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SEDIMENT TRANSPORT, TURBIDITY, CHANNEL CONFIGURATION, AND POSSIBLE EFFECTS OF IMPOUNDMENT OF THE MAD RIVER, HUMBOLDT COUNTY, CALIFORNIA

GEOLOGICAL SURVEY

PREPARED FOR

ARMY ENGINEER DISTRICT

DECEMBER 1975

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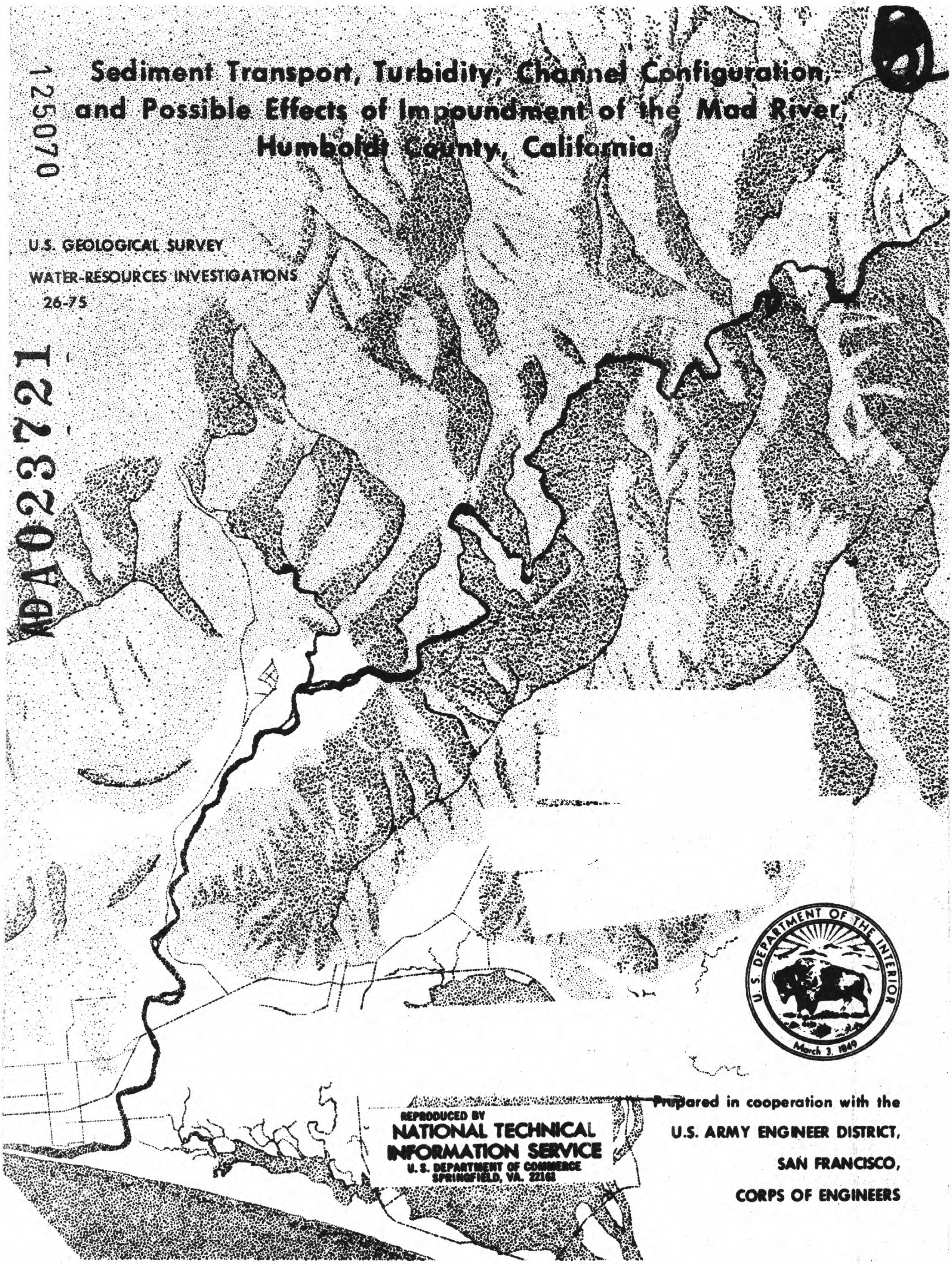

Sediment Transport, Turbidity, Channel Configuration, and Possible Effects of Impoundment of the Mad River, Humboldt County, California

U.S. GEOLOGICAL SURVEY

WATER-RESOURCES INVESTIGATIONS 26-75

Prepared in cooperation with the
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By William M. Brown III

U.S. GEOLOGICAL SURVEY

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December 1975

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II

PREFACE

From 1956 through 1973 the U.S. Army Engineer District, San Francisco, Corps of Engineers, was engaged in studies of the Butler Valley Dam and Blue Lake Project. Construction of Butler Valley Dam would create a multipurpose reservoir (Blue Lake) on the Mad River, Humboldt County, California. In 1973 a vote by Humboldt County residents halted advanced planning that was to lead to construction of the project. Halting the planning also ended many of the study programs for specific project elements for which the Corps of Engineers had contracted with various private companies and public agencies.

The program to study the effect of the proposed project on ground- and surface-water quality and on stream morphology and hydraulics was a cooperative venture between the Corps of Engineers and the U.S. Geological Survey begun in 1970. The program was designed to provide background data to assess the environmental impact of the project and to identify problems that might have affected the operation of the proposed project. The program was also designed to be evaluated annually for the adequacy of changes in project planning, new techniques of investigations, and pertinence in understanding the complex environment of the Mad River basin. These program elements, especially the latter, have proven to be all-important to the meaning of this report and to the future usefulness of the data collected in relation to the Butler Valley Dam and Blue Lake Project. Despite the termination of project planning that resulted from the vote of the residents, the environmental information resulting from this study should be beneficial to future studies of the Mad River and similar basins.

The Butler Valley Dam and Blue Lake Project remains an authorized project that has been placed in an inactive status. Therefore, project studies could be reactivated should the project regain the support of the local people.

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CONVERSION FACTORS

Factors for converting English units to metric units are given below to four significant figures. However, in the text the metric equivalents are shown only to the number of significant figures consistent with the values for the English units.

English	*Multiply by*	*Metric*
acre-ft (acre-feet)	1.233×10^{-3}	hm^3 (cubic hectometres)
ft (feet)	3.048×10^{-1}	m (metres)
ft/mi (feet per mile)	1.894×10^{-1}	m/km (metres per kilometre)
ft/s (feet per second)	3.048×10^{-1}	m/s (metres per second)
ft^3/s (cubic feet per second)	2.832×10^{-2}	m^3/s (cubic metres per second)
ft^3/s-day (cubic feet per second-day)	2.832×10^{-2}	m^3/s-day (cubic metres per second-day)
in (inches)	2.540×10^{1}	mm (millimetres)
lb/ft^3 (pounds per cubic foot)	1.602×10^{1}	kg/m^3 (kilograms per cubic metre)
mi (miles)	1.609	km (kilometres)
mi^2 (square miles)	2.590	km^2 (square kilometres)
ton/yr (tons per year)	9.072×10^{-1}	t/yr (tonnes per year)
ton/mi^2 (tons per square mile)	3.502×10^{-1}	t/km^2 (tonnes per square kilometre)

SEDIMENT TRANSPORT, TURBIDITY, CHANNEL CONFIGURATION, AND POSSIBLE EFFECTS OF IMPOUNDMENT OF THE MAD RIVER, HUMBOLDT COUNTY, CALIFORNIA

By William M. Brown III

SUMMARY

The effects of a proposed U.S. Army, Corps of Engineers impoundment on the Mad River, projected on the basis of a regulated flow model for the river, include the following:

1. The proposed impoundment would trap about 60 percent of the potential beach-forming sediments transported by the river under unregulated conditions.

2. Release flows from the impoundment would have the capacity to transport the expected inflow of sediment particles less than 2 mm in diameter for the reach of river downstream from the impoundment site.

3. Release flows from the proposed impoundment would have the capacity to transport about 130,000 ton/yr (120,000 t/yr) of bed material particles less than 3 in (76 mm) in diameter. The release flows would be expected to degrade the Mad River channel for a maximum of about 15 mi (24 km) downstream from the impoundment. Degradation of the Mad River channel would ultimately reduce the number and scale of preimpoundment lateral adjustments of the channel for the 15-mi (24-km) reach. Downstream from the initial 15-mi (24-km) reach, artificial adjustments of the channel and flood plain would be expected to override most release-flow effects on channel adjustments.

4. Turbidity of impoundment release flows could approximate preimpoundment turbidity for an average year, under highly controlled operation of the proposed multiple-outlet release system. Releases to meet desired turbidity conditions would also require great flexibility in the location, mixing, and timing of the releases to meet downstream temperature, dissolved oxygen, and other requirements.

The study area is about 150 mi^2 (390 km^2) of the Mad River basin downstream from Butler Valley, the proposed site of the Butler Valley Dam and Blue Lake Project. In the study area, the Mad River flows in the narrow bottom of a steep-sided canyon for about 15 mi (24 km) before debouching onto two major flood plains connected by a short canyon. The study area includes lowland flats and terraces abutting the flood plains and having semi-rural landscapes characterized by farmlands, small towns, and light industries. Farther inland, the study area includes rugged, heavily logged uplands having landscapes of grasslands, clear-cut areas, and mixed conifer-hardwood forests, and numerous road-cut and landslide scars. The climate of the area is a moist, mediterranean type distinguished by rainy winters and cool, foggy summers. Average annual precipitation ranges from about 40 in (1,000 mm) to 65 in (1,600 mm) from the coastal plain inland to Butler Valley. The geology of the area comprises deeply weathered Jurassic, Cretaceous, and Tertiary bedrock units overlain in stream valleys and the near coastal plains by Quaternary terraces, alluvium, and dune sand.

Sediment-transport conditions of the Mad River were determined using existing data, results of a periodic suspended-sediment and bedload sampling program, a model of preproject and expected postproject daily streamflows, and a weighting system to account for the influence of rare storm events. The flow model and the weighting system were built on the basis of a 100-year period, 1975-2075, because of the anticipated 100-year economic life of the proposed impoundment.

Long-term (100-yr) suspended-sediment discharge at Mad River near Arcata is computed to be 2,220,000 ton/yr (2,000,000 t/yr), of which 615,000 ton/yr (558,000 t/yr) is sand size. Bedload transport at Mad River near Arcata was an estimated 60,000 ton/yr (54,000 t/yr) or about 2 percent of the suspended-sediment discharge for the years 1971-72.

Suspended-sediment discharge at Mad River near Kneeland for 1971-72 was 1,786,000 ton/yr (1,620,000 t/yr), of which 472,000 ton/yr (428,000 t/yr) was of sand size. Bedload transport at Mad River near Kneeland was an estimated 170,000 ton/yr (150,000 t/yr) or about 10 percent of the suspended-sediment discharge for 1971-72.

The long-term relation between suspended-sediment discharges at the Arcata and Kneeland stations was computed using an empirical equation and the release-flow model. The equation states that the suspended-sediment discharge at the Kneeland station is about 60 percent of the suspended-sediment discharge at the Arcata station based on the flow correlation given in the model.

Turbidity in the study area is highly correlative with streamflow and suspended-sediment discharge, particularly at high flows. Empirical equations for estimating turbidity were developed for comparisons with postproject turbidity data.

Field and photointerpretive studies showed that the Mad River adjusts its channel for a 15-mi (24-km) reach downstream from the proposed impoundment site largely by aggradation and lateral corrasion. Lateral corrasion commonly is controlled by bedrock protrusions and colluvial boulders. However, aggradation commonly produces corrasion at the bases of landslide deposits abutting the channel.

The hydraulic geometry of the channel, encompassing relations of width, depth, and velocity of flow to discharge, was integrated with bedload-transport data to determine the effects of discharge on channel configuration. Between Butler Valley and the Mad River Hatchery significant changes in channel configuration began at flows of about 1,000 ft^3/s (28 m^3/s), and lateral corrasion began at flows between 1,000 and 4,000 ft^3/s (28 and 113 m^3/s) for most of the reach.

The removal of Sweasey Dam in 1970 released 3,000 acre-ft (3.7 hm^3) of dominantly coarse sediment into the Mad River channel about 6 mi (10 km) downstream from Butler Valley. The reworking of the sediment by the river from 1971 through 1973 resulted in major channel changes for about 1.5 mi (2.4 km) downstream to a large depositional area at Camp Flat.

The reach of the Mad River from the Mad River Hatchery to the Pacific Coast was pervasively and extensively altered during the study period by gravel-mining operations, revetment works, grading in the channel and flood plain, and other activities. The gravel extractions in the reach were an estimated 200,000 to 500,000 ton/yr (180,000 to 450,000 t/yr) for 1961-70. The quantities mined directly from the active channel could not be determined for this study for comparisons with the bedload-transport capacity of the river.

INTRODUCTION

The effects of changes in river hydraulics downstream from an artificial impoundment are currently of major concern because of potential impacts on the river environment. The principal downstream hydraulic alterations of the river relate to changes in the overall river flow regimen and consequent changes in the sediment-transport characteristics of the river. The river, imposed with such changes, must ultimately readjust the geometric configuration of its channel to one consistent with the new conditions. In general, the river will erode (degrade) its channel for some distance downstream from an impoundment and redeposit the eroded channel material farther downstream. In the new depositional area, the river commonly adjusts itself laterally and erodes its channel banks. The sediment-induced turbidity characteristics of the downstream flow also change.

In 1970, the U.S. Geological Survey, in cooperation with the U.S. Army Engineer District, San Francisco, Corps of Engineers, began a program to collect, analyze, and interpret data on the various effects of the Corps of Engineers' proposed Butler Valley Dam and Blue Lake Project on the hydraulics and quality of the Mad River (fig. 1). The program was terminated in 1974 as the result of a special public vote that halted the continuation of Butler Valley Dam and Blue Lake Project planning. The Butler Valley Dam and Blue Lake Project remains an authorized project that has been placed in an inactive status. Therefore, project studies could be reactivated should the project regain the support of the local people. The details of the evolution, scope, and preliminary results of the program were reported by Brown (1973). This report presents the results of studies on the hydraulics of the Mad River system through October 1973 and is the final report on river hydraulics planned for the Butler Valley Dam and Blue Lake Project. Another report (Fuller, 1975) presents results of a companion water-quality study made in the project area.

Purpose and Scope

The specific purposes of this report are to present data on and analyses of the following: (1) The effect of the proposed reservoir water releases on the turbidity of downstream flow, (2) the capacity and competence of reservoir release flows to transport channel sediment supplied by tributaries downstream from the impoundment, (3) the effects of the reservoir release flows on the configuration of the downstream channel system, and (4) the effect of the reservoir on the transport of potential beach-forming sediment by the Mad River.

The scope of this report includes: (1) The analysis of hydraulic data available through September 1973 for the Mad River stations near Arcata, Blue Lake, and Kneeland, and North Fork Mad River near Korbel (table 1 and fig. 1), (2) the analysis of aerial imagery of the study area available through March 1973, and (3) the analysis of field observations of the study area made in October 1970, December 1971, September 1972, and April 1973.

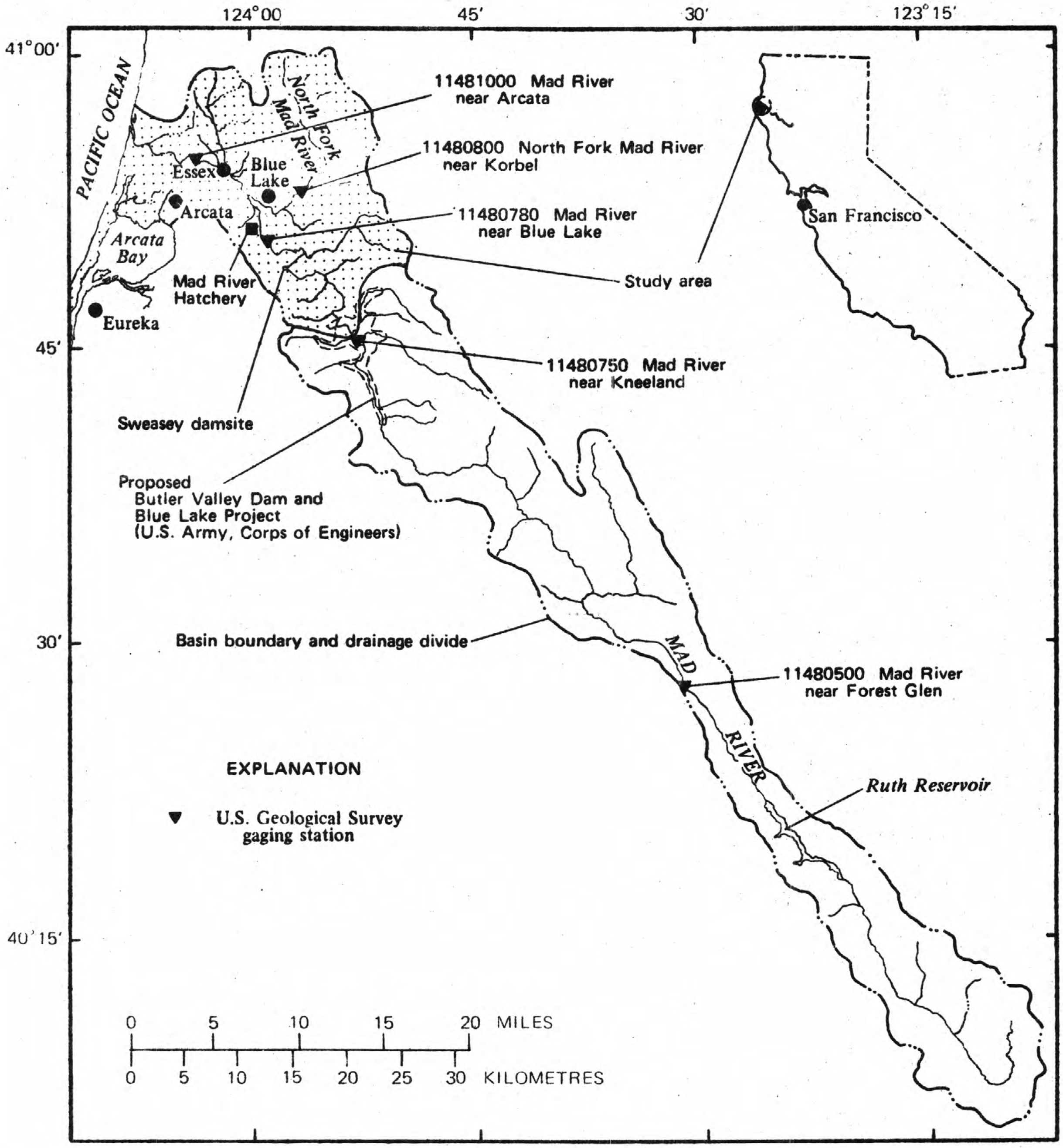


FIGURE 1.--Mad River basin showing the locations of the Butler Valley Dam and Blue Lake Project and the area of study.

TABLE 1.--*Periods of operation of surface-water and sediment-sampling stations and periods of collection of turbidity samples at selected sites through 1973*

[Location of stations shown in figure 1]

Station number and name	Drainage area (mi^2)	Period of operation of station and type of sampling		
		Surface Water	Sediment	Turbidity
11480750 Mad River near Kneeland	352	October 1965-September 1973: Daily records	October 1970-September 1973: Periodic sampling of suspended sediment October 1972-September 1973: Periodic sampling of bedload	October 1970-September 1973: Periodic sampling
11480780 Mad River near Blue Lake	393	October 1972-September 1973: Daily records	October 1972-September 1973: Periodic sampling of suspended sediment and bedload	October 1972-September 1973: Periodic sampling
11480800 North Fork Mad River near Korbel	40.4	October 1957-September 1964; October 1972-September 1973: Daily records	October 1972-September 1973: Periodic sampling of suspended sediment and bedload	October 1972-September 1973: Periodic sampling
11481000 Mad River near Arcata	485	October 1910-September 1913; August 1950-September 1973: Daily records	September 1955-July 1957: Periodic sampling of suspended sediment December 1957-September 1973: Daily sampling of suspended sediment October 1971-September 1973: Periodic sampling of bedload	October 1970-September 1973: Periodic sampling

Acknowledgments

This report was prepared in cooperation with the U.S. Army Engineer District, San Francisco, Corps of Engineers, as a part of an investigation of the Mad River basin.

Acknowledgments are due the following: Personnel of the Humboldt Bay Municipal Water District, Eureka, Calif., for data on turbidity; the National Aeronautics and Space Administration, Ames Research Center, Moffett Field, Calif., for high resolution, color infrared photographs of the study area; Simpson Timber Co., Arcata, Calif., for the use of its property for gaging-station locations and general access to the Mad River and North Fork Mad River channels; J. O. Armstrong, Menlo Park, Calif., for his photographs used in this report; L. E. Jackson, Jr., and H. M. Kelsey of the Geological Survey for valuable assistance in field observations and interpretations of the geomorphic setting of the study area; the personnel of the Geological Survey field office, Eureka, Calif., for their excellent work in data collection and analysis for this project; and M. E. Jennings and J. O. Shearman of the Geological Survey's Gulf Coast Hydroscience Center, Bay St. Louis, Miss., for the development of streamflow and sediment-transport models of the Mad River.

PHYSICAL SETTING

The Mad River flows northwesterly through the northern Coastal Ranges of California and enters the Pacific Ocean about 300 mi (480 km) north of San Francisco (fig. 1). The river is about 100 mi (160 km) long and drains 497 mi^2 (1,290 km^2) of rugged, mountainous country. The study area is about 150 mi^2 (390 km^2) of the Mad River basin downstream from Butler Valley, the proposed location of the Butler Valley Dam and Blue Lake Project.

