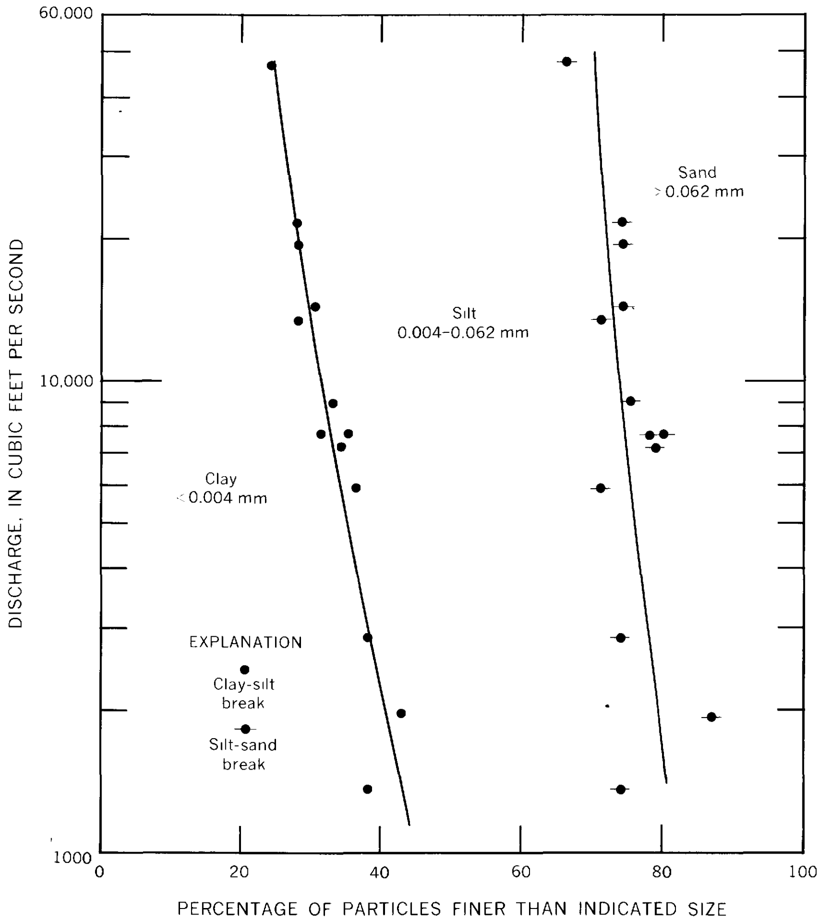

FIGURE 29.—Particle size versus water discharge, South Fork Eel River near Miranda, 1958–62 water years.

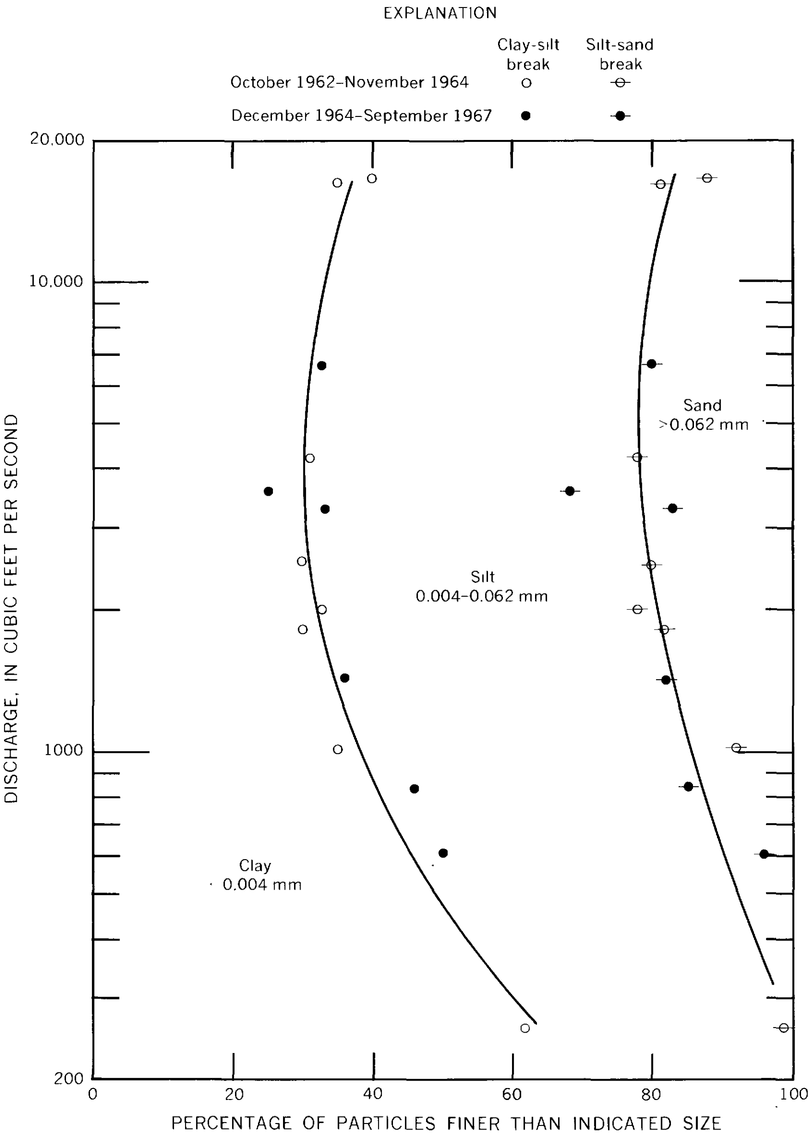

FIGURE 30.—Particle size versus water discharge, South Fork Eel River near Branscomb, 1963–67 water years.

