

THE EEL RIVER, NORTHWESTERN CALIFORNIA; HIGH SEDIMENT YIELDS FROM A DYNAMIC LANDSCAPE

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The Eel River draining the Coast Range of northwestern California has the highest recorded average suspended sediment yield per drainage area of any river of its size or larger unaffected by volcanic eruptions or active glaciers in the conterminous United States (1,720 t/km²yr from 9,390 km²; Brown and Ritter, 1971). These high rates of erosion and sediment transport result from a combination of widespread tectonic deformation of the underlying rocks, recent rapid uplift of the landscape, high seasonal rainfall, and widespread disruption of the ground surface by man in the last century. Not surprisingly, the basin has some unusual geomorphologic characteristics. Sediment-transporting processes on hillslopes and in channels are closely linked, and as a result, high-magnitude, low-frequency climatic events are more responsible for forming channels than in most other areas.

BASIN CHARACTERISTICS

Geology

The Eel River basin is underlain almost entirely by the Franciscan assemblage of complexly deformed, continental margin deposits of Late Jurassic to mid-Tertiary age (Bailey and others, 1964; Jones and others, 1978). The area has undergone uplift since mid-Miocene time (Bailey and others, 1964). Franciscan rocks are predominantly sandstone and shale, but also include tectonically emplaced blocks of volcanics and low-grade metamorphic rock. Bedrock has been pervasively sheared to various intensities over the basin. Zones of weakness trending generally north-northwest have created a trellis network of drainages. Narrow, deeply cut canyons incised below moderately dipping upper slopes, on which older soils are developed, attest to recent or ongoing uplift of the area, although local downwarping has formed isolated depositional basins in the Eel valley (Kelsey, 1982).

Hydrology

The Mediterranean climate of the area is conducive to the production of high sediment yields. Annual precipitation is heavy (averaging 1,500 mm basinwide and 2,800 mm at high elevations) and seasonal, with 90 percent falling between October and April. During winter, northern California has the highest latitudinal temperature gradients of any area in the Pacific Northwest (Janda and Nolan, 1979). This produces intense storms that commonly travel perpendicular to the trend of the Coast Range, which are as high as 2,000 m in the Eel basin. As a result, large cyclonic storms lasting several days have produced widespread rainfall totaling more than 250 mm on several occasions in the last 40 years (Harden and others, 1978).

Runoff from the basin, averaging 890 mm annually, is highly variable because of seasonality of rainfall, infrequent large storms, and poor retention of water in the basin. At Scotia (Fig. 24), the discharge equaled or exceeded 99 percent and 1 percent of the time equals 0.0004 m³sec⁻¹km⁻² and 0.8 m³sec⁻¹km⁻², respectively (Rantz, 1972). Most importantly from a geomorphic standpoint, large flood flows are generated by moderately intense rain falling over the entire basin for a number of days and, in some cases, by snowmelt during warm winter storms (Harden and others, 1978). Little flood runoff is stored in the basin due to the steep slopes and constricted valley bottoms.

Sediment yield

High suspended-sediment discharges from this area result from a combination of high sediment concentrations (averaging 3,000 ppm over discharge at Scotia; Holeman, 1968) and, particularly, high rates of runoff (Janda and Nolan, 1979). Gullying and mass movement accelerated by human disturbance of the erodible terrain provide inexhaustible supplies of fine sediment that can be carried quickly to stream channels (Nolan and Janda, 1982). With increasing precipitation, there is greater surface erosion of broken ground in active earthflows and on soil bared by grazing, timber harvesting, and road building. Also, increasing soil moisture and erosion of toes of streamside slides and earthflows can accelerate mass movement directly into channels. Finally, high annual precipitation in the basin does not promote a denser protective cover of vegetation than in areas with less precipitation. Little of the precipitation falling in winter can be utilized for plant growth, and under natural conditions the basin is already well vegetated except on steep hillslopes along downcutting channels. As a result, sediment discharge increases with annual precipitation in the Coast Range (Janda and Nolan, 1979), unlike most other areas (Langbein and Schumm, 1958; Wilson, 1973).