In the study area the Mad River flows in the narrow bottom of a steep-sided canyon for about 15 mi (24 km) from Butler Valley to the Mad River Hatchery near the town of Blue Lake (fig. 2). At the hatchery, the canyon opens onto a broad flood plain through which the Mad River flows for about 4 mi (6 km) (fig. 3). The North Fork Mad River, having a drainage area of nearly 50 mi^2 (130 km^2), enters the Mad River on the flood plain about 2 mi (3 km) downstream from the hatchery. Near the town of Essex the Mad River enters a small canyon where it cuts through a low ridge for 2 mi (3 km) on its way to another broad flood plain adjacent to the Pacific Ocean (fig. 4). The Mad River presently flows near the northern boundary of this coastal flood plain which extends southward to Arcata Bay. During periods of flooding a part of the flow of the Mad River may inundate the Arcata Bottoms and discharge via Mad River Slough into Arcata Bay.

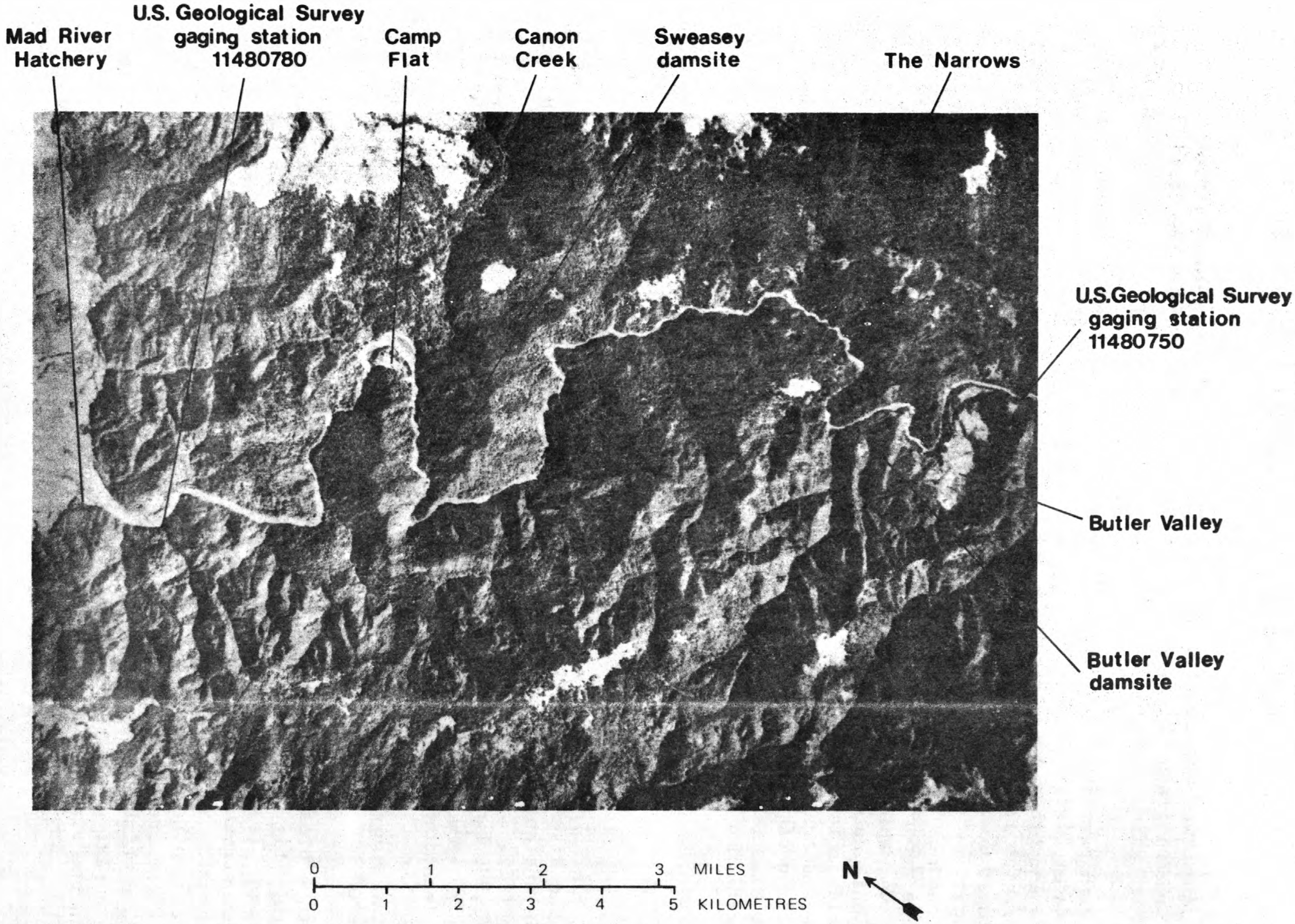


FIGURE 2.--Mad River between Butler Valley and the Mad River Hatchery. Compare with detailed channel map, figure 15. Photograph adapted from color infrared imagery taken January 22, 1973, courtesy of NASA-Ames, Moffett Field, Calif.

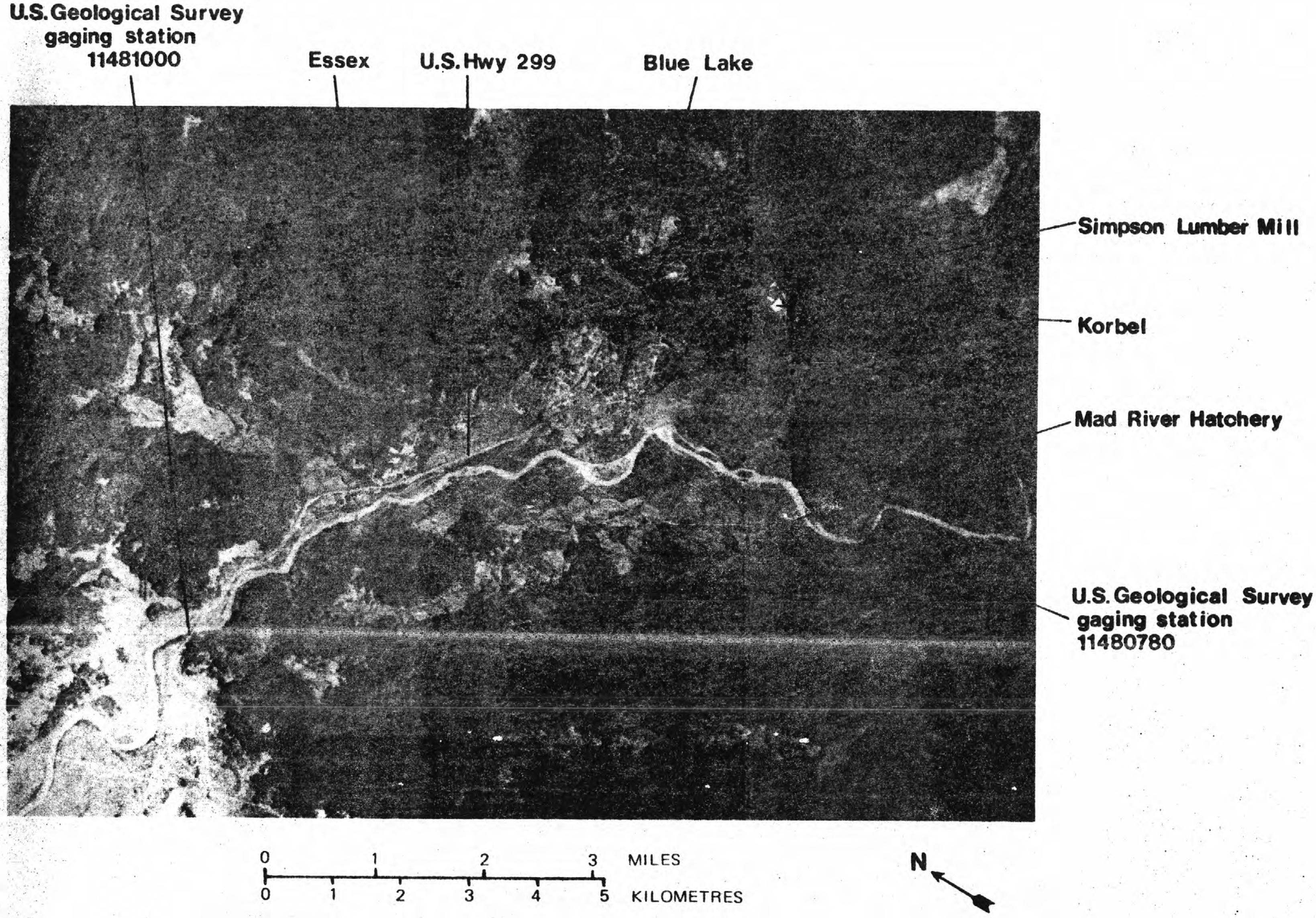


FIGURE 3.--Mad River in the vicinity of Blue Lake. Note the transition of the river channel from a narrow, confined type near the Mad River Hatchery to a broad, braided type near Blue Lake. Photograph adapted from color infrared imagery taken January 22, 1973, courtesy of NASA-Ames, Moffett Field, Calif.

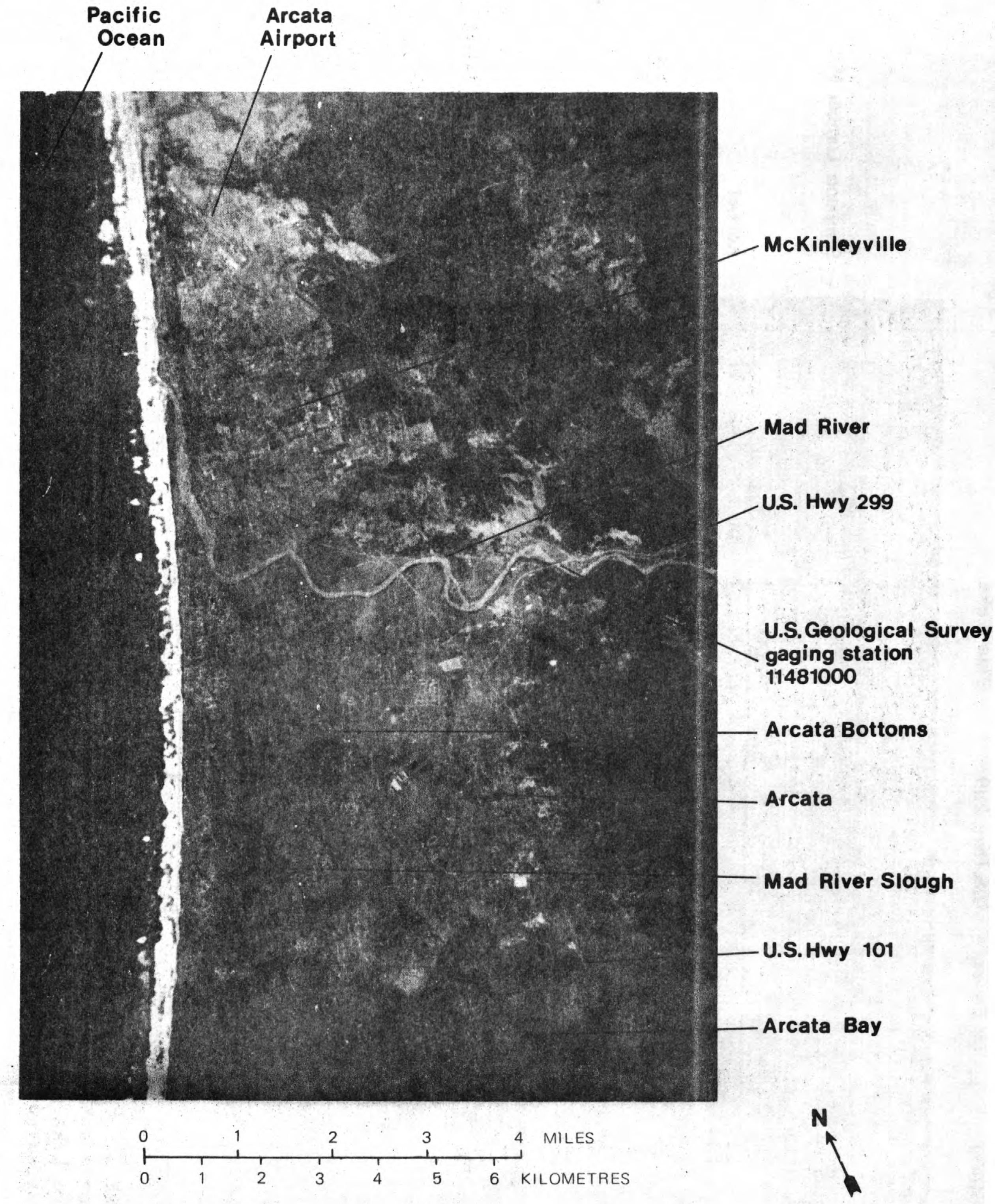


FIGURE 4.--Coastal reach of the Mad River and vicinity. Note the sediment plume extending offshore at the mouth of the Mad River and the sand dunes extending inland along the Pacific Coast south of the rivermouth. Photograph adapted from color infrared imagery taken January 22, 1973, courtesy of NASA-Ames, Moffett Field, Calif.

The geology of the study area was described by Manning and Ogle (1950) and Evenson (1959) and comprises Jurassic, Cretaceous, and Tertiary bedrock units overlain in stream valleys and the near-coastal plains by Quaternary terraces, alluvium, and dune sand. The bedrock units are commonly deeply weathered and are mantled by moderately deep and loamy soils, landslide debris, and colluvium. The terrace deposits are overlain by shallow silty and sandy soils, and the active channel and dune alluvia support little or no soil profile.

Vegetation in the study area includes a mixed conifer-hardwood forest that grows primarily on upland slopes and ridges. The forest has been logged extensively for about a century and presently is interspersed with grasslands, clear-cut areas, and numerous road-cut and landslide scars. Forest and brush have generally been cleared from terraces and lowland flats that today are used dominantly for farmland and townsites. Thus, agricultural crops, including grasses for grazing, compose most of the terrace and lowland vegetal covering. A variety of annual plants grow during extended periods of low streamflow in the seasonally active channel and flood-plain areas.

Annual precipitation ranges from about 40 in (1,000 mm) near the mouth of the Mad River to 70 in (1,800 mm) near the headwaters of the North Fork Mad River and is about 65 in (1,600 mm) in the vicinity of Butler Valley. The rainfall is seasonal, and most of it occurs in the winter months from October to May. Summer fog frequently penetrates the Mad River and North Fork Mad River canyons during the summer months, and much of the study area is thereby kept moist throughout the year.

Logging, agriculture, gravel mining, road building, and development on the flood plains dominate the land uses that ultimately affect the Mad River channel system in the study area.

The numerous factors that influence the character of the Mad River channel system deserve at least a cursory analysis, especially where these factors would conflict with the effects of the Butler Valley Dam and Blue Lake Project. In the subsequent text, the significant factors, such as gravel mining, revetment construction, and flow diversion, that affect ongoing or potential changes in the Mad River will be discussed.

FLUVIAL SEDIMENT

Definition of Terms

The terminology used in this report is based on the following definitions:

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).

Epilimnion is the uppermost layer of water in a lake, characterized by an essentially uniform temperature that is generally warmer than elsewhere in the lake and by a relatively uniform mixing caused by wind and wave action; the light (less dense), oxygen-rich layer of water that overlies the *metalimnion* in a thermally stratified lake.

Fluvial sediment or *sediment* includes fragmental materials that originate from weathering of rocks and organic materials that are transported by, suspended in, or deposited by streams.

Ft^3/s-day, as used in table 3 in this report, is an expression of the volume of streamflow. For example, an average streamflow of 100 ft^3/s ($3\ m^3/s$) for a period of 10 days is equal to 1,000 ft^3/s-day (30 m^3/s-day). This term is used for consistency with basic-data reports published by the Geological Survey. To convert ft^3/s-day to acre-ft, multiply ft^3/s-day by 1.98.

Hypolimnion is the lowermost layer of water in a lake, characterized by an essentially uniform temperature (except during a turnover) that is generally colder than elsewhere in the lake and often by relatively stagnant or oxygen-poor water; the dense layer of water below the metalimnion in a thermally stratified lake.

Metalimnion is the horizontal layer of a thermally stratified lake in which the temperature decreases rapidly with depth. The metalimnion lies between the *epilimnion* and the *hypolimnion*.

Sediment discharge is the quantity of sediment, as measured by dry weight, that passes a given section of a stream in a given time.

Sediment sample is a quantity of water-sediment mixture that is collected to determine the concentration of suspended sediment and the particle-size distribution of suspended sediment.

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).

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.

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 undissolved 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) as defined by Newell (1902, p. 1-4).

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 (ft^3/s). The water contains both dissolved solids and suspended sediment.

Water year is a 12-month period, beginning October 1 and ending September 30 of the year given. All years referred to in this report are water years unless otherwise noted.

Sediment Transport by the Mad River

In order to determine the sediment-transport characteristics of the Mad River, sediment-monitoring stations were constructed at Mad River near Blue Lake and North Fork Mad River near Korbel (fig. 1) in the summer 1972. The periods of operation and the types of sampling for each of the stations in the study area are listed in table 1. Simultaneously, the sampling of bedload was begun at an established station, Mad River near Kneeland, and sediment sampling at Mad River near Arcata was continued. 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 U.S. Inter-Agency Committee on Water Resources (1963) and Porterfield (1972). The procedure for measuring water discharge was described by Carter and Davidian (1968). The bedload sampler used for this study was described by Helley and Smith (1971). Data collected during the operation of these stations, previously obtained related data, and reports available through September 1973 were reviewed and analyzed. The following text briefly describes the methods of analyzing the sediment-transport data and presents a station-by-station analysis of sediment transport in the study area.

Methods of Analysis

The methods used in this report for analyzing sediment-transport characteristics generally are those described by Porterfield (1972) and Knott (1971, p. 14-40). Basically, the logarithms of water discharge and sediment discharge were plotted against each other (sediment-transport curves) for several ranges of sediment-particle size. These relations were then used in conjunction with the known or synthesized flow regimen of the river at each of the gaging stations to estimate annual quantities of sediment discharge, seasonal variations in sediment discharge, and other sediment-transport characteristics. However, the following variations in and qualifications of the analysis of sediment transport for this report are noteworthy.

In order to determine the effects of an altered streamflow regimen on sediment transport, turbidity, and channel configuration, a model of daily streamflow was developed for the reach of the Mad River downstream from Butler Valley. First, a correlation was established between recorded daily flows at the Kneeland and Arcata stations. On the basis of that correlation, the daily streamflow record at the Kneeland station was synthetically extended to the longer period of record of the Arcata station. The synthesized daily flows at the Kneeland station were then routed downstream according to the projected operating rules for flow releases at Butler Valley Dam. A final correlation was then made to determine the projected regimen of daily flows at the Arcata station following releases at Butler Valley Dam. The details of the streamflow model are discussed in the section "Supplemental Information," and applications of the model are discussed in the main text.

A base period of 100 years was chosen for projecting the long-term sediment discharges reported herein because of the anticipated 100-year economic life (1975-2075) of the Butler Valley Dam and Blue Lake Project (U.S. Army Corps of Engineers, 1968b, p. 46). First, a 100-year base period for streamflow was synthesized by assuming that the 25-year period of streamflow record (1911-13, 1951-72) for Mad River near Arcata is representative of the 100-year period.[1] Second, long-term sediment discharges were determined by extrapolating weighted sediment-transport relations to the synthesized 100-year streamflow record. The sediment-transport relations were weighted in consideration of the large shifts in the relations that occurred in 1965 (Brown, 1973, p. 17-19, 32). The shifts apparently were related to runoff from rainfall of unusual intensity that helped to alter riverscapes throughout northwestern California (Waananen and others, 1971, p. A139-A146).

[1]The 25-year observation period was marked with a wide spectrum of hydrologic conditions that are probably representative of at least the past 75 years on the basis of comparisons with long-term conditions recorded in nearby basins (Rantz, 1964, p. 3). The presumption of applicability of the 25-year record to the next century is for planning purposes only, and the limitations on 100-year planning should be fully recognized by the users of data and interpretations presented in this report. At least these data and interpretations should be updated at any time when their use bears upon decisionmaking.

The shifts were not observed during major floods at other times either in the Mad River basin or nearby basins. Therefore, the shifts were assumed to be related only to the 1965 flood for weighting purposes.

For this report, the 1965 flood was assigned a recurrence interval of 100 years.[2] Additionally, the annual sediment-transport curves showed a progressive return from the 1965 shift to pre-1965 conditions by 1971 at Mad River near Arcata (fig. 5). On these bases, the recurrence interval of the 7-year period of shifts in the sediment-transport curves was assumed to be 100 years.

The pre-1965 sediment-transport conditions are based on sediment data for 1957-64, a period used to represent long-term sediment-transport conditions in northwestern California. That is, the 1957-64 sediment-transport situation is assumed to represent the background or stable conditions of the basin that prevail in the absence of a major basin-altering event. That the conditions measured during 1957-64 are representative of a much longer period is subject to question, and needs to be carefully verified as new data become available.

On the basis of the foregoing assumptions, the 1957-64 sediment-transport relations were assigned a weight of 0.93 for a 100-year period, and the 1965-71 relations were assigned a weight of 0.07.[3] That is, the 1957-64 relations apply to 93 percent of the projected flows for the 100-year period; the 1965-71 relations apply to 7 percent of the projected 100-year flows.

