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The recovery of aggraded stream channels at gauging stations in northern California and southern Oregon

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Abstract. Discharge measurements at nine gauging stations in northern California and southern Oregon document episodes of channel bed aggradation lasting 5 to 15 years after the flood of December 1964 to January 1965. Bed elevations rose 1 to 4 m, then gradually declined to a stable level at or above the pre-flood level. Seven gauging sections widened by 7 to 105 per cent during the aggradation episodes. Channels formed within aggraded material narrowed during degradation; in one case, the pre-flood width was attained. Eroded streambanks formed in non-alluvial material rarely advanced because of 1) post-1964 flood flows, 2) the slowness of processes forming non-alluvial streambanks, and 3) the difficulty of establishing riparian vegetation under the conditions of coarse substrate and seasonal rainfall. These results suggest that infrequent large floods are more effective in shaping stream channels in highly erosive terrane with seasonal rainfall than in less erosive humid areas with comparable amounts of annual precipitation.

L'retablissement de agradé sur les lits fluviaux à des stations de jaugeage dans l Californie du nord et l'Oregon du sud

Résumé. Les rapports des mesures de décharge à neuf stations de jaugeage dans la Californie du nord et l'Oregon du sud documentent des épisodes d'agradation de lit fluvial qui ont duré de cinq à quinze ans suivant l'inondation de décembre 1964 et de janvier 1965.Les élévations de lit

sont montées de 1 à 4 m, et ensuite elles ont baissé et se sont stabilisées au niveau d'avant inondation ou audessus. Sept sections de jaugeage se sont élargies de 7 à 105 pour cent pendant les épisodes d'agradation. Les rigoles creusées dans le matériel agradé se sont rétrécies pendant la dégradation; dans un cas, la largeur d'avant inondation a été atteinte. Les bords fluviaux érodés et composés de matérial non-alluvial se sont rarement avancés grâce aux débits d'inondation après 1964, à la lenteur des processus qui forment ces rives non-alluviales, et à la difficulté d'établir une végétation riveraine dans des conditions de gros sous-sol et de précipitation saisonnière. Des épisodes d'agradation ayant rapport à l'inondation de 1964 et le rétablissement lent des rives érodés indiquent qua de grandes inondations peu fréquentes font plus d'effect sur la formation de lits fluviaux dans des terrains fort érosifs avec une précipitation saisonnière que dans des régions humides moins érosives avec un total comparable de précipitation annuelle.

INTRODUCTION

In a definitive paper, Wolman and Gerson (1978) stated that the effect--tiveness of a climatic event in shaping the landscape depends not only on the work done during the event but also on the subsequent geomorphic processes which restore the landscape to the conditions existing beforehand. Accordingly, the recovery of a stream channel from a major flood involves the net displacement of the volume of flood debris out of the channel and the reshaping of the channel to its former morphological charac-teristics. These authors state, "While rainfall intensities and maximum discharges are quite similar in different regions, their effectiveness as formative agents on channels and hillslopes is not." They illustrate this point by showing that channel widths recover faster in humid climates than in arid climates.

The flood of December 1964 to January 1965 in the Pacific Northwest caused extensive bank erosion and the transfer of large volumes of coarse debris from headwater areas to stream channels (Stewart and La Marche, 1967; Janda et al., 1975; Kelsey, 1980). The great amount of material moved during the "1964 flood" was documented in the Van Duzen River basin by Kelsey (1980) and in the Redwood Creek basin by Colman (1973). Aggradation of stream channels has been particularly severe in coastal basins of the Klamath Mountains and adjacent Franciscan terrane in northern California and southern Oregon (Hickey, 1969; Knott, 1971, 1974). This area yields the greatest mean annual volumes of sediment per basin area in the contiguous United States (Judson and Ritter, 1964). Such high yields are attributed to the combination of rapid uplift, pervasively sheared bedrock, high seasonal rainfall, and the accelerated human disturbance of the land (Janda and Nolan, 1979). This erosive combination of climate and geology does not fall within the categories of conditions considered by Wolman and Gerson (1978).