Also unlike most areas, suspended sediment discharge per unit area in the Eel River increases with basin size (Brown and Ritter, 1971; Janda and Nolan, 1979). Because of ongoing uplift, main channels are commonly more deeply incised than their tributaries, and so streamside landslides, which are major sources of sediment, are particularly abundant along main channels. Parent material is generally soft and friable, and thus, bed particles rapidly break down into smaller sizes (Knott, 1971). Consequently, suspended-sediment load increases downstream at the expense of bedload (Brown and Ritter, 1971).

VARIATIONS IN GEOMORPHIC FORMS AND PROCESSES

The geologic complexity and youthfulness of the landscape are reflected in the variety of hillslopes and channels. Lithology and the degree of fracturing of the bedrock control local erosion rates, erosional landforms, and channel morphology (Janda; 1979).

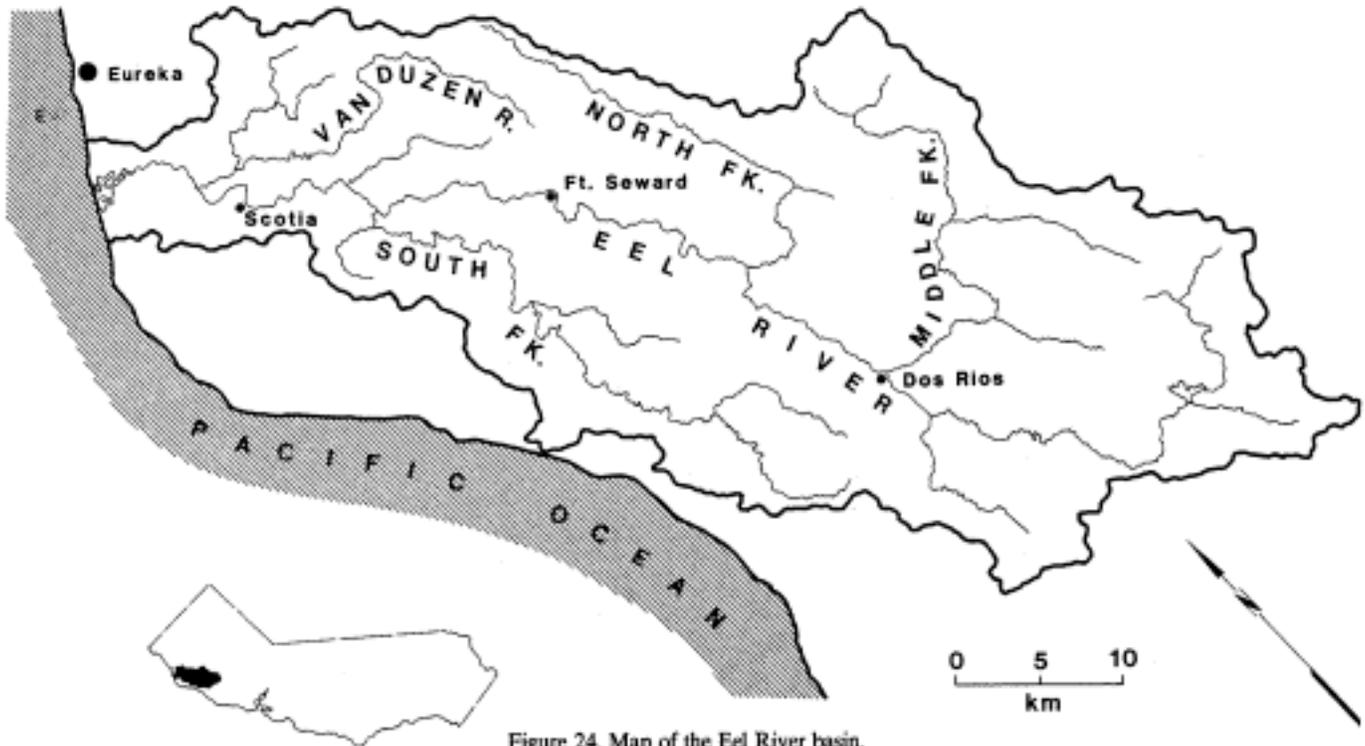


Figure 24. Map of the Eel River basin.