QUANTITY AND DISTRIBUTION OF FLUVIAL SEDIMENT

The suspended-sediment discharge determined at Eel River at Scotia was 313,900,000 tons for the 10-year period beginning October 1957. By use of this figure and the data presented in table 8, the quantity and distribution of suspended-sediment discharge throughout the basin may be computed. A lack of data concurrent with the 10-year record at Scotia precludes an exact analysis of sediment sources in some areas of the basin; however, reasonable estimates and computations can be made where significant trends exist in the concurrent records of shorter periods.

The Middle Fork Eel River, which drains 24 percent of the Eel River basin above Scotia, discharged about 42 million tons, or 13.4 percent, of the suspended load at Scotia during the 10-year period of record. The suspended-sediment discharges of other subunits of the Eel River basin were not determined for a comparable period; thus, an approximation of the yields of these basins must be made by using the average percentages shown in the last column in table 9. On this basis, the Eel River above its confluence with the Middle Fork Eel River contributes about 6 percent of the annual suspended load at Scotia, although sedimentation along the upper Eel River is influenced by Lake Pillsbury, Van Arsdale Reservoir, and the diversion of water into Potter Valley. Thus, the suspended sediment derived from the upper Eel River was about 19 million tons during the period cited above.

The South Fork Eel River drains 17 percent of the basin above Scotia, and the suspended-sediment discharge of the South Fork constituted 13 percent of the discharge at Scotia from the 1958 water year through the 1962 water year. Projection of the 13 percent figure through the 1967 water year would show that the suspended sediment carried by the South Fork was about the same as that of the Middle Fork for the 10-year period. Data from South Fork Eel River near Branscomb do not show a significant change in the percentage of suspended sediment delivered downstream to Scotia in the 5 years following the discontinuation of sampling at South Fork Eel River near Miranda. Thus, a reasonable estimate of the suspended-sediment discharge of the South Fork Eel River is about 13 percent of the discharge at Scotia, which is 41 million tons for the 10-year period beginning October 1957, or about 7,600 tons per square mile per year. This figure is consistent with the figures derived for stations in the basin where preflood sediment yields were considerably less than the 10-year average sediment yield which included the 1964–65 flood period. For example, the average sediment yield at Middle Fork

TABLE 8.—*Summary of suspended-sediment and water discharge in the Eel River basin, October 1957–September 1967*

Water year	Water discharge (acre-feet)	Suspended-sediment discharge, Q_s (tons)	Suspended-sediment yield (tons per sq mi)	Days per year required for transport of 50 percent Q_s	Percent of discharge at Scotia	
					Water	Suspended-sediment, Q_s
11-4725. Eel River above Dos Rios [Drainage area, 705 sq mi]						
1958	2,051,000	2,062,000	2,925	9	17.9	7.0
1959	479,000	332,100	471	4	12.0	3.3
1960	943,700	1,803,000	2,557	2	20.8	11.9
1961	757,200	412,900	586	5	14.6	5.0
1962	630,500	430,800	611	4	16.8	9.0
1963	1,105,000	1,715,000	2,433	2	16.0	8.1
1964	376,000	240,500	341	2	11.3	4.2
1965	1,822,000	9,571,000	13,580	2	19.7	5.7
Avg	1,021,000	2,071,000	2,938		16.9	6.3
11-4729. Black Butte River near Covelo [Drainage area, 162 sq mi]						
1966 [1]	169,600	474,300		3	3.5	1.7
1967 [1]	304,200	930,800		5	4.8	4.0
Avg	236,900	[2] 702,100	4,330		4.2	2.7
11-4730. Middle Fork Eel River below Black Butte River, near Covelo [Drainage area, 367 sq mi]						
1963	829,100	1,618,000	4,409	2	12.0	7.6
1964	334,900	105,300	287	2	10.1	1.9
1965	1,339,000	10,100,000	27,520	4	14.4	6.0
1966	559,000	1,116,000	3,041	5	11.3	4.0
1967	798,700	1,974,000	5,379	7	12.5	8.4
Avg	772,100	2,983,000	8,041		12.5	6.0
11-4739. Middle Fork Eel River near Dos Rios [Drainage area, 745 sq mi]						
1958	[3] 2,498,000	4,157,000	5,580		21.8	14.1
1959	[3] 746,900	841,900	1,130		18.9	8.5
1960	[3] 886,000	2,649,000	3,556		19.6	17.5
1961	[3] 1,110,000	847,900	1,138		21.5	10.2
1962	[3] 857,600	579,000	777		22.7	12.2
1963	[3] 1,614,000	4,710,000	6,322		23.4	22.3
1964	[3] 647,300	759,400	1,019		19.4	13.4
1965	[3] 2,768,000	18,700,000	25,100		30.2	11.2
1966	1,062,000	4,330,000	5,812	3	21.3	15.4
1967	1,434,000	4,880,000	6,550	7	22.3	20.7
Avg	1,363,000	4,245,000	5,698		22.8	13.6
11-4750. Eel River at Fort Seward [Drainage area, 2,107 sq mi]						
1966	2,657,000	13,210,000	6,270	2	53.5	46.8
1967	3,818,000	16,000,000	7,594	6	59.6	68.0
Avg	3,238,000	14,600,000	6,872		57.0	56.0