Several lines of evidence indicate that large climatic events are highly effective in shaping channels in this area. Erosion and deposition of the channel and floodplain of Coffee Creek, northern California, as a result of the 1964 flood led Stewart and La Marche (1967) to conclude that catastrophic floods determine the gross features of streams in this area. The coarseness of many streambeds raises the threshhold of entrainment of the bed, particularly in upstream reaches and in those armoured with large landslide debris (Kelsey, 1980: p. 1183). High magnitude flows are more important in shaping the channel under high threshhold conditions (Baker, 1977).

A highly seasonal rainfall produces two effects. Firstly, the dry season hinders the establishment and growth of vegetation which may stabilise streambanks and erosional features on hillslopes. For example, landslides that were triggered or accelerated by the 1964 flood continued to produce large volumes of debris for several years afterward (Harden et al., 1978: p. 15). Continued inputs of sediment tend to prolong aggradation and, thus, delay channel recovery. Secondly, as flow variability in a channel increases as a result, for instance, of seasonality of rainfall, a greater proportion of the sediment load tends to be carried by less frequent flows (Wolman and Miller, 1960).

The purpose of this paper is to assess the duration of the recovery period of stream channels affected by the 1964 flood. Such an assessment should help in understanding the effectiveness of large climatic events in highly erosive areas with seasonal rainfall such as those that rim the Pacific Ocean.

Two approaches were used in the study. Records of discharge measurements at gauging stations provided the information to assess

these two elements of channel recovery. One approach was to determine the period for the recovery of widened channels to pre-flood widths. A second approach was to determine the period of time covered by the passage of flood-generated debris out of channels. Concentrations of suspended sediment declined to pre-flood levels within periods up to nine years long in ten basins (Anderson, 1972). The decline began the year after the flood,, before the channel had aggraded to peak levels in many stations. In others, pre-flood concentrations were reached while the bed was still aggraded (Knott, 1974). The final flushing of flood debris is marked by the decline of bed elevations to apparent base levels. Kelsey (1980) and Nolan and Janda (1979) documented such episodes of aggradation lasting up to the present in the Van Duzen River and Redwood Creek. To characterize the recovery period in this region, I studied stream channels over a wide area (Fig. 1).

An episode of aggradation is defined in this study as the occurrence of channel bed levels that are higher than the nearly constant levels existing before and afterward. An episode consists of an initial period of progressive fill or aggradation, followed later by a period of progressive scour or degradation. Often channel widening accompanies episodes of aggradation. This paper reports time sequences of change of bed elevation and channel width at nine gauging stations in northern California and southern, Oregon that aggraded as the result of the 1964 flood.

DATA FROM GAUGING STATIONS

The behavior of sections used for gauging and consistent criteria for locating gauging sections make them well suited for studying changes in bed elevation on a regional scale. Fixed cables for measuring discharge above wadable stages are preferably located in a straight reach shelving up to a control section. Such reaches usually have a uniform cross-sectional distribution of velocity and depth. Gauging sections scour and fill annually but the stability of the control section limits changes in bed elevation due to changes in local base level.

Records from 31 stations located from south coastal Oregon to the Russian River basin in California were initially analysed for changes in bed elevation. More recent records of 18 previously studied stations (Hickey, 1969; Knott, 1971, 1974) were analysed to investigate later phases of aggradation episodes. Only two of the previously unstudied stations showed aggradation.

I finally chose to study nine stations that aggraded 1 m or more (Fig. 1, Table 1). All but one of the stations were visited to observe expressions of the impact of and recovery from the 1964 flood.

Average values of median streambed elevation and thalweg (minimum) elevation at the cable sections were computed using from one to three cross sections for each year. The median was used in order to de-emphasize the elevation of streambank segments in computing a value that characterizes the entire streambed. Geomorphic datums such as bankfull elevation were usually not recognizable.

