A sediment budget and an analysis of geomorphic process in the Van Duzen River basin, north coastal California, 1941–1975: Summary

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The Coast Ranges of northern California are the most rapidly eroding region of comparable size in the United States (Judson and Ritter, 1964; Brown and Ritter, 1971). This area has undergone recent (post-Miocene) uplift and is underlain by highly deformed and faulted sandstone and melange units of the Franciscan assemblage. This study investigates the sources of the large amount of sediment, the processes by which the sediment moves, and the times of sediment transport in the upper half of the Van Duzen River basin in the California Coast Ranges (Kelsey, 1977). The Van Duzen is the northernmost tributary of the Eel River and flows into the Eel at a point ~ 480 km north of San Francisco (Fig. 1). I documented sediment transport and changes in hillslope and channel morphology during the period 1941–1975 by using six sets of aerial photographs, early land surveys, U.S. Geological Survey water and sediment discharge records, and data from surveying and sediment sampling for 1973 to 1978.

The climate consists of high annual rainfall (125 to 250 cm) that occurs mostly from October through April; the majority of the sediment transport occurs each winter during the two to six most intense storms. Infrequent high-intensity storms of long duration, which are major sediment-transporting events, recur every 100 to 500 yr. One such storm occurred in December of 1964, and it serves as a major focus of this study.

The two main physiographic types in the Van Duzen basin are (1) grasslands and grass-oak woodlands underlain by melange; and (2) the more competent, forested sandstone slopes. Whereas the competent sandstones and siltstones form straight, forested slopes with relatively sharp ridge crests and V-shaped canyons, the Franciscan melange hillslopes range in morphology from smooth, undulating grassland or grass-oak woodland slopes to hummocky, boulder-strewn, poorly drained grasslands sculpted by active mantle creep or earthflow landslides. Since European settlement in the 1870's, grazing has been the major grassland land use. Timber harvesting on the sandstone slopes started in about 1950 and still continues. The lower portion of the study area was extensively logged prior to the 1964 storm, but the upper watershed was not logged until after 1965.

This study presents a sediment budget that summarizes the major erosional and depositional processes in the Van Duzen basin during the 35-yr study period (Table 1). Although the budget spans 35 yr (1941–1975), major changes in slope sta-

