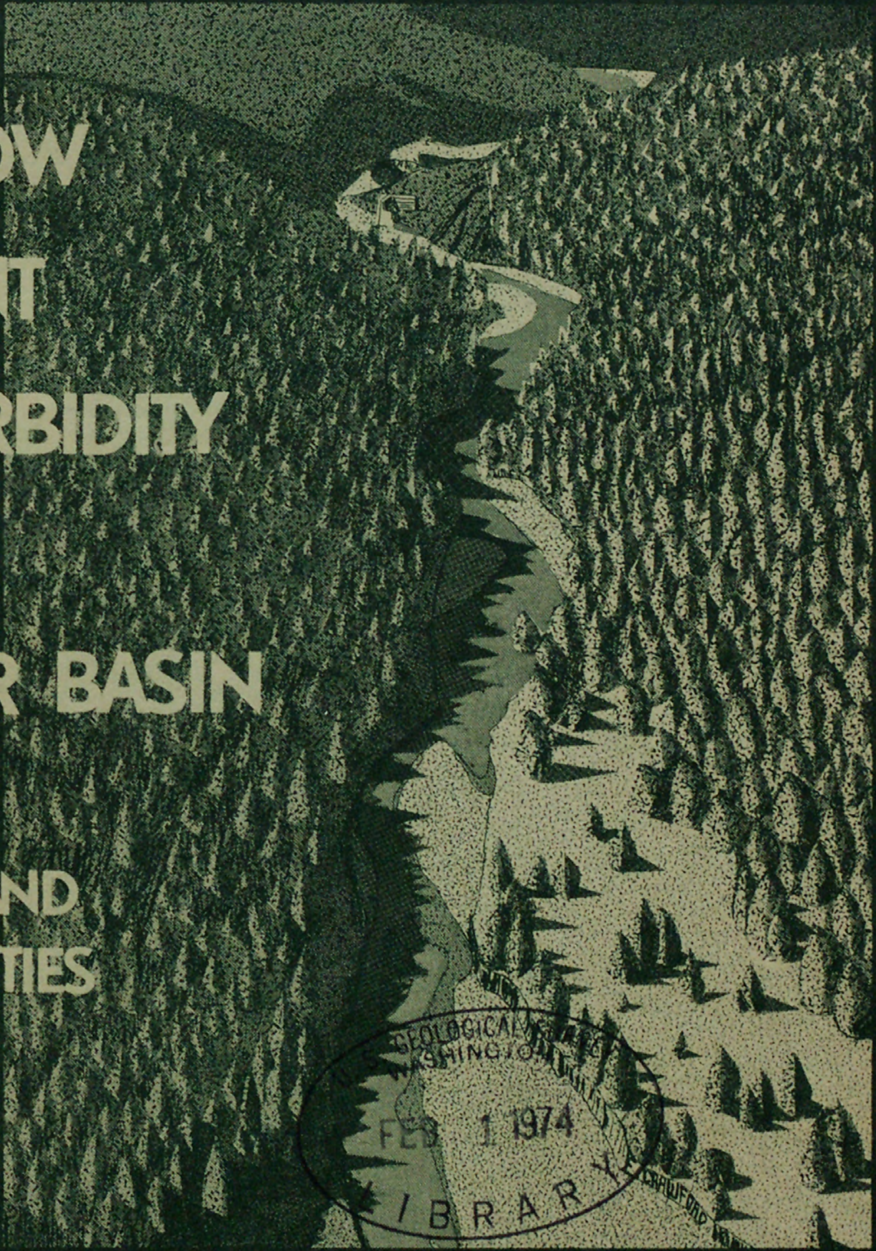
U.S. GEOLOGICAL SURVEY

WATER-RESOURCES INVESTIGATIONS 36-73

STREAMFLOW SEDIMENT AND TURBIDITY IN THE MAD RIVER BASIN

HUMBOLDT AND TRINITY COUNTIES CALIFORNIA



Prepared in cooperation with the

U.S. Army Engineer District, San Francisco
Corps of Engineers

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BIBLIOGRAPHIC DATA SHEET	1. Report No.	2.	3. Recipient's Accession No.

4. Title and Subtitle

STREAMFLOW, SEDIMENT, AND TURBIDITY IN THE MAD RIVER BASIN, HUMBOLDT AND TRINITY COUNTIES, CALIFORNIA

5. Report Date
December 1973

6.

7. Author(s)
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8. Performing Organization Rept. No. WRI 36-73

9. Performing Organization Name and Address
U.S. Geological Survey, WRD
California District, Menlo Park Subdistrict
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Menlo Park, Calif. 94025

10. Project/Task/Work Unit No.

11. Contract/Grant No.

12. Sponsoring Organization Name and Address

Same as 9 above

13. Type of Report & Period Covered Interim report
Period of record through Sept. 1971

14.

15. Supplementary Notes
Prepared in cooperation with U.S. Army Engineer District, San Francisco, Corps of Engineers, 100 McAllister Street, San Francisco, Calif. 94102

16. Abstracts

The Mad River discharged an average suspended-sediment load of 2,710,000 tons per year during a 13-year period beginning October 1957. Preliminary analysis of data collected during the 1971 water year indicated that about 66 percent of the suspended sediment was derived from sources upstream from a proposed reservoir site on the Mad River near Butler Valley. The high rate of suspended-sediment discharge and the corresponding sediment-induced turbidity of the streamflow constitute potential problems in the operation of the proposed reservoir.

17. Key Words and Document Analysis. 17a. Descriptors

Sediment transport; sedimentation; reservoir operation; sediment discharge; reservoir silting; stream erosion; turbidity; streamflow; erosion; runoff

17b. Identifiers/Open-Ended Terms

California; Mad River basin; Franciscan assemblage; California Coast Ranges

17c. COSATI Field/Group 02J

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
No restrictions on distribution. Available from National Technical Information Service, Springfield, Va. 22151	UNCLASSIFIED	57
	20. Security Class (This Page) UNCLASSIFIED	22. Price

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U.S. GEOLOGICAL SURVEY. Water Resources Division.

Water-Resources Investigation 36-73

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U.S. Army Engineer District, San Francisco

December 1973

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STREAMFLOW, SEDIMENT, AND TURBIDITY IN THE MAD RIVER BASIN

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ABSTRACT

The Mad River discharged an average suspended-sediment load of 2,710,000 tons per year during a 13-year period beginning October 1957. Preliminary analysis of data collected during the 1971 water year indicated that about 66 percent of the suspended sediment was derived from sources upstream from a proposed reservoir site on the Mad River near Butler Valley. The high rate of suspended-sediment discharge and the corresponding sediment-induced turbidity of the streamflow constitute potential problems in the operation of the proposed reservoir.

This study is part of an ongoing study by the U.S. Geological Survey intended to determine streamflow, sediment discharge, and turbidity characteristics as they relate to the proposed reservoir and the river system downstream from it. Data from 15 sites in the Mad River basin available through the 1970 water year were reviewed, and the collection of additional data at three of the sites was begun in the 1971 water year. Reconnaissance trips were made in 1971 and 1972 to locate existing or potential problem areas related to sediment and turbidity in the basin. This report presents the interpretations of the data available through September 1971, and indicates the intended direction of the ongoing study.

The Mad River basin is an area of 497 square miles and is elongated between roughly parallel, northwest-trending ridges in a geomorphic province characterized by complex folding, faulting, and tectonic uplift. Altitudes range from sea level to about 6,000 feet in a maturely dissected landscape characterized by narrow, V-shaped canyons and having few summit or valley flats. Most of the basin slopes have a moderately deep mantle of loamy soils that support a dense vegetal covering of grasses, brush, hardwoods, and conifers. The climate of the basin is a moist, mediterranean type distinguished by rainy winters and cool, foggy summers, and average annual rainfall is about 64 inches.

The geology of the basin is dominated by the Franciscan assemblage of Jurassic-Cretaceous age that comprises highly unstable and easily eroded rock units. The surface features formed on these units include massive landslides in a variety of sizes, stages of activity, and degrees of complexity. These landslides may mantle entire slopes from a streambed nearly to the adjacent ridgecrest, and cover several hundreds of acres. Such landslides occur throughout the central part of the Mad River basin and are primary contributors to the extremely high sediment yield of the basin.

The suspended-sediment yield for that part of the basin upstream from Ruth Reservoir, an existing water-supply reservoir, was about 760 tons per square mile per year for the period 1958-70 water years. The suspended-sediment yield for the remainder of the basin downstream from Ruth Reservoir (about 70 percent of the basin) was about 7,600 tons per square mile per year for the same period. The great disparity in the sediment yields from the different parts of the basin apparently was related to the sediment derived from the landslide-prone region between the Mad River gaging stations near Kneeland and Forest Glen.

Long-term suspended-sediment discharge was determined by extrapolating weighted suspended-sediment transport relations to a 100-year period on the basis of the 24-year period of streamflow record for Mad River near Arcata. The long-term suspended-sediment discharge was computed to be 2,220,000 tons per year, or about 4,600 tons per square mile of drainage basin per year. Using the data collected in the 1971 water year and correlations of streamflow data, the estimated 100-year suspended-sediment inflow to the proposed reservoir was about 1,420,000 tons per year.

Turbidity data for 12 stations in the basin showed that stream turbidity was highly correlative with suspended-sediment concentration, and followed an annual pattern that approximated the pattern of annual runoff. Anomalous high values of turbidity observed for short periods during the drier months of the years studied were related to (1) the presence of phytoplankton and other organisms; (2) release flows from Ruth Reservoir that carried suspended sediment derived from deposits on the reservoir bottom; and (3) gravel-mining operations and other activities that introduced previously deposited fine sediments into the flowing water. In most cases, the anomalous high turbidities at low flows persisted only for very short periods.

Turbidity in flows entering the proposed Butler Valley reservoir is expected to diminish rapidly following winter storm periods, and the inflow of "clear" water (turbidity <30 JTU's) may be expected for a 4- to 6-month period during most years. Sediment-induced turbidity in the proposed reservoir related to the inflow of sediment-laden water at a given time will behave as a complex function of such factors as the altitude of the reservoir water surface, the thermal stratification of the reservoir, the size distribution of influent sediment, the antecedent turbidity conditions, and the magnitude and duration of sediment inflow. The effect of proposed reservoir water releases on the turbidity of downstream flows will be heavily dependent upon the location and timing of the releases in a multiple-outlet system. It will be necessary to monitor the vertical distribution of turbidity in the proposed reservoir to select an optimum altitude, quantity, and duration of release flows to guarantee minimum downstream turbidity.

INTRODUCTION

The Mad River basin (fig. 1) is one of several coastal basins in northwestern California that is currently in the forefront of study and planning by a myriad of local, State, and Federal agencies; private companies; special-interest organizations; student groups, and private individuals. A 2-day public symposium on the general topic of the Mad River basin in April 1971 was well-attended, and ascertained the diverse interest in the possible futures of the basin. This symposium, sponsored by Humboldt State College (1971), stimulated the establishment of a series of public workshops directed toward a more complete understanding of the basins' complex environment. These workshops were instructed by panels of experts in numerous fields, and were broadly educational, although focused on the possible effects of the Butler Valley Project being studied and designed by the U.S. Army Engineer District, San Francisco, Corps of Engineers.

The conception, design, and evolution of the Butler Valley Project is best presented in a compilation of letters and reports issued in 1968 as House Document 359.90/2 (U.S. Army Corps of Engineers, 1968a), and as an interim review report (U.S. Army Corps of Engineers, 1968b). Briefly, expected water-supply, flood-control, and recreation-use requirements of Humboldt and Trinity Counties have resulted in proposals for the construction of several water-related facilities in the Mad River basin. The primary facility currently under consideration is a multipurpose reservoir proposed by the Corps of Engineers at a site near Butler Valley (fig. 1). This reservoir is intended to serve the municipal and industrial water-supply needs of the Eureka and Arcata areas, provide flood protection for areas along the river flood plain downstream from the proposed dam, and provide a recreational facility for a part of the growing northwestern California local and vacationist populations. Studies on the reservoir project were begun in 1956 when the Committee on Public Works of the House of Representatives requested a review of reports to determine the advisability of such a project.

Since 1956, the Corps of Engineers has been engaged in numerous studies aimed at (1) an effective and economical project design in view of the intended service of the project, and (2) an evaluation of the impacts of the project on the existing environment and the means to alleviate adverse impacts. The parts of these studies related to the water resources of the Mad River basin have been made largely on the basis of water-resources data made available during generalized, cooperative data-collection programs among the Corps of Engineers, the California Department of Water Resources, and the U.S. Geological Survey.

In order to supplement the existing data with new data specifically oriented toward the Butler Valley Project, additional water-related studies were begun in 1970. These studies were cooperatively organized between the Corps of Engineers and the U.S. Geological Survey to collect, analyze, and interpret data on the quality of ground and surface waters, streamflow, sediment discharge, and turbidity in the Mad River basin. In addition to environmental impact assessment, these studies were intended to provide background data and to identify problems that may affect the operation of the proposed Butler Valley facility. This report is addressed to the results of streamflow, sediment discharge, and turbidity studies through September 1971.

Purpose and Scope

Part of the ongoing cooperative program designed by the Corps of Engineers and the Geological Survey in 1970 was intended to provide data that would allow the determination of the following: (1) The quantity of sediment that would be transported into the proposed Butler Valley reservoir by flowing water during the 100-year economic life of the reservoir; (2) the effect of sediment on the turbidity of the proposed reservoir; (3) the effect of the proposed reservoir water releases on the turbidity of downstream flows; (4) the capacity and competence of reservoir release flows to transport channel sediment and sediment supplied by tributaries downstream from the impoundment; (5) the effects of the reservoir on the hydraulics and configuration of the Mad River channel system downstream from the reservoir; and (6) general information on streamflow, sediment discharge, and turbidity characteristics throughout the Mad River basin. In this report, parts (1), (2), and (6) are discussed in some detail. Because much of the data needed to evaluate parts (3), (4), and (5) was not available, the text for these parts is necessarily generalized. The data collection necessary to aid in completing the evaluation of parts (3), (4), and (5) was begun in the 1972 water year, and will be discussed in two subsequent reports to be prepared in the 1973 calendar year.

The scope of the program included the following: (1) An analysis of streamflow, sediment, and turbidity data available through September 1971 for gaging stations on the Mad River near Arcata, Kneeland, Forest Glen, and at Ruth Reservoir (fig. 1); (2) collection and analysis of sediment and turbidity data at Mad River stations near Arcata, Kneeland, and Forest Glen during the 1971 water year; and (3) a reconnaissance of the basin to locate any problem areas of large sediment yield or tributary inflow that would excessively influence sediment concentration and corresponding sediment-induced turbidity in or downstream from the proposed Butler Valley reservoir.

This report presents the interpretations of the data collected for the project, as well as pertinent related data, and summarizes the status of the project through September 1971.

Personnel and Acknowledgments

This report was prepared by the Geological Survey for the U.S. Army Engineer District, San Francisco Corps of Engineers, as part of an investigation of the water resources of the Mad River basin.

Important data for this project were commonly collected during periods of heavy flooding under extremely adverse and often hazardous conditions. Thus, a special acknowledgment is due the personnel of the Eureka, Calif., Geological Survey field office under the direction of Gerald W. LaRue for their sustained, creditable efforts in data collection.

The author wishes to express his gratitude to the following: R. F. Clawson, for consultation and the provision of data on turbidity collected by the California Department of Water Resources; personnel of the Humboldt Bay Municipal Water District for consultation and the provision of data on turbidity; personnel of Humboldt State College for consultation and assistance on various phases of the project; and J. O. Armstrong for his photographs used in this report.

PHYSICAL SETTING

The physical characteristics of the Mad River basin are described both generally and circumstantially by the California Department of Water Resources (1965a, b), the U.S. Army Corps of Engineers (1968a, b) and in several other reports. Briefly, the Mad River system is similar to several river systems in northern coastal California in its geomorphic history, underlying geology, prevailing climatic conditions, soils, vegetal covering, and types of land usage.

The Mad River flows northwesterly throughout most of its 100-mile course and empties into the Pacific Ocean about 10 miles north of Eureka. However, the location of the river mouth is migratory, and during periods of unusual flooding a part of the flow may enter the north end of Arcata Bay. The drainage basin of the Mad River is an area of 497 square miles and is elongated between roughly parallel, northwest-trending ridges in a geomorphic province characterized by complex folding, faulting, and tectonic uplift. Altitudes range from sea level to about 6,000 feet in a maturely dissected landscape characterized by narrow, V-shaped canyons, and having few summit or valley flats. The geology of the basin has not been mapped in detail, but generally comprises the Franciscan assemblage of Jurassic-Cretaceous age, the Falor Formation of Pliocene age, nonmarine sedimentary rocks of Pleistocene age, and Quaternary alluvium and dune sand of Holocene age (Strand, 1962). Most of the basin slopes have a moderately deep mantle of loamy soils that support a dense vegetal covering of grasses, brush, hardwoods, and conifers.