The latest measurements taken in the high runoff season were selected in order to avoid differences in bed elevation due to seasonal scour and fill. In two cases it was necessary to augment records of cable measurements in order to document lower bed elevations before the 1964 flood. This was done with data from wading measurements which are taken at low flow at any convenient section. Mean streambed elevation was computed as the difference between gauge height and mean depth.

Considerable error lies in the variable location of wading sections, but these values followed the trend of median values generated from cable measurements at all but one of the nine stations.

Channel width was measured in two ways for each set of cross sections for a particular gauging section: (a) Width was measured at the intersection of an elevation datum with the streambank segments. This datum, from 0.5 to 2 m above the median bed elevation, was chosen to intersect the steep ($\geq 10^0$) portions of the streambanks of as many cross sections as possible in each set. (b) Width was measured at a fixed height above the median bed elevation of each cross section. This height was approximately equal to the one used in choosing the datum for the first method. Width was not measured when the datum intersected a bank with a slope less than 10^0. The first method could not be used when the bed rose above the datum. Changes in width measured by the first method express erosion and accretion of streambanks; changes measured by the second method express adjustments of width at constant depth to a changing bed elevation.

EPISODES OF AGGRADATION

Occurrence

Episodes of aggradation are caused by combinations of conditions that increase the ratios of sediment supply to transport capacity or particle size to competence. Despite the widespread high runoff and erosion generated by the 1964 storm, I found that only 29 of 64 stations aggraded immediately afterward. Several factors influenced the occurrence and level of aggradation observed at gauging stations: (1) Some basins did not undergo as much erosion as others because of differences in geology and land use (Anderson, 1970) and storm intensity (Harden et al., 1978).

(2) As sediment is transported downstream, concentrations of sediment disperse, large particles are deposited, and many bedload particles disintegrate into suspendible fractions. These processes tend to decrease aggradation downstream of sources, as was observed at the Middle Fork Eel River (Knott, 1974). (3) Most river channels in this area are only intermittently bounded by valley flats, and sources of sediment from streamside landslides are distributed throughout their courses (Janda and Nolan, 1979). (4) Channel segments with lower gradients than upstream or downstream segments possess lesser transport capacity and competence and have shown a greater tendency to aggrade (Kelsey, 1980: p. 1181; Nolan and Janda, 1979). (5) Aggradation sequences that propagated downstream may not have arrived during the period of analysed record at some stations. Upstream reaches of Redwood Creek that aggraded after 1964 are currently degrading, while downstream reaches are aggrading (Nolan and Janda, 1979). None of the stations I studied, however, showed an aggradation episode that did not immediately follow an extreme runoff event. Most likely, because of factors (1), (3) and (4), I found no apparent correlation between basin area and the level or amount of aggradation at the 29 stations which aggraded immediately after the 1964 flood.

Temporal form

Aggradation became apparent immediately after the flood and reached peak levels of up to 4 m after one to seven years (Fig. 2) (Knott, 1971, 1974; Kelsey, 1980). A sharp rise in streambed elevation preceded a more gradual decline to a stable level approximately equal to or higher than the pre-flood level (Fig. 2). Main stem stations and those with low gradients--Smith River, Noyo River, Black Butte River, Van Duzen River (Kelsey, 1980, Fig. 20)--showed a more gradual rise and fall of

bed elevations. This probably resulted from dispersion of sediment during a long period of transfer from remote sources.

The proximity of a large sediment source affected the temporal form of the aggradation episode observed at two gauging stations on the Van Duzen River (Kelsey, 1980: p. 1188). A station downstream of voluminous debris sliding into the river remained aggraded by about 3 m of alluvium 12 years after the flood because of channel armouring by coarse debris. Another station 4 km downstream aggraded gradually and has since degraded nearly to the former level. The fill material, which is finer than that deposited over the upstream station, was presumably sorted from the heterogeneous landslide debris. Therefore, the coarseness of the flood deposits, which depends on the proximity to coarse sediment sources, locally affects the period of the aggradation episode.