Footnotes at end of table.

TABLE 8.—*Summary of suspended-sediment and water discharge in the Eel River basin, October 1957–September 1967*—Continued

Water year	Water discharge (acre-feet)	Suspended-sediment discharge, Q_s (tons)	Suspended-sediment yield (tons per sq mi)	Days per year required for transport of 50 percent Q_s	Percent of discharge at Scotia: Water	Percent of discharge at Scotia: Suspended-sediment, Q_s
11-4755. South Fork Eel River near Branscomb [Drainage area, 43.9 sq mi]						
1958	219,200	[4] 88,000	2,000		1.9	0.3
1959	81,590	[4] 10,000	230		2.0	.1
1960	110,300	[4] 330,000	7,500		2.4	2.2
1961	116,600	[4] 10,000	230		2.2	.1
1962	77,480	[4] 8,000	180		2.1	.2
1963	133,200	61,760	1,407	4	1.9	.3
1964	87,550	26,330	600	1	2.6	.5
1965	194,300	502,800	1,145	2	2.1	.3
1966	107,400	154,500	3,519	1	2.2	.6
1967	124,300	55,340	1,261	5	1.1	.2
Avg, 1958–67	125,200	125,000	2,850		2.1	.4
Avg, 1963–67	129,400	160,100	3,583		2.1	.3
11-4765. South Fork Eel River near Miranda [Drainage area, 537 sq mi]						
1958	2,444,000	[4] 3,900,000	7,300		21.3	13.3
1959	970,200	[4] 1,300,000	2,400		24.3	13.1
1960	1,142,000	[4] 2,000,000	3,700		25.2	13.2
1961	1,299,000	[4] 1,200,000	2,200		25.1	14.5
1962	847,000	[4] 470,000	880		22.5	9.9
Avg	1,340,000	1,774,000	3,300		23.2	13.0
11-4770. Eel River at Scotia [Drainage area, 3,113 sq mi]						
1958	11,470,000	29,420,000	9,450	12	100	100
1959	3,991,000	9,936,000	3,192	5	100	100
1960	4,532,000	15,120,000	4,857	2	100	100
1961	5,178,000	8,279,000	2,659	9	100	100
1962	3,764,000	4,758,000	1,528	6	100	100
1963	6,883,000	21,190,000	6,807	6	100	100
1964	3,329,000	5,652,000	1,816	2	100	100
1965	9,242,000	167,800,000	53,900	2	100	100
1966	4,963,000	28,220,000	9,065	3	100	100
1967	6,407,000	23,530,000	7,558	7	100	100
Avg	5,976,000	31,390,000	10,080		100	100
11-4785. Van Duzen River near Bridgeville [Drainage area, 216 sq mi]						
1958	1,006,000	[4] 2,000,000	9,260			
1959	491,200	[4] 2,600,000	12,037			
1960	467,700	[4] 2,000,000	9,260			
1961	586,200	[4] 790,000	3,657			
1962	417,600	[4] 300,000	1,389			
1963	770,600	[4] 1,000,000	4,630			
1964	455,800	[4] 800,000	3,704			
1965	791,000	[2] 3,530,000	16,343			
1966	538,000	[2] 1,350,000	6,250			
1967	617,200	[2] 1,200,000	5,555			
Avg	614,100	1,557,000	7,208			

[1] Figures based on partial records, from November to May, 1966 water year, and from November to September, 1967 water year.
[2] Computed by flow-duration and sediment-rating-curve method (Miller, 1951).
[3] Discharge computed as difference between discharges at Eel River above Dos Rios and Eel River below Dos Rios.
[4] Hawley and Jones (1969).

Eel River near Dos Rios was 2,400 tons per square mile between October 1957 and September 1962 and was increased to 5,700 tons per square mile with the inclusion of subsequent data for the 1963–67 water years.