The climate of the region is a moist, mediterranean type distinguished by rainy winters and cool, foggy summers. The conifer forests predominant in the region thrive in the year-around moisture and include California Coastal Redwood (*Sequoia sempervirens*) and Doulgas-fir (*Pseudotsuga menziesii*) that provide resources for the timber industry. This industry is the most important segment of the economy of the region, and timber production predominates over the other principal land-use categories of agriculture and recreation.

The intergradational array of geology, topography, climate, vegetation, soils, land usages, and runoff from rainfall exerts varying localized and basin-wide controls on the erosion, transportation, and deposition of sediments, and the corresponding sediment-induced turbidity of water. Thus, the understanding of sediment and turbidity problems requires at least a general consideration of the interaction of the several aforementioned parameters. An important control in sediment and turbidity problems--the geology of the Mad River basin--is discussed in the following section to illustrate a unique situation. Otherwise, the detailed discussion of the remaining parameters affecting sediment and turbidity is beyond the scope of this report.

FRANCISCAN TERRAIN AND SEDIMENT YIELD

Perhaps the most unusual and least understood factor in problems related to sediment yield and turbidity in several large river basins in northern coastal California is the geology of the Franciscan assemblage. This assemblage is composed primarily of consolidated graywacke and subordinate quantities of siltstone, shale, chert, conglomerate, limestone, altered mafic volcanic rocks (greenstone), ultramafic rock (chiefly serpentine), and metamorphic rocks of the zeolite, blueschist, and eclogite facies as described by Bailey, Irwin, and Jones (1964, p. 5-7). These rocks have been largely tectonically mixed into a heterogeneous mass that is pervasively folded, crushed, and sheared, and generally lacks significant stratigraphic continuity. Because of the intense mechanical alteration of the rock units, they are highly susceptible in their present geomorphic setting to rapid weathering, landslide development, and other factors that facilitate their rapid erosion.

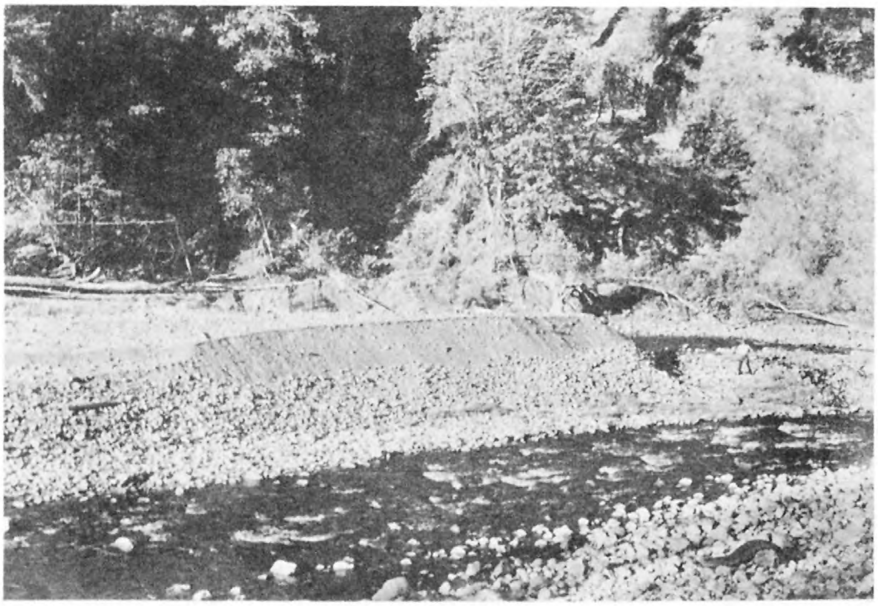
Recent mapping of the Franciscan assemblage (Blake, and others, 1971; Cotton, 1972) shows a division of the assemblage into three general bedrock units that may be superficially distinguished as massive, bedded, and mélange. R. H. Wright (written commun., 1972) also includes a volcanic unit. The massive unit contains predominantly massive, well-indurated, metagraywacke-type sandstone and poorly-indurated, highly-fractured sequences of metagraywacke interlayered with varying thicknesses of siltstone and shale. The bedded unit is a Flysh-like sequence composed dominantly of thinly-bedded, metagraywacke sandstone interbedded with siltstone and shale (fig. 2). The mélange unit is characterized by a pervasively sheared silty to shaly matrix containing abundant, hard, resistant tectonic blocks of metagraywacke-type sandstone, greenstone, chert, and metamorphic rock. The volcanic unit consists of large, relatively unaltered, unsheared greenstone masses composed of pillow lava, tuff, breccia, other volcanic rocks and thin-bedded chert. The Mad River basin includes all of these units, although they have not been mapped in detail. However, detailed mapping is in progress by the Corps of Engineers in the vicinity of the proposed Butler Valley Project (R. H. Gelnett, oral commun., 1972).

From the standpoint of sediment yield, the major source areas of sediment ultimately transported by the stream system occur in terrain underlain by mélange units. This terrain is dominated by landslides in a variety of sizes, stages of activity, and degrees of complexity with respect to differential movement within individual landslide units. Typical landslide units in the mélange involve soil creep, gullying, rotational slumps, debris slides, and debris flows. These complex landslides may mantle entire slopes from a streambed nearly to the adjacent ridgecrest, and may cover several hundreds of acres. Surficial movement often is sufficiently rapid to preclude the establishment of a conifer forest such as that which grows readily on more stable slopes in the basin. Thus, the large, slowly-moving rock and soil masses commonly support only grasslands and scattered thickets of hardwoods or mixed hardwood-conifer units that offer less resistance to erosion from runoff than the established forest.

Where the landslide masses within the Franciscan mélange meet a stream channel, the channel is characterized by a disarray of massive boulders of several rock types. The larger rocks are left behind as the stream removes the finer matrix material within which the larger blocks floated as isolated lenticles in the landslide mass (fig. 3). The matrix material consists of a supply of transportable particles that exceeds the transport capacity of the stream for most of the range of streamflow observed. Also, the heterogeneity of the matrix material is such that there is apparently an excess supply of particles for each of the particle-size ranges observed. Therefore, the percentages of suspended-sediment carried as colloids, clay, silt, and sand, for example, remain somewhat constant with increasing discharge (Brown and Ritter, 1971, p. 38-39). These relations apply so long as runoff, landslides, and lateral corrasion by the stream continue to introduce the matrix material into the flowing water. The relations generally do not apply during the dry summer season, as few mechanisms exist then to supply sediment to the flowing water. Thus, the low summer flows transport an almost insignificant quantity of sediment by comparison with storm-period flows.

FIGURE 2.--Intensely faulted drag folds in thinly-bedded Franciscan sandstone and shale in the central part of the Mad River basin. The bed of the river is shown in the foreground of the view at left. The photograph on the right shows a more detailed view of an adjacent outcrop. Faulting and fracturing of the beds are discernible throughout the view. Similar but less striking exposures of thinly-bedded Franciscan rocks occur in the vicnity of the proposed Butler Valley damsite. Similar rocks were also exposed by an extensive, shallow slope failure near Sweasey damsite that is discussed subsequently in this report. Photographs by J. O. Armstrong.

FIGURE 3.--Landslide debris adjacent to the channel of the Mad River in the central Mad River basin. In the view at left, debris is flowing toward the viewer, and the large "floating" block of darker rock in the center is about 10 feet wide. The lower view shows channel conditions downstream from a large debris deposit. A bar of coarse rock has formed in the center of the channel, and will move slowly downstream as bedload. Finer sediment has been transported away, and large blocks, like the one in the upper picture, have been left upstream in the channel at the toe of the debris deposit. Photographs by J. O. Armstrong.



During periods of high flow, the Mad River constantly interacts with the landslide toes that impinge on the stream channel, rapidly removing the matrix material and lending to progressive upslope failure that supplies more sediment to the stream. In turn, the sudden movement of a landslide into the stream may deflect the river toward the opposite bank resulting in the initiation of additional erosion there. In the central part of the basin for about 15 miles downstream from the mouth of Pilot Creek (fig. 1), the Mad River channel is consistently unstable as a result of massive landslides encroaching on both sides of the river channel.

The massive, bedded, and volcanic units of the Franciscan assemblage act as sediment contributors in somewhat different fashions than the mélange unit. These rock units commonly form very steep but relatively stable slopes that can support a soil and forest covering capable of retarding rapid erosion. However, on slopes disturbed by any of several processes including lateral corrasion by the river or roadbuilding by man, large, very shallow landslides may occur (fig. 4). These slides carry considerable organic debris (including full-grown conifers and other trees) as well as forest soil and weathered bedrock into the stream channel. The sediment contribution of these slides probably consists of a much smaller range of particle sizes than that present in the mélange, although no definitive local measurements of these sediments were made for this study.

Many other types of landslides and sediment-source areas exist within the basin, but their analysis and explanation are generally beyond the scope of this study. A more detailed examination of the types of gravitational mass movement common to the terrain dominated by the Franciscan assemblage is available in a memorandum report of the California Department of Water Resources (1971). Additional information on sediment-source types and areas in the Eel and Mad River basins is available in a U.S. Department of Agriculture report (1970). Also, several publications are available on the study and explanation of Franciscan mélanges and other attributes of the Franciscan assemblage, including Hsü (1968, 1969), and Blake, and others (1967).

FLUVIAL SEDIMENT

Definition of Terms

Many terms relating to fluvial sediment are not completely standardized or may be somewhat obscure; thus, 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.

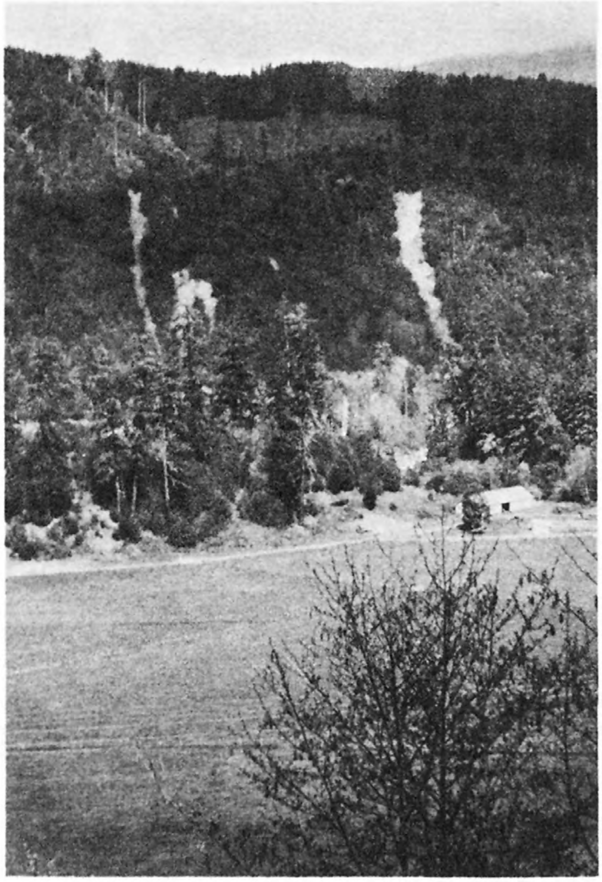


FIGURE 4.--Two views of shallow landslides similar to those formed on massive, bedded, and volcanic units of the Franciscan assemblage. The landslide on the right is about 300 feet long and about 50 feet wide at the top.

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 the quantity of sediment, as measured by dry weight or by volume, that passes a given section of a stream 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 such as cubic feet per second (cfs). The water contains both dissolved solids and suspended sediment.

Turbidity is 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. In this report, turbidity generally refers to a water-sediment mixture in which the presence of suspended sediment obstructs the passage of light. Turbidity is measured in Jackson Turbidity Units (JTU's) as defined by Newell (1902, p. 1-4).

Water year is a 12-month period, October 1 through September 30. The year is designated by the calendar year in which it ends and which includes 9 of the 12 months. All years referred to in this report are water years unless otherwise noted.

Cfs-days, as used in several tables in this report, is an expression of the volume of streamflow. For example, an average streamflow of 100 cfs for a period of 10 days is equal to 1,000 cfs-days. This term is used for consistency with basic-data reports published by the Geological Survey. To convert cfs-days to acre-feet, multiply cfs-days by 1.98.

The general principles of sediment-discharge measurement as well as the practical aspects of selecting sampling points and determining the frequency of sampling are discussed in several reports. Suitable references on methods of measurement and analysis of sediment loads are Report 14 of the U.S. Inter-Agency Committee on Water Resources (1963) and Porterfield (1972). The procedure for the measurement of water discharge was described by Carter and Davidian (1968).

Rainfall, Streamflow, and Suspended-Sediment Discharge

The prevailing climate of the Mad River basin includes a distinctly seasonal pattern of precipitation wherein the bulk of annual rainfall occurs between late October and early April, and the remaining period is comparatively dry. Average annual rainfall for the basin is about 64 inches based on precipitation records synthesized by Rantz (1964, p. 7). Precipitation ranges from about 40 inches per year in the coastal part of the basin to about 80 inches per year in the central part and about 70 inches per year in the upstream parts. Winter rainstorms frequently are intense and tend to be regional, so that the entire basin is commonly affected during storms; thus, the unit frequency distribution of runoff is similar for most individual streams. Most runoff occurs very rapidly during and shortly after the storms because base flow is poorly sustained owing to the impermeability of the bedrock underlying steep slopes throughout the basin. The characteristics of streamflow in the basin are demonstrated by interpretations of records collected at stations along the Mad River (table 1). The following sections present some of these interpretations, and the relations of streamflow to suspended-sediment discharge.

Mad River near Arcata

Mad River near Arcata (fig. 1) is the farthest downstream gaging station on the Mad River, having a drainage area of 485 square miles, or about 98 percent of the total Mad River basin area. The station is located at the west end of a narrow valley where the Mad River transects a low ridge between two broad alluvial flats. At the station site, the streambed is a shallow layer of gravel resting on bedrock, and the bottom topography generally consists of shifting gravel bars and exposed bedrock. The channel banks are steep and covered with brush, and neither bank is subject to overflow.

The availability and variability of streamflow at the station are shown by the flow-duration curve based on streamflow records for the period 1951-70 (fig. 5). Mean daily discharge (Q_{mean}) for this period was 1,520 cfs, a quantity equalled or exceeded about 25 percent of the time. The momentary maximum discharge was 77,800 cfs on December 22, 1955, prior to the construction of Ruth Reservoir (fig. 1). Minimum daily discharges were about 20 cfs (adjusted for diversion at Sweasey Dam[1]) in 1951 and 1959 before water storage began at Ruth Reservoir in July 1961. For the period 1961-70, discharges at Mad River near Arcata ranged from a daily minimum of 0.75 cfs on July 31, 1970, to a momentary maximum of 81,000 cfs on December 23, 1964.

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[1] Sweasey Dam, impounding a 3,000-acre-foot reservoir, was constructed in 1938 for the export of water from the Mad River basin to the city of Eureka (California Department of Water Resources, 1965b, p. 34). The reservoir ultimately filled with sediment, apparently during flood periods in the 1950's, and was no longer functional for water-supply purposes by the early 1960's (Humboldt State College, 1971, p. 69-75). The dam was removed by dynamiting in August 1970, and most of the sediment impounded behind the dam has since been transported downstream. Apparently, the quantity of impounded sediment available for transport in suspension was small with respect to inputs from farther upstream. Excessive turbidity was observed at the Essex and Arcata stations from August 1970 through the early part of the 1970-71 rainy season. However, the suspended-sediment discharge for the 1971 water year at the Arcata station showed no significant variation with respect to discharges for previous years. Apparently, the major part of the impounded sediment was coarse sand and gravel that is being transported as bedload. The effects of this bedload are discussed briefly on page 35 of this report, and will be examined in more detail in a report to be prepared in the 1973 calendar year.

TABLE 1.--*Periods of operation of surface-water and sediment-sampling stations, and periods of collection of turbidity samples at sites in the Mad River basin through the 1971 water year . Site locations are shown in figure 1*

Station number and name	Drainage area (sq mi)	Period of operation of station and type of sampling		
		Surface water	Sediment	Turbidity[1]
11-4804.00 Ruth Reservoir near Forest Glen	119	Oct. 1966 to Sept. 1971:[2] Daily records (reservoir contents)	-	Included in Humboldt Bay Municipal Water District sampling program (see below)
11-4805.00 Mad River near Forest Glen	143	June 1953 to Sept. 1971: Daily records	Jan. 1957 to Sept. 1971: Periodic sampling of suspended sediment	Feb. 1964 to Sept. 1967: Periodic sampling[3]
11-4807.00 Maple Creek near Blue Lake	12.1	Aug. 1961 to Sept. 1971: Periodic determinations of discharge	-	-
11-4807.5 Mad River near Kneeland	352	Oct. 1965 to Sept. 1971: Daily records	Oct. 1970 to Sept. 1971: Periodic sampling of suspended sediment	Oct. 1970 to Sept. 1971: Periodic sampling
11-4808.00 North Fork Mad River near Korbel	40.4	Oct. 1957 to Sept. 1964: Daily records	-	-
11-4810.00 Mad River near Arcata	485	Oct. 1910 to Sept. 1913: Aug. 1950 to Sept. 1971: Daily records	Sept. 1955 to July 1957: Periodic sampling of suspended sediment Dec. 1957 to Sept. 1971: Daily sampling, suspended sediment Periodic bedload	Oct. 1970 to Sept. 1971: Periodic sampling
Humboldt Bay Municipal Water District sites A through H	-	-		Feb. 1964 to Sept. 1971: Weekly sampling

[1]Sampled by U.S. Geological Survey unless otherwise noted.
[2]Records prior to October 1966 in files of Humboldt Bay Municipal Water District H.B.M.W.D.).
[3]H.B.M.W.D. collected weekly samples near this site for a concurrent period (H.B.M.W.D. site no. H).