Local residents and stream gaugers have noted a decrease in size of streambed material accompanying aggradation (Nolan and Janda, 1979; Kelsey, 1980: p. 1181; John Palmer, pers. com.). Their observations probably pertain to most aggraded reaches. Most commonly, pebbles to cobbles armour aggraded material whose mean size falls within the range of sand to medium gravel.

The post-flood sequence of high streamflows that transport large amounts of sediment strongly influenced the temporal form of aggradation episodes. High magnitude floods that caused either scour or further aggradation occurred in 1972, 1974, and 1975 (Harden et al., 1978), but these floods were more localized than the 1964 flood. The thalweg of the Noyo River gauging section, for instance, degraded to its pre-1964 flood level after a record high flow in March 1974 (Fig. 2A). High flows in 1972 in the Smith River and Willow Creek, however, caused other episodes of aggradation (Fig. 2E, 2F). A similar period of aggradation occurred on the Smith River as a result of three floods from 1953 to 1955.

Episodes of aggradation lasted from 5 to more than 15 years at the nine stations. These time periods were uncertain when bed elevations decreased gradually. to stable levels that were higher than than the pre-flood level (e.g., Fig. 2D). The period for the Black Butte River, Willow Creek, Smith River, and Elk Creek were estimated by extrapolating the degrading trend of bed elevation to the pre-flood level. Episodes of aggradation are expected to persist longer in the lower reaches of Redwood Creek (M.A. Madej, pers. com.) and the Van Duzen River (Kelsey, 1980: p. 1194).

Changes in width

Changes in channel width observed after the 1964 flood were closely related to the episodes of aggradation and to the processes that form channel margins.

As a result of the 1964 flood, the channel widened at five of six stations with pre-flood data (Fig. 2). In the exceptional case (Indian Creek), the left bank was composed of competent bedrock and the right bank was ill-defined. Of three gauging sections without pre-flood data, two showed channel widening after 1965. At the other one, the banks were not adequately defined by the cross sections. Seven of nine stations, therefore, showed channel widening resulting from the 1964 flood.

Aggradation apparently extended channel widening that was initiated by flood flows because four gauging sections with pre-flood measurements of width continued to widen after 1965 (Figs. 2A, 2B, 2C, 2D) (Kelsey, 1980: Fig. 20). The rise of the channel bed would cause high shear stress to develop along the banks more frequently and at higher elevations.

Bank erosion also may be attributed to major changes in the channel thalweg accompanying aggradation. In some cases, the thalweg preferentially filled, and, thus, the bottom profile became flatter (Fig. 3) (Hickey, 1979: p. 30-33). In others, the thalweg shifted toward the opposite bank (Fig. 4), or split in two, forming a central bar or braided pattern at low flow (Figs. 5 and 6). In all cases, bank erosion was enhanced by increases in flow velocity near the channel margins. Even without bank erosion, aggradation within sloping streambanks produced a wider channel. Values of width measured at constant depth usually showed a greater increase during aggradation than values measured at a fixed datum (Figs. 2A, 2B, 2E).

Non-alluvial channels and alluvial channels formed in flood deposits showed an important distinction in the erosion and accretion of streambanks. Due to the active incision of stream valleys into the rapidly rising landscape, most channels in the study area are non-alluvial to the extent that their streambanks are not composed of alluvium. Alluvial channels most frequently occur in the lower reaches of major streams and in valley flats isolated from downstream base level changes by resistant bedrock. In non-alluvial channels, marginal depositional sites are restricted. Non-alluvial streambanks are cut along hillslopes and strath terraces and are composed predominantly of colluvium and bedrock, and thin or isolated deposits of alluvium.

Sections on the Noyo River (Fig. 3), Outlet Creek (Fig. 4), and North Fork Trinity River, represent non-alluvial channels. These sections showed a modest change in cross-sectional form and an increase in width amounting to 10 to 20 per cent. Their streambanks had not begun to advance by the end of the period of record (Figs. 2A, 2B, 2D), except at outlet creek, which showed deposition of a bar along the left bank in 1979 and its partial removal in 1980 (Fig. 7). Eroded banks have not advanced at two other sections--the Van Duzen River near Bridgeville (Kelsey, 1980: Fig. 20), and Elk Creek--which are cut partially in older alluvium.

