Erosion and Sedimentation in the Pacific Rim (Proceedings of the Corvallis Symposium, August, 1987). IAHS Publ. no. 165.

Bankfull discharge and sediment transport in northwestern California

K. M. NOLAN
U.S. Geological Survey, Menlo Park, CA, USA
T. E. LISLE
U.S. Forest Service, 1700 Bayview Dr., Arcata, CA, USA
H. M. KELSEY
Western Washington University, Bellingham, WA, USA

ABSTRACT High-magnitude, low-frequency discharges are more responsible for transporting suspended sediment and forming channels in northwestern California than in previously studied areas. Bankfull discharge and the magnitude and frequency of suspended sediment discharge were determined at five gaging stations in northwestern California. Although discharges below which 50 percent of the suspended sediment was transported and discharges which transport the greatest suspended sediment (effective discharge) occurred relatively frequently, recurrence intervals for these discharges were relatively high when compared to data from other areas. Likewise, discharges below which 90 percent of the suspended sediment was transported were also relatively infrequent. In most cases, the recurrence interval of bankfull discharge was several times greater than that of the effective discharge. This is because floodplain formation appears to be due more to overbank deposition during large sediment-laden discharges than to lateral channel migration and point bar formation.

INTRODUCTION

Every flow that transports sediment affects channel form. Ever since the classic paper by Wolman and Miller (1960), researchers in various geographic areas have measured the relative effectiveness of stream discharges in terms of sediment transport and then queried which discharges influence channel form. Several other factors, such as effects from a large flood, can also affect channel form causing the response of channels to the suite of events occurring over time to be rather complex (Baker, 1977; Wolman and Gerson, 1978; Beven, 1981). Investigating the correspondence between magnitude and frequency of sediment transport and channel capacity provides, however, a basis for comparisons between areas with different geology and climate.

Data collected in northwestern California over the last several decades present the opportunity to study the relation between the magnitude and frequency of sediment transport and major channel shaping events in a different type of terrane than studied previously. Northwestern California is characterized by erodible, mountainous terrane with high, seasonal rainfall. Suspended-sediment discharge has been measured in this area for as long as 21 years, during which time several major floods occurred. Large floods in northwestern California have created important long-lasting effects on channels (Helley and LaMarche, 1973; Lisle, 1981; Kelsey, 1980; Nolan and Marron, in press). It was not previously known, however, whether high-magnitude, low-frequency discharges also transport a large proportion of sediment and correspond to bankfull channel capacity. The study reported here investigated the magnitude and frequency of suspended-sediment transport and the relation between effective and bankfull discharge. Five gaging stations were investigated (Fig. 1, Table 1). These stations were selected because they had either a long record of sediment discharge, well documented historic changes in channel geometry, or both.

STUDY AREA

Climate and geology combine to make northwestern California conducive to large floods and high sediment yields. Average annual precipitation ranges from 1016 mm to 2032 mm, 80 percent of which