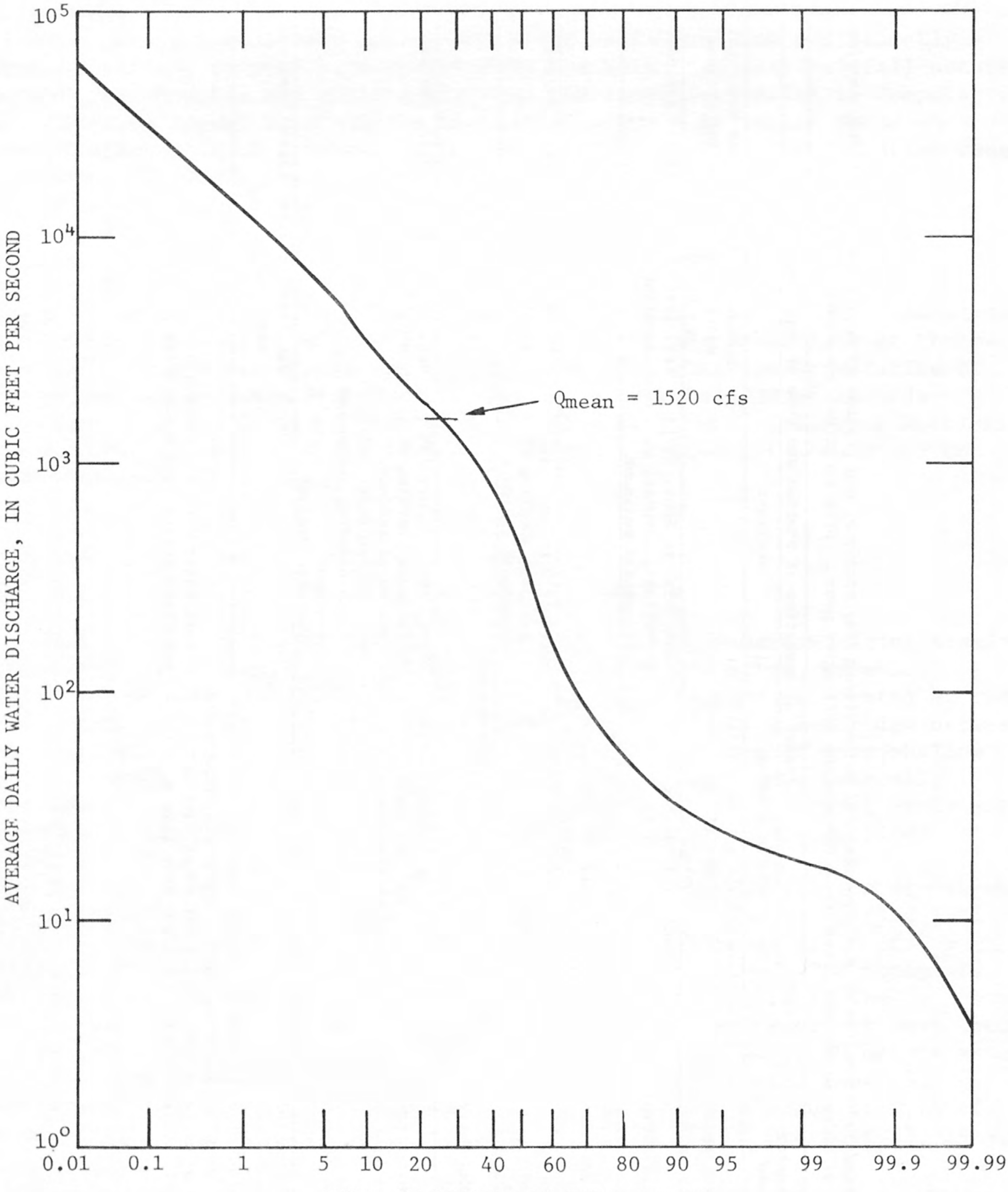

FIGURE 5.--Flow-duration curve for Mad River near Arcata, Calif., for 1951-70 water years.

The variable streamflow conditions expressed previously are accommodated at Mad River near Arcata in a manner which produces similarly variable sediment discharges. Suspended-sediment discharge based on daily samples collected at Mad River near Arcata was about 35,000,000 tons during the period 1958-70 (table 2). About 33 percent of this discharge occurred during fewer than 60 consecutive days (1 percent of the period) in 1965 when rainfall of historically unprecedented intensity produced severe flood conditions throughout north coastal California (Waananen, Harris, and Williams, 1971, p. A9). The maximum daily suspended-sediment discharge for the period of record was 3,140,000 tons during the peak day of flooding on December 22, 1964. Minimum discharges have dropped to 0.1 ton per day or less during the summer months in several years. During the period of record, more than 50 percent of the suspended sediment was transported in fewer than an average of 6 days per year (less than 2 percent of the time).

The relations between water discharge and suspended-sediment discharge for the periods 1958-64 and 1965-70 are depicted in figures 6 and 7. The curves in figure 6 show that the sediment-transport characteristics at the Arcata station responded dramatically to the flooding in 1965, and that the preflood sediment-transport relation had not been reestablished as of the end of 1970. That is, for the streamflows occurring since 1965, the suspended-sediment discharge was higher than might normally have been expected for flows of those magnitudes. This contention, however, assumes both normal conditions of the Mad River basin hydrologic regime for the period 1958-64 and a normally stable sediment-transport curve, and may be somewhat misleading. The transport of sediment in the Mad River (and in many streams) is so highly responsive to anomalous peak flows and alterations of the basin by man that a stable sediment-transport relation may not be adequately defined for the prediction of long-term sediment yield. Thus, the segment of the curve envelope indicated by the dashed lines in figure 6 represents a limiting or minimum condition of sediment transport for the 13-year period of record, and is stable only in that it reflects the extant geomorphology of the basin.

TABLE 2.--*Summary of water and suspended-sediment discharge at Mad River near Arcata, Calif.*
[Sta. 11-4810.00, drainage area = 485 sq mi]

Water year	Water discharge, Q_w (cfs-days)	Suspended-sediment discharge, Q_s (tons)	Suspended-sediment yield (tons/sq mi)	Mean daily discharge (cfs)	Instantaneous peak discharge (cfs)	[1]Average suspended-sediment concentration, C_s (mg/l)	Suspended-sediment yield for drainage area between Sta. 11-4805.00 and Sta. 11-4810.00 (drainage area = 342 sq mi) (tons/sq mi)
1958	867,500	[2]2,870,000	5,920	2,380	44,900	1,220	7,830
1959	413,100	1,360,000	2,800	1,130	33,700	1,220	3,850
1960	396,200	1,290,000	2,660	1,080	48,000	1,210	3,530
[3]1961	478,200	990,000	2,040	1,310	24,200	767	2,820
1962	356,800	400,000	820	980	23,500	415	1,150
1963	642,600	1,800,000	3,710	1,760	28,900	1,040	5,020
1964	463,800	1,240,000	2,560	1,270	45,200	990	3,560
1965	709,200	12,300,000	25,400	1,940	81,000	6,420	34,600
1966	445,700	3,350,000	6,910	1,220	35,800	2,780	9,500
1967	464,000	1,810,000	3,730	1,270	30,900	1,440	5,180
1968	312,600	1,310,000	2,700	860	15,800	1,550	3,740
1969	638,300	3,270,000	6,740	1,750	32,700	1,900	9,200
1970	522,000	3,280,000	6,760	1,430	33,500	2,330	9,040
Average	516,000	2,710,000	5,590	1,410	--	1,950	7,610

[1]Computed from the sediment-discharge equation, $Q_s = Q_w \times C_s \times K$, (Porterfield, 1972, p. 43).

[2]Suspended-sediment discharge for the period October 1 to December 20, 1957, was computed on the basis of periodic sampling. Suspended discharge for the period December 21, 1957, to September 30, 1958, was 2,740,000 tons on the basis of daily samples.

[3]Storage begun at Ruth Reservoir in July 1961.

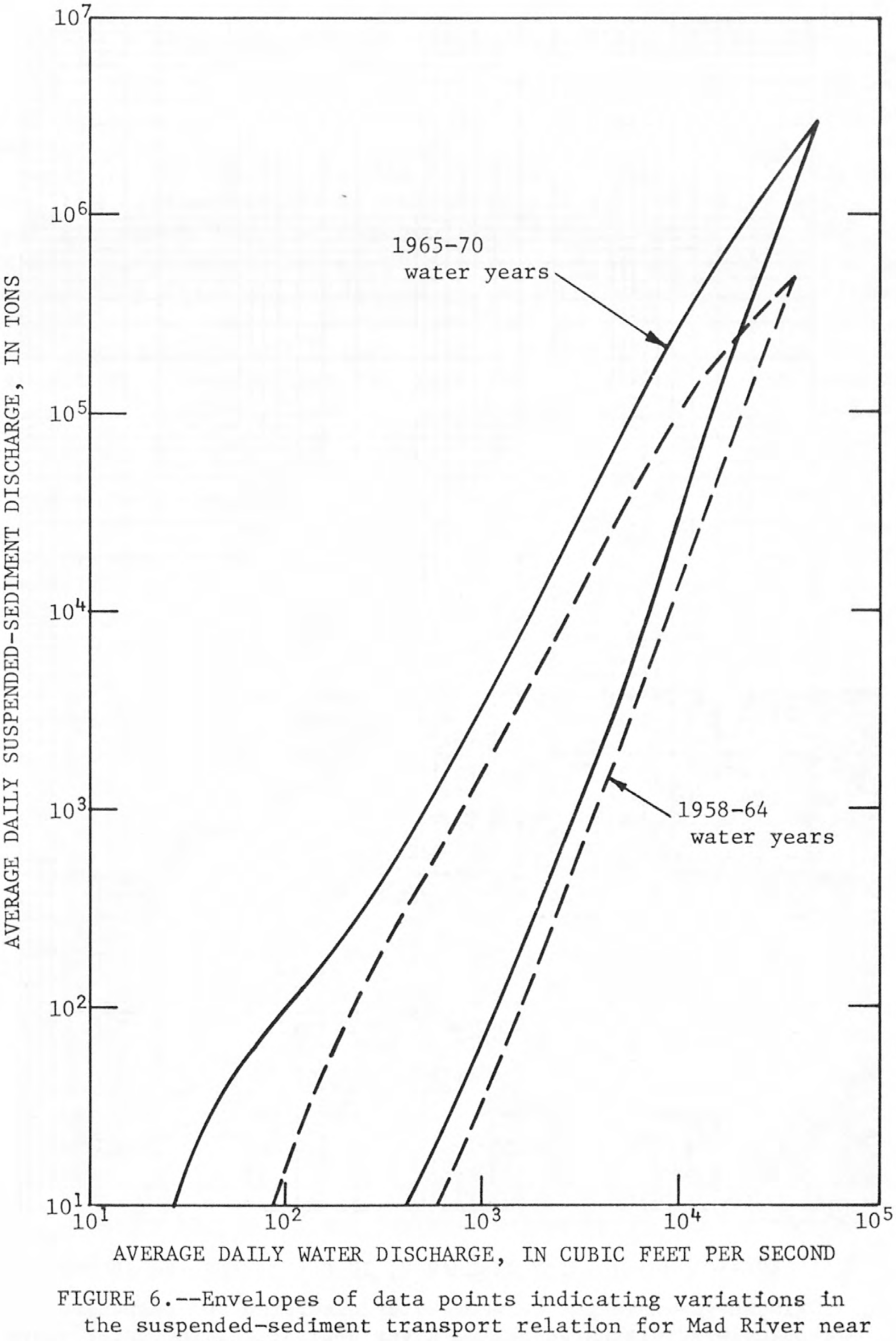

FIGURE 6.--Envelopes of data points indicating variations in the suspended-sediment transport relation for Mad River near Arcata, 1958-70 water years.

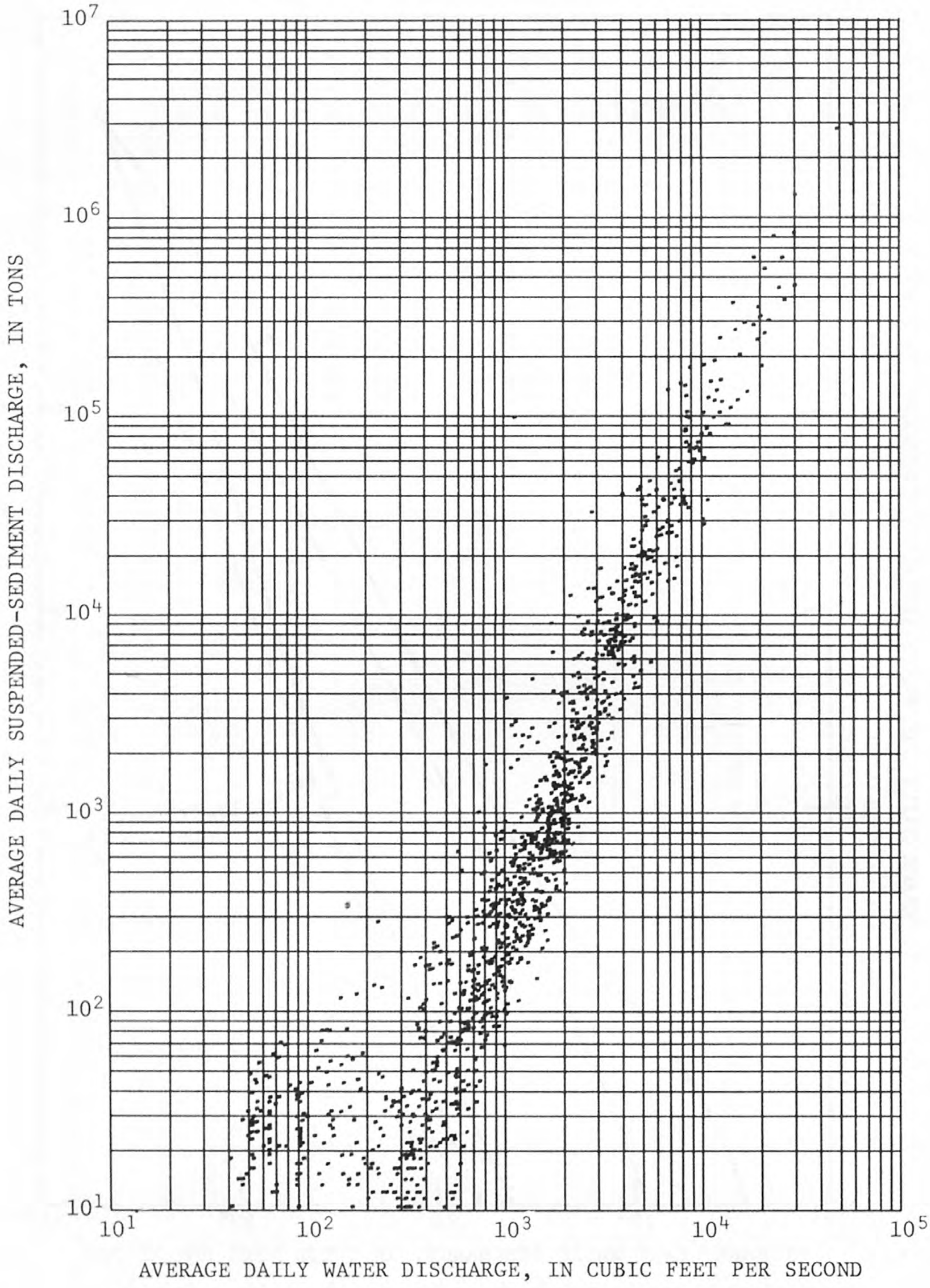

FIGURE 7.--Relation between water discharge and suspended-sediment discharge at Mad River near Arcata for water years 1965-70.

Mad River near Kneeland

The gaging station Mad River near Kneeland (fig. 1) is located at a bridge across the Mad River about 2 miles upstream from the proposed Butler Valley damsite. The drainage area upstream from the station is 352 square miles, or about 71 percent of the Mad River basin area. In the vicinity of the station, the stream channel is characterized by a shifting gravel bed bounded by high, steep banks of exposed Franciscan bedrock (fig. 8). The channel is somewhat constricted at this site, and is atypical of the general reach of channel in that the bridge supports interfere with high flows.