Sections on the Black Butte River (Fig. 5), Willow Creek (Fig. 6), and the Smith River are examples of alluvial channels formed in flood deposits contained within a narrow valley bottom. These sections underwent more cross-sectional change than the non-alluvial channels. They show pronounced lateral shifting of the thalweg, the formation of a central bar, and greater channel widening amounting to an increase of as much as 105 per cent in the Willow Creek section. These examples of alluvial channels illustrate a wide spectrum of the recovery of channel width. Streambanks of the Smith and Black Butte sections accreted as their beds degraded (Figs. 2C and 2F). The streambanks of the Black Butte section advanced far enough to create the pre-flood channel width before the bed degraded to its pre-flood elevation. The Smith section did not narrow to the pre-flood width before the channel again aggraded. The Willow Creek section has not narrowed since its maximum aggradation in 1972.

Alluvial channels are self-formed in material transported by the stream, and thus the channel margins may be active sites of erosion and deposition. In the Black Butte section, a narrower channel was formed by a gravel bar deposited along the right bank (Fig. 5). A gauging section on the South Fork of the Van Duzen River formed three such inner bars as the banks advanced during an aggradation episode (Kelsey, 1977: p. 302). Such rapid accretion of streambanks in coarse alluvium is a characteristic common to active braided channels which have abundant

supplies of bedload material and readily adjust their form to changing stages. Braided channels form in aggraded reaches in this region, but the narrow valley bottoms usually do not provide room for an anastomising network of channels.

Because of the prevalence of non-alluvial channels and the rarity of significant recovery of their eroded streambanks, most channels in this region that aggraded still show effects of the 1964 flood. Narrower channels adjusted to annual peak flows, however, have formed in flood deposits, but these alluvial channels appear to be more susceptible to aggradation and channel widening. Possible explanations for the slow recovery of non-alluvial channels include the prolonged erosional impact on the drainage basins, the occurrence of extreme floods after 1964, and the slowness of recovery processes.

Recovery of streambanks along non-alluvial channels will presumably involve the mass wasting of material down to the channel margins, the deposition of alluvium in protected areas, and stabilization by riparian vegetation. Degradation promotes streambank recovery by reducing the frequency of reworking of bars of aggraded material by storm flows (Kelsey, 1977: p. 305). Preferential degradation of the thalweg may effectively initiate this process (Fig. 7). There is then greater opportunity for deposition of fine sediment along channel margins and its stabilization by riparian *vegetation, e.* g., red alder (Alnus rubra) and willow (Salix sp.).

In humid climates, rapid re-establishment of riparian vegetation hastens the recovery of stream channels within a few months to several years (Wolman and Gerson, 1978). The spread and growth of riparian vegetation is hindered in north coastal California, however, because exposed flood deposits which are coarse and permeable, quickly dry out during the long dry season.

The coarseness of bank materials may be indirectly affected by seasonality of rainfall. In two otherwise comparable basins with similar bedrock, Gupta (1975) found that streambanks in the basin with a non-seasonal rainfall were covered with silt and sand. In the basin with seasonal rainfall, the bank surface material was similar to the bed material, which also included pebbles and cobbles.

Substrate size and interstitial moisture and the frequency of abrading storm flows add considerable variability to the density and vigor of the riparian vegetation observed at the gauging stations and elsewhere in this region. In many areas, perennial vegetation on the 1964 flood deposits remains very sparse.