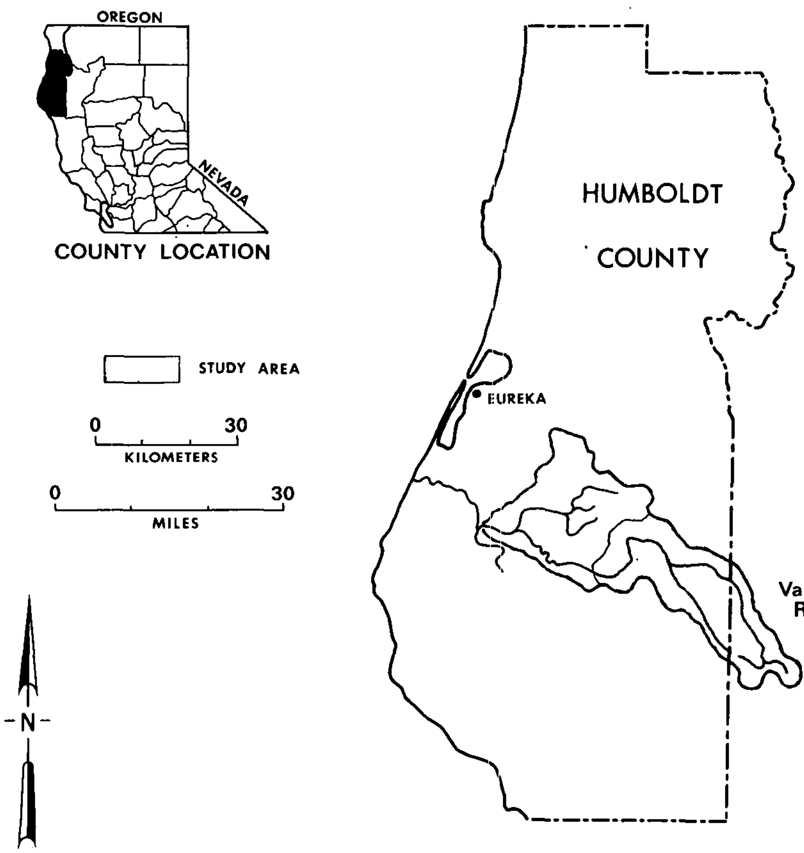


Figure 1. Location map of the 1,111-km² Van Duzen basin, showing the 575-km² study area in the upper half of the basin. This illustration appears as the upper part of Figure 1 in the accompanying article in *Part II*.

The complete article, of which this is a summary, appears in *Part II* of the *Bulletin*, v. 91, no. 4, p. 1119–1216.

Geological Society of America Bulletin, Part I, v. 91, p. 190–195, 4 figs., 2 tables, April 1980, Doc. no. S00402.

TABLE 1. COMPARISON OF ACTUAL COMPUTED SEDIMENT BUDGET TO HYPOTHETICAL SEDIMENT BUDGET EXCLUDING THE EFFECTS OF THE DECEMBER 1964 STORM FOR THE VAN DUZEN BASIN, 1941–1975

	Actual sediment budget (metric tons)	Hypothetical budget without 1964 storm (metric tons)
Fluvial sediment yield from hillslopes	45,509,000	38,254,000
Landsliding		
Debris slides, debris avalanches	10,630,000	1,120,200
Earthflows	2,931,000	1,834,500
Streambank erosion		
Melange bank erosion	426,000	66,100
Flood plain and fill terrace erosion	2,619,000	131,000
Aggradation	10,601,000	none
Total sediment discharge out of basin	51,036,000	41,405,000

bility, channel morphology, and sediment transport are largely due to the effects of the December 1964 storm and flood, and the budget is therefore weighted by the effects of the storm. Because the 1964 storm is an infrequent event, I also present a hypothetical budget that estimates sediment transport if the 1964 storm had not occurred (Table 1). The differences between the two budgets point out those geomorphic processes most influenced by the 1964 storm.

The vast majority of landslides occur on basin slopes immediately adjacent to the main channels or on headwater slopes where landslide debris moves directly into headwater tributaries. Earthflow landslides (Kelsey, 1978) are confined to grassland slopes underlain by highly sheared Franciscan melange. They seasonally move colluvial debris into the major channel at rates that average from 2.4 to 4.0 m/yr. Earthflow colluvium is composed primarily of fine-grained, sheared siltstone and is carried away in suspension upon entering the river. In contrast, debris slides occur in competent massive Franciscan sandstone units on basal slopes bordering the Van Duzen and South Fork Van Duzen Rivers. Debris avalanches are most common on competent sandstones and siltstones in the headwater region where they occur in the mid-slope or upper-slope areas. Both debris slides and debris avalanches deliver coarse material to the channels, ~ 70% of which cannot be carried away in suspension and remains in the channel to be slowly transported as bedload during major streamflow events. A large amount of debris sliding and avalanching occurred during the December 1964 storm, which resulted in widespread channel aggradation.

Bank erosion along main channels and in headwater reaches is confined mainly to unconsolidated alluvium in flood plains and along stream reaches where bare melange colluvium makes up the channel margins. Bank erosion is a slow, persistent process each winter, but relatively short periods of accelerated bank retreat triggered by unusually high streamflows and associated channel aggradation probably account for most of the bank erosion.

Fluvial erosion from hillslopes is a highly significant sediment transporting process on melange grassland and grass-oak woodland slopes but is of negligible importance on forested sandstone slopes. High fluvial erosion rates in melange terrain are mainly due to extensive gullies developed on slopes subject to active mantle creep or faster, earthflow movement. The more mobile hillslopes have increasingly greater surface breakage and disruption and subsequently a higher density of gullies than more stable terrain. Mobile earthflow melange slopes with high gully density have the greatest fluvial erosion rate.