Between the Kneeland and Forest Glen stations (fig. 1), the Mad River drops at a rate of about 60 feet per mile through a narrow, V-shaped canyon characterized by a boulder-strewn stream channel, and massive landslides in varying stages of activity forming the canyon sides. The annual rainfall in this part of the basin averages 70 to 80 inches and is the highest in the Mad River drainage. The specific runoff from the rainfall is about 1,330 cfs-days per square mile per year (table 4), and it passes the Kneeland gage as turbulent flow commonly having velocities greater than 6 feet per second at higher stages (fig. 10).

FIGURE 8.--View looking downstream at the channel of the Mad River and the site of station 11-4807.50. Streamflow, sediment discharge, and other measurements are made from the bridge at higher stages of flow.

TABLE 3.--*Summary of water discharge at Mad River near Kneeland, Calif.* (Sta. 11-4807.50, drainage area = 352 sq mi)

Water year	Water discharge Q_w, (cfs-days)	Mean daily discharge (cfs)	Instantaneous peak discharge (cfs)	[1]Percent of water discharge at Mad River near Arcata (Sta. 11-4810.00)	Specific runoff in cfs/sq mi/yr	
					Between Sta. 11-4805.00 and Sta. 11-4807.50 (area = 209 sq mi)	[1]Between Sta. 11-4807.50 and Sta. 11-4810.00 (area = 133 sq mi)
1966	357,200	980	24,600	77.2	1,060	790
1967	372,500	1,020	20,100	76.1	1,110	880
1968	270,000	740	18,000	79.2	780	530
1969	552,600	1,510	32,200	82.8	1,710	860
1970	469,500	1,290	30,100	84.8	1,460	630
[2]1971	574,200	1,570	27,000	79.5	1,400	1,120
Average	432,700	1,180	--	80.2	1,330	800

[1]Adjusted for diversion between Sta. 11-4805.00 and Sta. 11-4810.00 (table 4).

[2]1971 data are preliminary, and subject to revision.

TABLE 4.--*Annual water discharge at Mad River near Arcata (Sta. 11-4810.00), and annual streamflow diversion at Essex station*[1]

Water year	Water discharge at Sta. 11-4810.00 Q_w (cfs-days)	Streamflow diversion at Essex (cfs-days)	Adjusted discharge at Sta. 11-4810.00 (cfs-days)
1963	642,600	3,270	645,900
1964	463,800	3,620	467,400
1965	709,200	11,640	720,800
1966	445,700	16,920	462,600
1967	464,000	25,200	489,200
1968	312,600	28,200	340,800
1969	638,300	29,100	667,400
1970	522,000	31,500	553,500
1971	695,200	27,380	722,600
Average	543,700	19,650	563,400

[1]Essex station is the site of collection fields and pumping stations for water released from Ruth Reservoir. For details see Humboldt State College (1971, p. 37-48).

Streamflow characteristics at the Kneeland site are exemplified by the data in table 3 and the flow-duration curve of figure 9. For the period of record, 1966-71, the momentary maximum water discharge was 32,200 cfs on January 13, 1969, and the minimum daily discharge was 55 cfs for several days in October-November 1966. Mean daily discharge for the period was about 1,180 cfs, a quantity equalled or exceeded 31 percent of the time. Average annual water discharge at Kneeland was 432,700 cfs-days, or about 80 percent of the average annual water discharge measured at Mad River near Arcata for the same period, adjusted for diversion at the Essex station (table 4).

Figure 10 shows some hydraulic characteristics of the stream channel at the Kneeland site that indicate the response of the channel to varying water discharge. As discharge increases, it is accommodated by the channel by a rapid change in depth, and lesser changes in velocity and width of flow. These changes, measured by the slope values f, b, and m (Leopold and Maddock, 1953, p. 5-9), are similar to those measured for stations along the Eel River to the south which flows in a geomorphic setting similar to that of the Mad River. The similarities between hydraulic characteristics and a variety of of other aspects of the two river systems suggests similar modes, and perhaps rates, of sediment transport for comparable subunits of the two basins (Brown and Ritter, 1971, p. 16-21). A thorough analysis of comparability of the two river systems, accounting for the constricting effects of the bridge, in an attempt to yield a more descriptive picture of streamflow and sediment yield in the vicinity of the Kneeland gage is generally beyond the scope of this report. However, the data and contentions presented here may be useful in future and more detailed studies.

Suspended-sediment samples were collected on a limited basis at the Kneeland site beginning in November 1970 in an attempt to define the relation between suspended-sediment discharge and water discharge. A preliminary expression of this relation is shown in figure 11 which indicates a significant difference in the nature of sediment transport during the major runoff events in 1971. Thus, suspended-sediment transport for the early part of the water year, October to December, was computed by flow-duration methods using the upper curve segment of figure 11, and suspended-sediment transport for January to September was computed using the lower curve segment. Suspended-sediment discharge on these bases was about 663,000 tons for October to December, and 1,168,000 tons for January to September, or 1,831,000 tons for the 1971 water year.

More data are needed for a better definition of the sediment-transport curve and to test for the magnitude of seasonal and annual shifts in the sediment-transport relation. Such shifts are both common and potentially large in the Mad and Eel River basins, and may have a major effect on the estimation of long-term suspended-sediment discharge (Brown and Ritter, 1971, p. 23-31; Knott, 1971, p. 16-24). Therefore, the preliminary sediment-transport data derived for the Kneeland site for 1971, and further applications of these data in this report, should be used with caution in application to periods other than 1971.

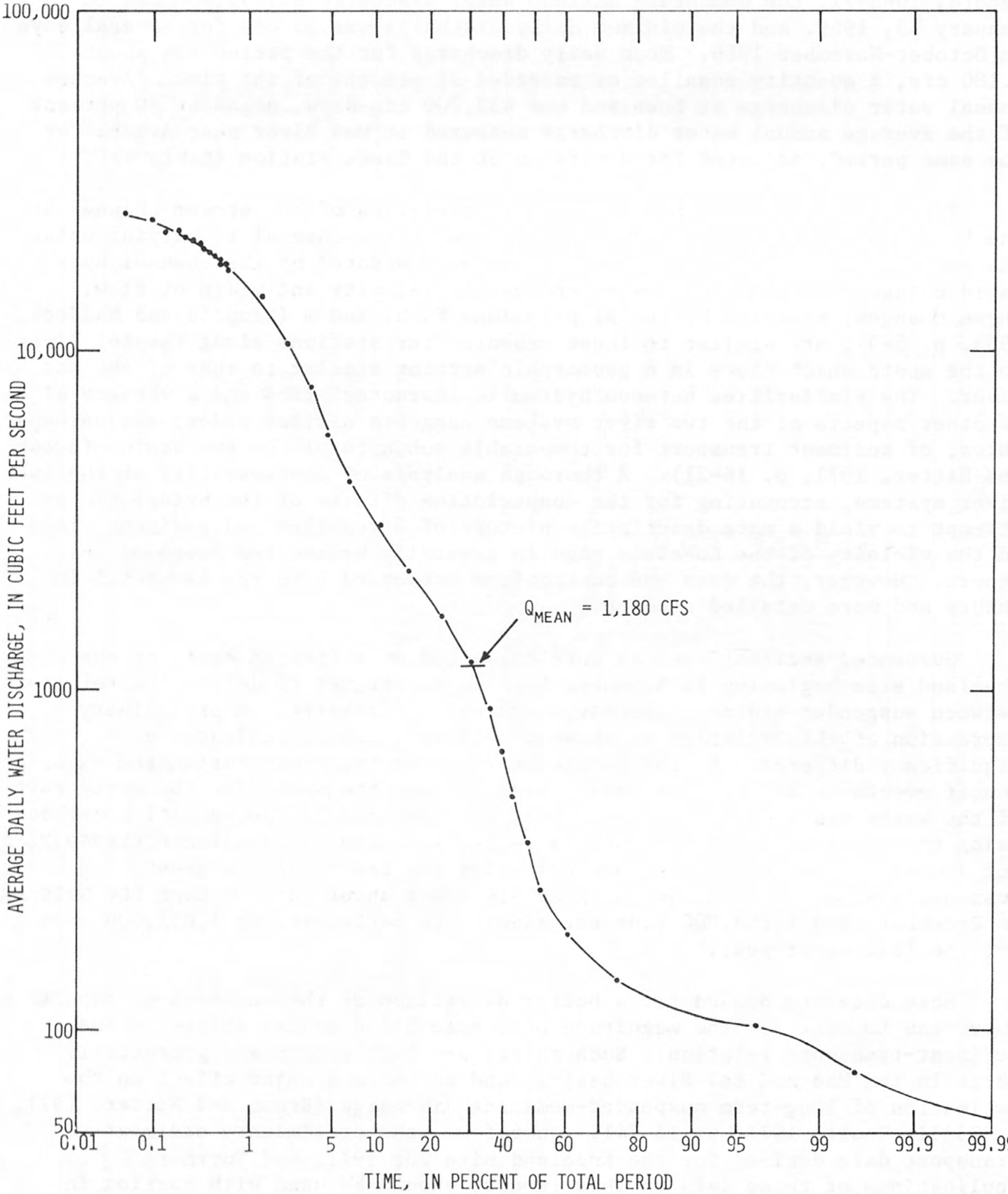

FIGURE 9.--Flow-duration curve for Mad River near Kneeland, 1966-71 water years

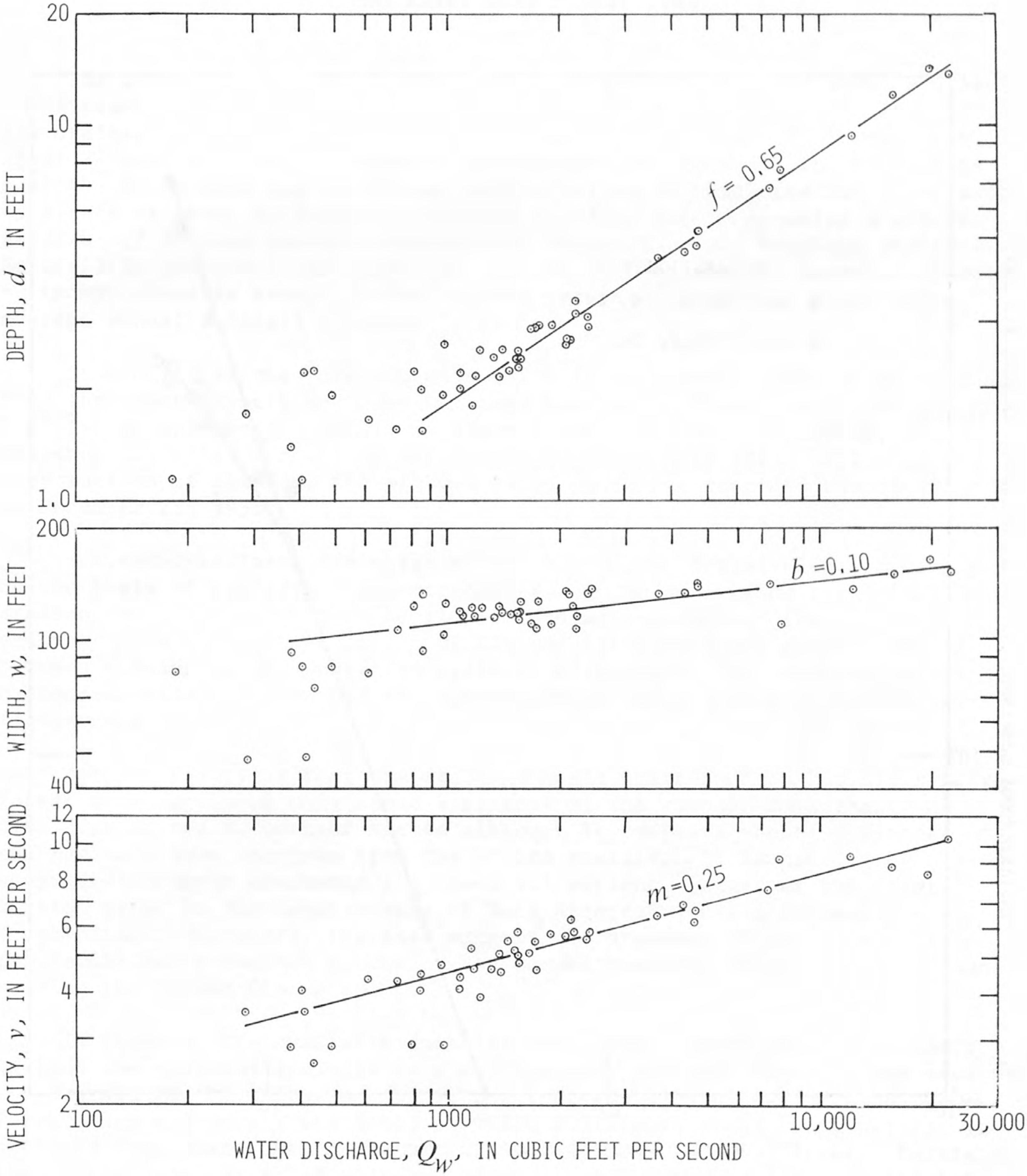

FIGURE 10.--Relation of depth, width, and velocity to discharge, Mad River near Kneeland, 1966-71 water years.

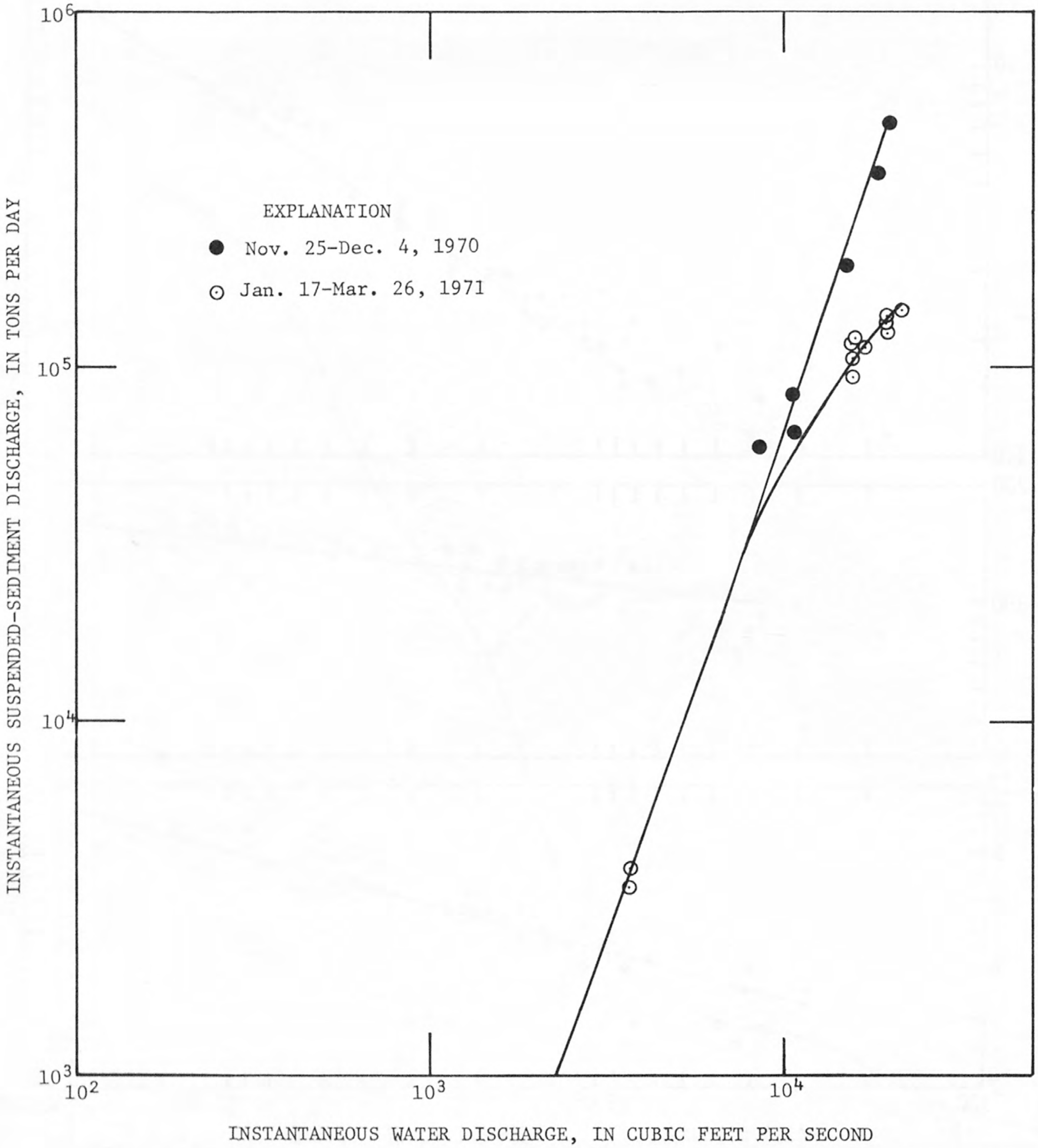

FIGURE 11.--Relation between suspended-sediment discharge and water discharge at Mad River near Kneeland, 1971 water year.