CONCLUSIONS

The recovery of the aggraded gauging sections from the 1964 flood involved two sequential processes: the flushing of the flood debris out of the channel and the restoration of streambanks to create the former channel width. Aggradation extended channel widening that was initiated by the 1964 flood flows and thus delayed the initial recovery of the channel. The episodes of aggradation lasted from 5 to more than 15 years. The narrowing of channels whose banks were formed in aggraded material roughly corresponded with degradation of the streambed. Streambanks formed in non-alluvial material rarely showed recovery, even after the end of the episode of aggradation. The period of recovery of these streambanks was prolonged by the slowness of hillslope processes to construct non-alluvial streambanks, the large flood flows occurring after 1964, and the difficulty of establishing riparian vegetation on xeric channel margins. Without knowing the duration of this last

stage of recovery, it is difficult to assess when these sections will return to their former condition, but it will probably take at least two decades.

Information gleaned from these nine channel reaches suggests that the effectiveness of a climatic event in shaping stream channels depends on more than annual precipitation as emphasized by Wolman and Gerson (1978). It appears that streams draining erosive terrane will recover more slowly than those draining more stable terrane. Non-alluvial channels will recover more slowly than alluvial channels. And recovery will be slower in a climate with great seasonal variability in precipitation than in one where a similar amount is more uniformly distributed throughout the year. Under these conditions, infrequent, large floods are far more effective in determining channel size and form than in less erosive humid environments

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TABLE 1. Gauging stations used to document episodes of channel bed aggradation, northern California and southern Oregon.

Gauging stations	Drainage area (km^2)	Period of daily records	Change in gauging section location
114685 Noyo R. nr. Fort Bragg, Calif.	276	8/51-pres.	none
114722 Outlet Cr. nr. Longvale, Calif.	417	10/56-pres.	none
114729 Black Butte R. nr. Covelo, Calif.	420	10/58-9/75	none
114738 Elk Cr. nr. Hearst, Calif.	219	8/64-9/73	none
115215 Indian Cr. nr. Happy Camp, Calif.	311	12/56-pres.	Moved 1.3 km down stream, 9/20/69.
115265 North Fork Trinity R. at Helena, Calif.	391	1/57-pres.	none
115298 Willow Cr. nr. Willow Creek, Calif.	106	8/59-9/74	Moved 2.3 km upstream after 12/22/64.
115325 Smith R. nr. Crescent City, Calif.	1577	10/31-pres.	10/27-9/79 at site 0.6 km upstream
143725 East Fork Illinois R. ar. Takilma; Oregon	110	10/26-pres.	Moved 1.0 km upstream, 8/23/65

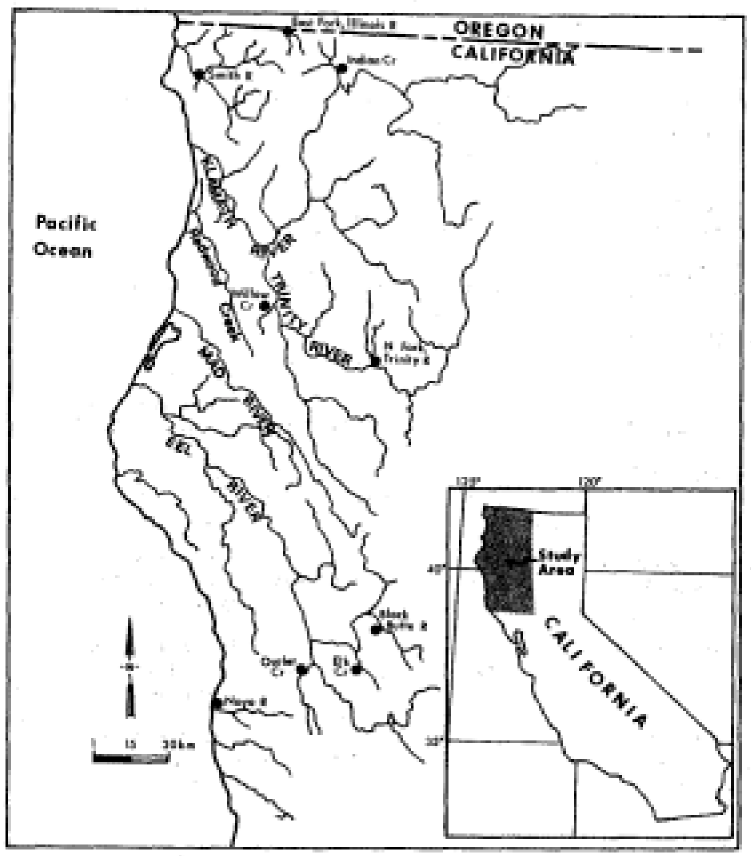

FIGURE 1. Location of nine gauging stations used in the study.