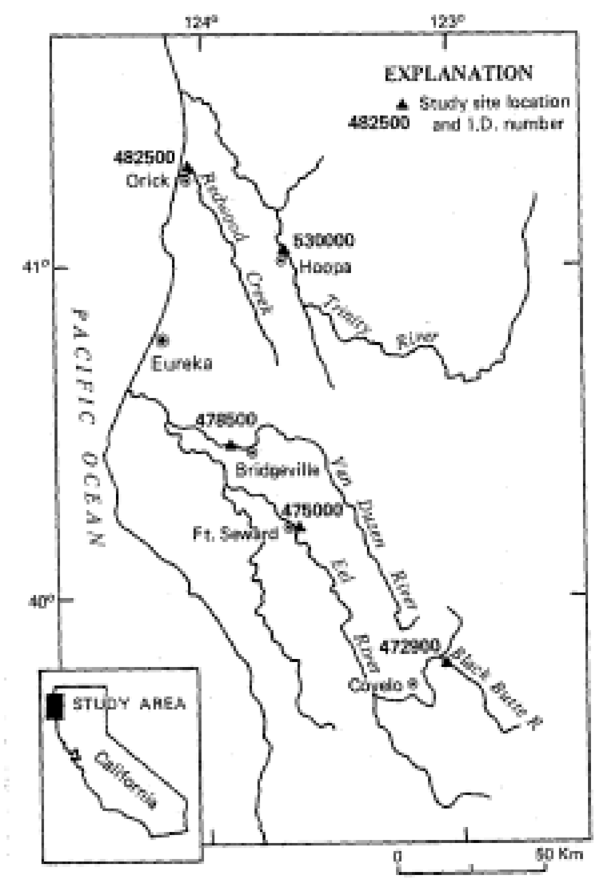

Figure 1. Map showing location of study sites. I.D. number is last 6 digits of U.S. Geological Survey identification number.

Table 1 . Gaging stations used in the analysis of magnitude and frequency of sediment transport.
[units: km^2 , square kilometers; m^3/s, cubic meters per second;
Mg/km^2, megagrams per square kilometer]

Station name and U. S. Geological Survey I. D. number	Drainage area (km^2)	Period of record: Water discharge (water years)	Period of record: Suspended-sediment discharge (water years)	Mean daily flow (m^3/s)	Skewness of mean daily flow	Average annual suspended sediment disharge (Mg/km^2)
Black Butte River near Covelo 11472900	420	1959 - 1975	1966 - 1973	9.4	10.3	3,600
Eel River at Ft. Seward 11475000	5,457	1956 - 1984	1966 - 1976	138	9.9	1,603
Van Duzen River near Bridgeville 11478500	575	1952 - 1985	1956-67,1975-76	25	5.3	3,092
Redwood Creek at Orick 11482500	720	1953 - 1985	1971 - 1984	31	6.1	1,670
Trinity River at Hoopa 11530000	7,389	1952 - 1985	1960 - 1979	155	5.4	430

falls during winter (Rantz, 1969). Large winter floods are generated in narrow valleys by runoff from frontal storms producing moderately intense rainfall over large areas for several days. The area is underlain by rocks primarily of the Franciscan Assemblage of Jurassic and Cretaceous age (Bailey and others, 1970). These rocks consist of mudstones, sandstones and schist which are often pervasively sheared and fractured. They are exceptionally susceptible to mass movement failure and supply large volumes of sediment to channels. A relatively small portion of the northern part of the study area is underlain by Paleozoic and Mesozoic crystalline rocks of the Klamath Mountains (Jones and others, 1978), which are generally less susceptible to erosion than Franciscan Assemblage rocks.

Annual suspended-sediment yields from rivers in northwestern California are among the highest recorded in the United States outside of areas draining active volcanoes or glaciers. Twelve of 19 gaging stations in the area with five or more years of record in 1977 had a mean annual suspended-sediment yield larger than 1000 Mg/km^2 (Megagrams per square kilometer) (Janda and Nolan, 1979). Northwestern California had major flood-producing storms in 1955, 1964, 1972, and 1975. The 1964 storm was by far the most damaging probably because of the large flow volumes associated with that storm (Harden and others, 1978). Effects of the 1964 storm were increased in some areas because of land disturbance associated with intensive timber harvesting.

METHODS

Magnitude and frequency of sediment transport

The magnitude and frequency of suspended-sediment discharge were analyzed for the five stream gaging stations (Table 1, Fig. 1) using techniques similar to those used by Wolman and Miller (1960). For each station, values of suspended sediment transported by ranges of mean daily discharges were calculated from suspended-sediment transport curves and flow duration curves for the period of record. In the cases of the Eel, Trinity, and Black Butte Rivers and Redwood Creek the suspended-sediment transport relations were based upon mean daily values of water and sediment discharge determined for the sediment record period (U.S. Geological Survey 1952-1970, 1971-1974, 1975-1985). The suspended-sediment transport relations for the Van Duzen River were based upon instantaneous values of water and suspended-sediment discharge (Kelsey, 1980).