Mélange terrain

Highly fractured *mélange* units in the middle reaches of the Eel and Van Duzen basins contain abundant streamside slumps and earthflows that directly contribute large volumes of sediment to channels (Brown and Ritter, 1971; Kelsey, 1980). Estimated average annual sediment yield from a stream draining an earthflow is 24,000 t/km² (Kelsey, 1980)-about ten times that for the Eel basin as a whole. Sixty-eight percent of the suspended sediment discharge of the Eel River upstream of Scotia comes from 36 percent of the basin-the reach between Dos Rios and the junction with the South Fork (Fig. 24) - which contains the greatest areas of *mélange*, earthflows, and streamside slides (Brown and Ritter, 1971).

Most of the sediment from *mélange* terrain is sand or finer material eroded from toes of earthflows (Nolan and Janda, 1989) and from gullies cut on steep and disrupted hillslopes (Kelsey, 1980). However, earthflows that impinge on channels can contribute blocks of exotic material as large as 10 m and more in diameter and create extremely narrow, steep, coarse channels. These constrictions have led to the formation of depositional reaches upstream that have wide, alluvial channels and gentler streamside slopes. The alternation of these contrasting reaches produces large-scale steps in longitudinal channel profiles (Kelsey, 1980).

Competent terrain

Areas of more competent, graywacke sandstone are generally forested, have lower mass transport rates than *mélange* ter-

rain, and contain "V"-shaped valleys with steep straight hillslopes. Debris slides and avalanches are the predominant sediment sources. These contribute abundant coarse material to channels, but maximum particle size is smaller than that from earthflows. Stream gradients are not unusually steep, and most coarse material entering from hillslopes can be transported downstream during annual floods. Average annual sediment yield from stable forested basins is estimated at 300 t/km² (Janda and Nolan, 1979; Kelsey, 1980)-only about one-tenth of the average for the Eel basin.

Effect of land use

Although soils are generally permeable and stable on slopes less than 30° (Brown and Ritter, 1971), disturbance of the ground cover can greatly accelerate surface and mass erosion in both stable and unstable areas. Despite the low population density, large areas of the basin are affected by grazing, timber harvesting, or associated road construction. Loss of tree-root strength in uncohesive soils (Ziemer, 1981) has probably helped to destabilize clearcut hillslopes; grazing and the replacement of native perennial grasses by European annuals with shallower roots has probably increased gully erosion of grasslands (Kelsey, 1980). Anderson (1970) estimated that intensive timber harvesting and associated road building from about 1950 to 1975 increased sediment yields several fold. Nolan and Janda (1981) measured a 10-fold increase in suspended-sediment discharge from tractor-yarded clearcuts in tributaries of Redwood Creek. The coincidence of concentrated timber harvesting and a series of large floods, how

ever, makes it difficult to separate the effects of these two impacts on erosion and sediment yield (Harden and others, 1978; Kelsey, 1980).

EFFECTIVENESS OF LARGE FLOODS IN SHAPING THE LANDSCAPE

Several authors have concluded that high-magnitude, infrequent floods have a greater impact on the landscape relative to smaller floods in northwestern California than in other areas (Janda and Nolan, 1979; Kelsey, 1980; Lisle, 1981; Nolan and Marron, 1985). During the flood of December 1964, rainfall recorded at more than 550 mm during 48 hr in some locations produced stages in the Eel River 2 to 5 m above previous records (Waananen and others, 1971; Brown and Ritter, 1971). Peak flood discharge of the Eel River near its mouth was 26,500 $\text{m}^3\text{sec}^{-1}$, corresponding to runoff rates of 2.82 $\text{m}^3\text{sec}^{-1}\text{km}^{-2}$. This flood ranks among some of the world's great recorded floods for a basin of this size (Wolman and Gerson, 1978). Kelsey (1980) estimated the recurrence interval of the 1964 flood in the Van Duzen River, a major tributary, at approximately 100 yr. The flood caused profound changes in sediment transport rates and long-lasting changes in hillslopes and channels. Some morphologic changes persist today.