---

[2]The sediment-transport period, because of its antecedent conditions and the rainfall intensity during the flood, is not necessarily dependent upon a specified water discharge such as that of a 100-year flood. The fact that flood peaks on the Mad River during 1965 were diminished by storage in Ruth Reservoir apparently is unrelated to the changes in sediment transport that took place. The recurrence interval for 1965 flooding has been an estimated 400 years (Helley and LaMarche, 1968, p. D36), 180 years (Ritter, 1973, p. 7), 113 years (Young and Cruff, 1967, p. 6) and 27 years (Waananen and others, 1971, p. A204), among other figures, depending upon the location of the affected river and the technique of flood frequency analysis.

[3]The 1972 data overlie the 1957-64 and 1971 data, indicating partly that the pre-1965 sediment-transport conditions had been regained at the Arcata station during 1971.

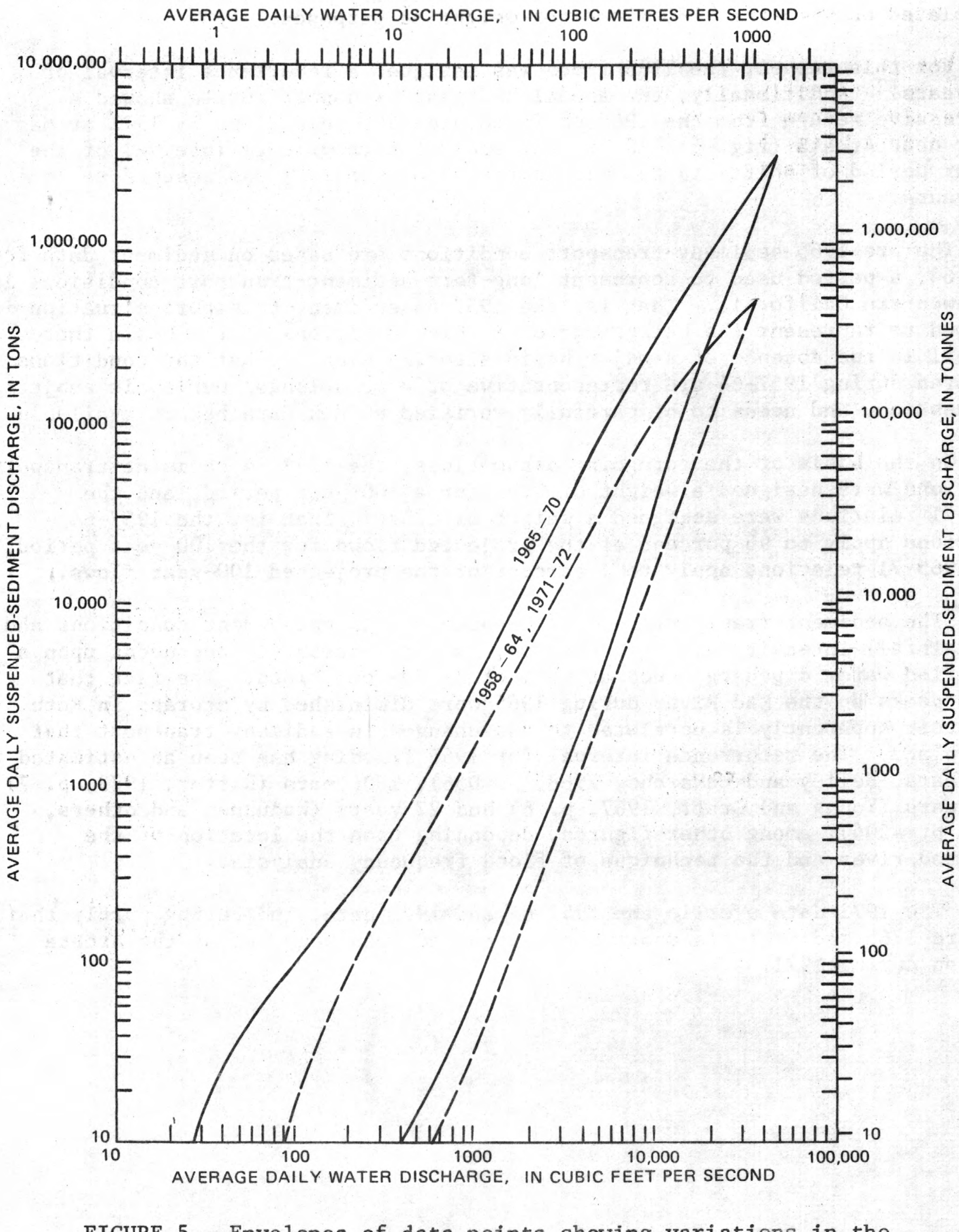


FIGURE 5.--Envelopes of data points showing variations in the suspended-sediment transport relation for Mad River near Arcata, 1958-72. Envelopes are adapted from data from Brown (1973, p. 19-20).

Preproject Sediment-Transport Conditions

Mad River near Arcata.--Mad River near Arcata has been the principal hydrologic-data station on the Mad River since streamflow measurements were first made in October 1910 at a site near the location of the present gaging station (fig. 1). Since 1910, data on channel geometry and flow hydraulics, as well as sediment and turbidity samples, have been collected according to the schedule shown in table 1. Interpretative reports using these data, however, have dealt primarily with streamflow and suspended-sediment transport.

Reports on flooding and the magnitude, duration, and frequency of streamflow at the Arcata station include those by Rantz (1959, 1964); Hofmann and Rantz (1963); Waananen and others (1971); and the U.S. Army Corps of Engineers (1968a, 1968b). Hawley and Jones (1969) reported the sediment yield of the Mad River basin for 1958-64 using the data from the Arcata station. Brown (1973) summarized streamflow, sediment-transport, and turbidity characteristics for Mad River near Arcata for 1958-71.

The drainage area upstream from Mad River near Arcata is 485 mi^2 (1,256 km^2), or about 98 percent of the total Mad River basin area. Thus, records from the Arcata station reflect broad, basin-wide conditions and provide a basis for extrapolating the shorter-term records of upstream stations. They also reflect a variety of conditions imposed by gravel mining, flow diversion, and other activities in the flood plain immediately upstream from the station. Therefore, such conditions must be considered in relation to stream and channel conditions farther upstream to determine adequately the effects of the Butler Valley Dam and Blue Lake Project.

Preproject conditions of sediment transport at Mad River near Arcata were determined primarily by augmenting previous work (Brown, 1973), interpreting 218 particle-size analyses made of suspended-sediment samples collected from November 1956 through September 1972, and interpreting bedload data from the years 1972-73. The following interpretations are based on these data:

1. The long-term (100-year) suspended-sediment discharge at Mad River near Arcata is computed to be 2,220,000 ton/yr (2,000,000 t/yr). This quantity comprises sediment particles less than 2.0 mm in diameter.

2. Of the long-term suspended-sediment discharge, 615,000 ton/yr (558,000 t/yr) is in the particle-size range 0.062-2.0 mm (table 2). Particles in this range are classified as sand, as distinguished from silt, clay, and other particles (Wentworth, 1922), and are potential beach-forming particles in the study area. That is, the particle-size range 0.062-2.0 mm generally overspreads the range of material observed on the beaches and dunes near the mouth of the Mad River (Ritter, 1973, p. 11; DeGraca and Ecker, 1974, p. 4). Further breakdowns of suspended-sediment transport by particles-size ranges are given in table 2, and representative suspended-sediment transport curves are shown in figures 6, 7, and 8.

3. Table 2 shows that 28 percent of the long-term annual suspended-sediment discharge at the Arcata station is sand and that most of the sand transported is in the particle-size range 0.062-0.250 mm. The maximum dimension of sand particles carried in suspension past the station is probably between 0.5 and 1.0 mm. Of the 218 samples analyzed for particle size, 69 contained particles in the range 0.50-1.0 mm. Only 6 of the 218 samples contained particles in the range 1.0-2.0 mm, and these particles probably were saltating near the streambed during medium stages of flow when sampled.

4. Sediment transported as bedload was estimated to be 60,000 ton/yr (54,000 t/yr), or about 2 percent of the suspended-sediment discharge for the years 1971-72. Figure 9 shows the bedload transport curve for the Arcata station based on data collected from 1972 through 1973. The data were collected using a sampler designed and described by Helley and Smith (1971). Because the sampler has an entrance orifice measuring about 76 mm by 76 mm, the data represent particles less than 76 mm in diameter. Because of the vagaries inherent in sampling bedload, however, a detailed analysis of particle-size distribution in the bedload samples was not considered useful for the purposes of this report. Bedload transport was computed using the curve shown in figure 9 and the streamflow record for 1971-72. This period was used for comparisons with table 2 and data for Mad River near Kneeland, discussed subsequently in this report.

TABLE 2.--*Summary of suspended-sediment discharge for Mad River near Arcata*

[U.S. Geological Survey gaging station 11481000. Location shown in figure 1. Drainage area 485 mi^2]

Period (water years)	Suspended sediment discharge, Q_s (ton/yr)	Suspended-sediment discharge for indicated particle-size range, in tons per year and percent of total Q_s									
		<0.062 mm	Percent	0.062-0.125 mm	Percent	0.125-0.250 mm	Percent	0.250-2.0 mm	Percent	0.062-2.0 mm	Percent
1957-64 (average)	2,100,000	1,514,000	72	296,000	14	215,000	10	75,000	4	586,000	28
1965-71 (average)	3,860,000	2,860,000	74	680,000	18	← [1]321,000		→	[1]8	1,001,000	26
Long-term (100-year)	2,220,000	1,605,000	72	323,000	15	222,000	10	70,000	3	615,000	28
1971-72 (average)	2,949,000	2,180,000	74	328,000	11	← [1]441,000		→	[1]15	769,000	26
1971	2,758,000	2,178,000	79	193,000	7	← [1]387,000		→	[1]14	580,000	21
1972	3,140,000	2,182,000	69	464,000	15	← [1]494,000		→	[1]16	958,000	31

[1]Estimated values.

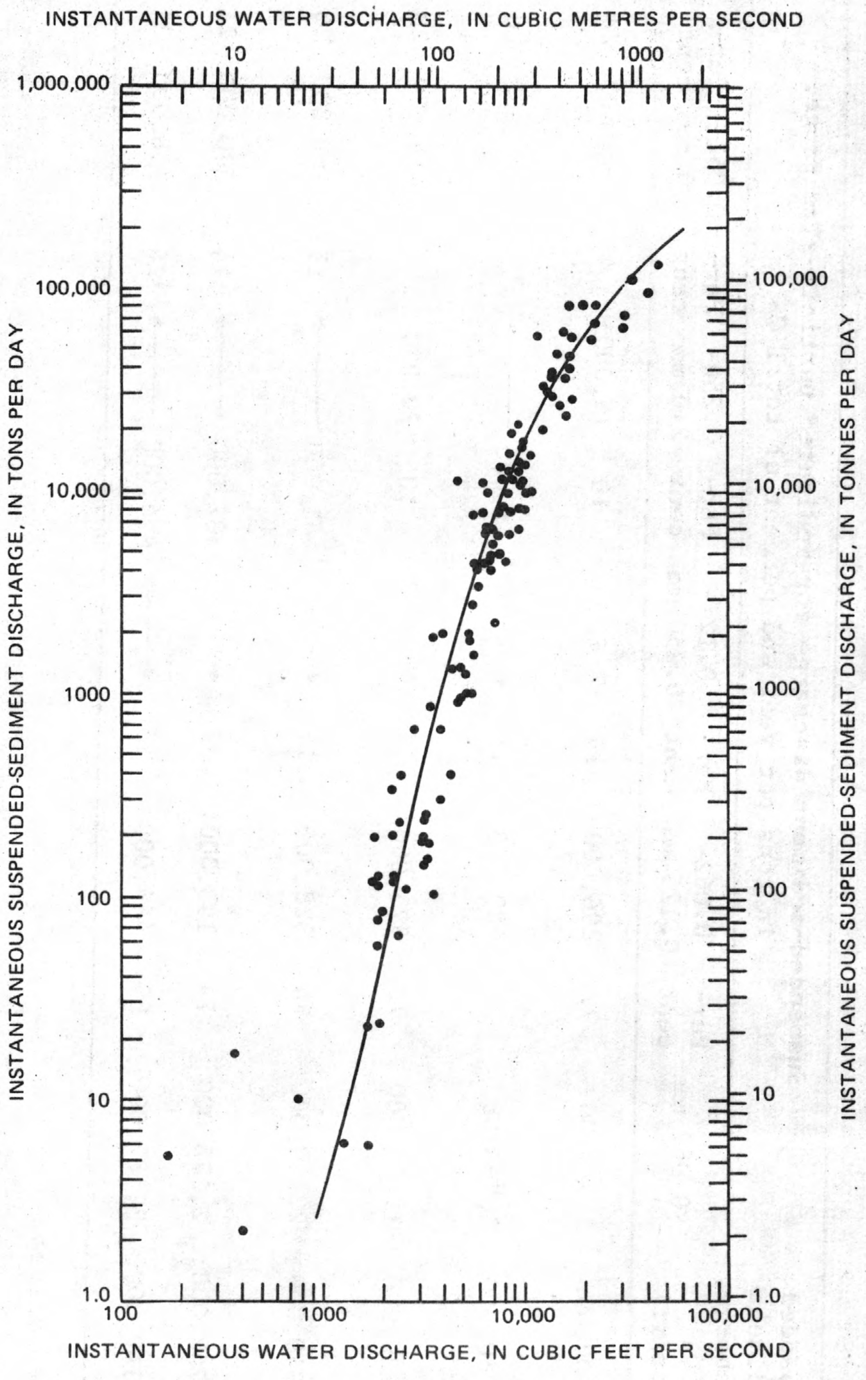


FIGURE 6.--Relation of suspended-sediment (particle-size range 0.062-2.0 millimetres) discharge to water discharge at Mad River near Arcata, 1957-64.

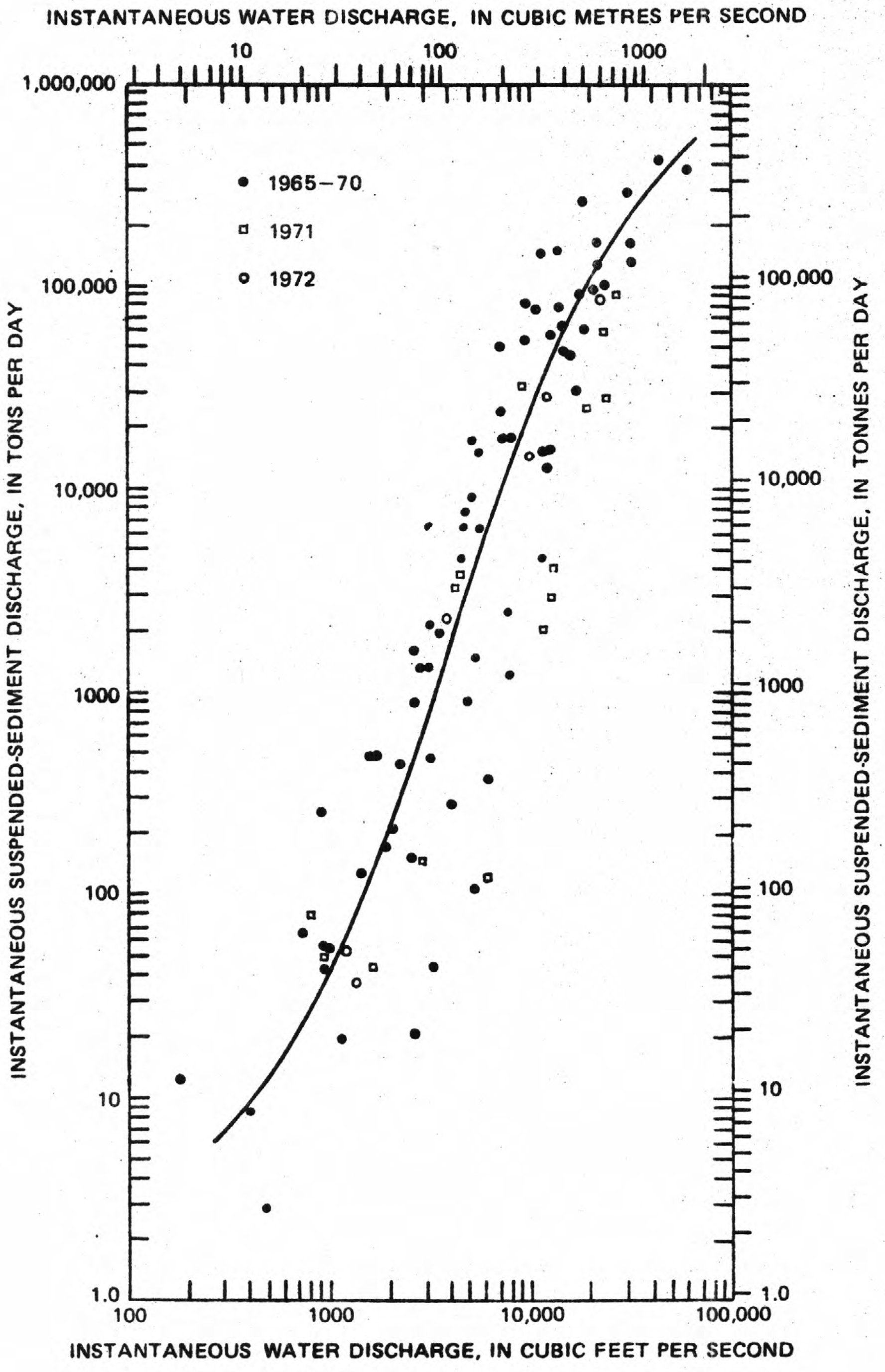


FIGURE 7.--Relation of suspended-sediment (particle-size range 0.062-2.0 millimetres) discharge to water discharge at Mad River near Arcata, 1965-72.

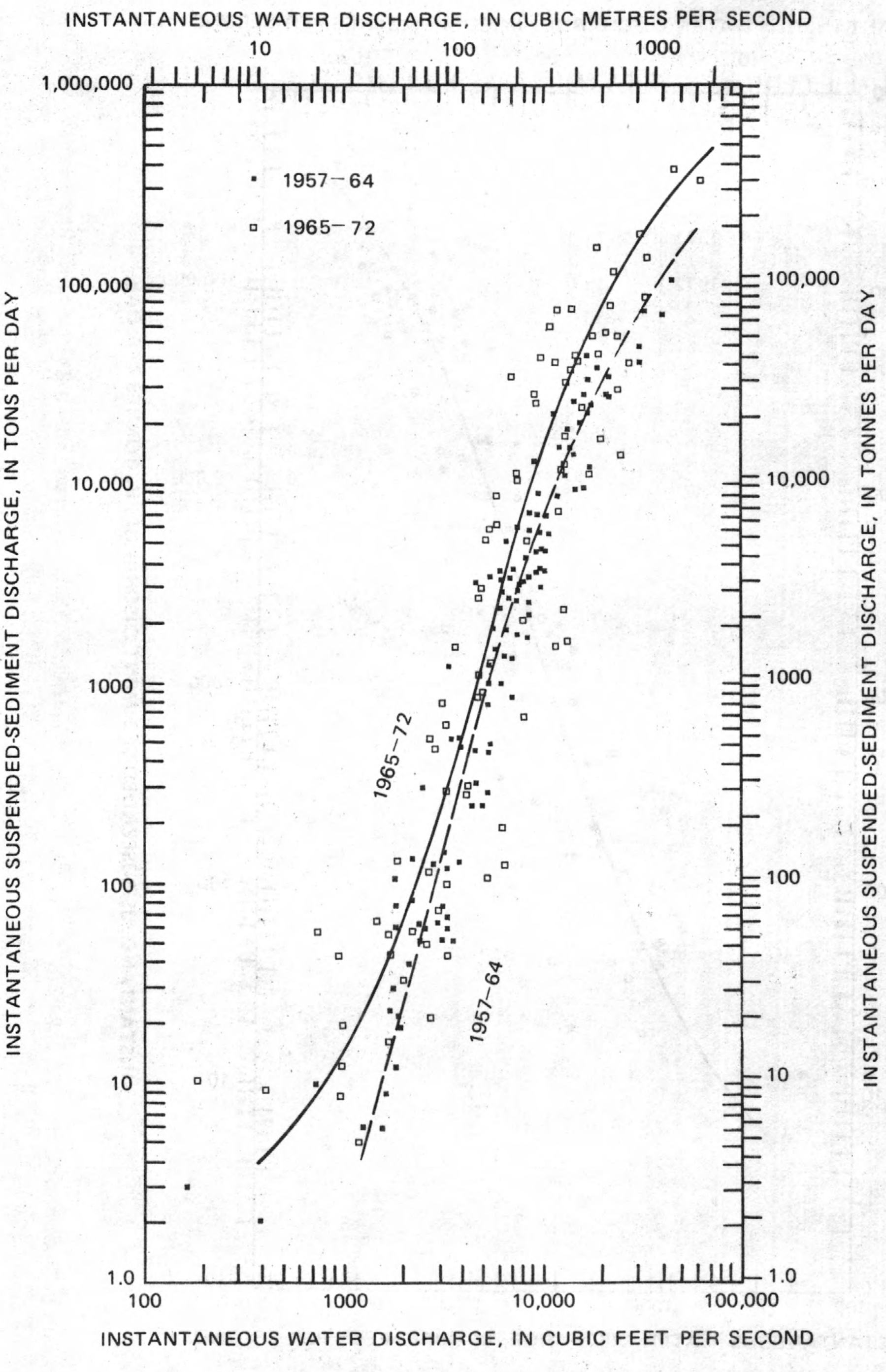


FIGURE 8.--Relation of suspended-sediment (particle-size range 0.062-0.125 millimetre) discharge to water discharge at Mad River near Arcata, 1957-72.