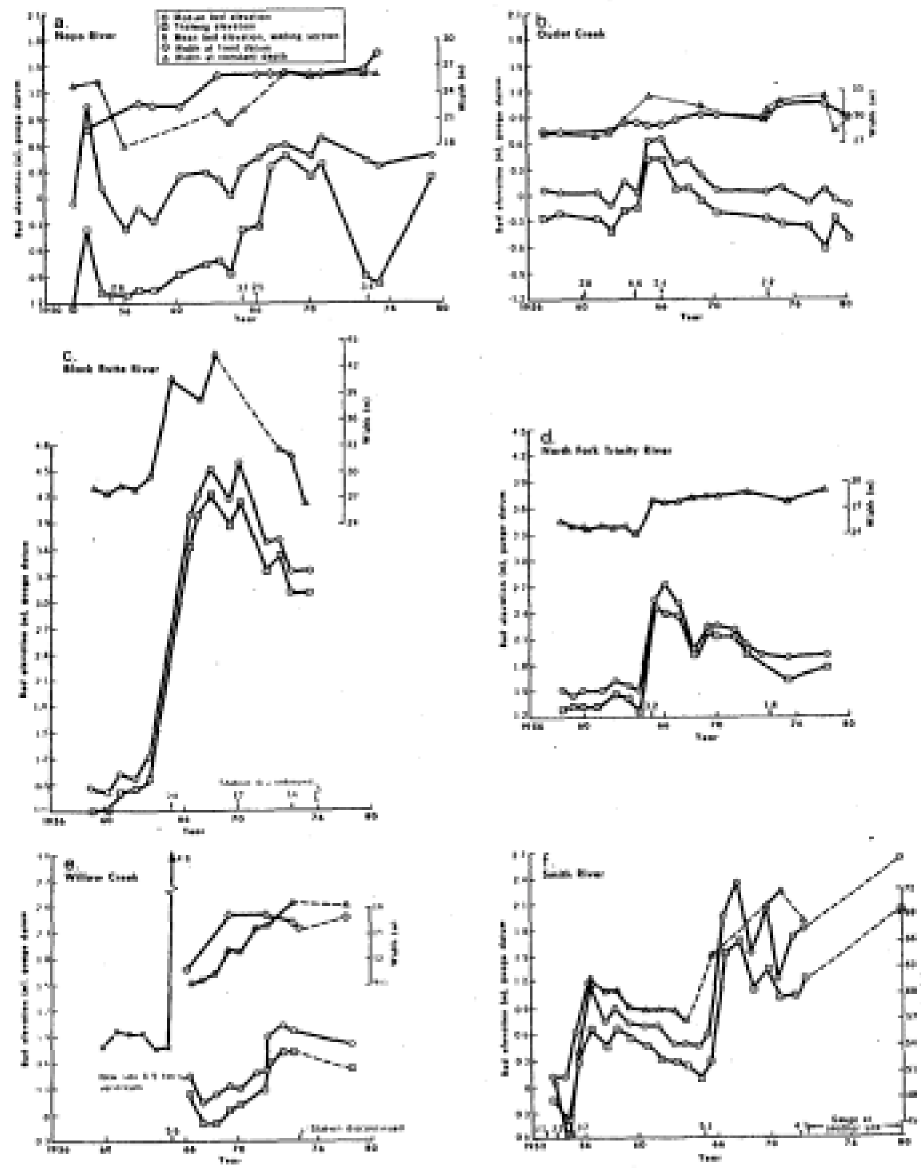

FIGURE 2. Changes in bed elevation and channel width at gauging sections: A: Noyo River; B: Outlet Creek; C: Black Butte River; D: North Fork, Trinity River; E: Willow Creek; F: Smith River. Numbers above abscissa are peak values of mean daily discharge ($m^3/s - km^2$).