Mad River near Forest Glen

The gaging station Mad River near Forest Glen is located about 8 miles downstream from Robert Matthews Dam which impounds Ruth Reservoir (fig. 1). The drainage area upstream from the station is 143 square miles, of which about 24 square miles lie between the station and the dam. The station is near the downstream end of a long, narrow valley in which the Mad River drops at a rate of about 20 feet per mile for 40 miles before assuming a steeper gradient of 60 feet per mile between the Forest Glen and Kneeland stations. Rainfall in the basin upstream from the Forest Glen station averages about 60 inches annually except in the extreme upstream end of the basin where average annual rainfall is about 70 inches.

Streamflow at the Forest Glen station is dominantly affected by releases from the nearby Robert Matthews Dam, and has ranged from a daily minimum of 0.6 cfs on September 15, 1961, to a momentary maximum of 20,100 cfs on December 22, 1964, since flow regulation began in July 1961. Prior to the construction of the dam, the minimum daily discharge recorded was 39,200 cfs on December 22, 1955.

Suspended-sediment discharge at Mad River near Forest Glen was computed on the basis of periodic sediment samples and the streamflow regime at the station for the period of collection of sediment samples. The periodic sediment data are plotted in figure 12, and illustrate the general relation between streamflow and suspended-sediment discharge. The computed values of suspended-sediment discharge are summarized in table 5 with attendant water-discharge data.

Table 5 indicates that the drainage basin upstream from Mad River near Forest Glen furnished only about 4 percent of the suspended-sediment discharge at Mad River near Arcata although it composes about 30 percent of the drainage area upstream from the Arcata station. It is noteworthy that suspended-sediment discharge was about 4.7 percent of that at the Arcata station prior to the construction of Ruth Reservoir, based on nearly 4 years of sampling. Therefore, the data suggest the presence of the reservoir apparently had a minimal effect on the annual quantity of suspended sediment passing the Forest Glen station.

In summary, the available data for the Forest Glen station apparently exclude the upstream drainage as a major source area of suspended sediment to the overall Mad River basin. Thus, the intervening drainage between the Forest Glen and Arcata stations, of which 209 square miles or 61 percent is upstream from the proposed Butler Valley reservoir site, apparently furnished the bulk of the suspended sediment transported by the Mad River during 1958-70 water years. The following section, using preliminary 1971 data, further explores the contribution of suspended sediment upstream and downstream from the proposed reservoir site, and longer-term trends in suspended-sediment discharge.

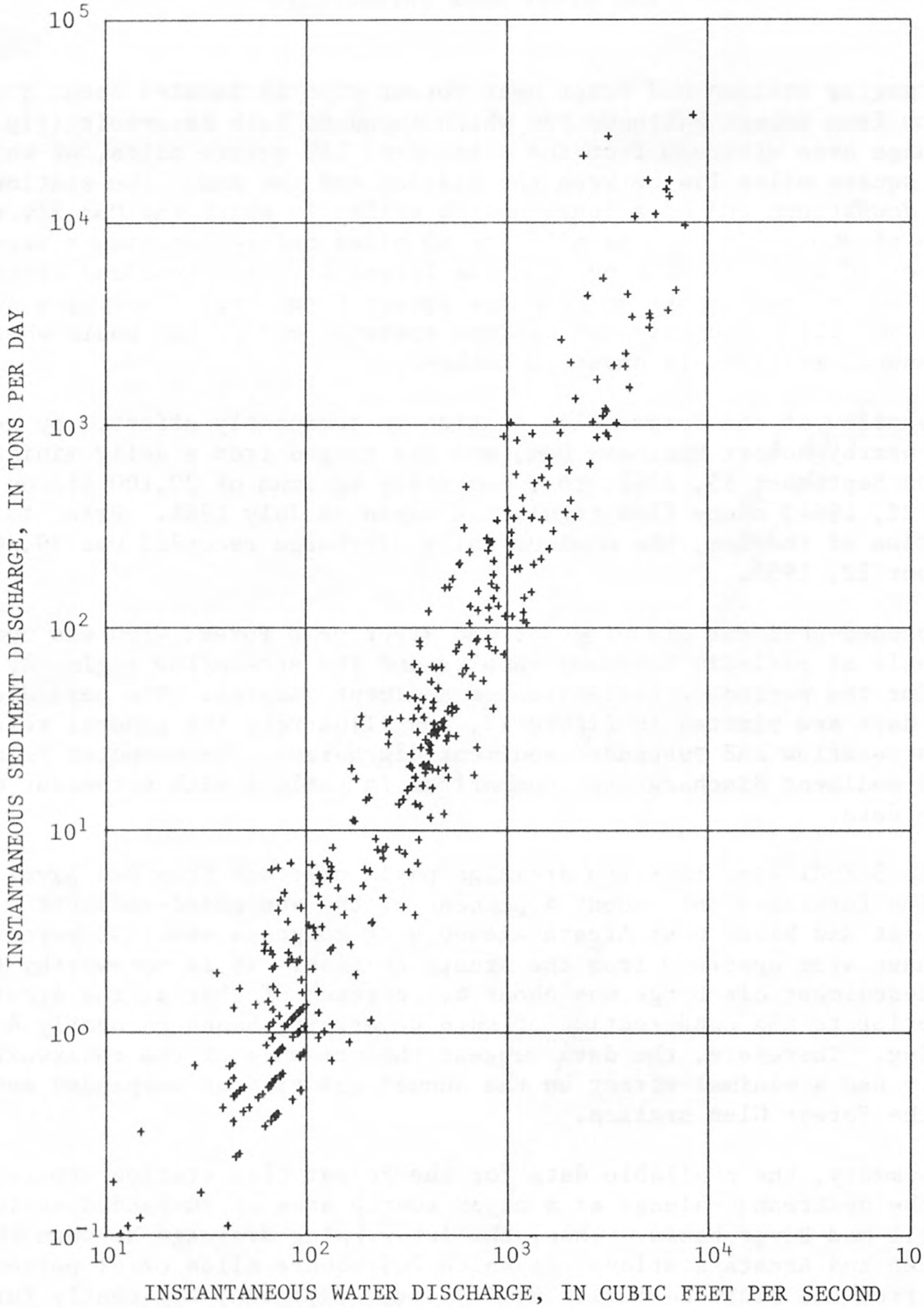

FIGURE 12.--Relation between water discharge and suspended-sediment discharge at Mad River near Forest Glen for 1957-70 water years.

TABLE 5.--*Summary of water and suspended-sediment discharge at Mad River near Forest Glen, Calif.*
[Sta. 11-4805.00, drainage area = 143 sq mi]

Water year	Water discharge, Q_w (cfs-days)	[1]Suspended-sediment discharge, Q_s (tons)	Suspended-sediment yield (tons/sq mi)	Percent of discharge at Mad River near Arcata (Sta. 11-4810.00)		Mean daily discharge (cfs)	Instantaneous peak discharge (cfs)	[2]Average suspended-sediment concentration, C_s (mg/l)
				Water, Q_w	Suspended sediment, Q_s			
1958	255,700	192,200	1,340	29.5	6.7	700	9,440	280
1959	86,090	44,300	310	20.8	3.3	236	7,620	190
1960	90,170	82,100	570	22.8	6.4	246	16,400	340
[3]1961	116,400	23,900	170	24.3	2.4	318	4,700	76
1962	56,580	6,100	43	15.9	1.5	155	1,380	40
1963	185,400	82,300	580	28.9	4.6	508	5,540	160
1964	82,930	21,400	150	17.9	1.7	227	7,300	96
1965	199,400	474,000	3,310	28.1	3.9	546	20,100	880
1966	134,900	100,800	700	30.3	3.0	370	9,490	280
1967	140,900	38,200	270	30.4	2.1	386	6,630	100
1968	106,800	31,100	220	34.2	2.4	292	4,060	110
1969	194,300	125,300	880	30.4	3.8	532	11,100	240
1970	163,600	187,400	1,310	31.4	5.7	448	11,900	420
Average	139,500	108,400	760	27.0	4.0	382	--	290

[1]Computed by flow-duration, sediment-transport curve method (Miller, 1951) using instantaneous sediment-transport curves for the period 1958-70 water years.

[2]Computed from the sediment-discharge equation, $Q_s = Q_w \times C_s \times K$, (Porterfield, 1972, p. 43).

[3]Storage begun at Ruth Reservoir in July 1961.

Distribution of Suspended-Sediment and Water Yields

Suspended-sediment yields for the 1971 water year were computed for three major subunits of the Mad River basin, and the yields and related data are summarized in table 6. The sediment yield figures show that about 60 percent of the suspended sediment derived from the basin in the 1971 water year emanated from the rugged, landslide-prone region between the Forest Glen and Kneeland gaging stations. Also, the runoff from that region composed about 56 percent of the total runoff for the water year. The average runoff contribution from the region was 54 percent of the total basin runoff on the basis of records for water years 1966-70, and ranged from 50 to 59 percent during that period.

These data probably are insufficient for determining a sound relation between suspended-sediment discharges at the Kneeland and Arcata stations. However, the regional nature of rainfall and runoff throughout the basin, the consistency of the relation between annual runoff values at the two stations (table 4), and the regional consistency of patterns of change of sediment-transport relations at stations in similar geomorphic settings (Brown and Ritter, 1971, p. 56-58) suggest that the percentage figures in table 6 may be representative of a longer term. The limitations on this suggestion are among the following possibilities: (1) Changes in land-use practices *downstream*[2] from the Kneeland gage that might grossly alter the suspended sediment-transport relation for that region; (2) changes in the patterns of major storms that would significantly alter the relation between annual runoff values at the Kneeland and Arcata stations; and (3) misinterpretation or incomplete interpretation of 1971 water year data for the Kneeland station. The latter limitation can be resolved as additional data are collected during subsequent water years.

For the purposes of this report, it is important primarily to recognize that the suspended-sediment yields upstream and downstream from the Kneeland gage may be different by a factor large enough to have a considerable impact on long-term planning for reservoir sedimentation and turbidity problems.

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[2]Note that alterations of the suspended-sediment transport conditions upstream from the Kneeland gage would be reflected not only at that gage, but at all downstream sites.

TABLE 6.--*Summary of water and suspended-sediment discharge in the Mad River basin, 1971 water year*[1]

USGS station name and number	Drainage area		Water discharge, Q_w (cfs/days)	Suspended-sediment discharge, Q_s (tons)	Suspended-sediment yield (tons/sq mi)	Percent of discharge at Mad River near Arcata (Sta. 11-4810.00)	
	Sq mi	Percent of total (Sta. 11-4810.00)				[2]Water, Q_w	Suspended sediment, Q_s
Mad River near Forest Glen 11-4805.00	143	29.5	181,700	[3]166,600	1,170	26.1	6.0
Intervening drainage area	209	43.1			7,960	56.4	60.3
Mad River near Kneeland 11-4807.50	352	72.6	574,200	[3]1,831,000	5,200	82.5	66.3
Intervening drainage area	133	27.4			6,980	17.5	33.7
Mad River near Arcata 11-4810.00	485	100.0	695,200	2,760,000	5,690	100.0	100.0

[1]1971 data are preliminary, and subject to revision.
[2]Not adjusted for diversion at Essex station (table 3).
[3]Computed on the basis of periodic sampling.

Long-Term Suspended-Sediment Discharge

Long-term suspended-sediment discharge was determined by extrapolating weighted suspended-sediment-transport relations to a 100-year period on the basis of the 24-year period of streamflow record (1911-13, 1951-71) for Mad River near Arcata. The sediment-transport relations were weighted in consideration of the large changes in the relations that occurred during the 1965 water year (fig. 6), and the indications of a progressive shift toward the 1958-64 preflood relation during a 7-year period beginning with the 1965 water year.[3] As an estimate based on the knowledge of sediment transport in the nearby Eel River basin (Knott, 1971, p. 24), the 1965 sediment-transport relation was assigned a recurrence interval of 100 years, and the relations for the ensuing 7 years affected by the 1965 flooding were adjusted accordingly.

It is not known whether the 1956 water-year flooding in the Mad River basin contributed to dramatic changes in the sediment-transport relation such as those noted in 1965 at the Arcata station. However, the 1958-64 records for that station show no evidence of the progressive shifting of sediment-transport curves such as that induced by the 1965 flooding. Thus, the 1956 flows were included in the 100-year sequence without adjustment for changes in sediment transport.

Long-term suspended-sediment discharge for Mad River near Kneeland was not computed by conventional methods owing to the paucity of data available for that station. Rather, the assumptions explained in the preceding section regarding the relations of streamflows and sediment discharges between the Kneeland and Arcata stations were used, and the long-term sediment record for the Kneeland station was computed as a straight percentage of the record for the Arcata station. Until more data are available, this procedure should be viewed with due caution, and the long-term sediment discharge for the Kneeland station should be considered only an estimated value.

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[3]The 7-year period 1965-71 was used because the data show that by 1971 the pre-1965 sediment-transport relation had been regained.

The value of long-term (100-year) suspended-sediment discharge for Mad River near Arcata was computed to be 2,220,000 tons per year, or about 4,600 tons per square mile of drainage basin per year. Given that about 4 percent of this amount is derived upstream from Mad River near Forest Glen (table 6), the long-term suspended-sediment yield downstream from that station may be computed to be about 6,200 tons per square mile per year. As preliminary estimates using the figures of table 6, the long-term suspended-sediment yield for the intervening drainage area between the Forest Glen and Kneeland gages would be about 6,400 tons per square mile per year, and that for the intervening drainage area between the Kneeland and Arcata gages would be about 5,600 tons per square mile per year. The long-term (100-year) suspended-sediment discharge past the Kneeland gage would be an estimated 64 percent of that at the Arcata station, or about 1,420,000 tons per year.

The conversion of this figure to a volume for use in reservoir-storage studies depends upon the particle-size distribution of the sediment, the shape of the reservoir, the timing and location of release flows, and other factors generally beyond the scope of studies for this report. Knott (1971, p. 44-58) described potential sediment accumulation in proposed reservoirs in the Eel River drainage basin, and suggested methods for computing such sediment accumulation.

For the purposes of this report, sediment accumulation was computed solely on the bases of the estimated unit weight of deposited sediment and the estimated inflow of suspended sediment.[4] Knott (1971. p, 48) and Porterfield and Dunnam (1964, p. EE37) report unit weights of 62 and 73 pounds per cubic foot,[5] respectively, for sediment deposits derived predominantly from Franciscan rocks in the Eel River basin. Also, Dendy and Champion (1965, p. 54-57) reports unit weights ranging from 30 to 80 pounds per cubic foot for sediment deposits derived from Franciscan and related rocks in the San Francisco Bay region. Table 7 lists the estimated 100-year sediment accumulation figures based upon unit weights of deposited sediment ranging from 30 to 80 pounds per cubic foot, and the suspended-sediment inflow discussed previously. Again, the values in table 7 are estimates and should be regarded accordingly until detailed checks are made.

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[4]Bedload was not measured or estimated for this study; however, a bedload-sampling program for the Mad River basin was begun in the 1972 water year, and some bedload data will be available for analysis by the 1973 water year. Bedload and the particle-size distribution of suspended load will be discussed in a subsequent report.

[5]These figures were derived using a bedload component.

TABLE 7.--*Summary of 100-year suspended-sediment accumulation figures for the proposed Butler Valley Reservoir based on preliminary suspended-sediment-discharge data for Mad River near Kneeland*

Estimated 100-year suspended-sediment discharge in tons for the drainage basin upstream from sta. 11-4807.50	Unit weight of deposited sediment, in pounds per cubic foot	[1]Suspended-sediment accumulation, in acre-feet per 100-years
142,000,000	30	217,000
	40	163,000
	50	130,000
	60	109,000
	62	105,000
	70	93,100
	73	89,300
	80	81,500

[1]These figures assume the trapping of 100 percent of the suspended-sediment inflow. However, the release of flows especially during storm periods will allow the passage of fine sediment through the reservoir outlets. The quantities of sediment to be passed downstream are being estimated for a report to be prepared in the 1973 calendar year. Using methods suggested by Brune (1953), however, the trap efficiency of the proposed reservoir is an estimated 95 percent. The unit weight of deposited sediment suggested for preliminary design purposes is 70 pounds per cubic foot. The suggested figures for trap efficiency and the unit weight of deposited sediment should be regarded as tentative until further work is done.

Channel-Problem Areas

Some problems in other areas in the basin not previously discussed, and related to the proposed reservoir or the channel system downstream from the reservoir were observed during 1970-72 reconnaissance work:

1. *Maple Creek* and *Boulder Creek*, two major tributaries to the proposed reservoir, and *Canon Creek*, downstream from the proposed reservoir site, experienced considerable but unmeasured channel changes in their lower reaches during flooding in the 1972 water year. Apparently, large quantities of organic and inorganic debris were deposited in the lower reaches of these streams, causing rapid channel aggradation and consequent channel widening. The channel widening was accompanied by the disturbance of riparian vegetation, including large trees that fell into the channels and accumulated in log jams and similar debris piles on the new channel floor. This debris is now available for transport into the proposed reservoir area in the cases of Maple and Boulder Creeks, and into the Mad River channel in the case of Canon Creek.