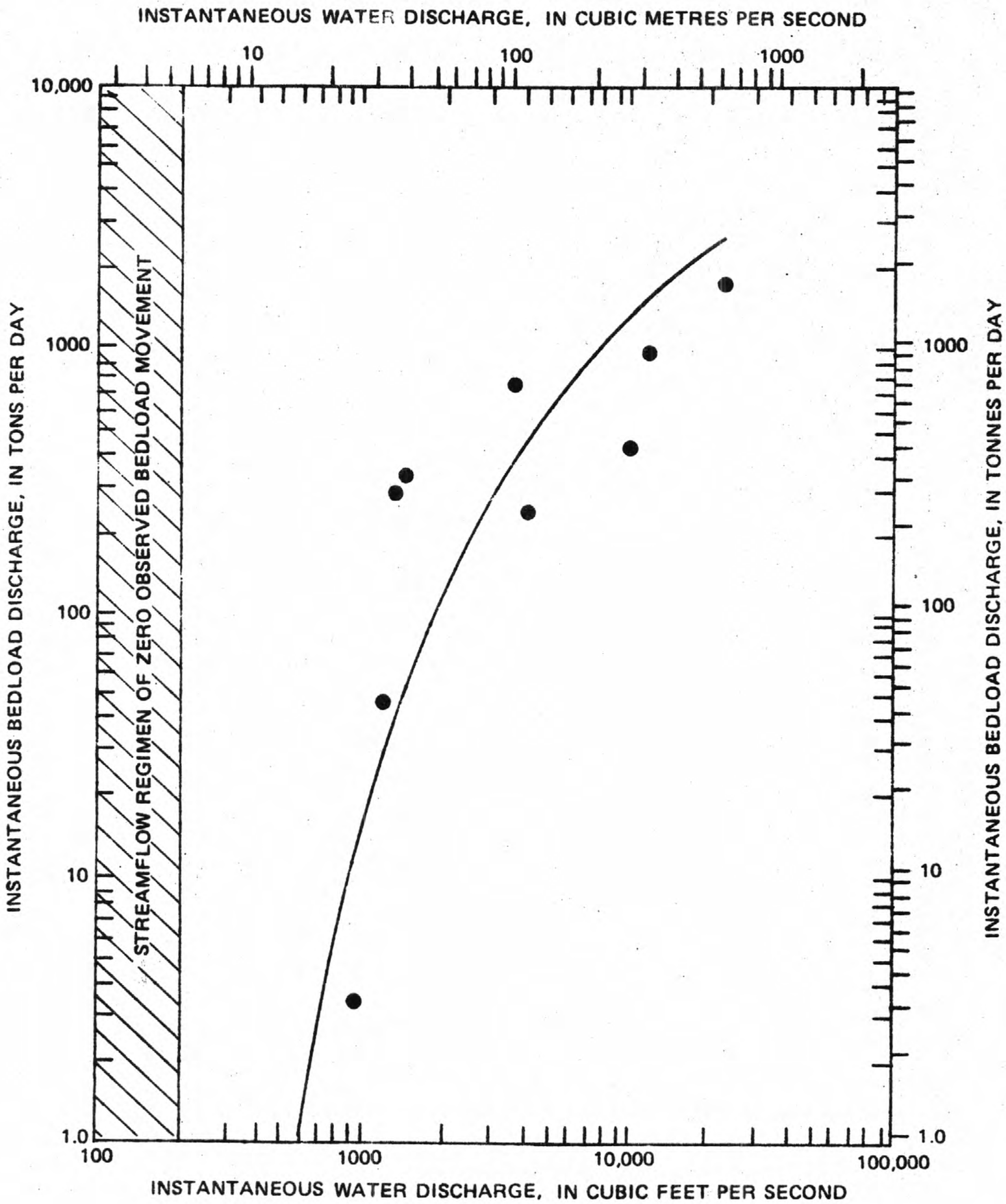


FIGURE 9.--Relation of bedload discharge to water discharge at Mad River near Arcata, 1972-73.

Mad River near Kneeland.--Mad River near Kneeland is the principal gaging station for sampling preproject conditions of surface-water influent to the Butler Valley Dam and Blue Lake Project area. Sediment and turbidity samples have been collected at the station since October 1970, and conditions of channel geometry and flow hydraulics have been measured since October 1965. Preliminary data on sediment transport, turbidity, and channel geometry at the Kneeland station were reported by Brown (1973).

On the basis of sediment samples collected from October 1970 through September 1972, sediment-transport relations were determined for sediment transported as bedload and for four particle-size ranges of sediment carried in suspension (figs. 10, 11, and 12). Using these relations, and the water-discharge regimen for October 1970 through September 1972, the following interpretations were made:

1. The average suspended-sediment discharge past the Kneeland station was 1,786,000 ton/yr (1,620,000 t/yr) for the years 1971-72 (table 3).

2. Fifty percent of the sediment transported in suspension during the 2-year period was transported during fewer than 15 days, or during about 2 percent of the period. Ninety percent of the suspended-sediment transport took place during fewer than 50 days, or during about 7 percent of the period. These figures are characteristic of the regimen of suspended-sediment transport for unregulated and partly regulated streams draining the Coast Ranges of northern California (Brown and Ritter, 1971, p. 57-58; Ritter and Brown, 1971, p. 27).

3. Of the sediment transported in suspension, 472,000 ton/yr (428,000 t/yr) for the 2-year period was in the particle-size range 0.062-2.0 mm. This size range generally overspreads the size range of material observed on the beaches and dunes in the vicinity of the mouth of the Mad River. Further breakdowns of suspended-sediment transport by size ranges are given in table 3.

4. The maximum dimension of sediment particles carried in suspension in the vicinity of the Kneeland station is probably between 0.50 and 1.0 mm. Of 19 samples analyzed for particle-size distribution during the 2-year period, 11 contained particles in the size range 0.50-1.0 mm, and 3 samples contained particles in the size range 1.0-2.0 mm. All 19 samples contained particles in the size range 0.25-0.50 mm, probably indicating the ability of flows at the Kneeland station to transport coarse sediment in suspension. The conditions of flow velocity and turbulence at the Kneeland station, however, may not be representative of the channel downstream to the Mad River Hatchery. Therefore, data collected at Mad River near Blue Lake need to be critically compared with the Kneeland station data to determine adequately the suspended-sediment transport ability of Mad River in its reach between the two stations.

5. Sediment transported as bedload was estimated to be 170,000 ton/yr (150,000 t/yr), or about 10 percent of the suspended-sediment discharge for 1971-72 on the basis of the limited data shown in figure 10. The data were collected during 1973 and were applied to flows that occurred during 1971-72 for comparison with the suspended-sediment transport discussed above and with data for Mad River near Arcata.

TABLE 3.--*Summary of water and suspended-sediment discharge for Mad River near Kneeland*

[U.S. Geological gaging station 11480750. Location shown in figure 1. Drainage area is 352 mi^2]

Water year	Water discharge, Q_w (ft^3/s-day)	Suspended-sediment discharge Q_s (ton/yr)	Suspended-sediment discharge for indicated particle-size range, in tons per year: <0.062 mm	0.062–0.125 mm	0.125–0.250 mm	0.250–2.0 mm	0.062–2.0 mm	Number of days required to transport given percent of annual Q_s: 50	70	90
1971	574,200	[1]1,831,000	-	-	-	-	-	9	15	20
1972	467,500	[1]1,741,000	-	-	-	-	-	6	13	30
Average	520,800	1,786,000	[1]1,314,000	[1]150,000	[1]200,000	[2]122,000	[1]472,000	8	14	25

[1]Computed on the basis of the relations shown in figures 11 and 12 and the regimen of streamflow for 1971 and 1972.

[2]Estimated value.

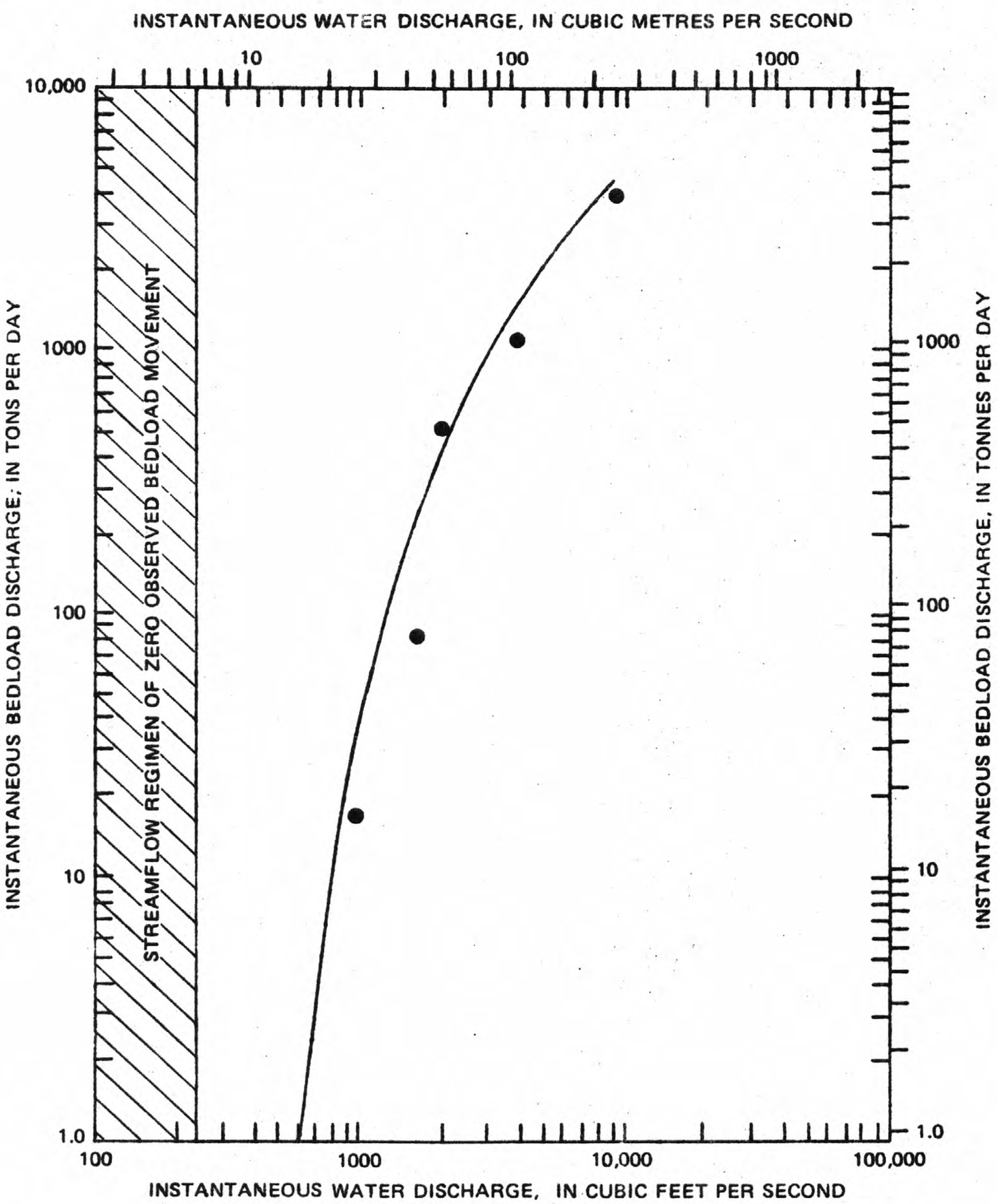


FIGURE 10.--Relation of bedload discharge to water discharge at Mad River near Kneeland, 1973. Compare with figure 9.

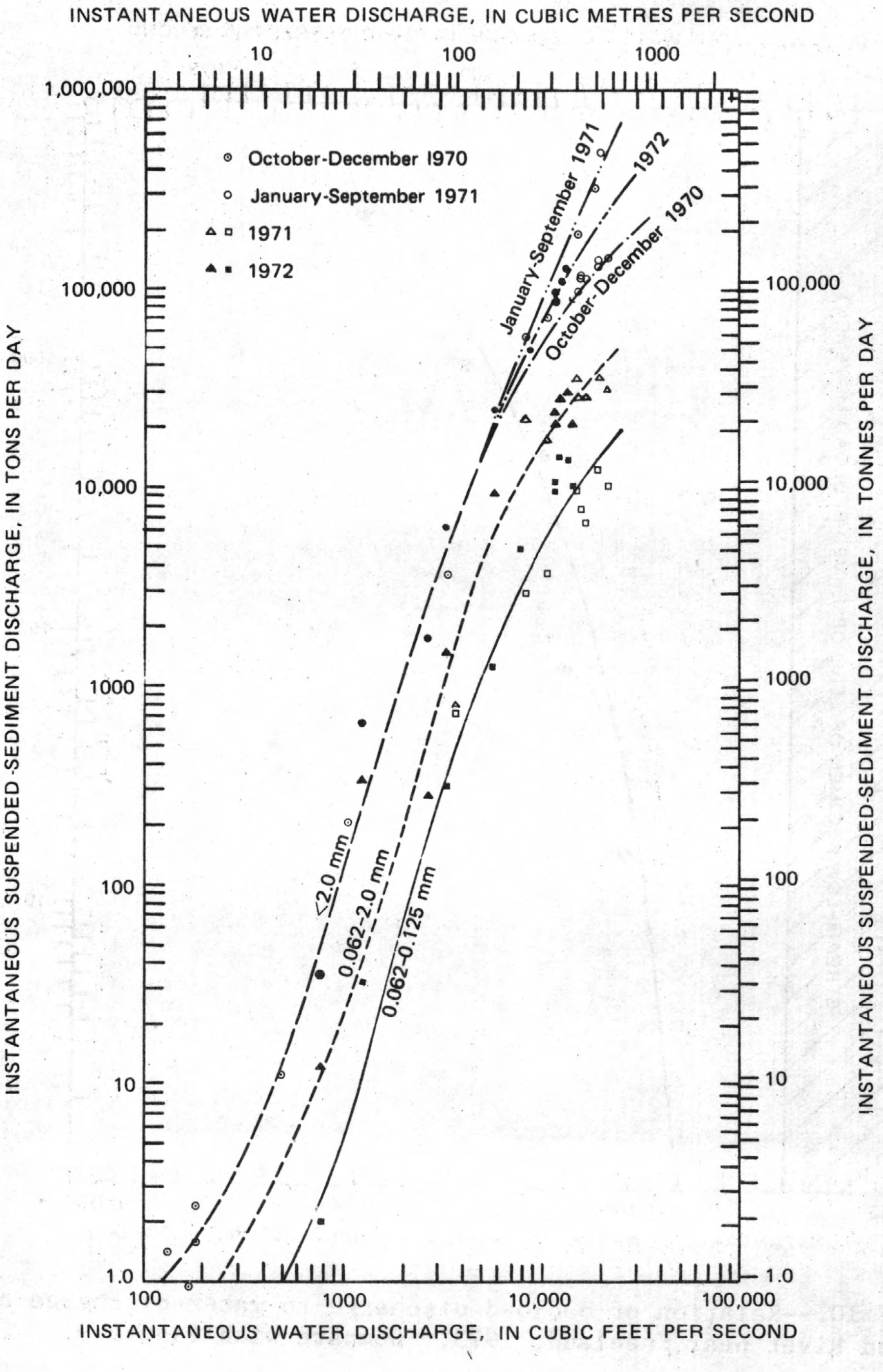


FIGURE 11.--Relation of suspended-sediment discharge (particle-size ranges: less than 2.0 millimetres, 0.062-2.0 millimetres, and 0.062-0.125 millimetre) to water discharge at Mad River near Kneeland, 1971-72.

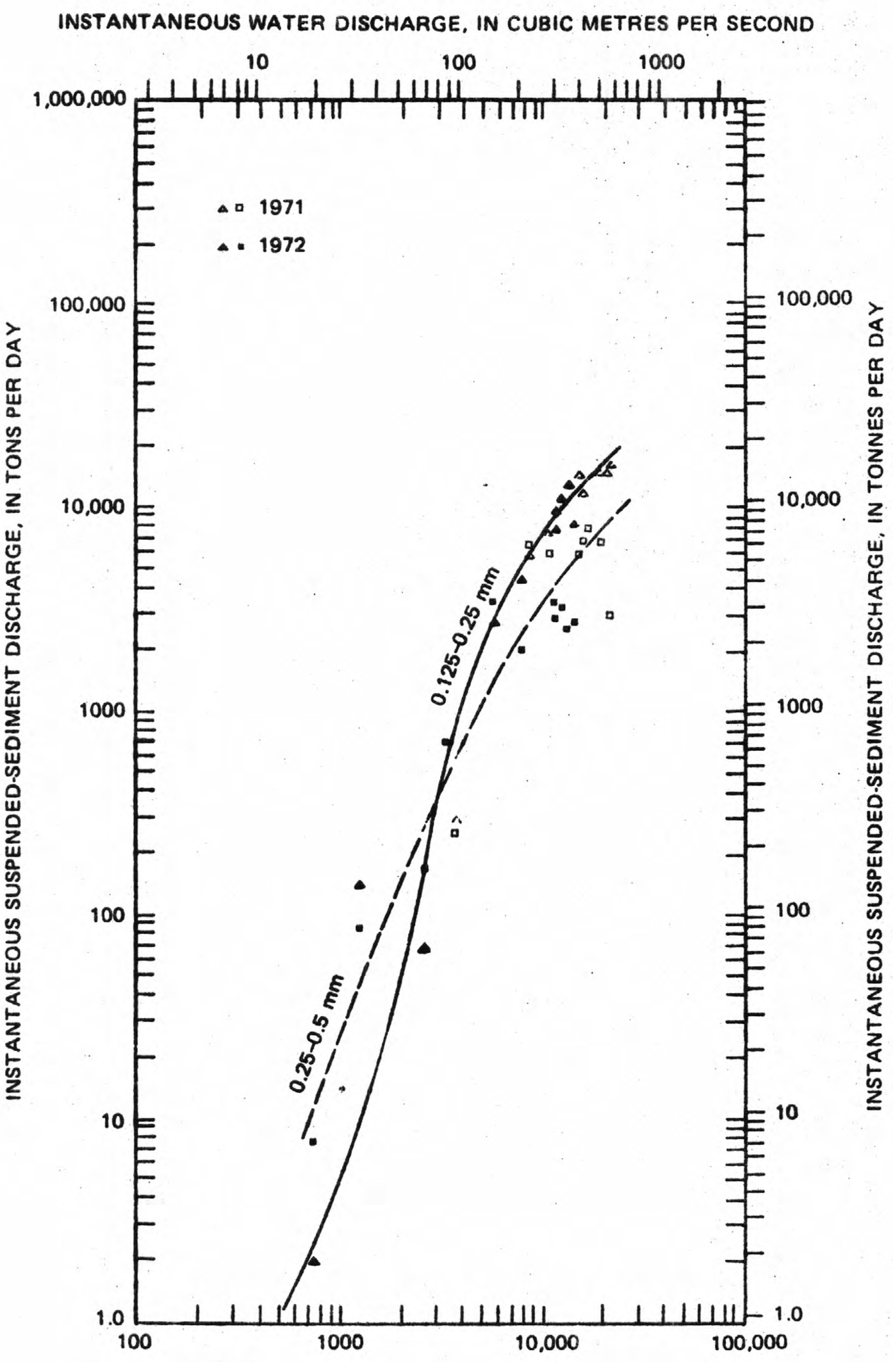


FIGURE 12.--Relation of suspended-sediment discharge (particle-size ranges: 0.125-0.25 millimetre and 0.25-0.5 millimetre) to water discharge at Mad River near Kneeland, 1971-72.

TURBIDITY

General Considerations

Turbidity is an optical property of the water-particulate mixtures that constitute the flow of the river and is defined as the ability of the mixtures to inhibit the passage of light. Turbidity in the Mad River basin is an unclear or cloudy condition caused by undissolved substances, notably plankton and suspended inorganic particles. These inorganic particles, clay, silt, and, to a lesser extent, sand, induce most of the turbidity in streams of the Mad River basin.[4] These turbidity-causing particles enter the Mad River and its tributaries primarily in runoff from rainfall and mass-wasting, such as landsliding, that are prevalent during the rainy season. Thus, the natural turbidity regimen of the Mad River closely parallels the regimens of runoff and suspended-sediment discharge. Variations from the parallelism among runoff, suspended-sediment discharge, and turbidity regimens are commonly related to artificial controls such as flow regulation and diversion and gravel mining and other activities in the stream channels. Planktonic growths induce minor amounts of turbidity, notably in ponded reaches of the river during the summer periods of low flow. Turbidity caused by planktonic growth during winter periods is virtually negligible compared to turbidity caused by suspended clay, silt, and sand.

The preproject turbidity conditions (fig. 13) are defined for this report by data collected at the Mad River stations near Arcata and Kneeland (fig. 1) and at Mad River near Forest Glen.[5] Turbidity data were collected at North Fork Mad River near Korbel and Mad River near Blue Lake (table 1); however, no analyses of these data were available at the time of this writing. Further information on turbidity in the basin and methods of turbidity analysis are described in Brown (1971, p. 37-51).

[4]This generality specifically excludes Ruth Reservoir, a water-supply reservoir on the Mad River upstream from the study area that may exhibit considerable turbidity attributable to planktonic growth.

[5]Mad River near Forest Glen is a gaging station about 40 mi (64 km) upstream from Mad River near Kneeland. Turbidity data from the Forest Glen station were incorporated to show the basin-wide characteristics of turbidity from which conclusions about the study area were drawn. Aspects of turbidity at the Forest Glen station were reported by Brown (1973, p. 46).