The three basins discussed, which make up 64 percent of the Eel River basin above the Scotia gage, contributed annually an average of 32 percent of the suspended-sediment discharge computed at Scotia. The remaining suspended-sediment discharge, about 212 million tons during the 10-year period, came from an area of 1,126 square miles in the central part of the basin which includes the North Fork Eel River basin. Further division of this area to pinpoint local areas of high sediment yield cannot be done adequately using the existing data. However, records from the 1966 and 1967 water years at Eel River at Fort Seward show that during these 2 years the sediment yield was divided about equally between the parts of this central area above and below Fort Seward.

Sediment yield is greatest in those parts of the basin where earthflows and landslides are adjacent to the stream channels. According to Soil Conservation Service studies (file data, 1968), streambank erosion at higher flows produces between 60 and 65 percent of the sediment yield in the basin; however, the combined effects of the erosion of channels and landslide debris contribute about 90 percent of the fluvial sediment in the basin. Ephemeral runoff from watershed slopes and roads accounts for the remaining 10 percent.

SEDIMENTATION IN LAKE PILLSBURY

Lake Pillsbury on the upper Eel River is an important source of information concerning the effects of reservoirs on sedimentation. Few data on reservoir sedimentation are available for northern coastal California watersheds; thus, past and present studies of Lake Pillsbury provide the principal usable data for planning additional reservoir projects along the Eel River.

Lake Pillsbury is the larger of two reservoirs which make up a part of the Potter Valley Project, a multiple-use facility designed to provide for irrigation and recreation needs and power development in the vicinity of the upper Eel River and Russian River basins. The drainage area of the lake encompasses 288 square miles of steep rugged terrain in which the maximum basin relief is about 5,200 feet. The lake is fed principally by the Eel and Rice Fork Eel Rivers, both of which have slopes greater than 160 feet per mile above the lake. Most of the sediment supplied to Lake Pillsbury is derived from the erosion of stream channels and the erosion of lands from which protective vegetal cover has been removed.

The accumulation and distribution of sediment in the reservoir were studied in some detail by Porterfield and Dunnam (1964) to evaluate changes which had taken place since water storage began in 1921. Data from their report show a sediment inflow between 1921 and 1959 of about 343,000 tons per year, of which 94 percent was deposited within the reservoir. The sediment inflow was computed using sediment-accumulation figures and a specific weight for sediment of 73 pounds per cubic foot (Porterfield and Dunnam, 1964, p. EE45). Thus, the average sediment load passing through the reservoir and carried downstream was about 21,000 tons per year and was composed primarily of sediment finer than sand. Most sediment of sand size and larger drops out of suspension in the lake.

Reservoir design in the Eel River basin should take into account the high trap efficiency observed at Lake Pillsbury as well as other factors which affect reservoir sedimentation such as bank slides, the effect of wave action on bank erosion, and reservoir orientation with respect to inflowing streams. Discussion and computations provided in the report by Porterfield and Dunnam, combined with a knowledge of sedimentation rates, provide useful information for future reservoir studies.

TURBIDITY

Part of the studies aimed at the development of northern coastal California watersheds is a study of the causes and effects of turbidity in streams and reservoirs. Turbidity may limit the use of water for public consumption, and it may make water unsatisfactory for recreational uses such as fishing. Recognizing that turbidity could be a major problem in the development of northern coastal streams, State and Federal agencies have initiated various sampling programs and other studies to gain more information about turbidity. The U.S. Geological Survey in cooperation with the State of California has collected turbidity samples and has made field turbidity measurements at several stations in the Eel River watershed. Turbidity measurement was begun in the latter part of the 1964 water year and was continued through the 1968 water year at several stations. The 1964 data were collected after most of the runoff for that water year had already occurred; thus, those data are considered incomplete and are not used in this report.

Turbidity was defined by Rainwater and Thatcher (1960, p. 289) as "the optical property of a suspension with reference to the extent to which the penetration of light is inhibited by the presence of insoluble material." Turbidity may be defined less precisely as an unclear condition or cloudiness of water. During the drier months of the year when runoff is low, turbidity in the streams and reservoirs of the Eel River basin is caused primarily by the presence of phytoplankton and other micro-organisms which proliferate in the presence of sunlight. During the rainy months when runoff is high, suspended sediment is the chief cause of turbidity. Phytoplankton, which usually is made up of diatoms and other algae, needs light to survive. The presence of suspended sediment in the winter months obstructs the passage of sunlight and precludes the reproduction of the phytoplankton. Thus, turbidity during periods of high suspended-sediment discharge may be attributed almost entirely to suspended sediment, and the effect of diatoms upon the turbidity during these periods may be considered negligible.