2. The channel system in the vicinity of Sweasey damsite (fig. 1) is undergoing considerable changes as the result of the removal of Sweasey Dam in August 1970. Figure 13 shows an aerial view in October 1970 of the Mad River flowing on sediment deposited behind Sweasey Dam. Since 1970, most of that sediment has been transported downstream, causing the channel of the Mad River to aggrade and widen slightly for a distance of about 1.5 miles. The extent and effects of the channel aggradation are being observed, and will be analyzed with respect to flow releases from the proposed reservoir as data are collected in the 1973 water year. However, an additional problem of undetermined origin and consequence exists in the form of an extensive, shallow slope failure along the far bank of the river at the place where figure 13 was taken. This slope failure may be related to channel processes, and should be analyzed with respect to proposed release flows.

3. The probable major source areas of sediment and sediment-induced turbidity are *Canon Creek* and the *North Fork Mad River* (fig. 1). The contribution of sediment and turbidity from the North Fork Mad River currently is being monitored. The contribution of sediment from Canon Creek can be estimated from data being collected at points upstream and downstream from its mouth on the Mad River. Secondary source areas include the massive slope failure at Sweasey damsite and other landslide areas and smaller tributaries currently being located and mapped. Additional source areas for turbidity during summer periods of low flow include gravel-mining operations at several sites downstream from the Mad River Hatchery, and other sites where construction equipment disturbs the channel bed and sides adjacent to flowing water.

FIGURE 13.--View looking northwest at the Mad River channel upstream from Sweasey damsite. The dam abutments, remaining after the central part of the dam was dynamited in August 1970, are out of view behind the trees at the right center of the photograph. The exposed slope at the upper left has undergone extensive failure since this photograph was taken, and an active area of landslide movement would now extend out of the photograph to the upper left. Photograph courtesy of Humboldt State College.

TURBIDITY

Turbidity, an unclear or cloudy condition of water caused by the presence of undissolved substances, is a classic and frequently misunderstood water-quality problem in streams throughout northwestern California. Turbidity is simply an optical property of water, and turbidity problems are primarily related to water aesthetics. For example, stream and reservoir turbidities in excess of 30 Jackson Turbidity Units (JTU's) commonly provoke complaints to water-management agencies from fishermen and other recreationists, and public drinking-water standards commonly require that turbidity not exceed 5 JTU's. However, high turbidity is not necessarily indicative of water unfit for several uses, including some industrial uses and even fishing, as not all turbidity-causing substances are toxic or even undesirable. Turbidity in itself, exclusive of the substance or substances that cause it, affects aquatic life by interfering with the penetration of light into water. Thereby, turbidity inhibits the photosynthetic process in the case of aquatic plants, and affects in some manner the food chains in which such plants are included. Principally in lakes and reservoirs, but also in ponded reaches of streams, turbidity may modify water temperature by causing reflection or scattering of sunlight energy at the level where the turbidity is present. Many other potential interactions among turbidity and the various elements of the aquatic ecosystem exist; however, few of these interactions have been well-defined, especially in terms of artificially-induced turbidity.

In the Mad River basin, turbidity is recognized as a problem affecting both water supply for domestic and industrial consumption and recreation values of the stream system and Ruth Reservoir. During the drier months of the year, turbidity in the water of the basin is caused primarily by (1) the presence of phytoplankton and other micro-organisms which proliferate in the presence of sunlight; (2) release flows from Ruth Reservoir that carry suspended sediment derived from deposits on the reservoir bottom; and (3) gravel-mining operations and other activities in the stream channels that introduce previously deposited fine sediments into the flowing water. During periods of high runoff in the rainy season, stream turbidity may be attributed almost entirely to suspended sediment derived from both natural and man-affected sediment-source areas. Phytoplanktonic reproduction, dependent upon the passage of sunlight through the water, is precluded by the high concentrations of suspended sediment, and the effects of phytoplankton upon stream turbidity during the rainy season may be considered negligible.

Turbidity caused by the presence of phytoplankton in Ruth Reservoir and the proposed Butler Valley reservoir is a biological problem generally beyond the scope of this report. An explanation of the phytoplanktonic life cycle and attendant problems in Ruth Reservoir, however, is presented in a report by Humboldt State College (1971, p. 88-95). The discussion of turbidity in this report will be confined to turbidity induced by suspended sediment.

Instrumentation

Confusion about the nature of turbidity persists partly because of the differences in instruments and methods used to measure it. Turbidity measurements in the Mad River basin, for example, have been made using four different types of instruments of which a well-defined comparability exists between only two (fig. 14). The Hach Laboratory Turbidimeter model 2100 and its predecessor, the model 1860, employ a nephelometric or light-scattering principle in which a light beam is reflected or scattered by particles in suspension, and the intensity of the reflected light is photoelectrically compared with a standard. A consistent relation exists between the values measured by the two instruments and, in this report, values measured by the model 1860 have been adjusted for comparability with values measured by the model 2100. The Hellige instrument used prior to August 1966 (fig. 14) is also a nephelometer; however, the reflected light beam is viewed by an observer as a circle of light in a field of Tyndall light (Rainwater and Thatcher, 1960, p. 70-71), and requires operator judgment in which inconsistencies are inherent. The Hach colorimeter is used for the comparison of the color of a given sample with a standard color, and thus does not necessarily measure turbidity as it is defined in this report. Also requiring operator judgment for obtaining values, the colorimeter is deficient from the standpoint of comparability with the more consistent photoelectric nephelometers.

Thus, the absolute turbidity values measured by the different instruments must be interpreted with the nature of the instruments in mind where specific standards are required. In many cases, however, the use of relative turbidity values is adequate to describe and analyze many problem situations. For example, the range of turbidity values during a typical water year is sufficiently large and the response of turbidity to its causative agents is sufficiently noticeable to be assessed by any of the aforementioned and similar instruments. The following text will discuss problems of absolute turbidity values and instrument comparability where appropriate. Also, further details on turbidity and its measurement in north coastal California are given in a report by the California Department of Water Resources (1966).

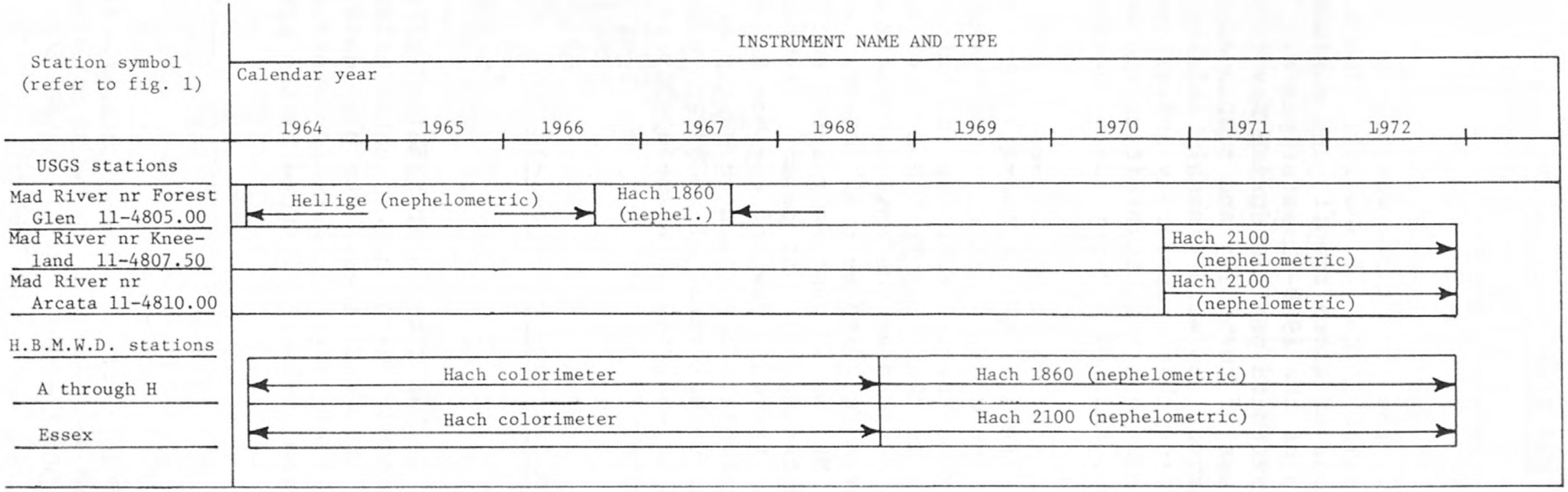

FIGURE 14.--Instrumentation used for the measurement of turbidity in the Mad River basin by the U.S. Geological Survey and Humboldt Bay Municipal Water District, February 1964 to October 1972.

Mad River near Arcata

Turbidity measurements at Mad River near Arcata and at the Essex site just upstream (fig. 1) showed that turbidity was highly correlative with suspended-sediment concentration (figs. 15 and 16). The highest turbidity values occurred during periods of storm runoff, and maximum turbidity values exceeded 1,000 JTU's in each of the 1969-71 water years. Turbidity commonly dropped below 30 JTU's for extended periods during May to October each year. However, anomalous high values of turbidity and suspended-sediment concentration at low flows were observed, and were probably related to gravel-mining operations and other activities that temporarily interferred with the flowing water. In all cases, the anomalous high turbidities and suspended-sediment concentrations at low flows persisted for periods of less than 24 hours.

The data for the Arcata station will best serve as an indirect indication of turbidity conditions related to the operation of the proposed Butler Valley reservoir. The location of the station is such that several conditions influencing stream turbidity may be reflected in the data. For example, altered turbidity conditions in the North Fork Mad River basin would be inseparable from altered conditions on the main stem of the Mad River without additional data from the North Fork and several intermediate points. Therefore, the data in this report for Mad River near Arcata reflect only the general turbidity conditions of the basin, and must be supplemented by a new data from the North Fork Mad River and the main stem of the Mad River to estimate the effects of the proposed reservoir. Such data currently are being collected at North Fork Mad River near Korbel (sta. 11-4808) and near the Mad River Hatchery (fig. 1), and will be analyzed in a subsequent report.

Mad River near Kneeland

Turbidity measurements at Mad River near Kneeland were begun in the 1971 water year; thus, only preliminary data on the characteristics of turbidity at that site are available. However, these data plus data from subsequent samples (taken prior to the beginning of reservoir construction) will aid in defining the changes in stream turbidity induced by the presence of the reservoir.

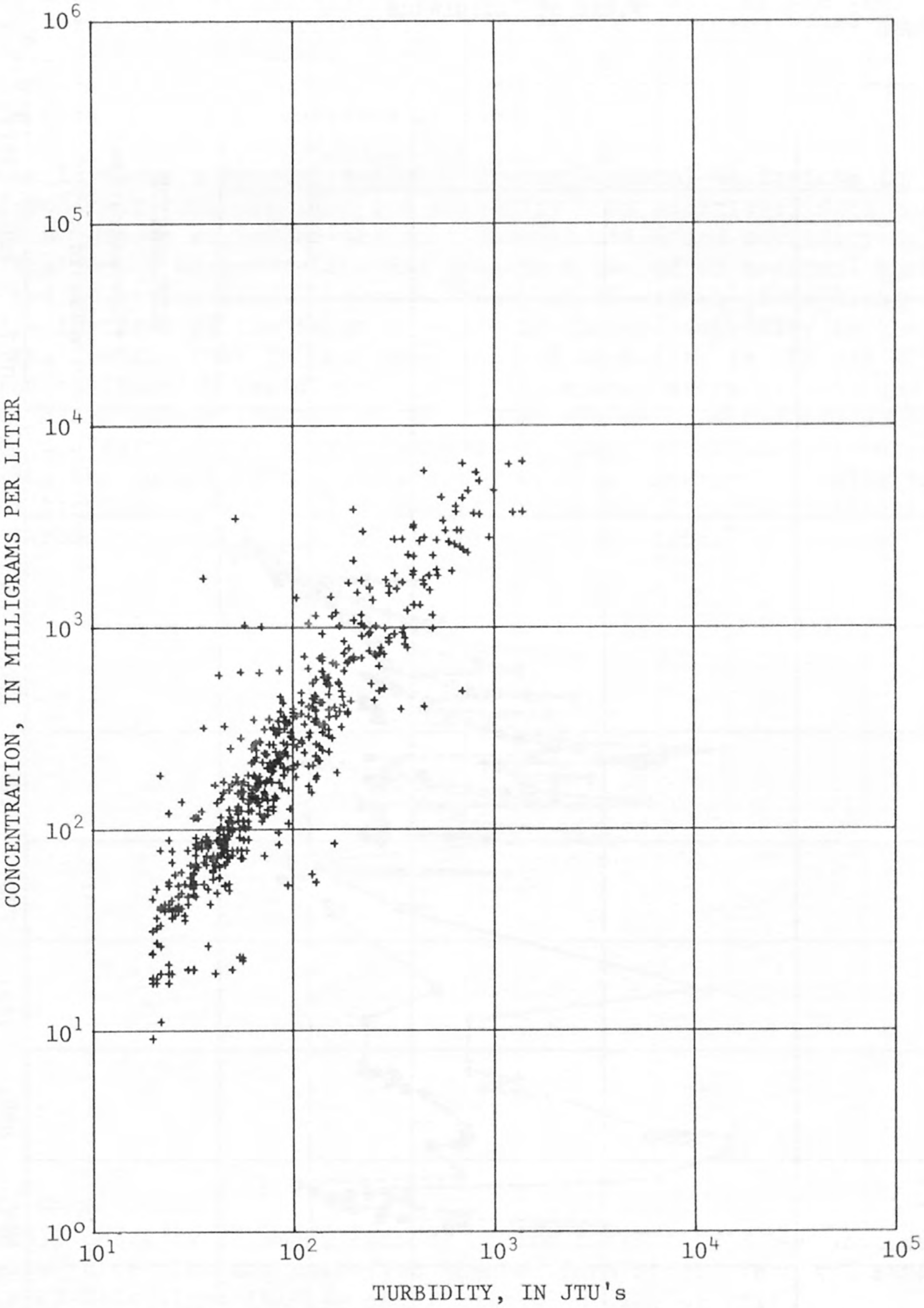

FIGURE 15.--Relation between turbidity at Essex station and the concentration of suspended sediment at Mad River near Arcata for period 1969-71. (Turbidity data supplied by Humboldt Bay Municipal Water District.)

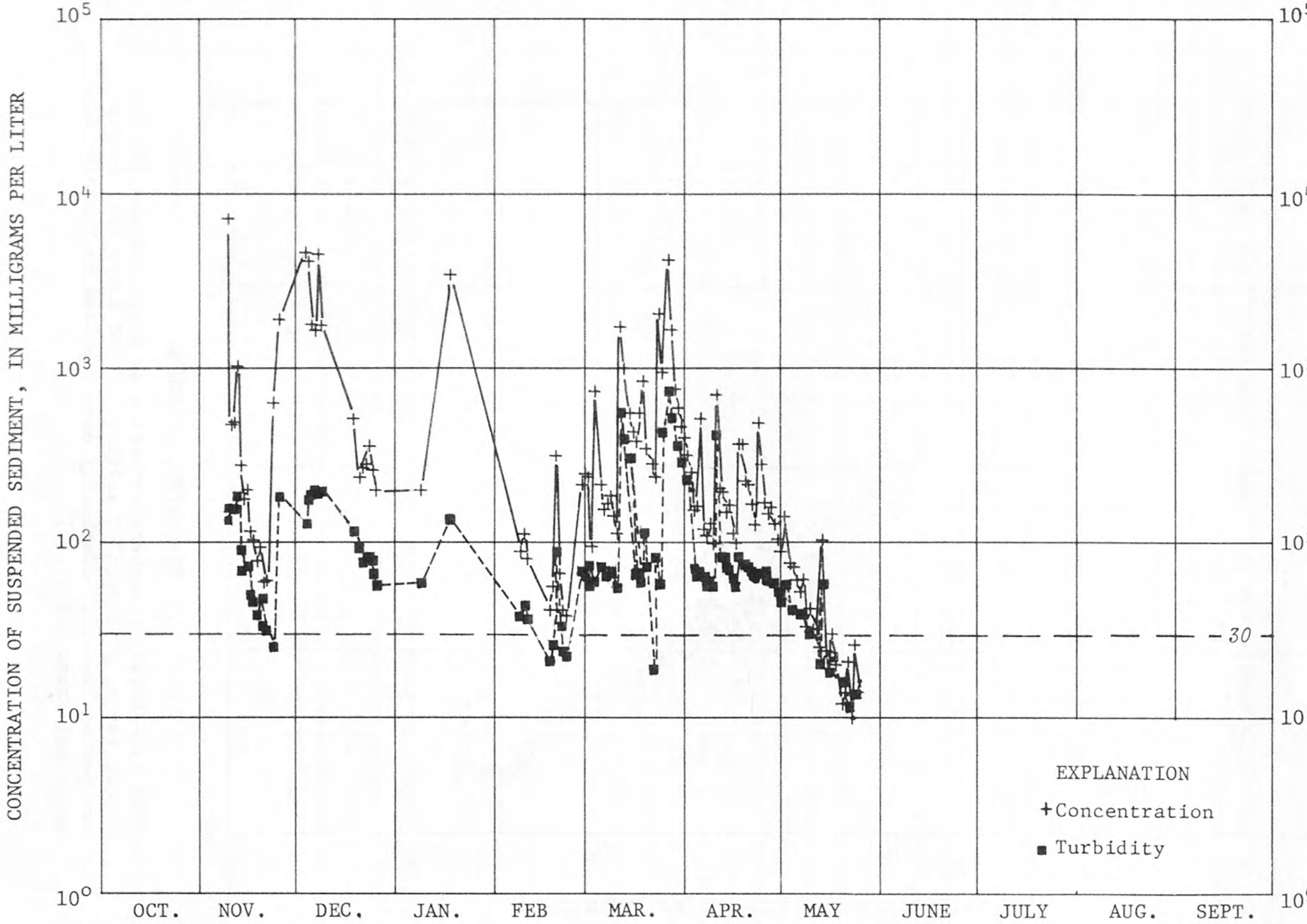

FIGURE 16.--Storm-period variations in suspended-sediment concentration and turbidity, Mad River near Arcata, 1971 water year.