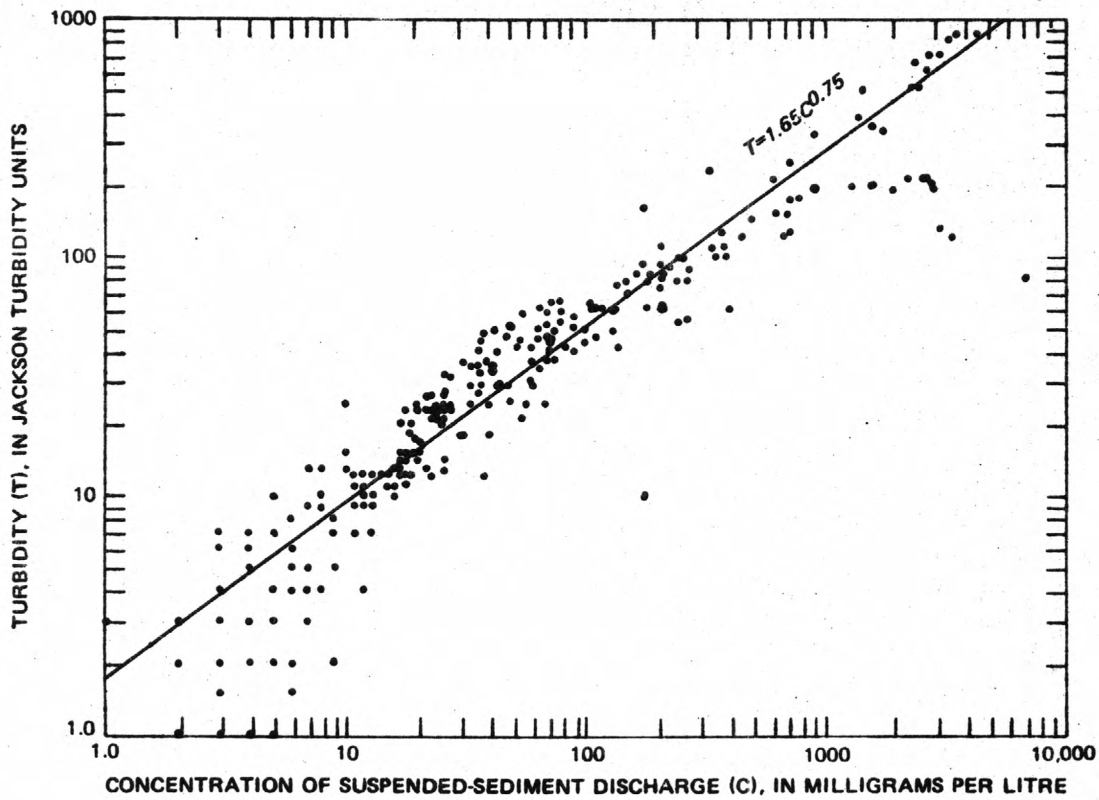


FIGURE 13.--Relation of turbidity to suspended-sediment concentration, 1964-72. Data are composited from Mad River stations near Arcata, Kneeland, and Forest Glen.

Preproject Turbidity Conditions

Turbidity in the Mad River is mostly sediment induced and responds almost directly to sediment-laden runoff. The water is most turbid during the annual storm-runoff period, generally October through May, when turbidity, water discharge, and the concentration of suspended sediment are highly interrelated. Most of the turbidity-causing particles of sediment, once in the flowing water, tend to remain in suspension until deposited in the estuarial reach of the river or in the Pacific Ocean. Therefore, the same particles that induce turbidity at the Kneeland station, for example, also induce turbidity at the Arcata station. Additional particles entering the reach of river between the two stations do so in proportion to the runoff influent to that reach. The runoff, in turn, reflects the general runoff conditions that prevail throughout the basin during the characteristic regional storms. Thus, turbidity between the Kneeland and Arcata stations during the winter runoff period can be defined in terms of both water discharge and suspended-sediment concentration, and the following empirical relations apply:

$$T=1.65C^{0.75} \text{ (fig. 13), and} \tag{1}$$

$$T=0.12Q_w^{0.90}; \tag{2}$$

where T=turbidity, in Jackson turbidity units (JTU),
C=suspended-sediment concentration, in milligrams per litre (mg/l),
Q_w=water discharge, in cubic feet per second (ft^3/s); and the relation between Q_w and the discharge of suspended sediment (Q_s) is

$$Q_s=KQ_w^{2.19}, \tag{3}$$

$$K=8.32\text{x}10^{-5} \text{ (fig. 14), and}$$

$$Q_s=0.27\text{x}10^{-2}Q_wC \text{ (Porterfield, 1972, p. 43).}$$

Equation 3 was determined from sediment-transport data collected at Mad River near Kneeland and Mad River near Arcata. Equation 3 applies to 93 years of the long-term (100-yr) sediment-transport regimen of the study area discussed on page 14. For the short-term (7-yr) regimen associated with a 100-year flood, the constant K would be different for each of the 7 years.

Equations 1 and 2 do not necessarily apply during summer periods of little or no direct runoff from rainfall, nor do they necessarily apply at discreet points and times during periods of storm runoff. Equations 1 and 2 reflect only the general, average conditions of the reach of river in the study area as the entire river responds to regional storms. The equations could be used to quantify the general effects of the Butler Valley Dam and Blue Lake Project on the turbidity regimen of the river if comparative, postproject data are collected downstream from the project site.

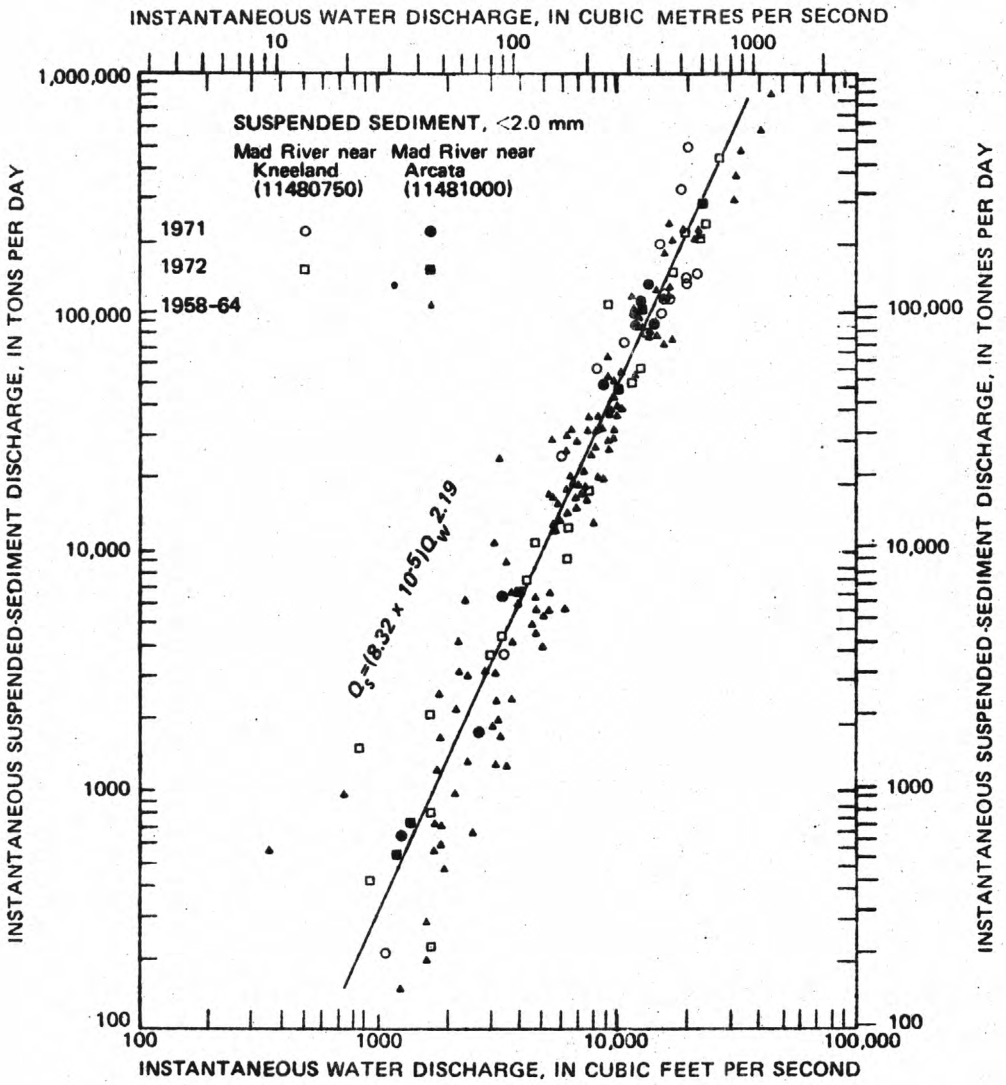


FIGURE 14.--Relation of suspended-sediment discharge to water discharge, Mad River near Kneeland and Mad River near Arcata. Curve was fitted to data for years 1971-72 only, and data for 1958-64 were then plotted to show correspondence with 1971-72 data. The 1958-64 data, however, were not used to fit the curve.

MAD RIVER CHANNEL FEATURES AND PROCESSES

Mad River near Kneeland to Mad River Hatchery

From the Kneeland station to the Mad River Hatchery (fig. 15), the Mad River flows in a composite channel comprising an alluvial gravel bed and heterogeneous bedrock banks. The bed is largely an alternating sequence of shifting gravel bars displayed during low flows along the insides of the sinuous bends of the low-water thalweg. The bars measure about 500 to 5,000 ft (150 to 1,500 m) in parallel dimension to the thalweg and extend as much as 500 ft (150 m) perpendicular to the bedrock channel banks. The bars characteristically form on the downstream sides of colluvial boulders or bedrock protrusions and measure as much as 20 ft (6 m) vertically from the low-water thalweg to the top of the bar. The width of the alluvial bed between the confining bedrock banks ranges from about 100 to 800 ft (30 to 240 m) except at The Narrows (fig. 16) where the entire channel is controlled by bedrock and massive boulders.

The bedrock banks primarily comprise the varied units of the Franciscan assemblage of Jurassic and Cretaceous age, a heterogeneous mass of pervasively folded, crushed, and sheared rocks of many types dominated in quantity by graywacke-type sandstone (Bailey, Irwin, and Jones, 1964, p. 5-8). However, the Mad River channel also intersects exposures of the Tertiary Falor Formation of Manning and Ogle (1950, p. 22) along a 0.5-mi (0.8-km) reach just north of The Narrows, for about 0.5 mi (0.8 km) opposite Camp Flat at the mouth of Canon Creek, and near the Mad River Hatchery. Just north of the mouth of Canon Creek the channel meets a striking, buff-colored cliff of fossiliferous sandstone of the Falor Formation. Quaternary terrace deposits also form channel banks locally, especially in the vicinities of Butler Valley, Camp Flat, and the Mad River Hatchery. Quaternary landslide deposits that occur principally on Franciscan bedrock abut the Mad River channel at many locations (fig. 15).

CORRELATION OF MAP UNITS

Qls Qt } QUATERNARY

Tf } TERTIARY

KJf } JURASSIC AND CRETACEOUS

DESCRIPTION OF MAP UNITS

Qls LANDSLIDE DEPOSITS – Gravel, sand, silt, and clay, poorly sorted

Qt TERRACE DEPOSITS – Gravel, sand, silt, and clay, poorly sorted

Tf FALOR FORMATION OF MANNING AND OGLE (1950) – Marine arkosic sand, clay, and conglomerate

KJf FRANCISCAN ASSEMBLAGE – Well-cemented arkosic sand, shale, chert, conglomerate, basic volcanic and basic and ultra-basic intrusive rocks; local glaucophane schist

ERODED CHANNEL BANKS

Erosion during study period

Inactive during study period, but showing signs of recent erosion

CONTROLS ON LATERAL CHANNEL MIGRATION AND GRAVEL-BAR FORMATION

Bedrock protrusions (generally not susceptible to significant erosion)

Colluvial boulders (generally not susceptible to transport)

ALLUVIAL DEPOSITS OF TRIBUTARY STREAMS, CONSISTING PRIMARILY OF FLUVIAL GRAVEL

Minor alluvial fan

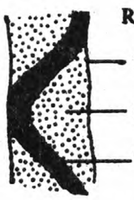
Alluvial plain

LANDSLIDE DEPOSITS IMPINGENT UPON THE ACTIVE RIVER CHANNEL AND SUBJECT TO DIRECT INTERACTION WITH RIVER FLOW – Arrows indicate the general direction of downslope movement

Active surface of deposit as determined by 1970 and 1973 photo interpretation. The boundary shown does not necessarily represent the areal extent of the entire deposit

Landslide deposit of uncertain areal extent of activity, including channel-side slope failures and the toes of larger landslide deposits

RIVER CHANNEL



Boundary of alluvial bed

Bar deposit, consisting primarily of fluvial gravel

Water surface at low flow (200 ft^3/s or 5.7 m^3/s)

FIGURE 15 (map follows on pages 36-41).--Mad River channel from Mad River near Kneeland to Mad River Hatchery showing the geologic and terrain conditions affecting channel morphology. Geologic data are modified from Manning and Ogle (1950). Compare with figure 2. Direction of flow is left to right.

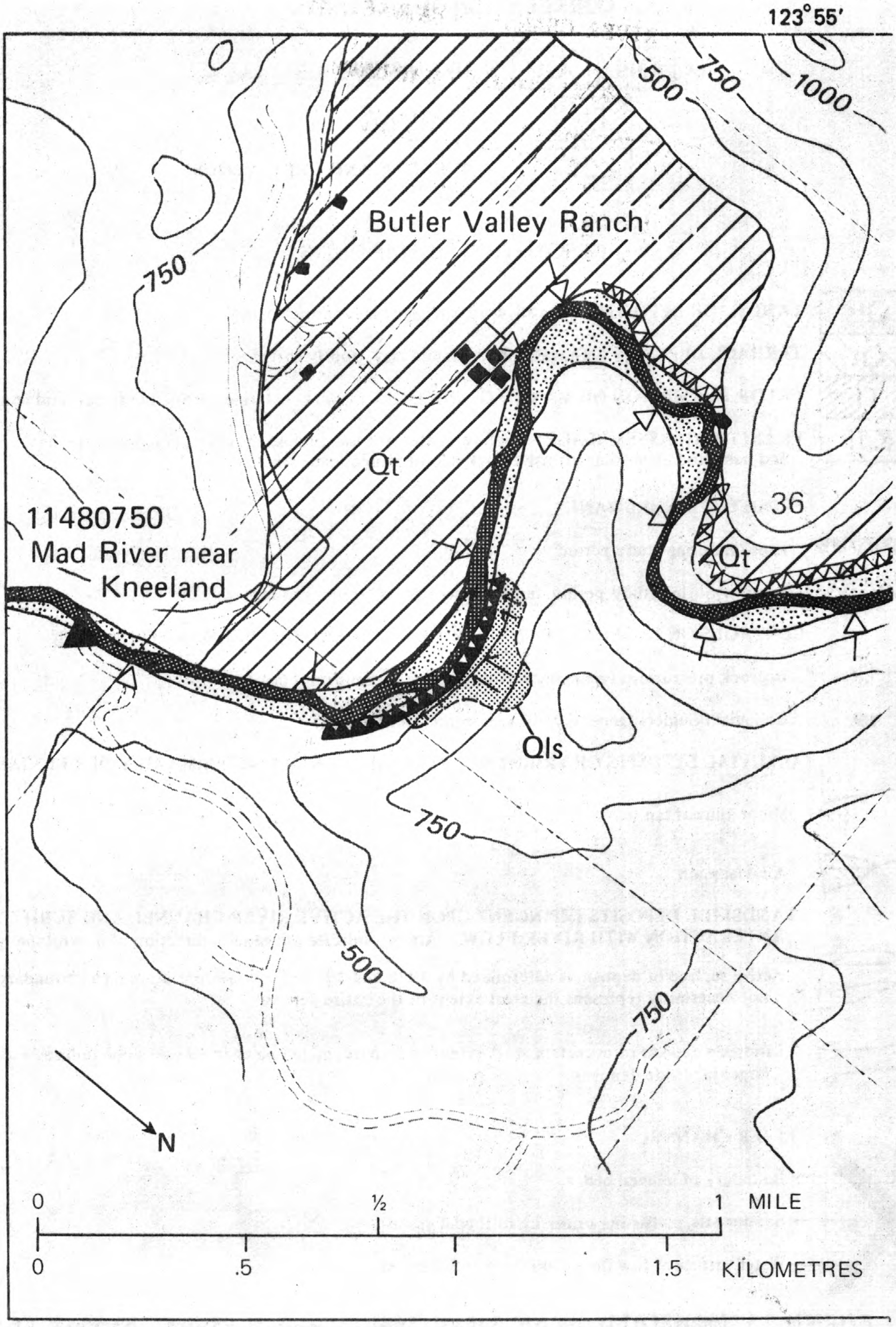


FIGURE 15.--Mad River channel from Mad River near Kneeland to Mad River Hatchery--Continued.

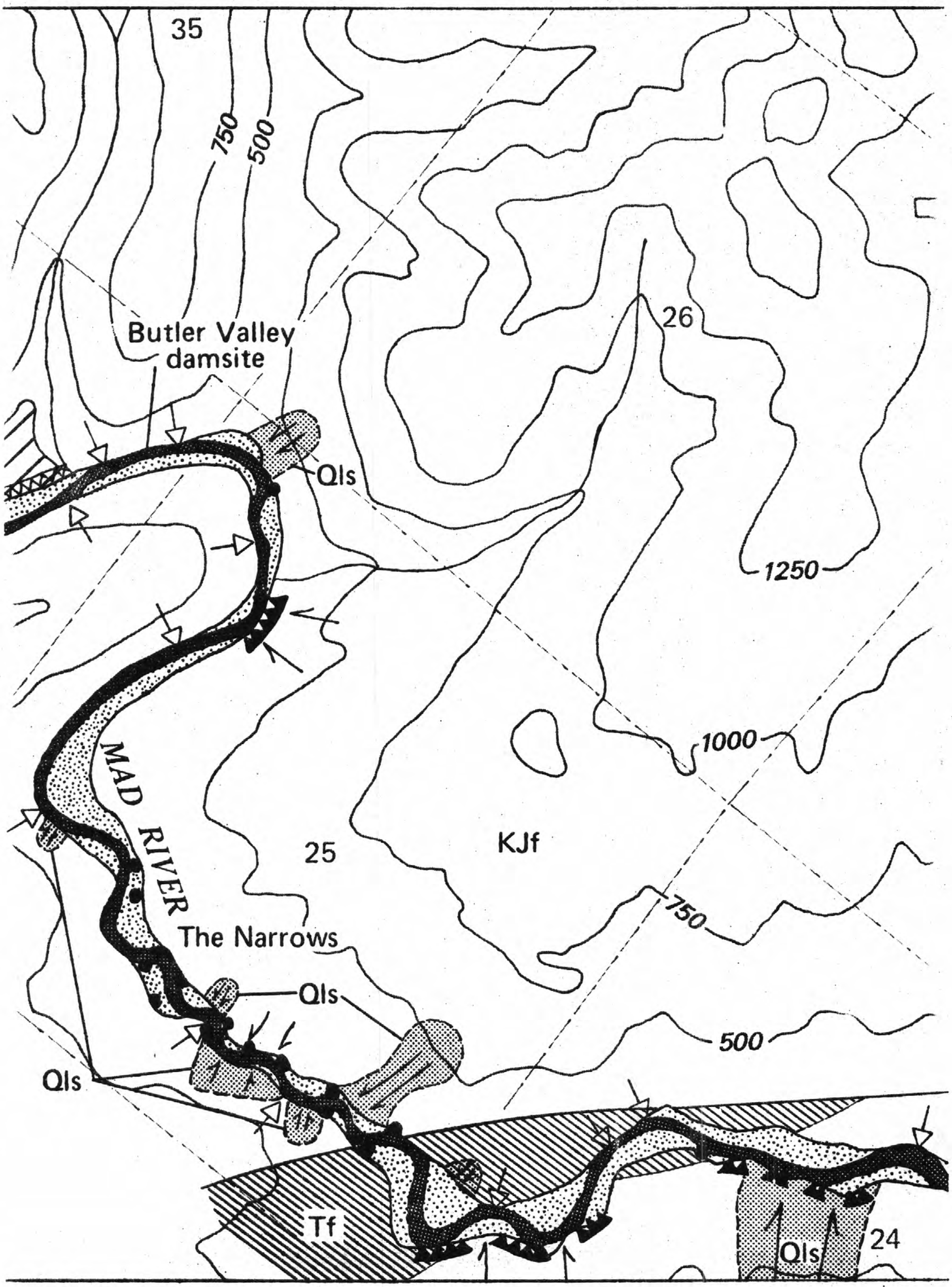


FIGURE 15.--Continued.