Bedload was not included in these computations because in two cases it did not change the values of magnitude and frequency of sediment transport. Bedload discharge data were collected at the Eel River between 1972 and 1976 and at Redwood Creek between 1974 and 1984. A separate analysis of the magnitude and frequency of total sediment discharge (suspended and bedload) was performed for these two streams. The flows below which 50 and 90 percent of the total sediment load was carried were identical to those for suspended sediment alone. For this reason, further comparisons in this report will be limited to suspended-sediment transport so as to include data from all five streams.

Bankfull discharge

We determined bankfull elevations at gaged sites by surveying the elevation of the most prominent floodplain at the gage. Floodplains were defined as low-relief surfaces adjacent to the channel upon which fine sediment had been deposited sometime during the last several decades. Bankfull discharge was not determined for Redwood Creek because flood control levees impose artificial constraints on channel formation. An electronic distance meter and theodolite were used to survey channel cross sections and longitudinal profiles of floodplain surfaces. We calculated bankfull discharge after the method of Williams (1978). Floodplain profiles were projected through the streamgage to measure bankfull elevation relative to the gage datum, and bankfull discharge was estimated using stage-discharge relations.

Determination of bankfull height was hampered in some cases because the height of floodplains above the bed varied longitudinally along the stream above and below the gaged cross-section. In those instances, we used an average height. At the two gage sites in the lower Eel River basin, Eel River near Fort Seward and Van Duzen River near Bridgeville, more than one level of active deposition was present along the channel. At the Van Duzen gage, four levels of active silt deposition were discontinuously developed along the banks below the prominent floodplain level.

These lower levels are too narrow to show in the cross-section (Fig. 2) and are probably due to a relatively small number of depositional events. For example, a February, 1986 flood event deposited one of these levels as a discontinuous silt bench along the river banks near the gage. At the Eel River near Fort Seward, two prominent floodplain levels were present, one 3.5 m higher than the other (Fig. 2).