The existing data (fig. 17) show that stream turbidity varied linearly with the concentration of suspended sediment on a log-log plot, and that turbidity values ranged from 1 to 850 JTU's during the sampling period. The apparently anomalous values falling above and to the left of the trend shown in figure 17 reflect the temporary input of excess suspended sand[6] upstream from the sampling site. Such an occurrence probably represents a landslide, a streambank failure, or a similar localized event having a short-term effect, and does not reflect the conditions of the basin as a whole.

Figure 18 shows a generalized plot of the seasonal variations in suspended-sediment concentration and turbidity. As additional data confirm the relation between suspended-sediment concentration and turbidity at the Kneeland station, a more complete and long-term record of seasonal turbidity patterns can be synthesized. However, the plot of figure 18 is highly descriptive in terms of the input of sediment-induced turbidity to the proposed reservoir. That is, sediment-induced turbidity in the Mad River may be expected to diminish rapidly following the winter storm period, and the inflow of "clear" water (turbidity <30 JTU's) may be expected for a 4- to 6-month period during most years. Anomalous rises in turbidity levels in the river during the summer months undoubtedly will be experienced owing to conditions previously described. However, as at Mad River near Arcata, the rises in turbidity generally should be of short duration.

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[6]A small quantity of sand, because of its surface area per unit weight, has a greater effect on concentration than on turbidity. That is, sand scatters much less light than an equal weight of clay or silt.

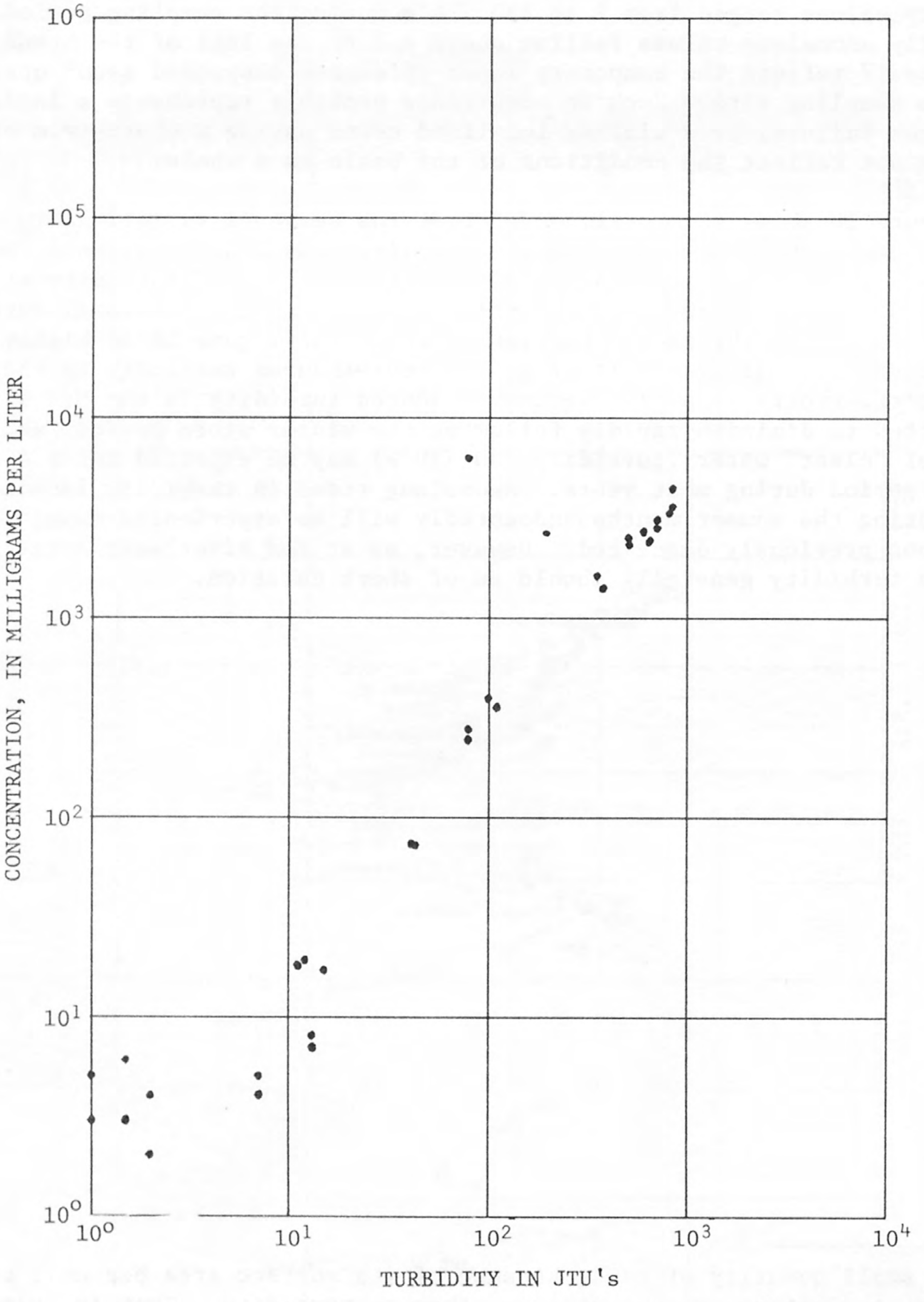

FIGURE 17.--Relation between concentration of suspended sediment and turbidity at Mad River near Kneeland, 1971-72 water years. (Data are preliminary and subject to revision.)

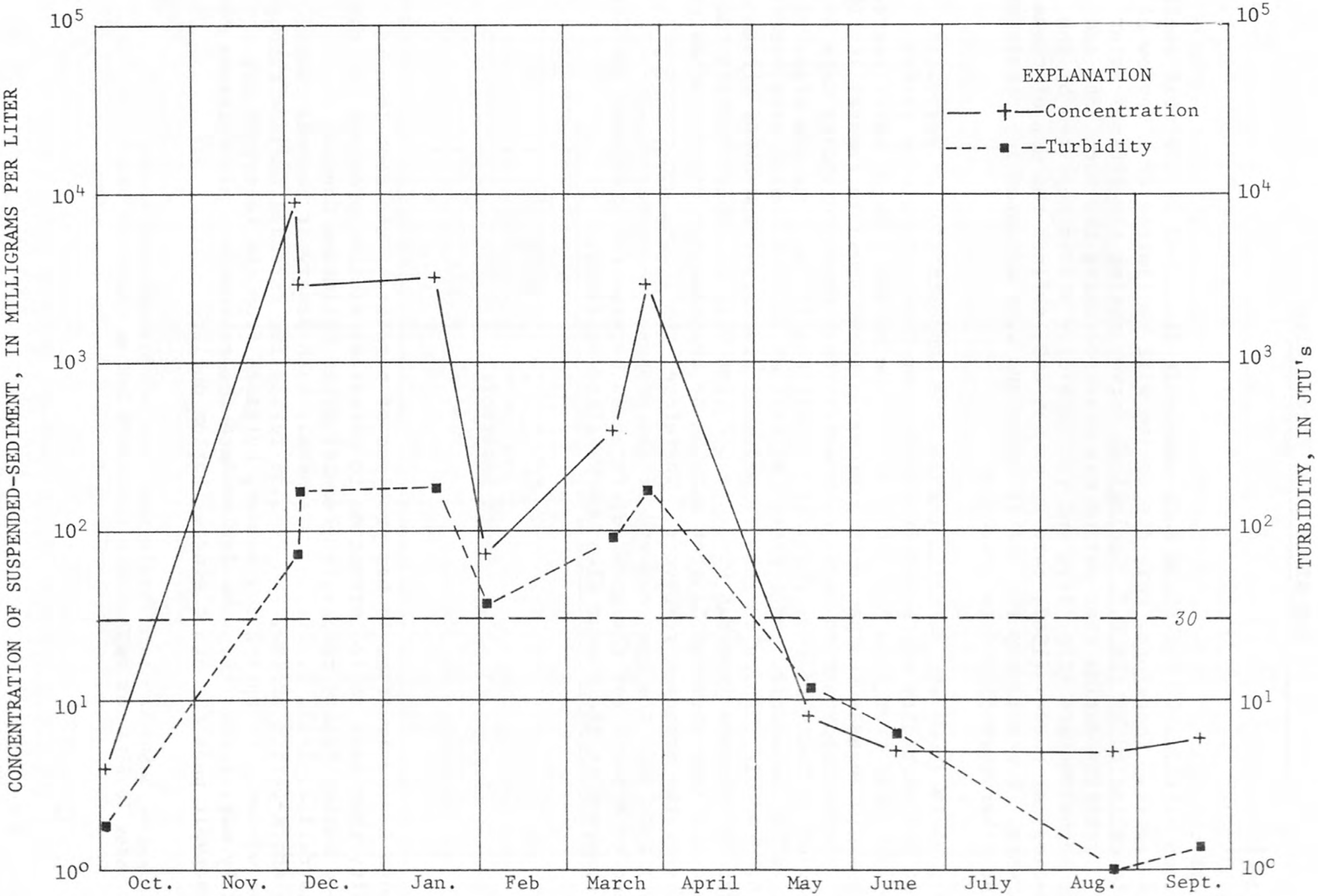

FIGURE 18.--General seasonal variations in suspended-sediment concentration and turbidity, Mad River near Kneeland, 1971 water year. Lines serve only to indicate general trend. Compare with figures 16 and 21.

Mad River near Forest Glen

Turbidity data collected at Mad River near Forest Glen reflect the conditions of release flows from Ruth Reservoir discussed in the next section of this report. Therefore, this discussion will be limited to a review of the data collected by the U.S. Geological Survey during the 1964-67 water years. Turbidity during that period was measured using the Hach 1860 and Hellige nephelometers (fig. 14), and the turbidity values reported by the U.S. Geological Survey (1967, part 2, p. 439-440) reflect the use of those instruments. For this report, turbidity values were adjusted for consistency with the other turbidity data presented.

Figure 19 shows the relation between the concentration of suspended-sediment and turbidity at Mad River near Forest Glen. Turbidity values generally ranged from 1 to 500 JTU's during the period 1964-67 water years, and behaved with seasonal patterns similar to those shown in figures 16, 18, and 21. It is important to realize, however, that these turbidity data do not provide an indication of turbidity conditions influent to the proposed Butler Valley reservoir. Data presented earlier in this report have verified that the dramatic changes in runoff, sediment discharge, and other stream processes downstream from Mad River near Forest Glen probably override the stream conditions observed at that station by the time Mad River reaches the vicinity of the proposed reservoir. Therefore, the future monitoring of stream inputs into the upstream end of the proposed reservoir should be designed to account for the great differences between the processes currently being observed at the Forest Glen and Kneeland stations.

Ruth Reservoir

Ruth Reservoir (fig. 1) has problems of persistent sediment-induced turbidity that have called attention to potential similar problems for the proposed Butler Valley reservoir (Federal Water Pollution Control Administration, 1967, p. 261). In general, Ruth Reservoir becomes turbid during storm-period inflow, and remains turbid for extended periods throughout the winter. In spring and summer, releases from the reservoir are generally more turbid than the inflow into the reservoir. All releases from the reservoir pass through a single, bottom outlet.

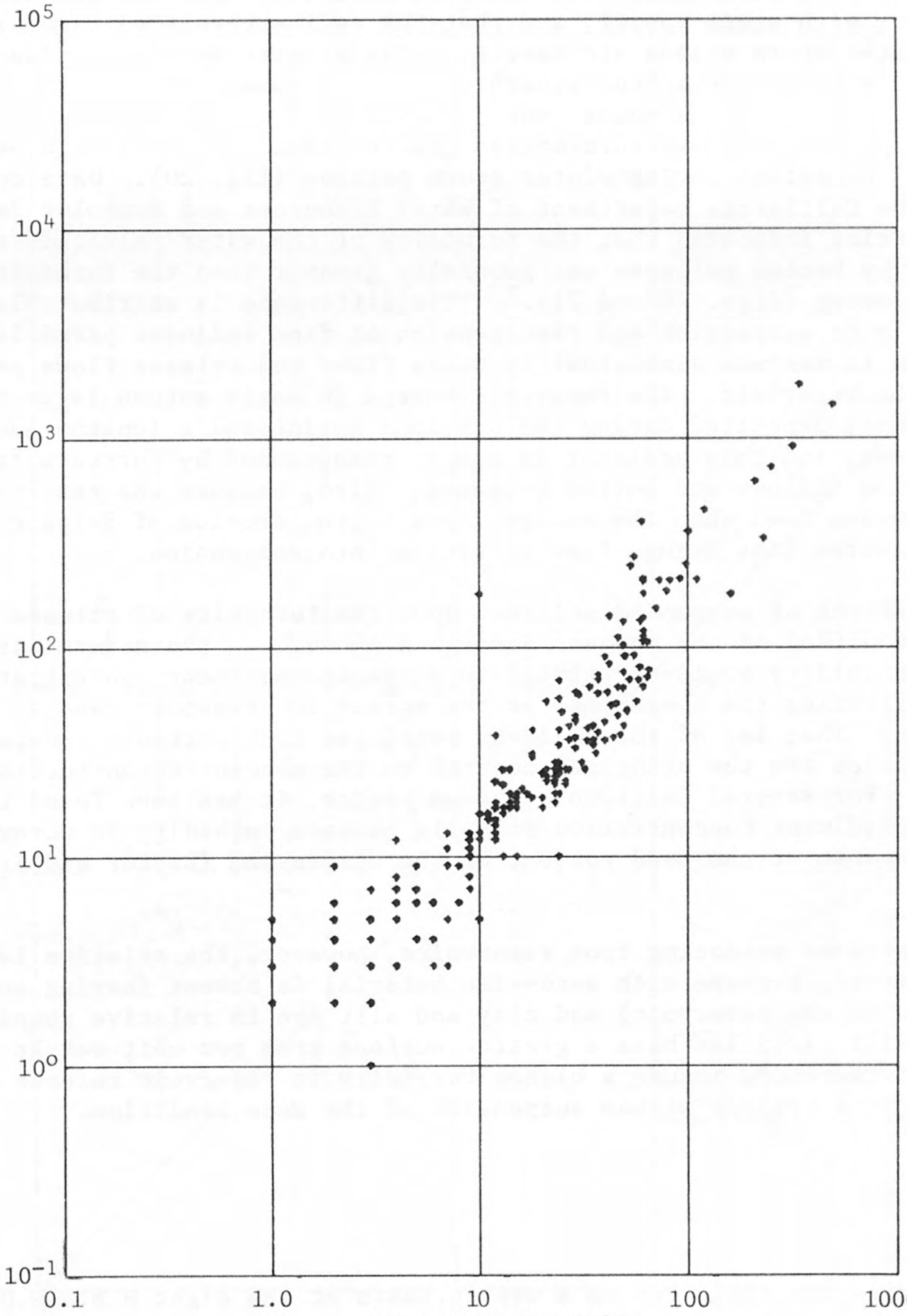

FIGURE 19.--Relation between concentration of suspended sediment and turbidity at Mad River near Forest Glen for 1964-67 water years.