Turbidity measurements were made with a Hellige turbidimeter prior to August 1966 and thereafter with a Hach turbidimeter model 1860. Both of these instruments employ a nephelometric or light-scattering principle in which a light beam is reflected or scattered by particles in suspension, and the intensity of this reflected light is compared with a standard. In the Hellige turbidimeter, the slit width that controls the amount of light passing up through the solution is controlled by a knob on the side of the instrument. This knob is calibrated in arbitrary units from standard solutions, and the readings from the knob are converted to milligrams per liter turbidity by means of appropriate curves developed in the laboratory. The transmitted light is viewed as a circle of light in a field of Tyndall light (Rainwater and Thatcher, 1960, p. 70–71). In the Hach instrument, the light scattered at right angles to the light beam is received by two photoelectric cells and converted into an electrical signal which is measured on a precalibrated meter to indicate turbidity units. The Hach turbidimeter, in contrast to the Hellige instrument, does not require operator judgment or interpretation; thus, the results obtained with the Hach turbidimeter are probably more consistent than those obtained with the Hellige turbidimeter. The Hach instrument measures turbidity in Jackson Turbidity Units (JTU's) as defined by Newell (1902); however, a calibration between JTU's and milligrams per liter silica from standard silica suspensions was made in the Geological Survey so that consistency might be maintained in the publication of turbidity data.

RELATION BETWEEN TURBIDITY AND THE CONCENTRATION OF SUSPENDED SEDIMENT

The turbidity, density, and other fluid properties of a water and sediment mixture are related to the concentration of suspended sediment. The relation between turbidity and concentration of suspended sediment for stations along the Eel River is typified by figure 21.

The data are taken from turbidity and concentration measurements made on individual samples, and an apparent trend exists when these data are plotted on full logarithmic paper. The scatter of points for the station used in figure 31 is characteristic of all the stations from which data were collected; however, with sufficient data, curves may be obtained which are usable approximations of the turbidity-concentration relation.

A rapid and simple method was used to obtain approximate curves for six stations along the Eel River for a variety of different periods and conditions. Turbidity and concentration data were recorded on punched cards, and these data were manipulated in appropriate computer programs for regression analyses and other studies. Linear

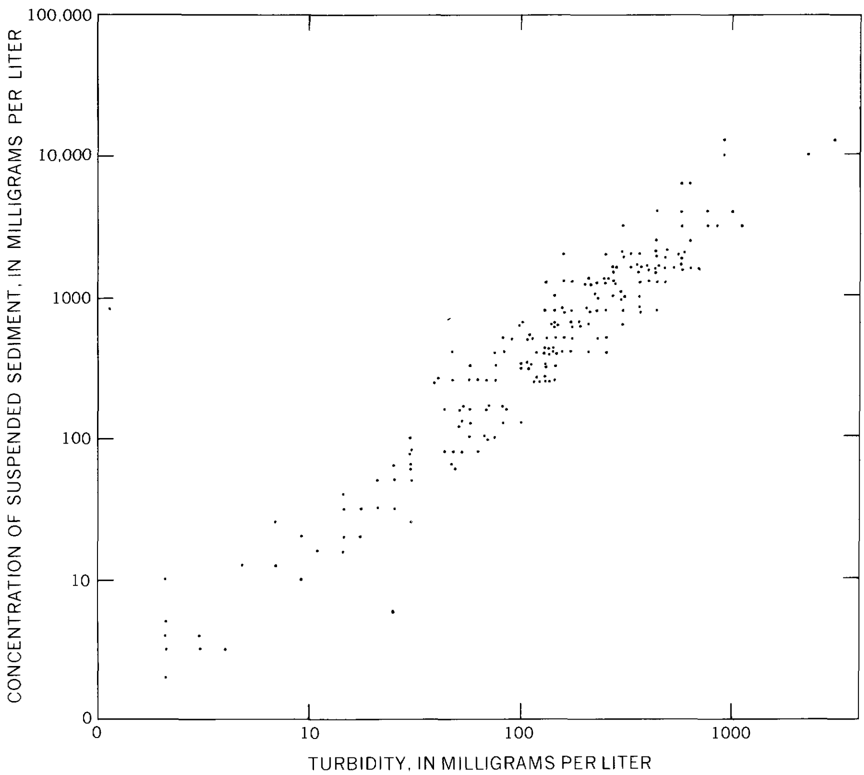

FIGURE 31.—Plot of turbidity versus concentration, showing trend typical of stations in the Eel River basin. Data are taken from observations at Middle Fork Eel River near Dos Dios during the 1966 water year.

logarithmic equations for each water year of record for each station studied were computed by a least-squares regression analysis, and the graphs of these equations are shown in figure 32. Some of the statistical parameters of the regressions are tabulated in table 9 to