The text of the extended report in *Part II* describes in detail the geomorphic processes operating in the basin and the quantitative data which form the basis for the sediment budget and the estimates of recurrence intervals of episodic events such as debris sliding and major channel aggradation. Following are the most significant findings of the study.

A major portion of the sediment discharge (45%) comes from a small fraction of the basin study area (5.5%) that consists of (1) the most densely gullied grassland slopes, (2) earthflow landslides in the melange, and (3) debris slides and avalanches in the Franciscan sandstone units. Most of the remaining sediment comes from moderately gullied grassland slopes with no large landslides. Forested slopes not directly adjacent to major streams contribute a minimal amount of sediment, even though they constitute 57% of basin area.

The December 1964 flood, which lasted for about three days, mobilized a large quantity of sediment; it alone accounted for 7% of the suspended sediment discharge during the 35-yr study period and mobilized, for the short flood period, almost as much bedload as moves out of the basin in a century.

The storm and flood caused massive amounts of debris sliding and avalanching. On streamside sandstone slopes in the lower portion of the study area, timber harvesting initiated debris sliding even before the 1964 storm, but many of the areas of the most extreme debris sliding were those where the 1964 storm and flood greatly enlarged slope failures initiated by timber harvest and road construction. In addition, bank corrasion by flood flows initiated many new debris slide failures on both logged and unlogged slopes. Table 2 shows the influence of large storms and timber harvesting on the time of initiation of debris slides in the lower part of the basin. Although logging significantly influenced the number and location of debris slides on basal slopes, the 1964 flood was responsible for actually mobilizing most of the material that entered the river from these debris slide failures. Logging is an effective trigger for debris slide events, but significant amounts of mass slope movement and sediment transport require the geomorphic work provided by large storms and floods.

Extensive storm-caused debris avalanching occurred on the unlogged headwater slopes, indicating that the 1964 storm would have been a major erosional event without any human modification of the basin (Fig. 2). The increase in bare slope and channel areas caused by this avalanching and channel widening in the headwater region significantly increased upper basin water yields compared to hydrologic conditions before the 1964 storm.

A storm and flood of similar magnitude to that of 1964 occurred in December of 1955, but the 1955 storm had minimal impact on streamside slope stability and channel geometry. The reason for the difference in geomorphic response is not obvious because the storms were more notable for their similarities than their differences (Harden and others, 1978). Perhaps the

TABLE 2. DEBRIS SLIDES IN LOWER WATERSHED — INITIAL OCCURRENCE OF SLOPE FAILURES AND AMOUNT OF SEDIMENT DELIVERED TO CHANNEL

	Total number of failures*	Occurrence of initial failures relative to time of 1964 flood†			Amount of sediment delivered to channel, metric tons × 10^3 (ρ = 1.92 g/cm^3)		
		Pre-flood	At time flood	Post-flood	Pre-flood	At time of flood	Post-flood
Slope failures in logged areas	56	52%**	37%††	11%	477	4769	123
Slope failures in unlogged areas‡	26	19%	77%	4%	77	1139	4

* Logged and unlogged land approximately equal in area.
† Pre-flood: 1941 through Dec. 1964; time of flood: Dec. 1964; post-flood: 1965–1975.
‡ Unlogged areas do not have any logging roads.
** 79% of these failures occurred on slopes traversed by logging roads.
†† 59% of these failures occurred on slopes traversed by logging roads.

1955 storm did initiate cracks on the steeper hillslopes, priming the slopes for massive failure during a succeeding large storm. It is certain that the timing of logging operations in the lower Van Duzen basin rendered hillslopes more prone to failure in 1964 than in 1955 because sufficient time had elapsed after logging to allow for the loss of slope shear strength due to the decay of tree roots.