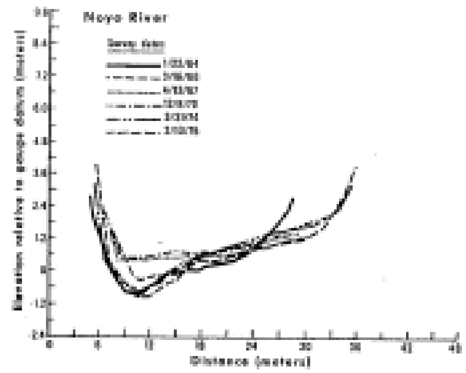

FIGURE 3. Gauging section, Noyo River near Fort Bragg, Calif.

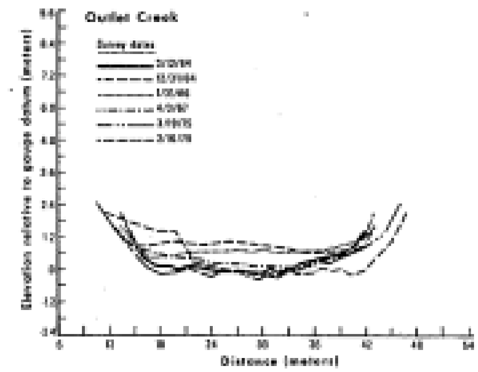

FIGURE 4. Gauging section, Outlet Creek near Longvale, Calif.

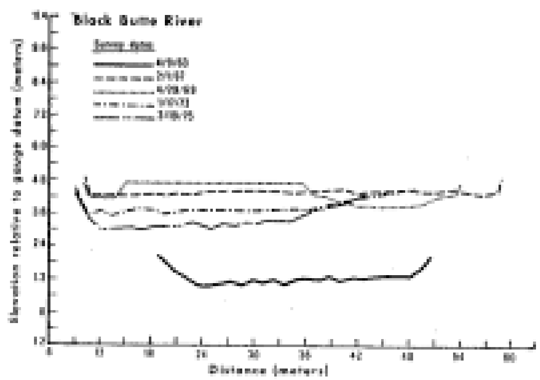

FIGURE 5. Gauging section, Black Butte River near Covelo, Calif.

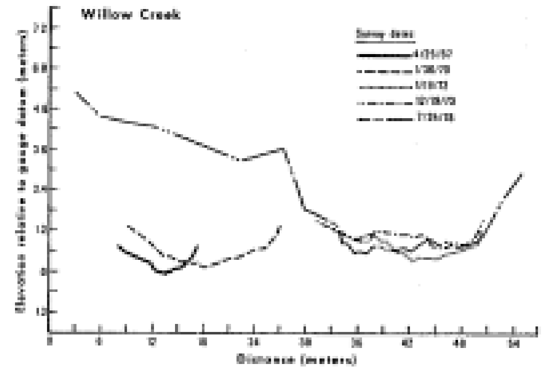

FIGURE 6. Gauging section, Willow Creek near Willow Creek, Calif.

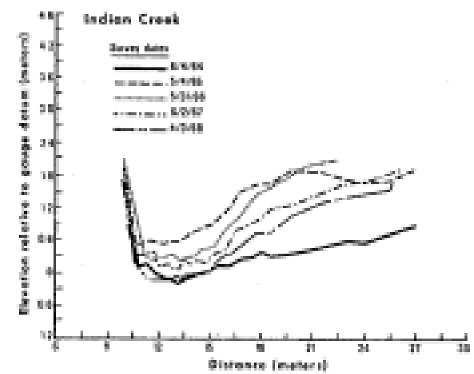

FIGURE 7. Gauging section, Indian Creek near Happy Camp, Calif.