Turbidity measurements at nine stations in the vicinity of Ruth Reservoir (stations A-H, 11-4805.00) verify that turbidity fluctuations both in the reservoir and in release flows downstream from the reservoir are highly correlative with storm runoff, and that the sediment-related turbidity values during winter storm priods are several times greater than the values associated with phytoplankton growth during the summer. The turbidity of release flows during the summer months has seldom exceeded 30 JTU's during the study period, whereas turbidities greater than 100 JTU's were measured on several occasions during winter storm periods (fig. 20). Data collected by both the California Department of Water Resources and Humboldt Bay Municipal Water District indicated that the turbidity of the water released from the reservoir by bottom releases was generally greater than the turbidity of the inflowing water (figs. 20 and 21).[7] This difference is attributable principally to suspension and resuspension of fine sediment particles (<0.062 mm in maximum dimension) by storm flows and release flows passing through the reservoir. The reservoir bottom in early autumn is overlain by fine sediment deposited during the previous spring and a lengthy summer period of low flows, and this sediment is easily resuspended by currents induced by storm period inflows and bottom releases. Also, because the reservoir is normally drawn down when the winter rains begin, erosion of deltaic deposits above the water line brings fine particles into suspension.

The effect of suspended sediment upon the turbidity of release flows is somewhat modified by the process described above. In the natural stream channel, turbidity would be related to suspended-sediment concentration in a manner reflecting the competence of the stream to transport sand in suspension. That is, of the sediment particles transported in suspension, sand particles are the principal control on the concentration-turbidity relation. For several California stream basins, it has been found that the suspended-sediment concentration normally exceeds turbidity in unregulated streams because of the sand content of the suspension (Ritter and Brown, 1971, p. 42).

For streams emanating from reservoirs, however, the relation is likely to be reversed, because much sand-size material is absent (having settled from suspension in the reservoir) and clay and silt are in relative abundance. The clay and silt particles have a greater surface area per unit weight than do sands, and therefore induce a higher turbidity in reservoir release flows than that in a typical stream suspension of the same condition.

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[7]Samples are collected on a weekly basis at the eight H.B.M.W.D. sites. The samples are collected within a few hours on the same day each week, and thereby are nearly simultaneous samples.

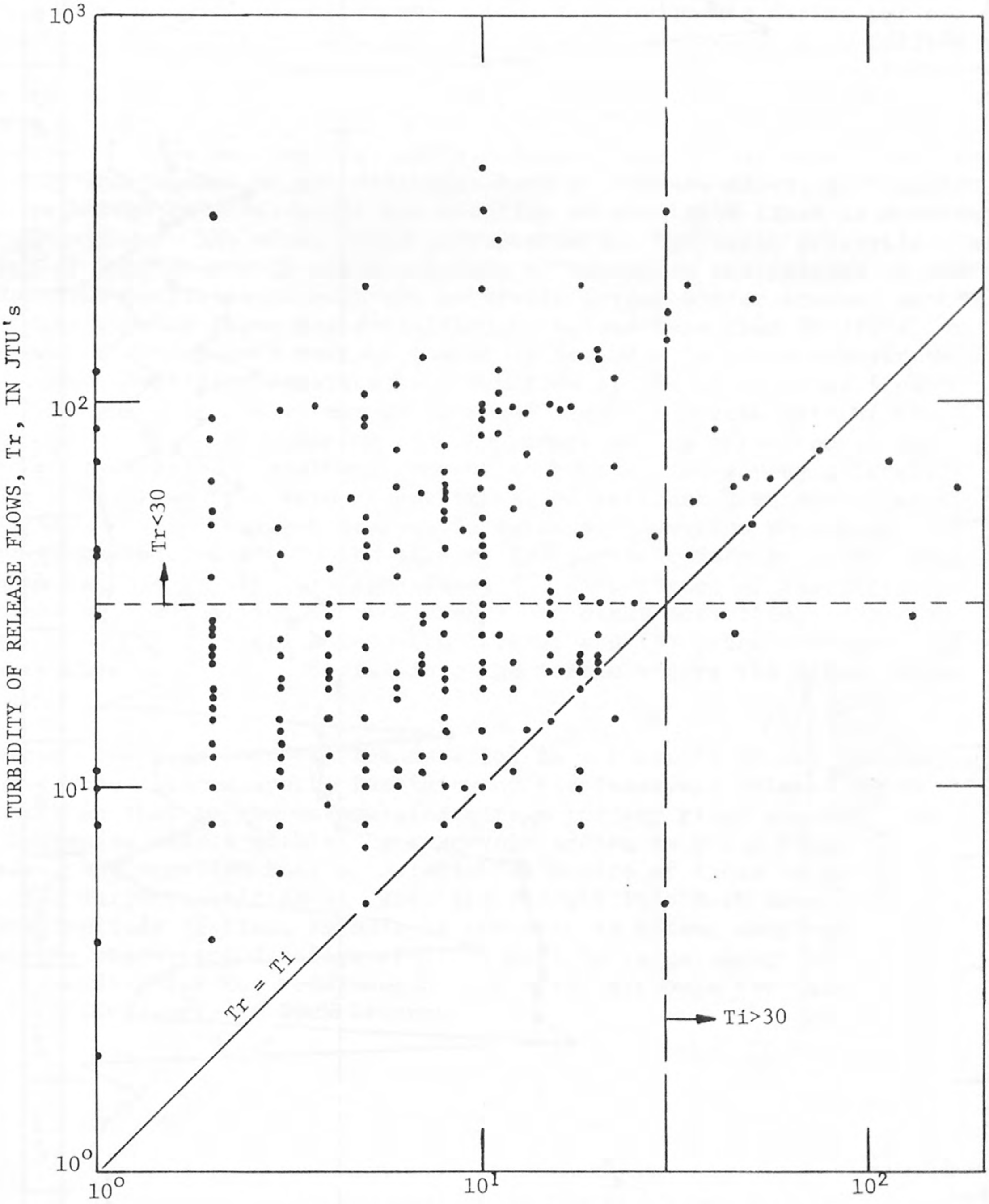

FIGURE 20.--Relation between turbidities of influent and release flows at Ruth Reservoir for period 1964-69 calendar years. Influent flows sampled at station G; release flows sampled at station A (fig. 1). [Data supplied by California Department of Water Resources]

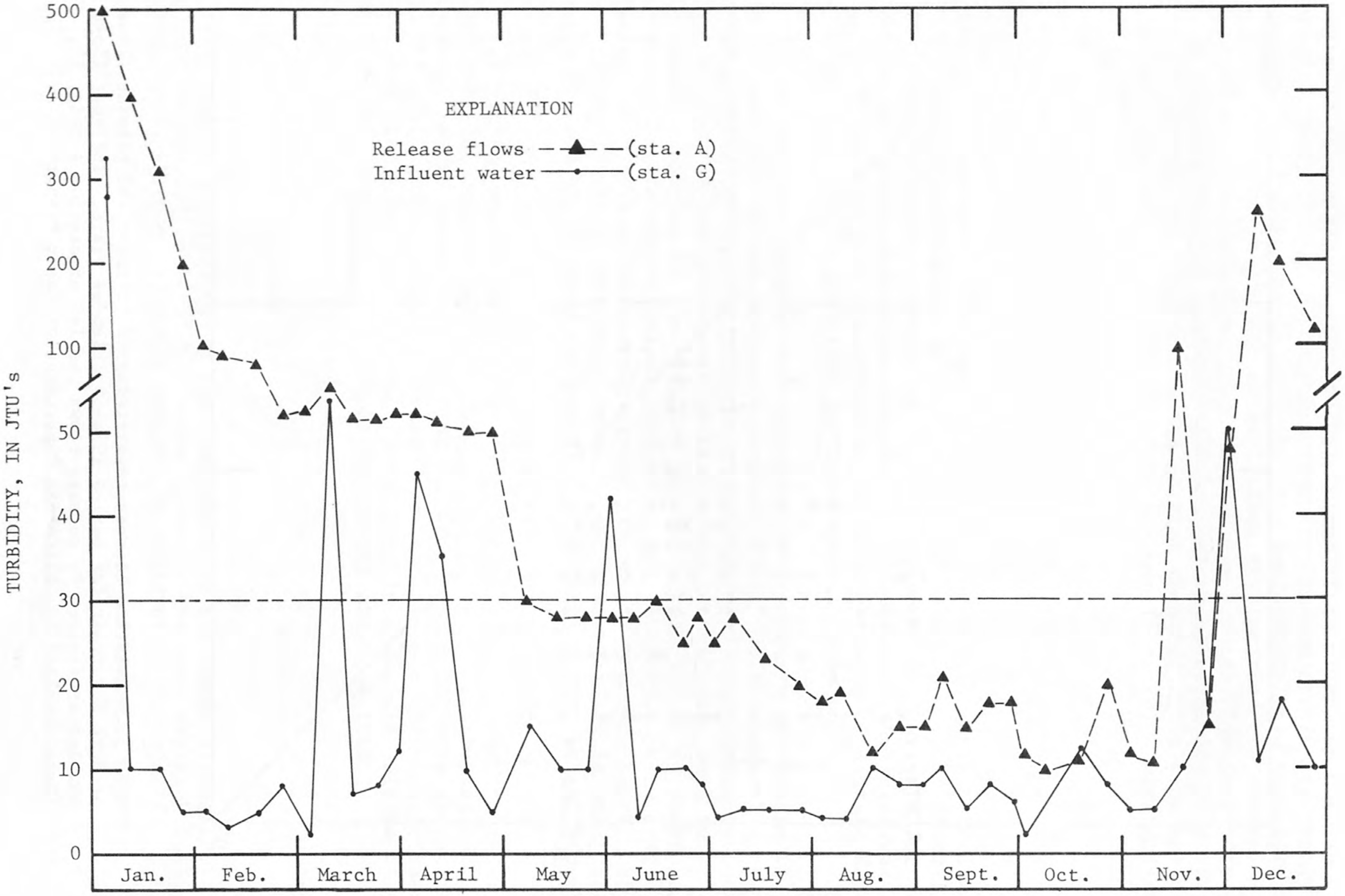

FIGURE 21.--Turbidities of influent water and release flows at Ruth Reservoir, 1966 calendar year. [Data supplied by Humboldt Bay Municipal Water District]

Bottom releases from Ruth Reservoir probably are responsible for inducing a bottom current with attendant hydraulic conditions capable of bringing fine sediment particles into suspension. Thus, the turbidity of release flows is moderated by reservoir operations which trap fine sediments during periods of low flows and during the first winter storms when the reservoir is filling. The transport of fine sediments by release flows during subsequent storms becomes dependent upon mechanisms for passing the mass of influent fine sediments completely through the reservoir and resuspending those fine particles which have settled previously. Because the transport of fines is essentially independent of the discharge rate of release flows, turbidity will persist in bottom releases until the quantity of available fines is substantially diminished. The size, shape characteristic, hydraulic properties, and operation of Ruth Reservoir are apparently suitable for the passage of most suspended fine particles through the reservoir during winter storms, as the turbidity of release flows has diminished to values less than 30 JTU's for several months during each year of the study period. In flows downstream from the reservoir, turbidity persists as a function of the quantity of fine sediment brought into the stream channel and the extant turbidity of the release flows. Therefore, during the dry summer months after the streams are cleansed of fine-grained sediment brought in by the last spring rainfall, turbidity downstream from Ruth Reservoir may be attributed to one or more of the following: (1) Sediment present in release flows from Ruth Reservoir; (2) phytoplanktonic growth in the stream; (3) sediment introduced by localized streambank failure or similar mechanisms; (4) disturbance of the streambed or streambanks by roadbuilding, gravel mining, or other activities; (5) the dumping of insoluble material into the stream; and (6) other processes that might introduce insoluble material into the stream before the first autumn rainstorms.

Because the transport of fine material is a function of the quantity of fines available for transport, turbidity of the reservoir release flows will be higher than that in the unregulated stream for any given discharge provided that a mechanism exists within the reservoir system to bring fines into suspension, and provided that a replenishing source of fines is available. Apparently, large quantities of fines are brought into Ruth Reservoir during very short periods of time, as must be the case to effect continuity. For example, the storm-period inflow of fines must be large enough to sustain the outflow turbidity for the remainder of the year, although the quantity of such inflow is not measured at Ruth Reservoir.

DISCUSSION

The quantity of suspended sediment that would be transported into the proposed Butler Valley reservoir is estimated to average 1,420,000 tons per year based on preliminary, short-term data collected at Mad River near Kneeland. These data were augmented by correlations with longer-term streamflow and suspended-sediment data collected at Mad River near Forest Glen and Mad River near Arcata, upstream and downstream, respectively, from the Kneeland gage. Both bedload and landslide debris expected to enter the reservoir are currently being investigated by the Geological Survey and the Corps of Engineers, and should be added to the suspended-sediment component to aid in completing the analysis of expected reservoir sedimentation.

Most of the inflow of sediment into the proposed reservoir probably will occur during winter storm periods between October and March each water year. Therefore, large sediment loads are likely to be introduced into the proposed reservoir at times when the reservoir is filling or full of water. The management of release flows during these times will influence the amount of fine sediment retained in the reservoir or passed downstream. Because the reservoir will be regulated by a multiple-outlet flow release system, the trap efficiency of the reservoir will be partly dependent upon the location as well as the timing and quantity of release flows. A schedule of anticipated releases from the reservoir is currently being analyzed for potential downstream effects on sediment transport. In the event of reservoir construction, monitoring of the release flows for the quantity and size distribution of sediment passing through the outlet system will enable comparison with the preconstruction conditions currently being monitored.

The inflow of suspended sediment into the proposed reservoir will induce turbidity in temporal and spatial patterns that are probably too complex to be analyzed in detail using the data thus far collected in the Mad River basin. Observations of sediment-induced turbidity of Ruth Reservoir outflows reveal that a set of conditions exist whereby annual turbidity patterns are modulated by the presence of the reservoir. The turbidity of reservoir-release flows persists for longer periods than would be expected for the unregulated stream. Apparently, this persistence of turbidity in the release flows is related to the single-outlet, bottom releases from Ruth Reservoir. combined with the conditions previously described in this report.

In the proposed Butler Valley reservoir, sediment-induced turbidity related to the inflow of sediment-laden water at a given time will behave as a complex function of the altitude of the reservoir water surface, the thermal stratification of the reservoir, the size distribution of influent sediment, the then-existing turbidity conditions, the magnitude and duration of sediment inflow, and a variety of other related factors. The size and shape of the proposed reservoir are such that the reservoir should have a marked stilling effect on inflowing water, thus allowing the eventual settlement of turbidity-causing particles. In contrast, the size, shape, and other characteristics of Ruth Reservoir permit contiguous movement of its entire water mass during periods of high inflow, and turbidity is present throughout the reservoir during such periods (R. F. Clawson, oral commun., 1971). A sediment and turbidity sampling program for the proposed Butler Valley reservoir would aid in determining the mechanisms of the movement of sediment and other particulate matter throughout the reservoir, and if the management of release flows can affect the magnitude and distribution of turbidity in the reservoir.

Turbidity at the reservoir surface will be affected to some extent by the interaction of the water surface with the reservoir shoreline. Water waves and changes in the water-surface altitude often provoke bank erosion, and lend to the instability of landslides along the water's edge. Bank erosion and slope failures will introduce at least small quantities of turbidity-causing sediment and other debris to the near-shore parts of the lake, reducing the attraction of the shoreline as a place for recreational activity. Also, turbidity will result from the erosion of future deltaic deposits especially at the upstream end of the reservoir, during periods of inflow when the altitude of the reservoir water surface is low relative to the altitude of the deltaic deposits.

The effect of proposed reservoir water releases on the turbidity of downstream flows will be heavily dependent upon the location of the releases in the multiple-outlet system. Monitoring the vertical distribution of turbidity in the proposed reservoir will aid in selecting an optimum altitude, quantity, and duration of release to gain minimum turbidity. Other elements of water to be released, especially temperature, should also be monitored in view of potential downstream effects on the river system (Ritter and Brown, 1971, p. 54-55).

The inclusion of the Butler Valley reservoir in the river system will affect principally the capacity of the Mad River to transport coarse sediment downstream from the reservoir. The discharge of fine particles, or those having a maximum dimension of about 0.062 mm, is mainly a function of the quantity of fine material available for transport. This quantity is generally much less than the river is capable of carrying in suspension, and moves almost continuously with the flowing water. The discharge of coarse particles, or those having a larger maximum dimension than about 0.062 mm, is a function of such factors as channel geometry, flow velocity, and water temperature.[8] The quantity of coarse materail available for transport is generally greater than the stream can carry in suspension. On these bases, a diminution of peak flows by the controlled reservoir outflow will decrease the capacity of release flows to carry (1) coarse material available in the channel bed downstream from the reservoir when the reservoir is being put into operation, and (2) coarse material introduced by any means into the channel downstream from the reservoir after reservoir operation begins. A quantitative expression of the latter may be determined from new data currently being collected at Mad River near Kneeland, and two gaging stations established in the 1973 water year at the site of station 11-4808.00 and just upstream from the Mad River Hatchery (fig. 1). A more detailed analysis of the channel system downstream from the proposed damsite is being made during the 1973 water year, and will be the subject of a separate report scheduled for completion in the 1973 calendar year.

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[8]The maximum dimension of rock particles carried in continuous or almost continuous suspension in the Mad River is between 1.0 and 2.0 mm. The conditions for the suspended transport of larger particles apparently require turbulence, flow velocity, and associated conditions only intermittently present in sampled reaches of the Mad River.

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