Debris sliding and avalanching during the 1964 flood contributed a large amount of coarse alluvial debris (10,601,000 t) to main river channels, causing from 1 to greater than 3 m of aggradation (Figs. 3 and 4); this aggradation buried former incised channels and triggered a period of prolonged and widespread bank erosion. In the 15 yr following the flood, some aggraded channel reaches have started to degrade after reaching peak stream-bed elevations 5 to 8 yr after the flood (Fig. 4), while other reaches are not degrading (or degrading very slowly) due to channel armoring by large flood-deposited clasts, as well as to the continued supply of coarse alluvium from aggraded upstream reaches (Fig. 3). Bank erosion is still continuing on many reaches, regardless of whether the reach is degrading or not (Fig. 4). Almost one-fifth of the total

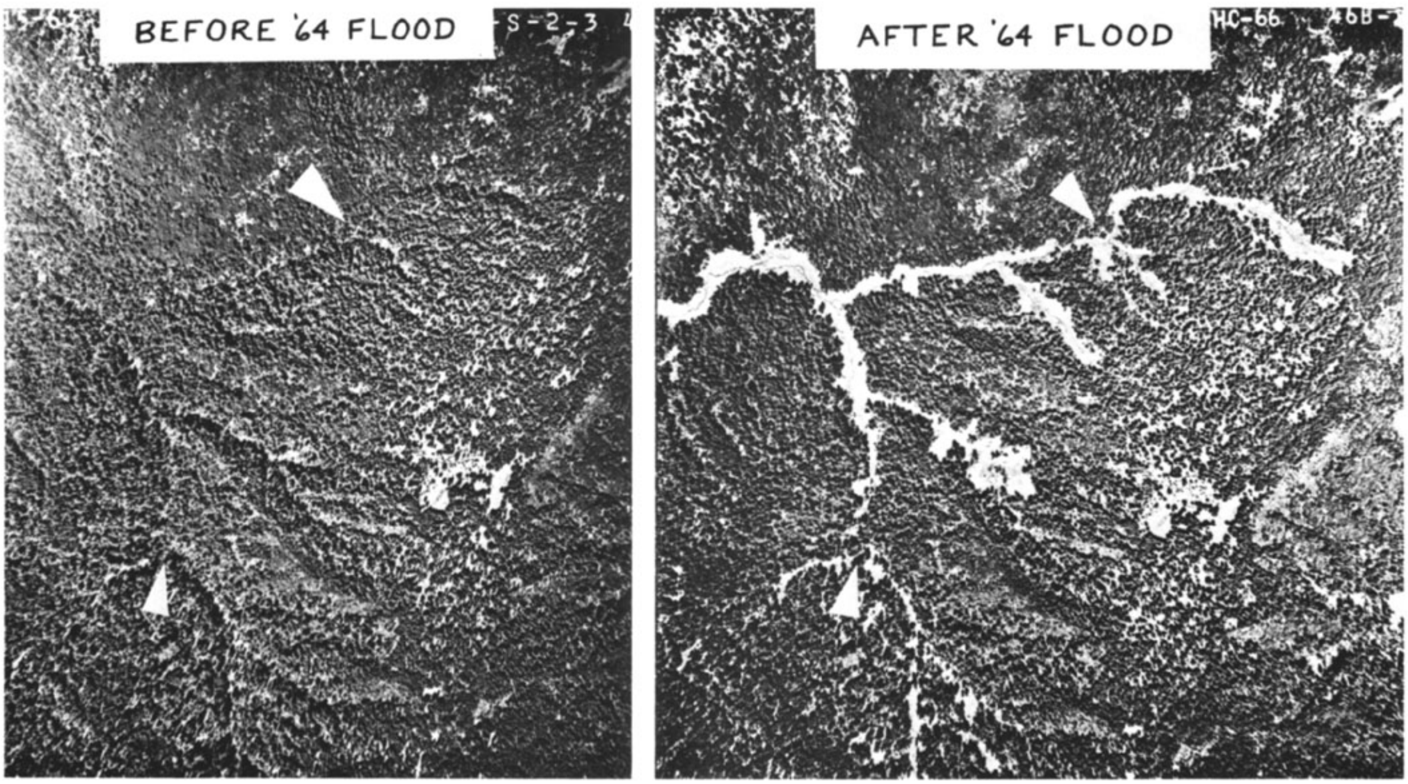
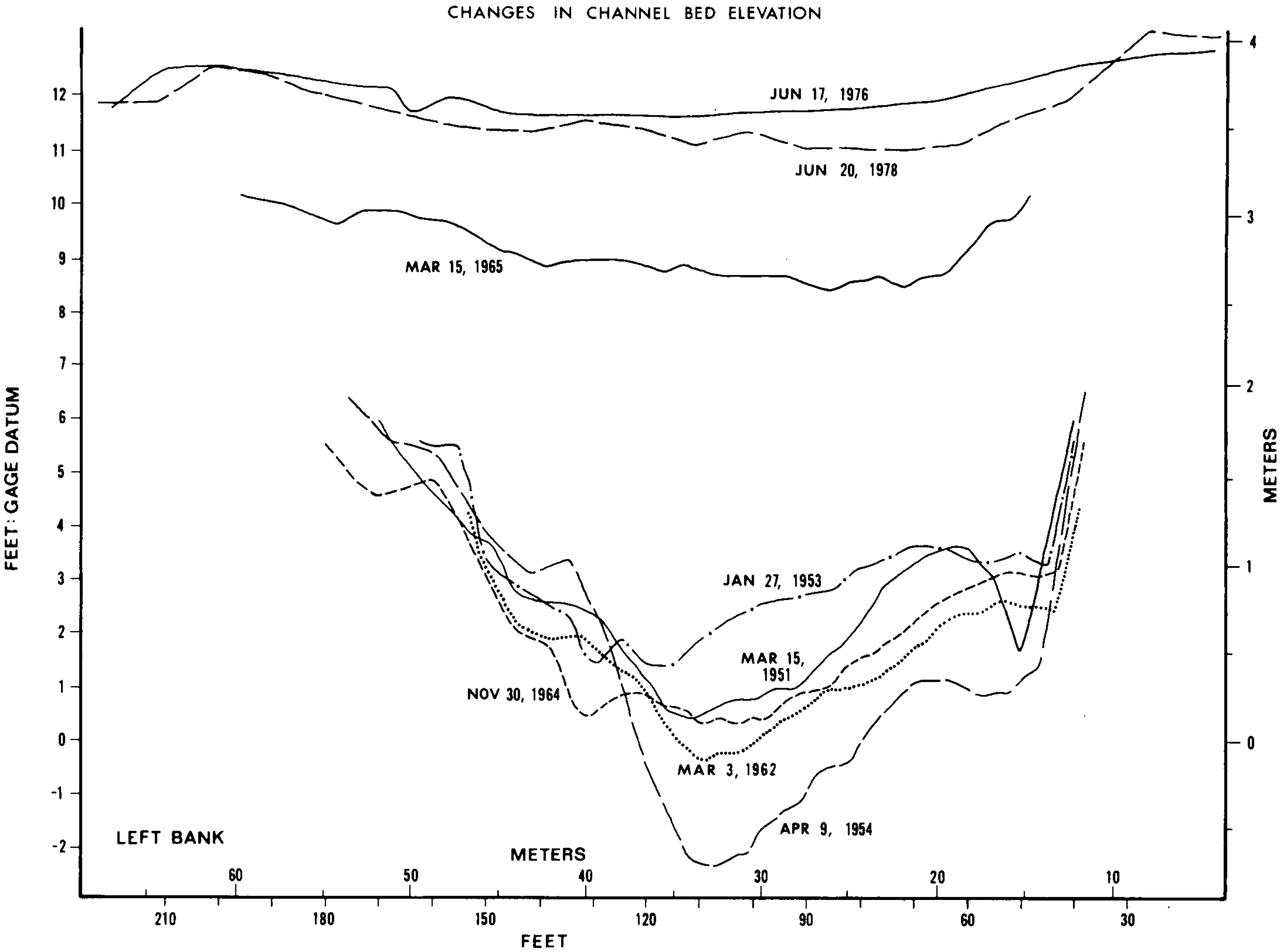