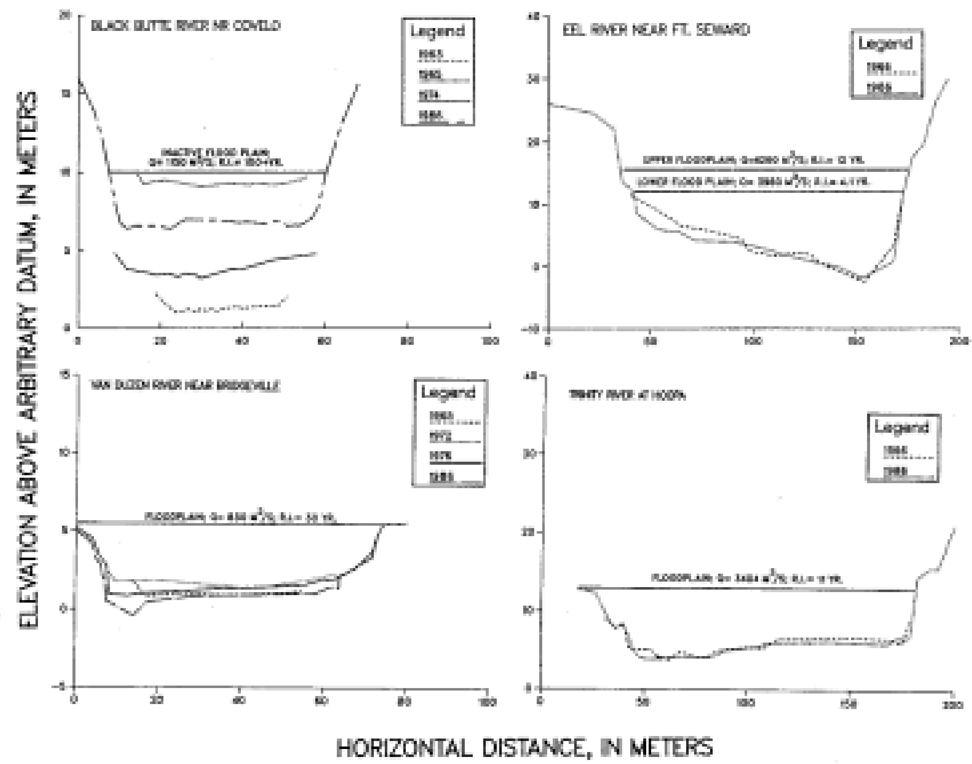

Figure 2. Channel cross sections at study sites. Water discharges (Q) and recurrence intervals of those discharges (R.I.) are shown on lines representing major floodplain levels. The inactive floodplain of the Black Butte River and the upper floodplain of the Eel River are located upstream of those sites.

RESULTS

Magnitude and frequency of suspended-sediment transport

As in many other areas, fairly frequent flows are responsible for transporting most of the sediment load in the northwestern California rivers. With the exception of the Black Butte River, the majority (> 50 percent) of sediment passing the five study sites was transported by flows that occurred at least 2 to 4 days per year (recurrence intervals of 0.42 to 0.27 yr.)(Table 2, col. 3). This is less frequent than found by Wolman and Miller (1960) (6 to

11 days per year) but about the same as found by Webb and Walling (1982) (3 days per year). Except for the Black Butte River, effective discharges have fairly low recurrence intervals of 1.2 to 4.6 years, which fall within the range found by Andrews (1980).

Table 2. Frequency of suspended-sediment transport and flow associated with prominent floodplain levels. Recurrence intervals of effective discharges are based on annual series of mean daily flows and were determined using techniques outlined in United States Water Resources Council (1981). (units: m^3/s, cubic meters per second)

Station name and U. S. Geological survey I.D. number (1)	Magnitude of flow below which 50 percent of total sediment was transported (m^3/s) (2)	Recurrence interval of flow in col. 2 (years) (3)	Magnitude of flow below which 90 percent of total sediment was transported (m^3/s) (4)	Recurrence interval of flow in col. 4 (years) (5)	Effective discharge: Discharge (m^3/s) (6)	Effective discharge: Recurrence interval (years) (7)	Flow that overtops most prominent floodplain level: Discharge (m^3/s) (8)	Flow that overtops most prominent floodplain level: Recurrence interval (years) (9)
Black Butte River near Covelo 11472900	178	1.25	424	16.1	481	16.1	1,150	100+
Eel River at Ft. Seward 11475000	2,070	0.27	9,350	10.0	1,416	1.2	6,260	17
Van Duzen River near Bridgeville 11478500	299	0.27	481	3.3	382	1.6	830	30
Redwood Cr. at Orick 11482500	311	0.36	1,130	6.7	425	1.8	No data	No data
Trinity River at Hoopa 11530000	1,780	0.42	4,750	11.1	2,524	4.6	3,404	11

Large infrequent flows transport a relatively large proportion of the sediment in northwestern California rivers. The best example of this is the fact that the Black Butte River transported 10 percent of the suspended-sediment load for the period of record during a single day in 1964. In northwestern California, discharges below which 90 percent of the sediment load was carried had recurrence intervals between 3 and 16 years (0.06 to 0.30 days/yr.). For comparison, comparable discharges in streams studied by Wolman and Miller (1960) had recurrence intervals of between 0.2 to 0.7 days per year. The mode of data presentation by other authors and the scarcity of this type of analysis makes it difficult to precisely compare results from other areas. Data presented by Webb and Walling (1982, fig. 4A) indicate that their results may be similar to those from northwestern California.