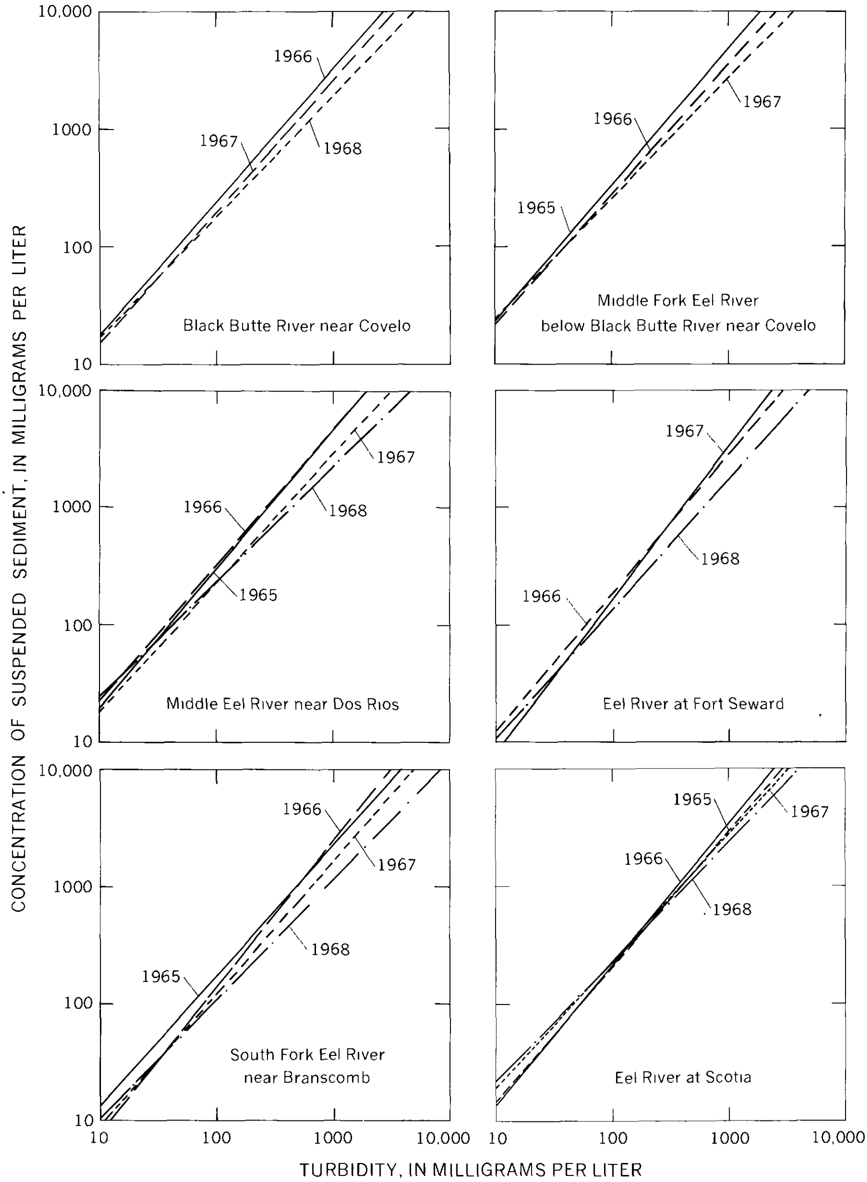

FIGURE 32.—Regression curves of the approximate relation between concentration and turbidity for successive water years.

TABLE 9.—*Regression equations and selected related statistics for the relation between concentration and turbidity at various stations along the Eel River*

Station No.	Station Location	Water year	Equation for concentration-turbidity relation (least-squares computation)	Number of observations	Correlation coefficient	Degrees of freedom	Standard error of estimate (log units)
11-4729	Black Butte River near Covelo.	1966	$C=1.220(T)^{1.108}$	102	0.9706	99	0.19462
		1967	$1.255(T)^{1.134}$	125	.9758	122	.18608
		1968	$1.540(T)^{1.034}$	116	.9792	113	.19573
11-4730	Middle Fork Eel River below Black Butte River near Covelo.	1965	$1.649(T)^{1.150}$	187	.9764	184	.23352
		1966	$1.736(T)^{1.102}$	162	.9717	159	.21897
		1967	$2.290(T)^{1.021}$	124	.9765	121	.20034
11-4739	Middle Fork Eel River near Dos Rios.	1965	$1.275(T)^{1.182}$	198	.9784	195	.23477
		1966	$1.521(T)^{1.160}$	249	.9820	246	.21492
		1967	$1.434(T)^{1.100}$	205	.9754	202	.17357
		1968	$2.351(T)^{0.995}$	145	.9736	142	.21175
11-4750	Eel River at Fort Seward.	1966	$.863(T)^{1.171}$	240	.9505	237	.31626
		1967	$.381(T)^{1.134}$	175	.9826	172	.19059
		1968	$.818(T)^{1.114}$	167	.9761	164	.18126
11-4755	South Fork Eel River near Branscomb.	1965	$1.025(T)^{1.117}$	37	.9662	34	.15615
		1966	$.862(T)^{1.057}$	45	.9672	42	.18738
		1967	$1.073(T)^{1.014}$	72	.9700	69	.16146
		1968	$.875(T)^{1.022}$	53	.9582	50	.14491
11-4770	Eel River at Scotia....	1965	$.984(T)^{1.160}$	243	.9593	240	.26993
		1966	$.837(T)^{1.203}$	210	.9739	207	.21311
		1967	$1.554(T)^{1.081}$	170	.9727	167	.24148
		1968	$2.327(T)^{1.005}$	109	.9723	106	.23510

indicate the degree of correlation between turbidity and concentration, and a confidence interval for values which may be estimated from the equations.