Figure 2. Comparative aerial photos taken in the summers of 1963 and 1966 showing the effects of the 1964 flood in the headwaters of the South Fork Van Duzen. White arrows identify the same channel locations on both photos. The post-flood photo shows four elongate debris avalanches that converge downslope into debris torrents along existing channels. Bank erosion in the channel reaches downstream of the avalanches initiated smaller streamside slides that can be seen in the post-flood photo. This illustration appears as Figure 11 in the accompanying article in *Part II*.



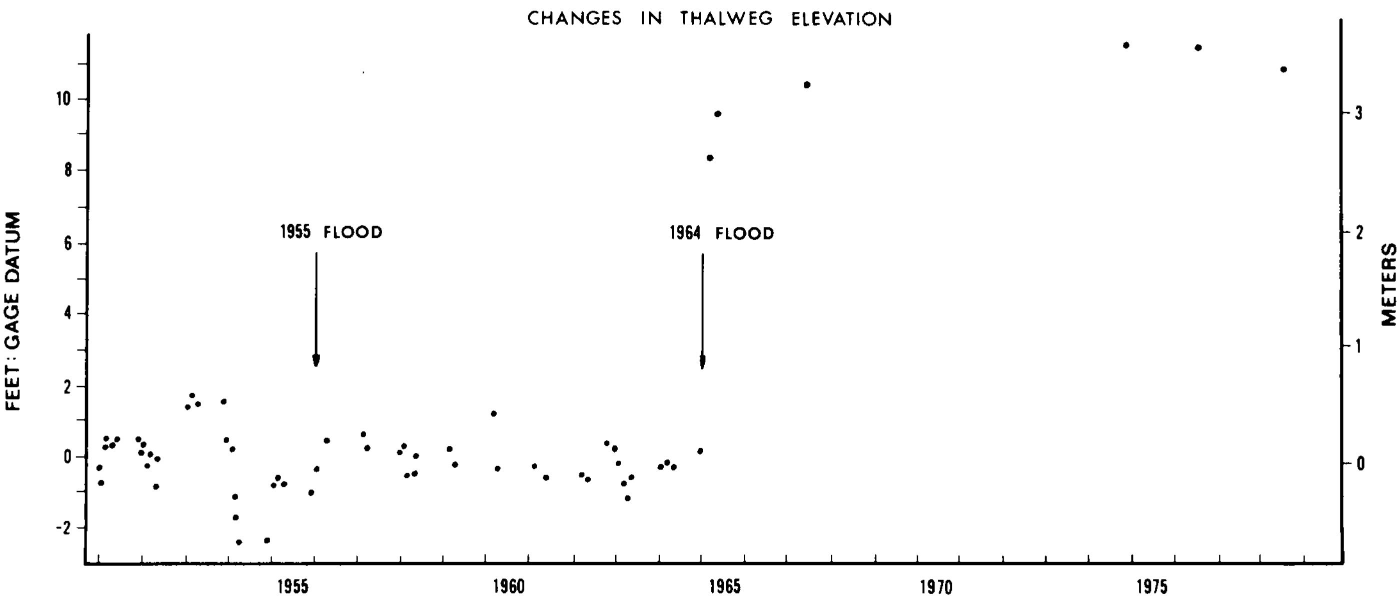


Figure 3. Changes in channel elevation on the Van Duzen River at Pepperwood Falls, 1951–1978 (site of former U.S. Geological Survey gage 11-4785). This illustration appears as Figure 18 in the accompanying article in ***Part II***.