The importance of both moderate and extreme discharges in transporting sediment can be explained by the form of the flow frequency distributions and the sediment transport curves (Fig. 3). The product of flow frequency and sediment transport rate reaches a maximum at moderate discharges (the effective discharge), but increases again at higher discharges in Black Butte and Eel Rivers and Redwood Creek, and decreases only slowly in the Trinity River. Flow frequency distributions are strongly skewed toward low and moderate discharges and although these discharges are associated

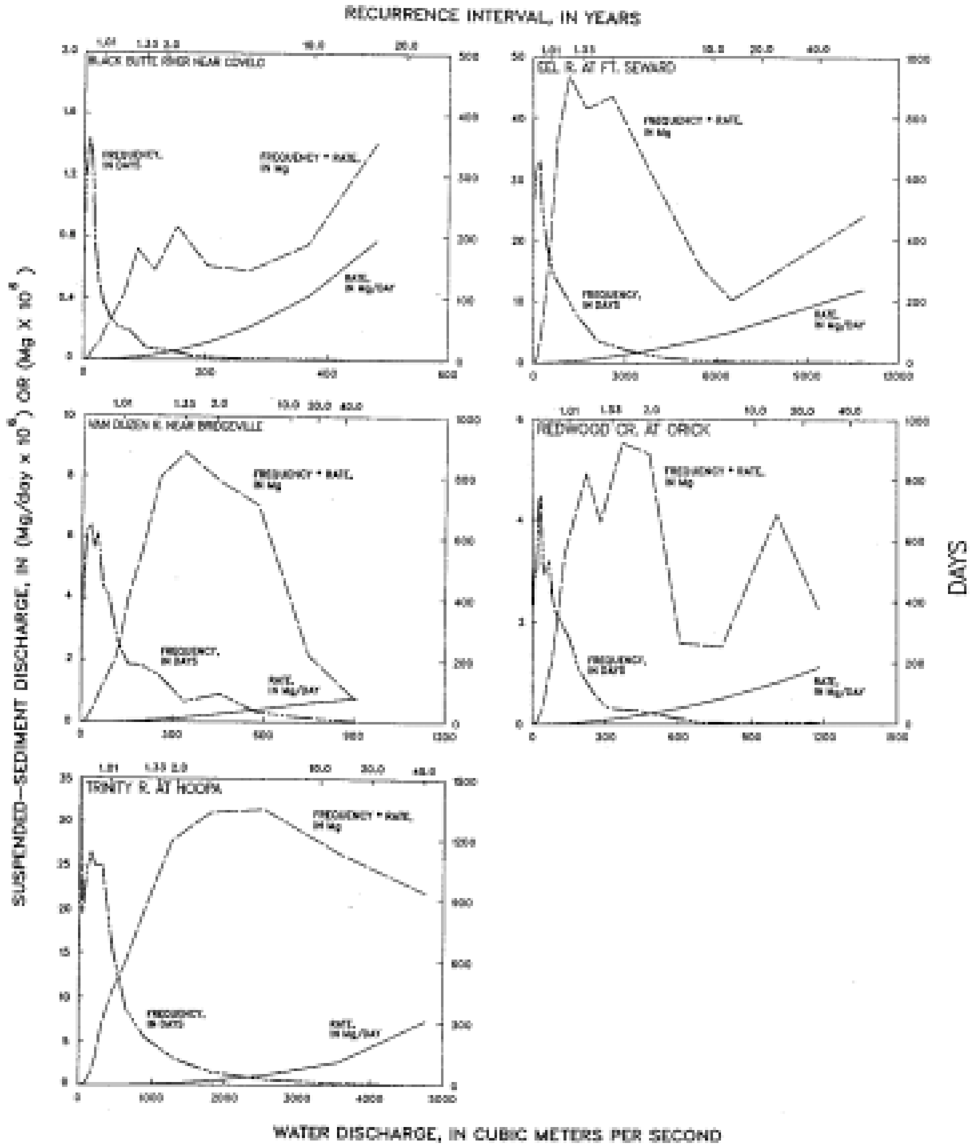

Figure 3. Graphs showing sediment transport rate (in Mg/day), frequency of occurrence of water discharge (in days), and the product of frequency of occurrence and sediment transport rate (in Mg) at study sites.

with relatively low sediment transport, such flows transport reasonable amounts of sediment because of their frequency.