The turbidity-concentration relation is very consistent for each station and throughout the basin. The slopes of the regression lines are much the same for all stations and for all the observed periods. However, there is an apparent trend for concentration to decrease slightly for a given value of turbidity with each succeeding year. In general, the computed slopes for the 1965 and 1966 water years are steeper than slopes computed for the 1967 and 1968 water years.[2] The regression lines not only have similar slopes, but they are also clustered about a common region of the graph. In virtually all the observed cases, the value of concentration is higher than the corresponding value of turbidity.

The year-by-year differences in the relations at each station are shown in figure 33. The graphs show that for a given value of turbidity, concentration is higher at stations on the Middle Fork Eel River and lower at South Fork Eel River near Branscomb than at the stations on the main stem of the Eel River.

The significance of the data presented in this section is apparent in the consistency of the form and correlation of the concentration-

[2] This effect may be related to the percentage of sand carried in suspension, although data are too limited to verify this assumption. The authors have observed that turbidity is higher at a given concentration for a water and sediment mixture which contains only silt and clay than for a mixture containing mostly sand.

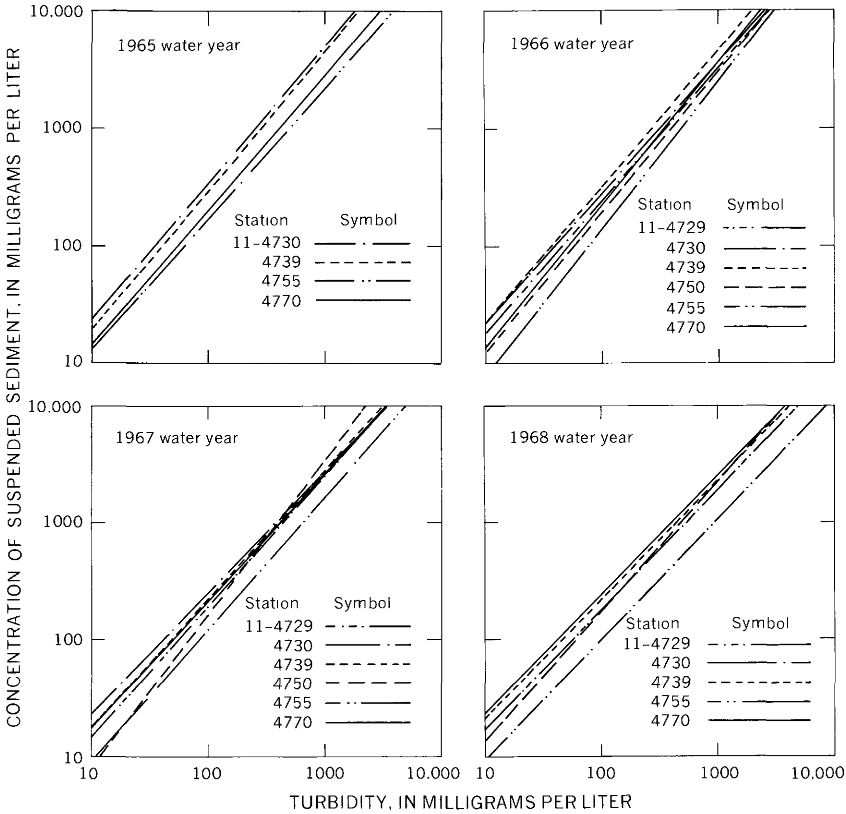

FIGURE 33.—Regression curves of the station-by-station relations between concentration and turbidity, Eel River basin.

turbidity relation throughout the Eel River basin. In the absence of a sediment-measurement program in the future, or at certain key sites within the basin where sediment sampling is not done, turbidity data might be used to obtain at least an approximation of suspended-sediment discharge. However, the concentration-turbidity relations obtained for the Eel River basin should not be used as indices for studies in other similar basins. For example, studies on the Russian River basin, which is immediately south of the Eel River basin and in a similar geologic and climatological evironment, show that the value of turbidity is higher than the graphically corresponding value of concentration for many of the stations observed.

The relations between turbidity and other properties and characteristics of a water and sediment mixture were of some interest in the study leading to this report, and are of special interest in a more detailed study currently being made of turbidity and its relation to suspended sediment. In the course of study of turbidity in the Eel River basin, many of these relations were explored, including the relations among turbidity, concentration and particle size of the suspended sediment, specific conductance of the water and sediment mixture, and depth of flow. Although certain trends existed among the relations developed, it was decided that the data were insufficient to provide conclusive information within the scope of this report other than the concentration-turbidity plots shown. More detailed aspects of turbidity are being studied, and a report in progress by the authors on turbidity in the Russian River basin will include comparisons of turbidity relations with several parameters in both the Russian and Eel River basins.

SELECTED REFERENCES

Bailey, E. H., Irwin, W. P., and Jones, D. L., 1964, Franciscan and related rocks, and their significance in the geology of western California: California Div. Mines and Geology Bull. 183, 177 p.