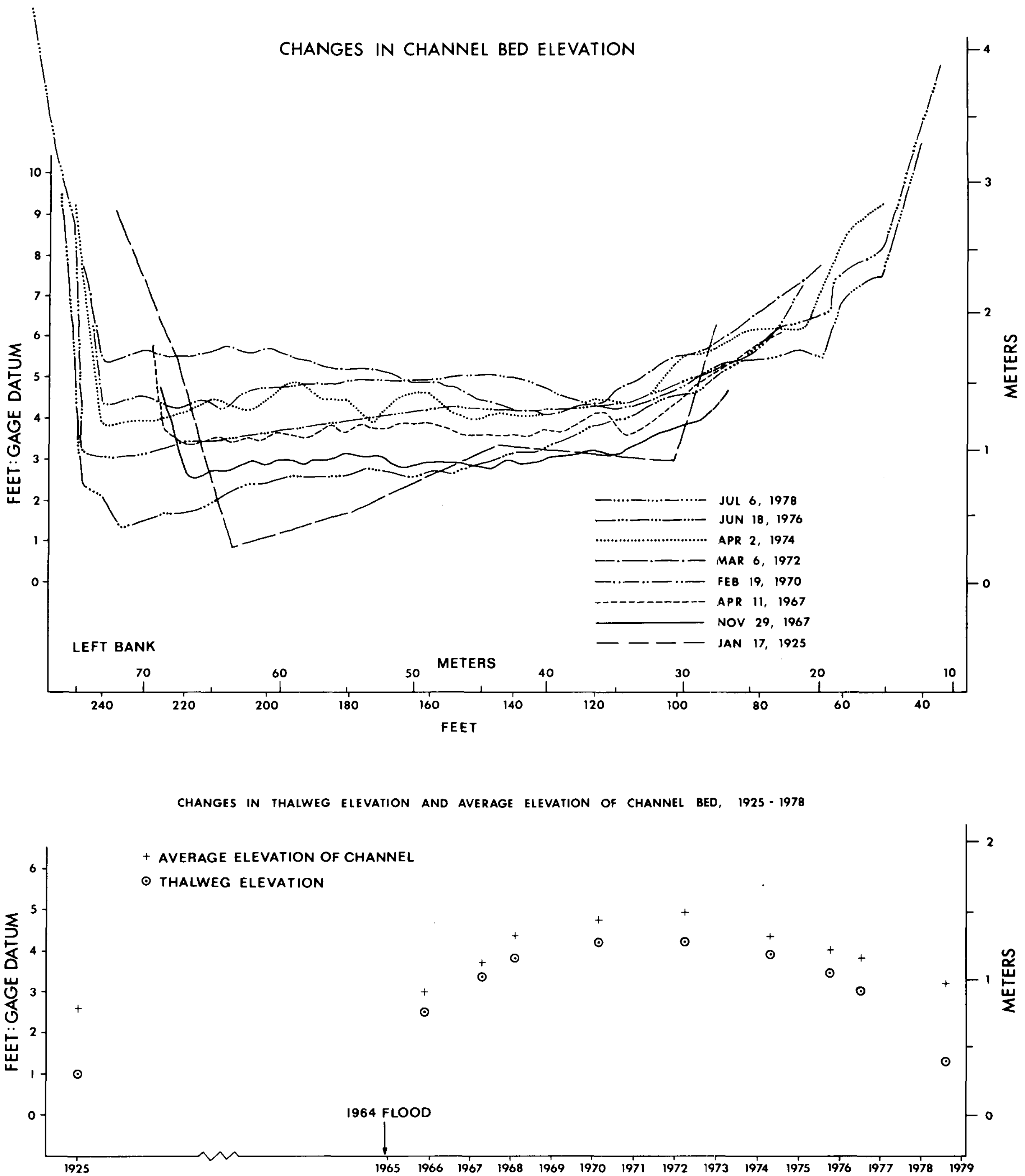


Figure 4. Channel changes at the downstream end of the study area on the Van Duzen River near Grizzly Creek State Park, 1925—1978 (U.S. Geological Survey gage 11-4785). This illustration appears as Figure 20 in the accompanying article in ***Part II***.

sediment supplied to the channel during the study period is stored (as of 1975) as aggraded sediment in major stream channels.