On the other hand, high variability of flow favors relatively large proportions of the sediment load being conveyed by infrequent large flows (Neff, 1967). The variability of streamflow can be measured by the skewness of mean daily flow, which ranged from 5.3 to 10.3 in the northwestern California streams (Table 1). In contrast, skewness was less that 2 for streams draining comparable drainage areas in the Yampa River basin of Colorado, where infrequent flows transport a small proportion of sediment (Andrews, 1980). In northwestern California large flows can be many times greater than the more common low and moderate flows. After the major peak at low water discharges, the streamflow distribution tails off gradually over a wide range of high discharges (Fig. 3). Not only are large discharges available for work during infrequent floods, but the weak rocks in the area generate an almost limitless supply of transportable sediment. Sediment transport relationships are generally quite steep (see Fig. 3, and Nolan and others, 1986). Depending on the relationship between flow frequency and sediment transport curves, high magnitude flows can transport exceptionally large percentages of sediment. This is best illustrated by the Black Butte River (Fig. 3, Table 2).

Bankfull discharge

Bankfull discharges generally exceeded effective discharges several-fold, and their recurrence intervals (11 to 100+ yr) were much greater than those of the effective discharges (Table 2). The study reaches had several common characteristics that may bear on the relative infrequency of bankfull discharge. These suggest that overbank deposition dominates over lateral channel migration as a mode of floodplain formation. First, lateral migration is slow because channels at the gaging sites are relatively straight and bedrock is exposed frequently in strath terraces or valley walls. Second, other than along the Black Butte and Trinity Rivers, recent overbank deposits of silt on floodplains are several centimeters or more thick.

Despite the fact that a dominant bankfull height could be identified for each gage site, the presence of multiple levels of deposition at channel margins at a few sites indicated that a range of flows is effective in eroding and depositing sediment at the channel margins. A range of flows, therefore, influences channel capacity, not just the computed bankfull discharge listed in Table 2. This suggestion is supported by the broad peak to the frequency times rate curves on Figure 3.

Rapid aggradation and degradation of the Black Butte River over the last two decades has hindered development of a floodplain in quasi-equilibrium with the channel. The channel aggraded 8 m from December, 1964 to January, 1965 and, thereafter, degraded 5.6 m by the time the station was discontinued in 1975 (Lisle, 1981). Our 1986 survey showed that the channel had aggraded 3.1 m since 1975 (Fig. 2). The 1986 channel is thus 5.5 m above the pre-1964 elevation and 2.5 m below the peak elevation of 1965. Two discontinuous gravelly surfaces 600 m upstream of the gaging station are within 1 m of the peak mean bed elevation of 1965, assuming aggradation there equaled aggradation at the gaging section. The estimated mean-daily discharge required to overtop the surfaces has a recurrence interval of over 100 yr (Table 2). Thus, the surfaces are probably remnants of the channel bed at the peak of aggradation.

Discussion and Conclusions

Wolman and Miller's method of combining flow frequency and sediment transport curves has proven to be widely useful in linking hydrologic and sediment transport regimes to channel capacity. When applied to five California stations, the exercise yields some new information for areas with highly variable flow and steep sediment transport relations. Although moderate flows are responsible for transporting the majority of sediment, the frequency of these flows, as well as the frequency of flows below which 90 percent of the sediment is transported, is equal to or less than frequencies of similar flows in other areas. The fact that a large proportion of sediment is transported by infrequent flows is expressed geomorphically by high bankfull channel capacities and the great effect that large floods have had on these channels. Unlike other areas, the return period of flows that exceed bankfull channel capacity is not consistent amoung sites in northwestern California.