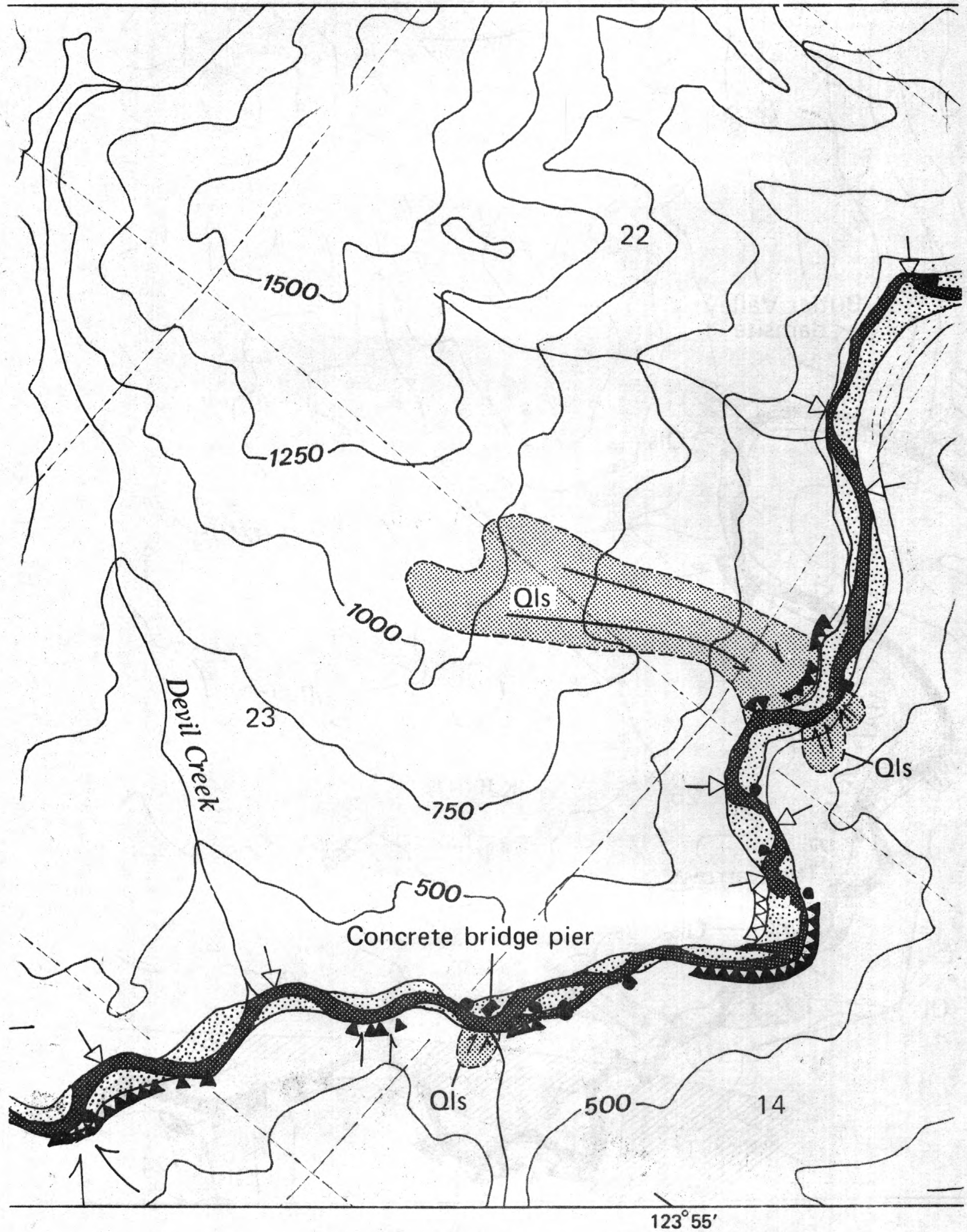


FIGURE 15.--Continued.

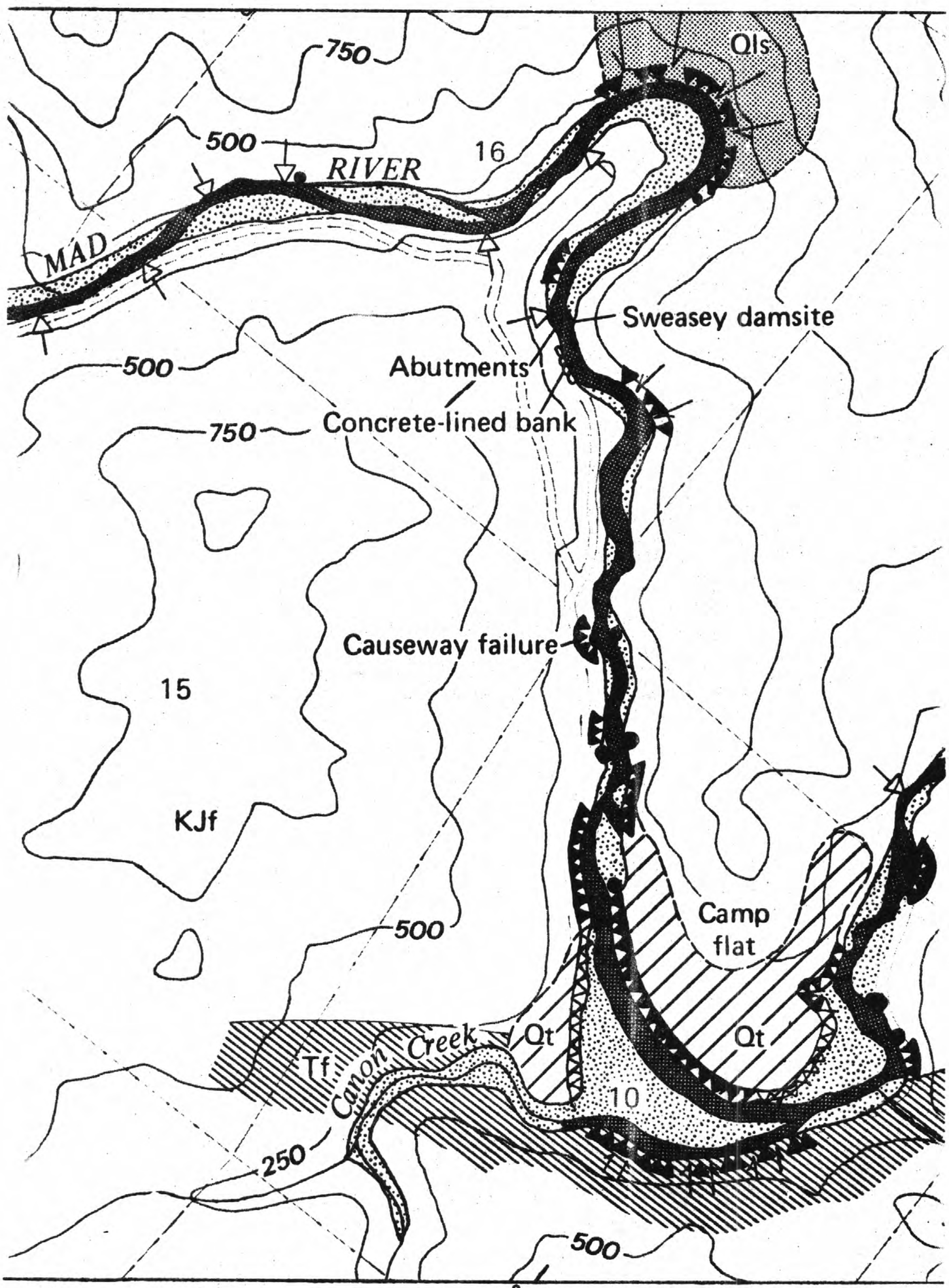
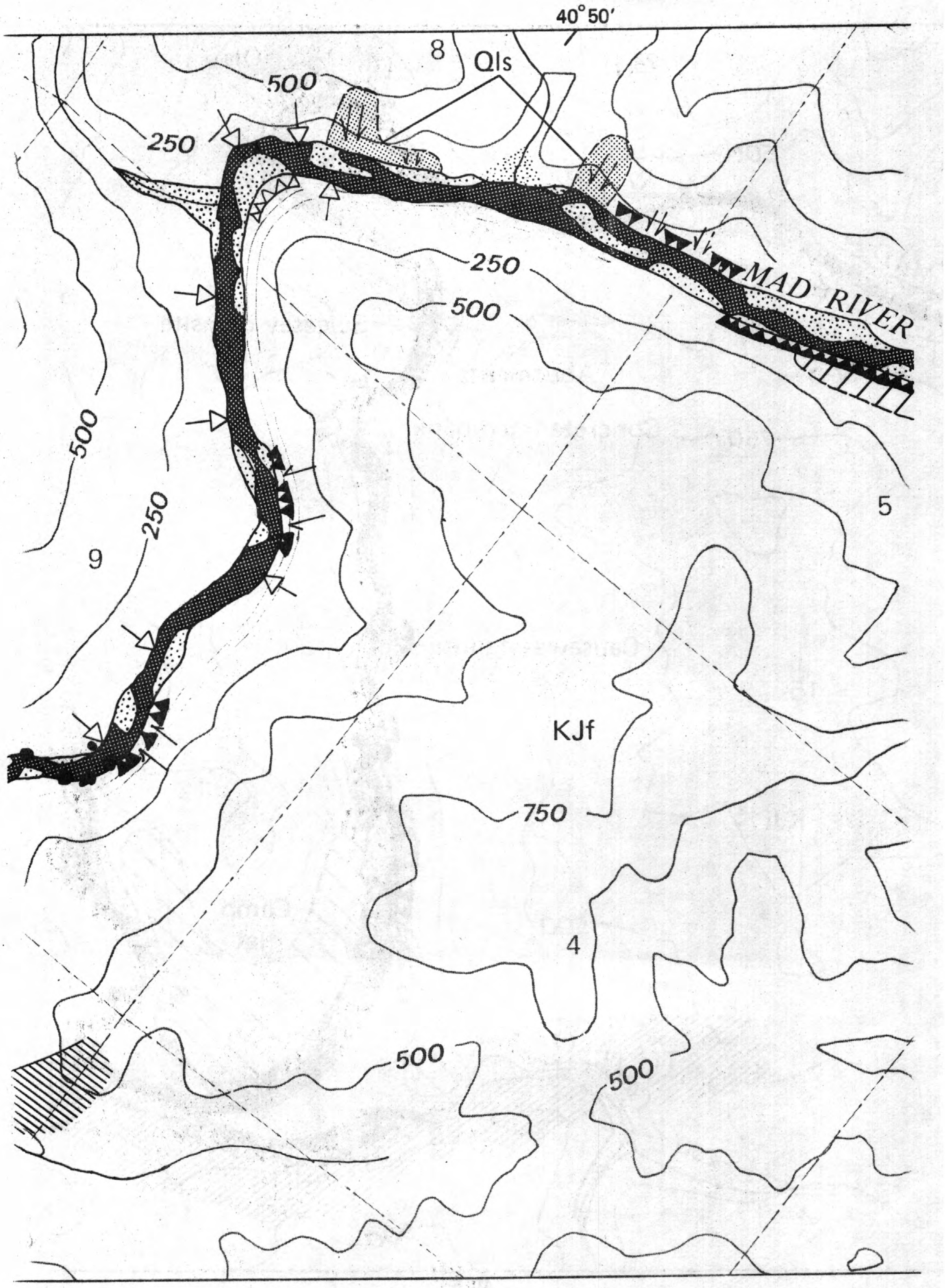


FIGURE 15.--Continued.



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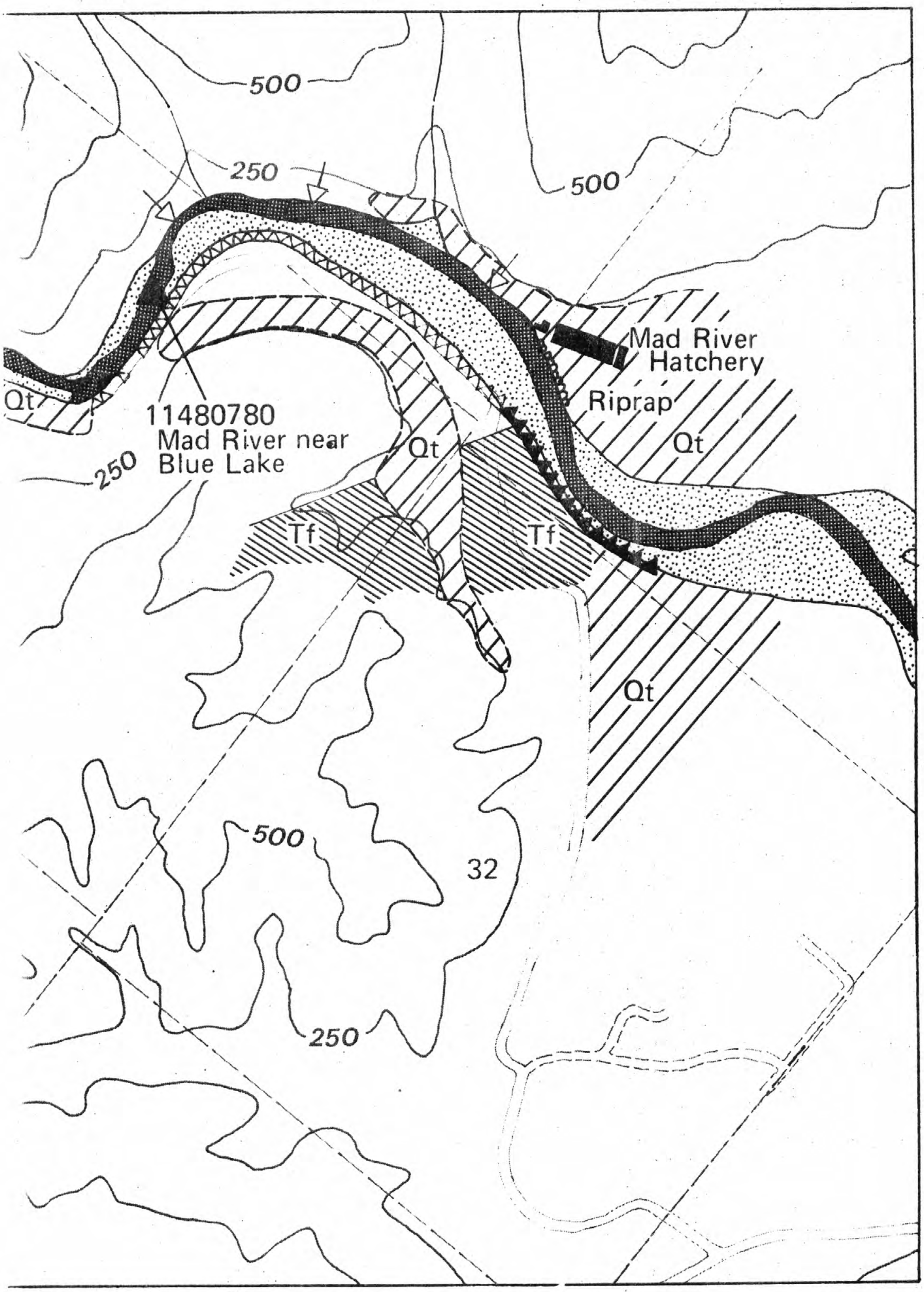


FIGURE 15.--Continued.

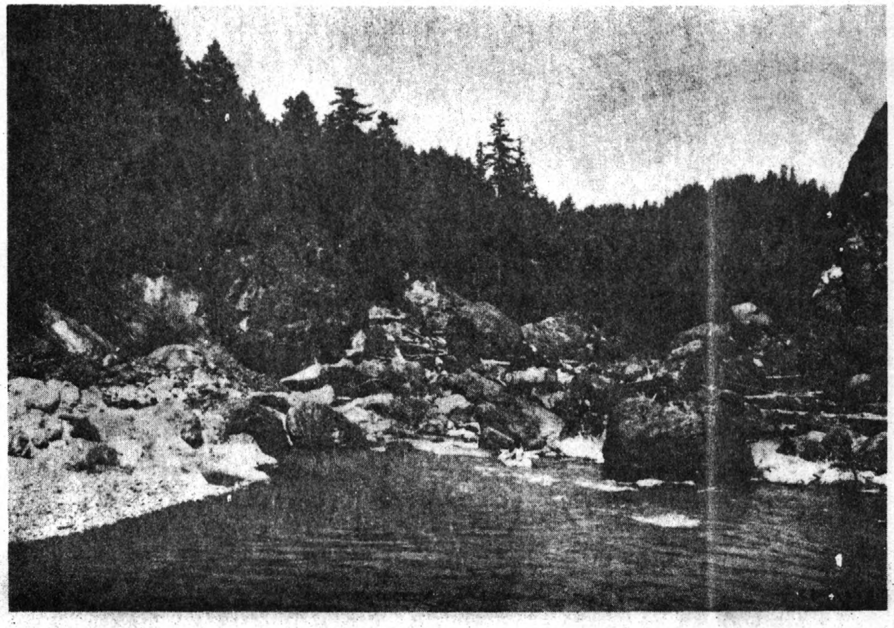


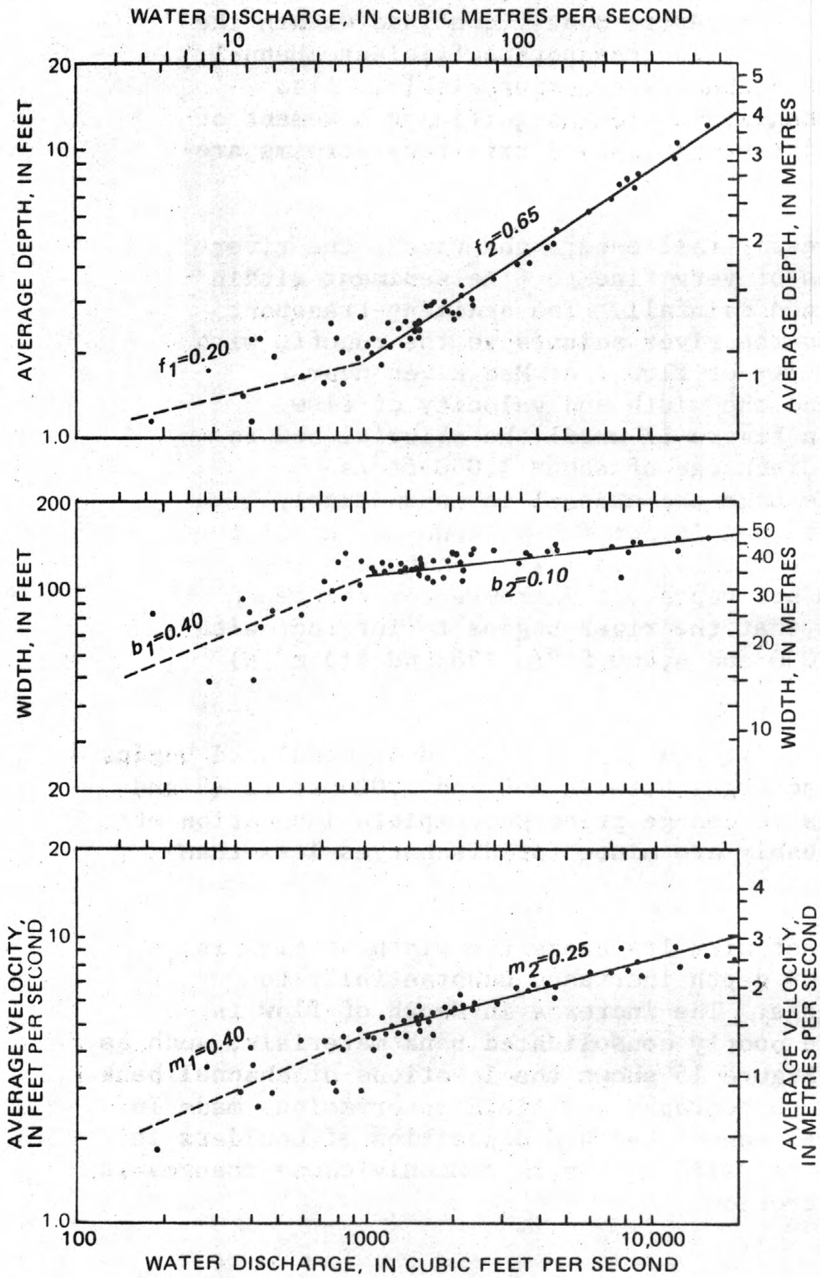
FIGURE 16.--View downstream at the Narrows, a constricted section of the Mad River channel containing massive boulders that are remnants of eroded landslide deposits. Raftsmen and observer in central foreground give scale. Photograph by H. M. Kelsey, April 21, 1973.

During a long summer period each year, beginning with the recession of storm runoff in late spring, the channel is virtually stable. From about May to October the flow of the river is mostly confined within the channel alluvium and lacks the capacity to transport sufficient channel bed and bank material to alter the channel shape appreciably. Also during the summer period, the mechanisms causing significant movement of material into the channel from adjacent slopes and tributary streams are generally absent.

As runoff from the rains of early fall enters the river, the river is loaded with high concentrations of very fine to fine sediment within a few hours of a period of sustained rainfall. The sediment-transport capacity of the river increases as the river adjusts to the runoff, with rapid increases of width and velocity of flow. At Mad River near Kneeland the channel is narrow, and the width and velocity of flow increase at the rates indicated in figure 17 until the alluvial bed is almost completely inundated at a discharge of about 1,000 ft^3/s (28 m^3/s). At Mad River near Blue Lake the channel is considerably broader (fig. 18), and the alluvial bed is not fully inundated until the discharge reaches an estimated 4,000 ft^3/s (113 m^3/s). Although the conditions at the two stations do not represent extremes for the reach shown in figure 15, it is assumed that the river begins to interact with its bank at discharges between 1,000 and 4,000 ft^3/s (28 and 113 m^3/s) for most of the reach.

According to the data shown in figures 10 and 19, the alluvial bed begins to move at the two stations at discharges between 300 and 1,000 ft^3/s (8 and 28 m^3/s). Thus the channel begins to change prior to complete inundation of the bed, although the changes probably are minor for discharges less than 1,000 ft^3/s (28 m^3/s).