On the basis of dating of debris avalanche-originated channel fills which form multiple levels of terraces along headwater channels, it appears that episodes of debris avalanching on steep headwater slopes in the upper basin have recurrence intervals of from ~ 300 to greater than 500 yr. The episodic introduction of large quantities of avalanche debris to headwater channels results in a pulse of aggradation which migrates down upper watershed channels at ~ 1 km/yr. Similar migrating pulses of aggradation cannot be documented in the higher-order channel of the Van Duzen River in the lower part of the study area, despite substantial aggradation in this channel reach, because of the fluctuations in channel gradient and the more complex routing of alluvium from diverse source areas through the main channel.

In summary, the major sediment source areas are the erosive grassland slopes (including earthflows) underlain by melange and debris slides and avalanches in the sandstone units, which together account for more than 90% of the sediment introduced to the Van Duzen River from only one-third of the basin area. Landslide areas alone (earthflows, debris slides, and debris avalanches) account for a quarter of the total sediment input to trunk streams from only 1% of basin area.

The 1964 storm caused 49% more sediment to enter the Van Duzen basin in the period 1941–1975 than would have been the case without the storm (Table 1). This increase was due to landsliding and bank erosion on trunk streams (64%) and increased fluvial transport off hillslopes (36%). No channel aggradation would have occurred without the 1964 storm. It appears that major landscape-altering storms such as that of 1964 recur on the average every 200 to 600 yr, on the basis of studies of alluvial fills generated by avalanching in the Van Duzen basin and elsewhere (Helley and LaMarche, 1973). The sediment budget for 1941–1975 therefore represents relatively high sediment transport that occurs approximately once every third or fourth century. However, recent land use has affected the land surface to a significant but undetermined extent, and the 35-yr budget that I present may now be more representative of future long-term rates of sediment transport than it would have been prior to intensive land use.

The current large sediment yield from melange grassland slopes results from extensive gullying and slumping that appear, in large part, to be recent features of the landscape; these features most likely reflect the impacts of grazing, and especially the weakening of the vegetation mat by the replacement of the native prairie bunch grasses by weaker, short-rooted annual grasses. This grassland species conversion occurred quite rapidly after the advent of grazing in about the 1870's, and many of the most obvious sources of sediment from the grasslands, such as shallow, extensive gully networks and small slump failures, do not appear more than a century old and could have commenced after prairie vegetative change.

Of the many factors which influence the sediment budget of the basin and the manner of sediment routing through the basin, it is evident that the role of major storms is crucial in initiating or accelerating large landslides, generating tremendous quantities of runoff, causing widespread gully widening and headward cutting, and mobilizing large amounts of bedload for short time spans. More frequent but less severe climatic events are important sediment transporters, but a significant amount of the sediment they move (especially bedload) is delivered to the stream network by the infrequent larger events. Much of the streamside landsliding and bank erosion during the smaller, more frequent storms are indirectly caused by channel and slope changes initiated by the high magnitude, infrequent storm event. In addition, catastrophic, rapid debris avalanching and sliding during major storms are the most important means of landform evolution on otherwise competent sandstone slopes. Therefore, large-magnitude and infrequent storms, such as that of 1964, have a significantly greater effect on total sediment discharge and on landscape formation and a much longer lasting effect on channel morphology in this region of high sediment yield than similar types of floods have on less mountainous terrain underlain by more stable geologic units.

The current sediment yield from the basin, 2,570 t/km^2/yr, is from three to six times the maximum possible long-term rate since the late Miocene, based on a landform reconstruction of the basin. The current rate, which is probably one of the highest ever, may in part reflect recent uplift, but land use of the past century has been a major contributing factor.

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