Sediment transport by large floods

Large, infrequent flows transport a relatively large proportion of sediment in the Eel River. At three gaging stations in the basin, discharges below which 90 percent of the suspended sediment load is carried have recurrence intervals between 3 and 16 years (Nolan and others, 1987). At these stations, the proportion of sediment carried by discharges of given frequencies increases with decreasing frequency of discharge and reaches a node at moderate frequencies (recurrence interval of 1.2 to 1.6 yr), as observed in other regions. The proportion remains high for infrequent discharges at the Van Duzen station, however, and increases again with further decrease in discharge frequency at the Fort Seward and Black Butte River stations. At Black Butte River, a major tributary upstream of Dos Rios, the greatest proportion of load has been transported by the most infrequent discharges.

During the 1964 flood, 105 million tonnes of suspended sediment were transported past Scotia during a 3-day period, compared to 85 million tonnes transported during the previous 8 years (Brown and Ritter, 1971). The flood accounted for 7 percent of the total sediment discharge of the Van Duzen River during a 35-yr period, and mobilized as much bed load as moves out of the basin in a century (Kelsey, 1980). Suspended-sediment concentrations at a given discharge increased several-fold and remained high for 2 to 5 years after the flood (Anderson, 1970; Knott, 1971).

Effects on channels and hillslopes

One reason why large floods are so important in shaping stream channels in the Coast Range is that material mobilized from landslides during large storms is commonly carried directly to stream channels instead of to lower hillslope sites or valley flats. Air photos of the basin taken before and after the 1964 flood (Fig. 25) show increased incidence of new landslides and long reaches of greatly widened channels (Brown and Ritter, 1971; Kelsey, 1977). For instance, the length of stream banks affected by debris avalanches increased 423 percent in the upper portion of the Van Duzen basin and 119 percent in the lower portion (Kelsey, 1977). Voluminous coarse debris from debris avalanches and torrents led to widespread channel braiding, channel widening commonly more than 100 percent, and aggradation more than several meters in some reaches (Hickey, 1969; Brown and Ritter, 1971; Knott, 1971; Kelsey, 1977). In areas where landslides were voluminous, aggradation and channel-widening downstream caused additional streamside failures by erosion of supporting material at the base of hillslopes (Kelsey, 1977; Janda and Nolan, 1979).

In addition to widening, channels adjusted to the increased sediment load by reducing bar-pool bed topography and thereby reducing hydraulic friction (Lisle, 1982). As a result, velocity increased and depth decreased at a given discharge, signifying an increase in bed-load transport capacity (Knott, 1971; Lisle, 1982). These adjustments may have accelerated the flushing of excess material from the channel networks. Associated changes in aquatic habitat may have contributed substantially to the decline in populations of anadromous salmonids in the basin (California Department of Water Resources, 1974).

Channel recovery

The 1964 flood appears to have been effective in shaping stream channels of the Eel basin, according to Wolman and Gerson's (1978) criteria, because the changes have persisted in some reaches up to the present (Lisle, 1981; Kelsey and Savina, 1985). In some reaches, channel patterns and flood deposits along the higher margins of channels will be altered little until a flood of equal or greater magnitude recurs (Kelsey, 1977).

Channels have recovered in overlapping stages dependent on a sequence of processes. First, suspended-sediment concentrations declined to pre-flood levels within about 5 years. Second, as excess bed material has been transported downstream, channel beds have degraded to stable levels at or above pre-flood elevations over periods of a few years or longer, and some reaches may remain aggraded into the next century (Kelsey, 1980; Kelsey and Savina, 1985; Lisle, 1981). These periods depend apparently on the volume and coarseness of aggraded material, channel gradient, and distance from sediment source. During channel-bed degradation, hydraulic geometries have recovered to some degree