Prominent floodplain levels in the northwestern California streams coincide with flows with recurrence intervals several times greater than that of the effective discharge. These results concur with those of Pickup and Warner (1976) who studied ephemeral channels in New South Wales that also had highly variable discharges and transported large volumes of suspended-sediment. As proposed by those authors, streams can construct high banks where overbank deposition is rapid relative to floodplain destruction by lateral channel migration. Such was the case in narrow valleys trenched by Brakenridge (1984) in the midwest of the United States. Floods in northwestern California are associated with relatively high river stages because flow is highly variable and storage of floodwater is limited by narrow valleys. Because of this and because large flows are associated with high suspended-sediment concentrations, large amounts of sediment can be deposited high above low-flow channels, thereby constructing high streambanks. In the California study reaches, channel migration is limited by bedrock exposed in valley walls and strath terraces. These outcrops tend to restrict outward migration and may further stabilize channels by fixing the position of bars and pools (Lisle, 1986).

In the lower Van Duzen River and parts of the Trinity River, however, freely meandering reaches in wide alluvial valleys have banks that are noticeably lower than those of the study reaches. Although we did not investigate the meandering reaches, we suspect that bankfull stages occur more frequently there than in straight bedrock controlled reaches. If so, the frequency of bankfull flow can vary with channel pattern in the same river. This supposition deserves further study.

At the other end of the spectrum from freely meandering channels, the Black Butte River represents an extreme case of the effectiveness of infrequent flows to transport sediment and form channel margins. The highest proportion of the sediment load for the period of record was carried by the largest flows. The large flood of 1964 caused such disequilibrium in bed elevation that active floodplains have not had time to develop.

The absence of active floodplains along the Black Butte River and small floodplains at variable heights above the streambed along the other study reaches suggest that where infrequent discharges are especially effective in channel processes, floodplains can be expected to be poorly developed and flooded at frequencies inconsistent with other reaches along the same river or in neighboring river basins. The range in flow events capable of affecting bankfull capacity by bank erosion, bed aggradation or degradation, or overbank deposition is large. Multiple levels of deposition along channel margins of these rivers, therefore, reflect the competing importance of a wide range of high-magnitude, low-frequency flows. As a consequence of this, bankfull capacity does not reflect a narrow range of discharges, but rather a broader range of flow events. As Beven (1981) pointed out, the sequence of these events in time is probably as important as the magnitude of the events themselves in influencing channel capacity and the morphology of the channel at any one instance in time.

REFERENCES

Andrews, E.D., 1980, Effective and bankfull discharges of streams in the Yampa river basin, Colorado and Wyoming: J. Hydrol., v. 46, p. 311-330.

Bailey, E.H., Blake, M.C., Jr., and Jones, D.L., 1970, On-land Mesozoic oceanic crust in California Coast Ranges: in Geological Survey research, 1970, USGS Prof. Pa. 700C, p. 70-81.

Baker, V.R., 1977, Stream channel response to floods, with examples from central Texas: _Geol. Soc. America Bull., v. 88, p. 1057-1076.

Beven, K., 1981, The effects of ordering on the geomorphic effectiveness of hydrolgic events: in Proceedings, Symposium on Erosion and Sediment Transport in Pacific Rim Steeplands, IAHS-AISH Publication 132, p. 510-526.

Brakenridge, G.R., 1984, Alluvial stratigraphy and radiocarbon dating along the Duck River, Tennessee: Implications regarding floodplain origin: _Geol. Soc. America Bull., v.95, p. 9-25.

Harden, D.R., Janda, R.J., and Nolan, K.M, 1978, Mass movement and storms in the drainage basin of Redwood Creek, Humboldt County, California-- A progress report: U.S. Geological Survey Open-File Report 78-486, 161 p.