As the river begins to interact with its banks the width of flow is confined, and the rate of change of depth increases substantially to accommodate the increasing discharge. The increase in depth of flow is accompanied by erosion of the more poorly consolidated bank materials, such as terrace and landslide deposits. Figure 15 shows the locations of channel bank erosion as determined from aerial photographs and field observations made in 1972-73. However, shifting of the channel bed and deposition of boulders in the channel during the erosion of landslide deposits commonly cause changes in the locations and extent of bank erosion.



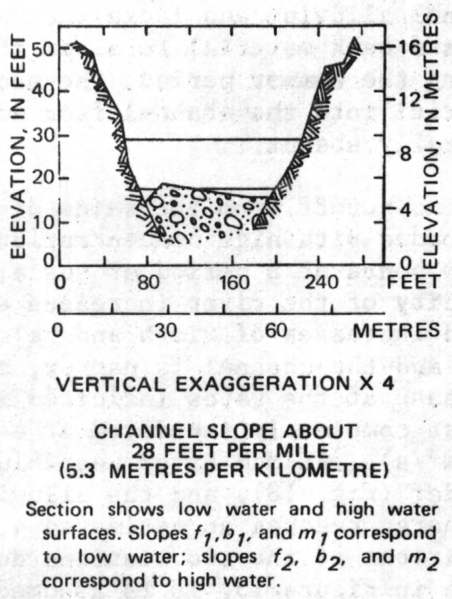


FIGURE 17.--Relations of velocity, width, and depth of flow to water discharge at Mad River near Kneeland, 1966-73. Compare with figure 18.

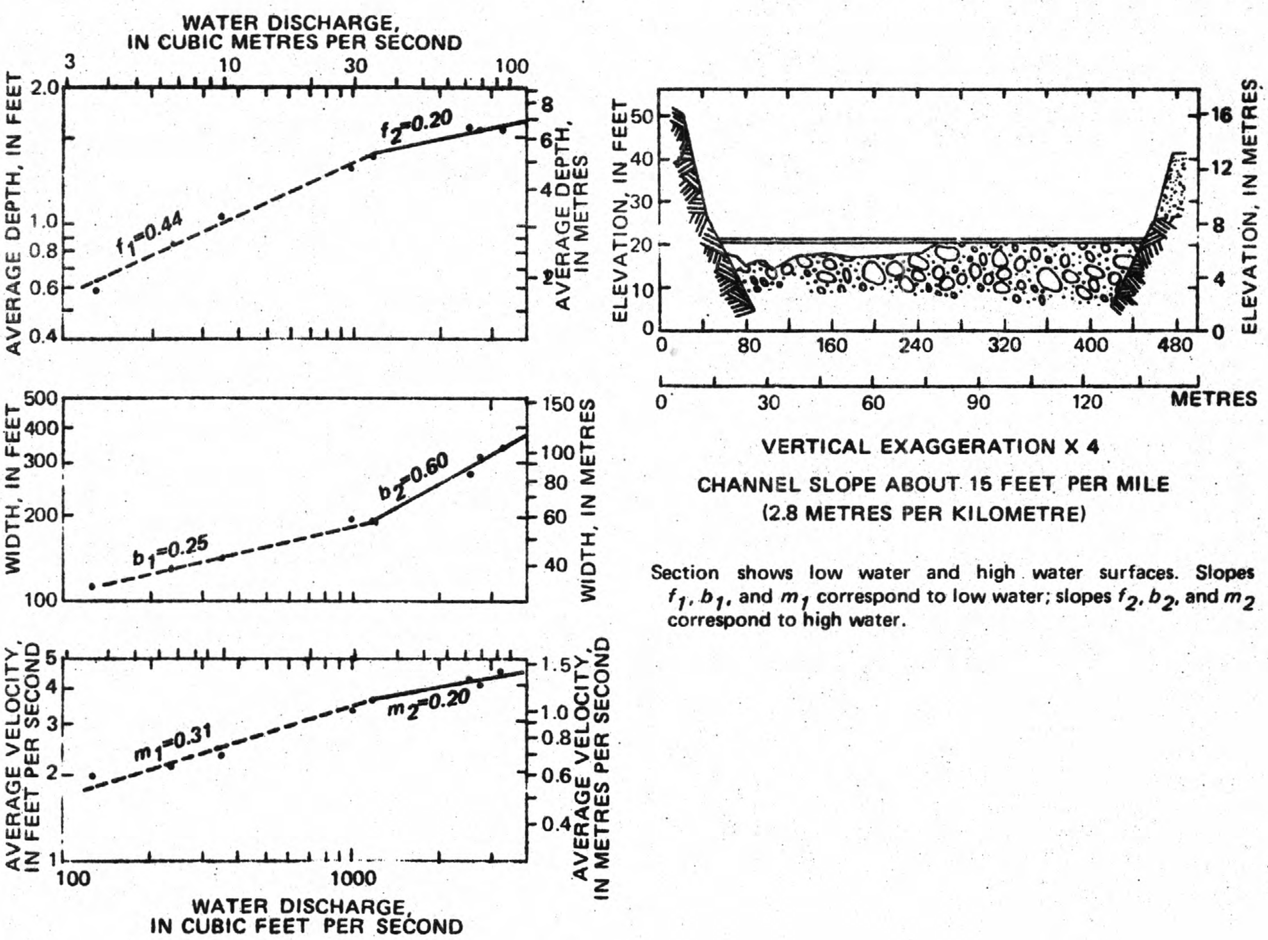


FIGURE 18.--Relations of velocity, width, and depth of flow to water discharge at Mad River near Blue Lake, 1973.

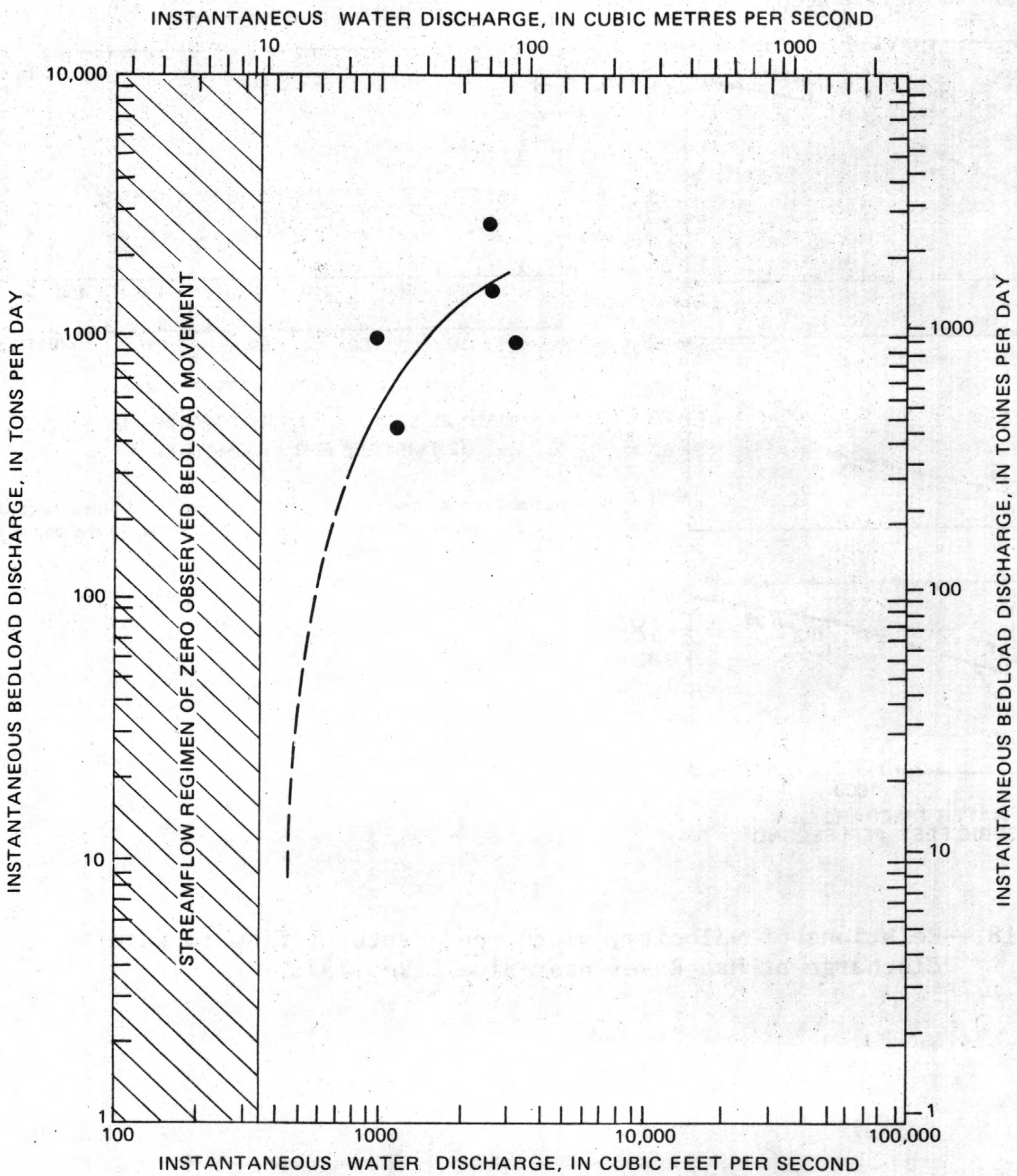


FIGURE 19.--Relation of bedload discharge to water discharge at Mad River near Blue Lake, 1973. Compare with figure 10.

Channel Features and Processes Related to the Removal of Sweasey Dam

Sweasey Dam (fig. 1), impounding a 3,000-acre-ft (3.7-hm^3) reservoir, was constructed in 1938 for exporting water from the Mad River basin to the city of Eureka (California Department of Water Resources, 1965, p. 34). The reservoir ultimately filled with sediment, apparently during flood periods in the 1950's, and was not 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 Essex and Mad River near Arcata (fig. 1) from August 1970 through the early part of the 1970-71 rainy season. However, the suspended-sediment discharge for 1971 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 was subsequently transported as bedload.

The channel in the vicinity of Sweasey damsite has changed considerably since August 1970. The channel downstream from the damsite to Camp Flat (fig. 15) has aggraded slightly, and, consequently, unstable channel banks have been scoured (figs. 20 and 21). Apparently, much of the coarse sediment transported downstream from the damsite was deposited in the vicinity of Camp Flat. At Camp Flat, an extensive depositional area was available for sediment as shown by the size of the active channel and older deposits of the Mad River and Canon Creek (fig. 15). Prior to the removal of Sweasey Dam, the low-water channel of the Mad River abutted the right bank, and the river eroded the terrace deposits east of Camp Flat. During storm runoff in 1970-71, the river changed its locus of scour to the left bank and began eroding the Camp Flat terrace.

During storm runoff in 1972, an unmeasured but significant quantity of sediment was deposited in the lower reach of Canon Creek, causing considerable channel aggradation and widening of Canon Creek. The channel widening was accompanied by the disturbance of riparian vegetation including large trees that fell into the channel and accumulated in log jams and similar debris piles on the new channel floor (Brown, 1973, p. 35). The deposition of debris by Canon Creek is related to erosional activity in the Canon Creek basin, aggradation of the Mad River at the mouth of Canon Creek, and the lack of competence of Canon Creek to transport coarse debris into the more competent part of the Mad River during high flows. Thus, the locus of scour of the Mad River has been further confined to the left (east) side of the channel at Camp Flat by the additonal deposition of Canon Creek.

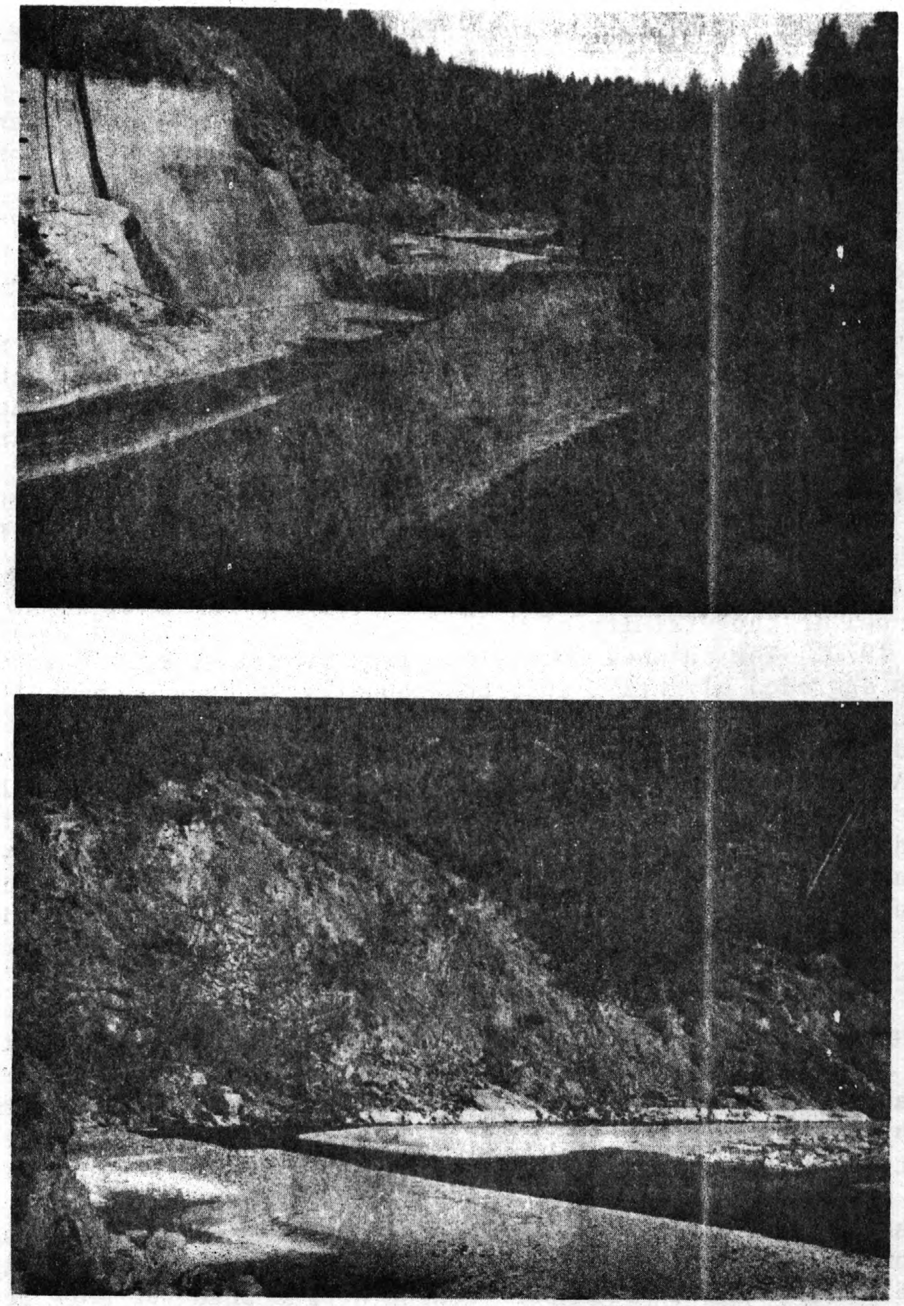


FIGURE 20.--Views downstream of the Mad River channel near Sweasey damsite. The top view shows the concrete abutments remaining after the dam was dynamited. Tunnel opening in left abutment is about 6 by 4 feet (1.8 by 1.2 metres). The bottom view shows the results of bank scour caused by channel aggradation. Note the tilted trees. Water discharge is about 115 cubic feet per second (3.3 cubic metres per second). Photographs by J. O. Armstrong, September 23, 1972.

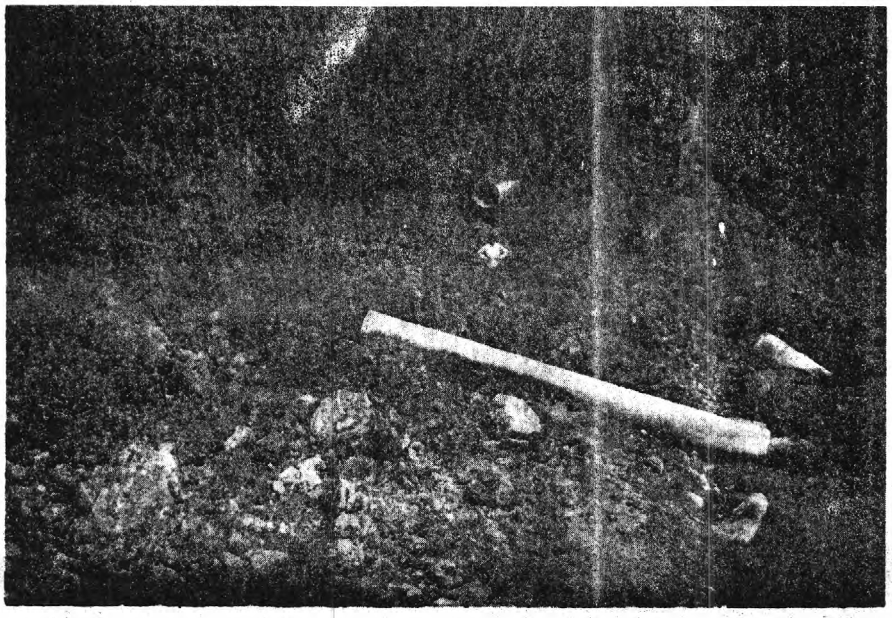


FIGURE 21.--Failure of causeway resulting from channel aggradation about 0.5 mile (0.8 kilometre) downstream from Sweasey damsite. The pipe buried in the causeway was used to transport water from Sweasey Dam to Eureka prior to sedimentation of the reservoir. Man in center of photograph gives scale. Photograph by J. O. Armstrong, September 23, 1972.

Downstream from Camp Flat the channel shifted slightly and aggraded locally during 1971-73. Such shifting and local aggrading is common throughout the reach and probably cannot be tied exclusively to the effects of removing Sweasey Dam. However, the debris loading imposed on the Mad River following the removal of Sweasey Dam has a significant impact on the bedload-transport data. The limited data for Mad River near Kneeland show a bedload transport rate of about 170,000 ton/yr (154,000 t/yr). Assuming that the bedload is deposited at a unit weight of 60 lb/ft^3 (960 kg/m^3), the bedload-transport rate at Mad River near Kneeland converts to about 130 acre-ft (0.2 hm^3) per year. Considering that more than 2,000 acre-ft (2.5 hm^3) of sediment was deposited behind Sweasey Dam, the excess of available material beyond the transport capacity of the river becomes apparent. However, the material derived from the reservoir has been distributed along several miles of the Mad River channel, and its effects are expected to diminish gradually in a downstream direction.

Before August 1970 the Mad River cut through and removed most of the sediment that was contained behind and upstream from the dam. Scattered remnants of the reservoir deposits, most now high above the active channel, are seldom subject to erosion by the river. The locations and extent of such deposits were not determined for this study. An example of the remaining deposits occurs just upstream from the left abutment of Sweasey Dam (figs. 22 and 23).

About 0.25 mi (0.4 km) upstream from Sweasey damsite an extensive, shallow slope failure occurred during the rainy season 1970-71. The approximate location and extent of the failure is shown in figure 15. Interpretation of aerial photographs taken in September 1970 indicated a probable landslide deposit covered with vegetation smaller and less dense than that on the surrounding terrain. The buildup of reservoir deposits behind Sweasey Dam probably stabilized the toe of the deposit. As the river began to remove the reservoir deposits in 1971, and simultaneously cut into the base of the slope on the outside of the bend in the channel, the slope failed. The slope failure introduced into the river an uncalculated quantity of debris that included trees and other organic material as well as rock fragments. The unstable state of the slope in 1972-73 and the lack of protection of the slope from the effects of rapid runoff suggest that the slope may continue to erode severely for several years, or until mediating practices are employed.

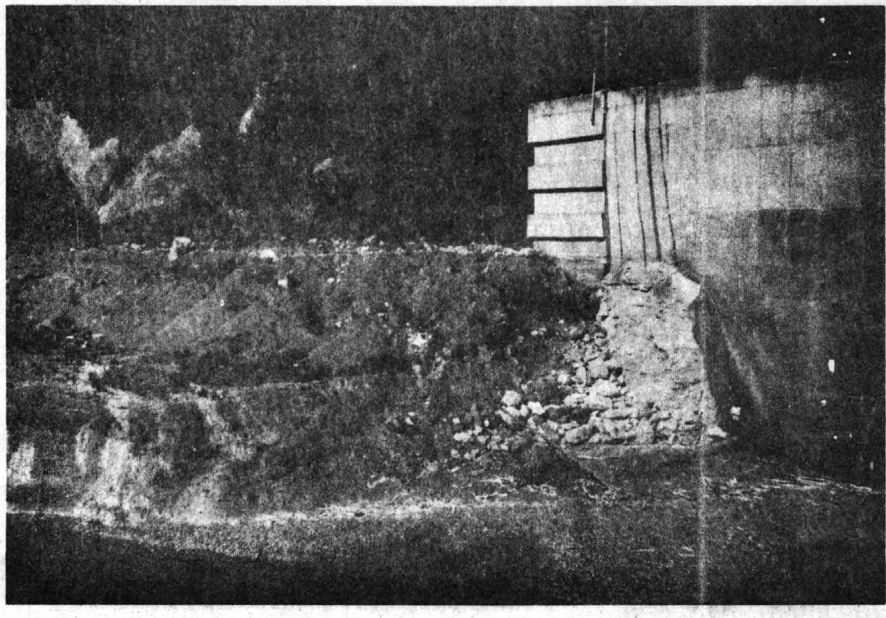


FIGURE 22.--View upstream at Sweasey damsite showing left abutment of dam and remnants of sediment deposited in old reservoir. Man standing on a log at the base of the abutment gives scale. The disturbed concrete and the surface extending horizontally across the left side of the photograph evidence the removed dam and the complete filling of the reservoir with sediment. The Mad River flows from left to right in the left foreground. Photograph by J. O. Armstrong, September 23, 1972. Compare with figure 20.