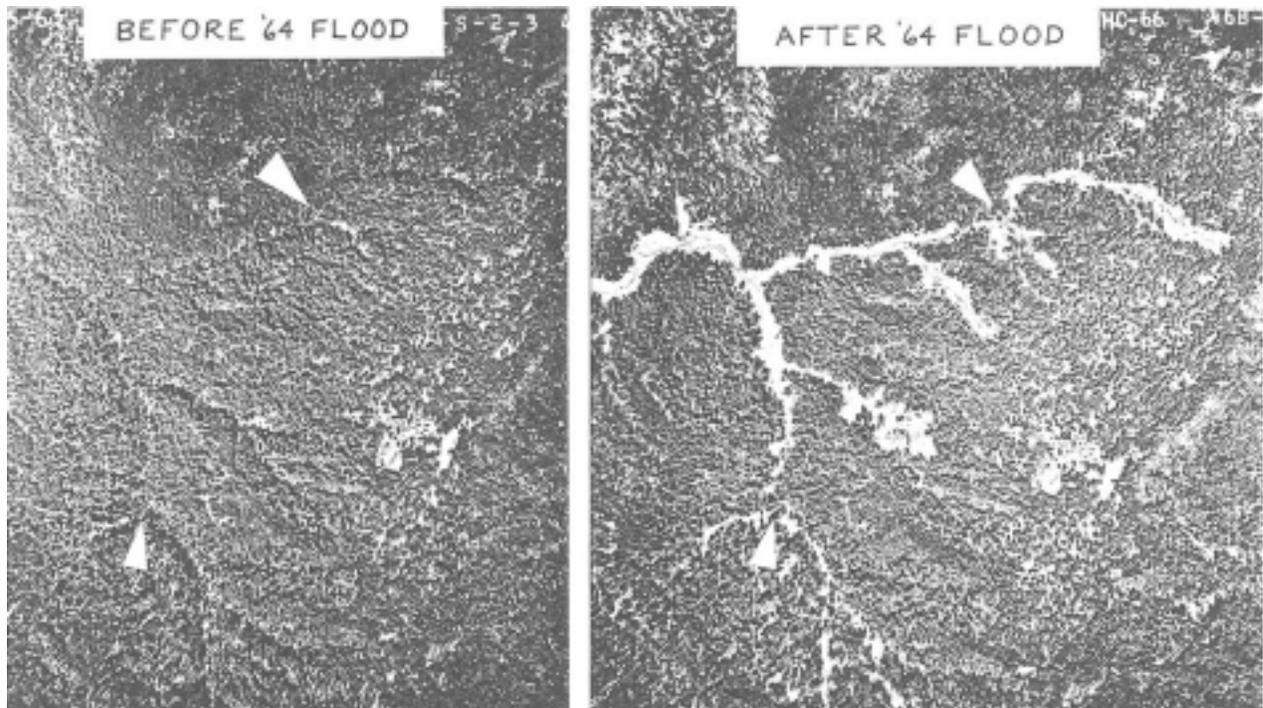


Figure 25. Aerial photographs taken in summers of 1963 and 1966 of the headwaters of the South Fork Van Duzen River, showing changes due to the 1964 flood. (From Kelsey, 1977, with permission). The white arrows identify the same channel reaches on both photos. Lighter areas in the 1966 photo were revegetated by debris avalanches, debris torrents, and widened, aggraded stream channels.

to pre-flood relations. The degree of recovery apparently depends on reestablishment of pre-flood channel widths (Lisle, 1982)--the third phase of channel recovery. Channels in alluvial reaches have incised into flood deposits, leaving a narrower channel bounded by sparsely vegetated flood deposits. Many tributary channels that are bounded on at least one bank by bedrock or colluvium have remained wide, however. Soil creep and dry ravel can be slow in replacing eroded banks, and new bank material is frequently scoured by high flows contained in narrow valley bottoms (Lisle, 1981). Riparian vegetation (primarily red alder and willow), which aids bank accretion along low-flow channel margins, is also subject to scour during high flows. Riparian trees are now well established along many reaches, however, due to the absence of large floods since 1975.

CONCLUSIONS

Erosive bedrock, rapid uplift, high seasonal rainfall, and recent disturbance by man have produced exceptionally high sediment yields from the Eel River basin. Because channels are commonly bounded by hillslopes in narrow valleys, channel morphology and sedimentology are strongly influenced by adjacent hillslope processes, which vary with the lithology and degree of shearing of bedrock. Because of the close linkage between channel and hillslope processes and the occurrence of high runoff events, large floods produce and transport a large proportion of fluvial sediment and cause widespread, persistent changes in

channels. Subsequent remolding of channels by smaller discharges proceeds with the transport of excess sediment out of channels and the reconstruction of streambanks. These sequences of channel recovery can require as long as several decades.