Helley, E.J. and LaMarche, V.C. Jr., 1973, Historic flood information for northern California streams from geologic and botanical evidence: USGS Prof. Pa. 485-E, 16p.

Janda, R.J., and Nolan, K.M., 1979, Stream sediment discharge in northwestern California:in Natural and management-related erosion in Franciscan terrane of northern California, Geological Society of America Cordilleran Section Guidebook, Field Trip 12, San Jose, California, San Jose State University, p. IV-1 to IV-27.

Jones, D.L., Blake, M.C., Jr., Bailey, E.H., and McLaughlin, R.J., 1978, Distribution and character of Upper Mesozoic subduction complexes along the west coast of North America: Tectonophysics,

v. 47, p. 207-222.
Kelsey, H. M., 1980, A sediment budget and an analysis of geomorphic process in the Van Duzen River basin, north coastal California, 1941-1975: Geol. Soc. America Bull., v.91, p. 119-1216.
Lisle, T.E., 1981, The recovery of aggraded stream channels at gauging stations in northern California and southern Oregon: in Proceedings, Erosion and Sediment Transport in Pacific Rim Steeplands, IAHS-AISH Pub. No. 132, p. 188-211.
Lisle, T.E., 1986, Stabilization of a gravel channel by large streamside obstructions and bedrock bends: Geol. Soc. America Bu1l., v. 97, p. 999-1011.
Neff, E. L., 1967, Discharge frequency compared to long-term sediment yields: in Proceedings, Symposium on River Morphology, IAHS_Pub_75, p. 236 -242.
Nolan, K.M., and Marron D.C.,-------, History, causes, and significance of changes in the geometry of Redwood Creek, 1936-1982: in Geomorphic and Biological Processes in the Redwood Creek drainage Basin, Humboldt County California: USGS Prof. Pa. 1445, in press.
Nolan, K. M., Janda, R.J., and Galton, J.H., 1986, Sediment sources and sediment-transport curves: in Proceeding of the Fourth Federal Interagency Sedimentation Conference, v. 1, Las Vegas, p. 4-70 to 4-79.
Pickup, G., and Warner, R.F., 1976, Effects of hydrologic regime on magnitude and frequency of dominant discharge: J. Hydrol., v. 29, p. 51-75
Rantz, S.E. 1969, Mean annual precipitation in the California region: U.S. Geological Survey basic data compilation, Menlo Park, 5 p., 11 maps.
U.S. Geological Survey, 1952-1970, Surface water supply of the United States -- part 11: USGS WSP (published annually).
U.S. Geological Survey, 1971-1974, Water-resources data for California, 1971-1974 -- part 2. Water-quality records: U.S. Geological Survey Water-Data Reports CA71-3 to CA74-3 (published annually).
U.S. Geological Survey, 1975-1985, Water-resources data for California, water years 1975-1985 - volume 2: U.S. Geological Water-Data Reports CA75-2 to CA85-2 (published annually).
U.S. Water Resources Council, 1981, Guidelines for determining flood flow frequency: Bull. 17 B.
Webb, B.W., and Walling, D.E., 1982, The magnitude and frequency characteristics of fluvial transport in a Devon drainage basin and some geomorphological implications: Catena, v. 9, p. 9-23.
Williams, G.P., 1978, Bank-full discharge of rivers: Wat. Resour. Res. v. 14, p. 1141-1154.
Wolman, M.G., and Gerson, R., 1978, Relative scales of time and effectiveness of climate in watershed geomorphology: _Earth Surf. Processes, v. 3, p. 189-208.
Wolman, M.G., and Miller, J.P., 1960, Magnitude and frequency of forces in geomorphic processes: J. Geol., v. 68, p. 54-74.
Wolman, M.G., and Leopold, L.B. (1957) River flood plains - Some observations on their formation: USGS Prof. Pa. 282-C, p. 87-109.