California Department of Water Resources, 1965, Land and water use in Eel River Hydrographic Unit, Volume I: Dept. Water Resources Bull. 94–8, 113 p.

——— 1966, Watershed management in the Eel River Basin, *in* North coastal area investigation: Dept. Water Resources Bull. 136, App. A, 143 p.

Carlston, C. W., 1969, Downstream variations in the hydraulic geometry of streams—special emphasis on mean velocity: Am. Jour. Sci., v. 267, p. 499–509.

Colby, B. R., 1956, Relationship of sediment discharge to streamflow: U.S. Geol. Survey open-file report, 170 p.

——— 1963, Fluvial sediments— a summary of source, transportation deposition, and measurement of sediment discharge: U.S. Geol. Survey Bull. 1181–A, 47 p.

Colby, B. R., Hembree, C. H., and Rainwater, F. H., 1956, Sedimentation and chemical quality of surface waters in the Wind River basin, Wyoming: U.S. Geol. Survey Water-Supply Paper 1373, 336 p.

Corbett, D. M., and others, 1943, Stream-gaging procedures, a manual describing methods and practices of the Geological Survey: U.S. Geol. Survey Water-Supply Paper 888, 245 p.

Hawley, N. L., and Jones, B. J., 1969, Sediment yield of coastal streams in northern California, 1958–64: U.S. Geol. Survey open-file report, 19 p.

Helley, E. J., and LaMarche, V. C., Jr., 1968, December 1964, a 400-year flood in northern California: U.S. Geol. Survey Prof. Paper 600–D, p. D34–D37.

Hickey, J. J., 1968, Variations in low-water streambed elevations at selected stream-gaging stations in northwestern California : U.S. Geol. Survey Water Supply Paper 1879–E, 33 p.

Holeman, J. N., 1968, The sediment yield of major rivers of the world: Water Resources Research, v. 4, p. 737–747.

Irwin, W. P., 1960, Geologic reconnaissance of the northern Coast Ranges and Kalmath Mountains, California: California Div. Mines and Geology Bull. 179, 80 p.

Judson, Sheldon, and Ritter, D. F., 1964, Rates of regional denudation in the United States: Jour. Geophys. Research, v. 69, no. 16, p. 3395–3401.

Leopold, L. B., and Maddock, Thomas, 1953, The hydraulic geometry of stream channels and some physiographic implications: U.S. Geol. Survey Prof. Paper 252, 56 p.

Leopold, L. B., Wolman, M. G., and Miller, J. P., 1964, Fluvial processes in geomorphology: San Francisco, Freeman, 522 p.

Miller, C. R., 1951, Analysis of flow-duration, sediment-rating curve method of computing sediment yield: U.S. Bur. Reclamation rept., 15 p.

Newell, F. H., 1902, Measurement of turbidity and color: U.S. Geol. Survey Div. Hydrography Circ. 8, 4 p.

Page, B. M., 1966, Geology of the Coast Ranges of California, *in* Geology of northern California: California Div. Mines and Geology Bull. 190, p. 253–321.

Porterfield, George, and Dunnam, C. A., 1964, Sedimentation of Lake Pillsbury, Lake County, California: U.S. Geol. Survey Water-Supply Paper 1619–EE, 46 p.

Rainwater, F. H., and Thatcher, L. L., 1960, Methods for collection and analysis of water samples: U.S. Geol. Survey Water-Supply Paper 1454, 301 p.

Rantz, S. E., 1964, Surface-water hydrology of coastal basins of northern California: U.S. Geol. Survey Water-Supply Paper 1758, 77 p.

——— 1968, Average annual precipitation and runoff in north coastal California: U.S. Geol. Survey Hydrologic Inv. Atlas HA–298.

Rantz, S. E., and Moore, A. M., 1965, Floods of December 1964 in the far western States: U.S. Geol. Survey open-file report, 205 p.

Ritter, J. R., 1968, Changes in the channel morphology of Trinity River and eight tributaries, California, 1961–65: U.S. Geol. Survey open-file report, 60 p.

U.S. Department of Agriculture River Basin Planning Staff, Soil Conservation Service and Forest Service, 1970, Appendix No. 1—Sediment yield and land treatment, Eel and Mad River basins, *in* North coastal area of California and portions of southern Oregon, *in* Water, land, and related resources: Portland, Oreg., U.S. Department of Agriculture Soil Conservation Service, 143 p.

U.S. Geological Survey, Water resources data for California—Part 1, Surface water records, Volume 1, Colorado River basin, southern Great Basin, and Pacific slope basins excluding Central Valley: U.S. Geol. Survey (published annually).

——— Water resources data for California—Part 2, Water quality records: U.S. Geol. Survey (published annually).

U.S. Inter-Agency Committee on Water Resources, 1963, Determination of fluvial sediment discharge, *in* A study of methods used in measurement and analysis of sediment loads in streams: Reptor. 14, 151 p.

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