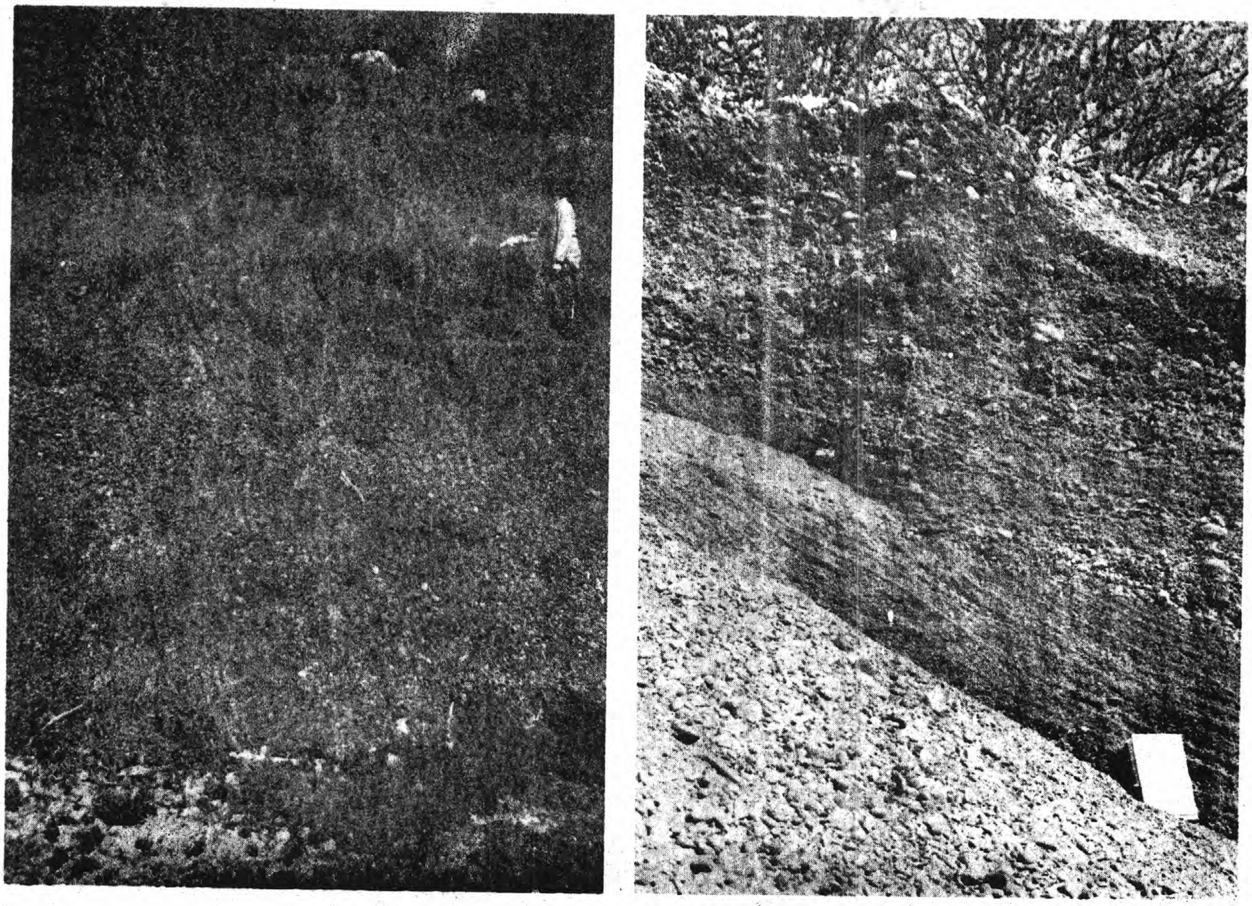


FIGURE 23.--Two views of reservoir deposits at Sweasey damsite exposed by downcutting by the Mad River after removal of Sweasey Dam. Man in left photograph is pointing to dipping foreset beds that are overlain by a horizontal stratum. The elevation of the upper surface of the horizontal stratum is coincident with the elevation of the top of the removed dam. At the time of deposition of the horizontal stratum, bed material was probably being transported over the dam. Photographs by J. O. Armstrong, September 23, 1972.

Mad River Hatchery to Pacific Coast

Just downstream from the Mad River Hatchery (fig. 3) the Mad River channel changes abruptly from a composite alluvial-bedrock channel to a dominantly alluvial channel imposed with numerous artificial constraints. The constraints, in downstream order beginning at the hatchery, included the following during the study period:

1. Riprap along the left bank at the hatchery to constrain the river from eroding the terrace on which the hatchery is built;

2. A system of groins on the right bank due east of the hatchery to constrain erosion of an artificially forested terrace;[6]

3. A gravel-mining operation about 0.5 mi (0.8 km) downstream from the hatchery that removes material from both the active channel and the flood plain on both sides of the channel;

4. An extensive levee beginning near the confluence of the Mad River and North Fork Mad River and extending along the right bank of the river for about 1 mi (1.6 km) to constrain the river from flooding built-up areas in the flood plain;

5. The roadway of California State Highway 299 in the vicinity of Essex that constrains the river from eroding terrace deposits along the right bank;

6. Bulldozing operations in the active channel from Essex downstream to Mad River near Arcata that alter the channel shape and constrain low flows to ponding in the vicinity of five Ranney water collectors;[7]

7. Gravel-mining operations about 0.25 mi (0.4 km) and 1 mi (1.6 km) upstream from Mad River near Arcata that remove material from both the active channel and the flood plain on the right bank of the river;

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[6]Severe erosion of the terrace began during 1970 and was probably related to a combination of channel aggradation and activities in the channel connected with construction and operation of the hatchery. The effects of bulldozing operations in the channel, the riprap configuration, and other activities and constructions in the vicnity of the hatchery have not been studied in detail.

[7]Further information on the collectors and the water diversion system that uses them is available in reports by Humboldt State College (1971, p. 37-43) and California Department of Water Resources (1965, p. 25-41).

8. Gravel-mining operations about 0.25 mi (0.4 km) and 1.5 mi (2.4 km) downstream from Mad River near Arcata that remove material from both the active channel and the flood plain on both sides of the channel;

9. Artificial levees in the vicinity of the U.S. Highway 101 crossing and downstream for about 2.5 mi (4 km) that constrain the river to some extent from spreading over its coastal flood plain during periods of high flow; and

10. Gravel-mining operations about 1 mi (1.6 km) and 2.5 mi (4.0 km) downstream from the U.S. Highway 101 crossing that remove material from both the active channel and the flood plain on the right bank of the river.

The foregoing descriptions do not fully detail the extent of artificial channel alteration between the Mad River Hatchery and the Pacific Coast. A detailed study of the alterations is beyond the scope of this report. However, the bed material and the shape of the alluvial channel are extensively and pervasively altered. Therefore, the effects of release flows from an upstream impoundment on channel configuration and bedload transport in the altered channel may be exceedingly difficult to predict except in general terms.

ESTIMATED POSTPROJECT CONDITIONS OF THE MAD RIVER

Reservoir Release Flows

The schedule of proposed reservoir release flows used to compute postproject conditions of the Mad River is discussed in "Supplemental Information." Such a schedule is tentative and normally would be redesigned until project operation actually began. Modifications in the schedule would probably occur during the operation of the project in response to new data on release effects or for a variety of special conditions. Therefore, the postproject conditions reported herein would be subject to change with changes in the operation of the reservoir.

Suspended-Sediment Transport

Using the data from table 2, the sediment-transport equation of figure 14, and the release-flow model discussed in "Supplemental Information," the following determinations were made:

1. An estimated 920,000 ton/yr (830,000 t/yr) of the sediment entering the Mad River between the Kneeland and Arcata stations would be carried in suspension.[8] The release-flow model shows that reservoir releases could transport 930,000 ton/yr (840,000 t/yr) in the vicinity of Butler Valley and 1,500,000 ton/yr (1,400,000 t/yr) near Arcata. Therefore, the projected release flows are apparently capable of transporting the expected inflow of sediment less than 2.0 mm in diameter for the reach between the proposed reservoir site and the Arcata station.

2. The reservoir would be expected to trap all material of sand size and larger (greater than 0.062 mm) carried into the reservoir either in suspension or as bedload. The reservoir would trap about 60 percent of the material of sand size (0.062-2.0 mm) that otherwise would be carried in suspension past the Arcata station during an average year. Thus, about 60 percent of the average annual discharge of beach-forming material in the particle-size range 0.062-2.0 mm would be retained in the reservoir. All beach-forming material in the size range 0.062-2.0 mm derived from the basin downstream from the proposed reservoir could be transported past the Arcata station to the estuarial reach of the river by the projected release flows.

Bedload Transport and Channel Configuration

Under the conditions observed during the study period, the significant bed-material movement begins in the channel reach between the proposed damsite and the Mad River Hatchery at about 1,000 ft^3/s (28 m^3/s). Because the magnitude of proposed release flows is expected to well exceed 1,000 ft^3/s (28 m^3/s) for extended periods each year, the initiation of channel scour would be expected soon after reservoir construction. Preliminary data and observations of the basin show that the replenishment of bed material between the damsite and the hatchery is likely to be small and that the major sources of bed material are upstream from the damsite.

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[8]The difference between the long-term (100-year) suspended-sediment discharges at the Kneeland and Arcata stations is 920,000 ton/yr (830,000 t/yr) on the basis of synthesized nonproject flows and the equation given in figure 14.

Applying the release-flow model to the preliminary bedload-transport curve shown in figure 10, it was determined that release flows would have the capacity to transport about 130,000 ton/yr (120,000 t/yr) of bed material that is less then 3 in (76 mm) in diameter. The transport rate applies only on the basis of the limited data shown in figure 10 and should be revised when more definitive data are available. It is significant, however, that the projected transport rate under regulated flow conditions is of the same order of magnitude as the rate computed for 1971-72 unregulated conditions (p. 55). Sustained, moderate release flows could have an annual bedload-transport capacity that is similar to the capacity of the higher, infrequent flows that transport the material under unregulated conditions.

The channel gradient between the proposed damsite and the hatchery probably exceeds the equilibrium gradient toward which the river is tending. Thus, lacking significant replenishment of channel-bed material, the river under regulated conditions could conceivably remove channel gravels until bedrock is reached.[9] However, equilibrium conditions probably would be established wherein a gravel channel bed would exist between points in the channel profile where the river scours to bedrock.

Channel degradation between the proposed damsite and the hatchery would result in deposition of the eroded material downstream from the hatchery. However, gravel mining, roadbuilding, grading associated with the Ranney water collectors, and other artificial adjustments of the channel downstream from the hatchery probably would obscure most effects of the deposition. A cursory review of gravel mining in Humboldt County revealed that at least eight companies claim to extract gravel from the Mad River channel and flood plain. Reports by the companies to the U.S. Bureau of Mines[10] suggest gravel extractions from the Mad River of 200,000 to 500,000 ton/yr (180,000 to 450,000 t/yr) for 1961-70. Gravel extractions from the river channel and flood plain are of the same order of magnitude as bedload transport measured during the study period.

Channel degradation between the proposed damsite and the hatchery would ultimately reduce many now-persistent lateral adjustments of the channel. However, lateral shifting of the channel would probably occur near the mouths of tributaries such as Canon Creek where extensive gravel deposits await reworking. Also, degrading of the main channel between the damsite and the hatchery may have some degrading effect on the tributaries in that reach as well. The extent of tributary degrading would depend on the conditions of each tributary.

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[9]The Mad River currently flows on bedrock at The Narrows, about 1 mi (1.6 km) downstream from Butler Valley and flows on a very thin layer of gravel at several other points along its course.

[10]The U.S. Bureau of Mines records the annual gravel extraction reports of the individual operators. However, these data may be kept confidential at the request of the operator. Data as to exact mining locations were not recorded, and research into such data required field inspections and personal interviews with operators.

Turbidity

Data on the interrelations of water discharge, suspended-sediment concentration, and turbidity show that a turbidity of 30 JTU[11] or less is met for flows less than about 500 ft^3/s (14 m^3/s) in the average, long-term situation. On the basis of the release-flow model, preproject flows meeting the requirements for turbidity less than 30 JTU could be expected for about 150 days during an average water year. Most of the 150-day period comprises June through September, based on previous records, and the remainder depends upon the periodicity of winter storms and the extent of the annual storm season. On this basis, the inflow of low turbidity (T less than 30 JTU) water into the proposed reservoir could be expected for an average of 150 days per year.

The outflow from the proposed reservoir would probably be moderately to highly turbid during any period when releases would be made from the bottom reservoir outlet. Turbid water would probably exist in the reservoir hypolimnion almost year-round. Even small disturbances of the reservoir floor (such as currents induced by bottom releases) would result in turbidity-causing particles becoming suspended in the moving water.

Low-turbidity water can be released from the reservoir provided that it is taken from the epilimnion and(or) metalimnion when the reservoir is stratified. However, such releases might not meet the temperature and other requirements for downstream flows.

Significant questions remain as to the mixing of reservoir water during the fall and spring overturn periods. Stratification of the reservoir could persist following the spring overturn period because the depth of the reservoir may be sufficiently great to inhibit the circulation of dense, turbid water from depth. Furthermore, the large size of the reservoir could have a considerable "stilling" effect on turbid inflows. The extent of "stilling" and the potential for rising bottom water to distribute fine, turbidity-causing particles throughout the reservoir during the autumn is a subject of speculation. The release of water to meet downstream turbidity, temperature, dissolved oxygen, and other requirements would require flexibility in the location, mixing, and timing of the multiple-outlet releases, as well as a careful monitoring of conditions throughout the reservoir.

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[11]Turbidity greater than 30 JTU is usually considered excessive for recreational uses by some. The 30-JTU figure therefore is an arbitrary standard. Further discussions of the nature of turbidity are presented in Brown (1973, p. 37-51) and California Department of Water Resources (1966).

Especially during the early years of operation of the reservoir, considerable near-shore turbidity would result from slope failures and from wave action on the unconsolidated soils and rock of the reservoir shoreline. Shoreline turbidity problems would be expected to persist because of the highly fractured, deeply weathered, unconsolidated material that underlies much of the reservoir site. That is, even if the soil mantle were completely removed by wave action around the reservoir periphery, erosion of the underlying rock would continue to supply enough particles to cause turbidity.

SUPPLEMENTAL INFORMATION

Flow Routing Procedures for the Extension of Daily Flow Records

The objective of the flow-routing phase of the study was to estimate daily preproject and postproject streamflows to be used in subsequent sediment-transport analyses.

Preproject Streamflow

Records of daily streamflow were available for Mad River near Arcata for 1911-13 and 1951-72. At Mad River near Kneeland, daily streamflow was recorded for 1966-72. According to the streamflow data, the annual and monthly runoff at the Kneeland station averaged 78 percent of the runoff at the Arcata station. For design purposes (U.S. Army Corps of Engineers, written commun., 1973) daily flows were assumed to have the same relation, and long-term daily flows at the Kneeland station were thus estimated. The estimated daily flows at the Kneeland station represent the inflow to the proposed reservoir.

The validity of the flow estimates was evaluated by comparing areas beneath the flow-duration curves of daily flows (flow volumes) for the estimated and observed flows at Kneeland for 1966-72. Comparisons were made for flows ranging from less than or equal to 1,000 ft^3/s (28 m^3/s) to those less than or equal to 25,000 ft^3/s (710 m^3/s) in increments of 1,000 ft^3/s (28 m^3s). Flows less than 1,000 ft^3/s (28 m^3/s) are of minimal interest because they commonly transport an extremely low percentage of the total annual sediment load. The average error of the estimated flow was minus 2 percent with extremes of plus 5 percent for the flows less than or equal to 6,000 ft^3/s (170 m^3/s) and minus 7 percent for the flows less than or equal to 25,000 ft^3/s (710 m^3/s), the latter being the total flow for 1966-72. The errors were considered acceptable for daily flow values to be used in sediment-transport analyses.

An estimate of the daily flows from the intervening drainage area between the Kneeland and Arcata stations thus is 22 percent of the daily flows at the Arcata station. The estimated flows from the intervening drainage area are defined for this discussion as local inflow.

Postproject, Regulated Streamflow

A digital model of the proposed reservoir was developed to estimate daily reservoir release flows. The model incorporated the then-current operating criteria proposed by the Corps of Engineers (written commun., 1973). The criteria used are summarized below.

Flood-Control Operation

The objective of the flood-control part of the Butler Valley Dam and Blue Lake Project was to minimize flooding in the vicinity of Arcata. The project operating criteria to achieve that objective were based on instantaneous peak flows. However, the criteria were applied to daily flows in the model on the assumption that essentially identical daily release-flow values would result. Only normal operation was included in the model. The criteria are:

1. When reservoir inflow exceeds 10,000 ft^3/s (280 m^3/s), reservoir releases are curtailed.

2. After the inflow peaks, releases will be made such that the flow at Mad River near Arcata will be the greater of (a) 10,000 ft^3/s (280 m^3/s) or (b) 85 percent of the local inflow peak. However, in no instance will voluntary reservoir releases be made such that the flow at the Arcata station exceeds 30,000 ft^3/s (850 m^3/s).

Water-Supply Operation

The reservoir was designed for an annual water supply of 114,000 acre-ft (140 hm^3). Because the Corps of Engineers assumes a constant demand, the model guarantees a daily release of 157 ft^3/s (4 m^3/s) for water supply. Maximum allowable water-surface elevations for water-supply storage are shown in figure 24. When the water-surface elevations are lower than the maximum allowable, and the inflow exceeds releases required for water supply and fisheries (discussed below), replenishment of storage would be permitted. When the maximum allowable elevations are exceeded, flood releases would be made according to the criteria discussed previously.

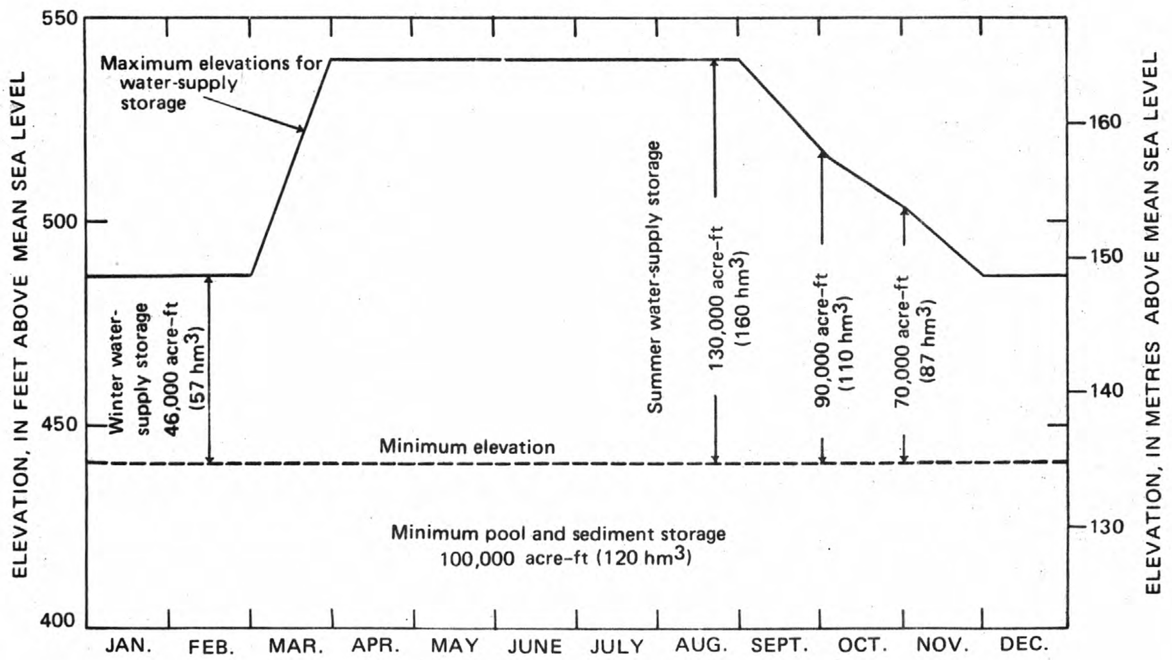

FIGURE 24.--Tentative regulation schedule for water-supply storage, Butler Valley Dam and Blue Lake Project. (Data from Corps of Engineers, written commun., 1973)

Required Fishery Releases

The model accommodates guaranteed releases for fishery uses in accordance with the following table:

Period	Release (ft^3/s)
October 16-April 30	300
May 1-June 30	200
July 1-October 15	100

Evaporation Losses

Evaporation losses from the reservoir were computed in the model on a daily basis in accordance with the assumptions made by the Corps of Engineers (written commun., 1973). The applicable evaporation losses are tabulated below. Reservoir storage was reduced each day by the product of the assumed loss and the reservoir surface area for that day. The elevation-area relation used in these computations was obtained from the Corps of Engineers' design files.

Month	Daily net evaporation loss (ft)	Month	Daily net evaporation loss (ft)
January	0	July	0.0194
February	0	August	.0194
March	0	September	.0133
April	0.0067	October	0
May	.0129	November	0
June	.0167	December	0

Using the criteria discussed above, a schedule of daily release flows was computed, and additions of local inflow were made to determine regulated flows passing Mad River at Arcata.

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