ELSEVIER

Geomorphology 36 (2001) 129–154

GEOMORPHOLOGY

www.elsevier.nl/locate/geomorph

Response and recovery of the Eel River, California, and its tributaries to floods in 1955, 1964, and 1997

Jan Sloan [a,*], Jerry R. Miller [b], Nicholas Lancaster [c]

[a] *Environmental and Resource Sciences Department, University of Nevada, Reno, NV 89509, USA*
[b] *Department of Geosciences and Natural Resources Management, Western Carolina University, Cullowhee, NC 28723, USA*
[c] *Quaternary Science Center, Desert Research Institute, Reno, NV 89512, USA*

Received 9 December 1999; received in revised form 9 March 2000; accepted 27 April 2000

Abstract

Northwestern California is prone to regional, high magnitude winter rainstorms, which repeatedly produce catastrophic floods in the basins of the northern Coast Ranges. Major floods on the Eel River in 1955 and 1964 resulted in substantial geomorphic changes to the channel, adjacent terraces, and tributaries. This study evaluated the changes and the effects of a moderate flood in 1997 through field observations and examination of aerial photographs that spanned from 1954 to 1996. The purpose was to document the nature and magnitude of geomorphic responses to these three floods and assess the rates and controls on the recovery of the Eel River and its tributaries. Channel widening from extensive bank erosion was the dominant geomorphic change along the lower Eel River during major floods. As a result of the 1964 flood, the largest amount of widening was 195 m and represented an 80% change in channel width. Channel narrowing characterized the periods after the 1955 and 1964 floods. More than 30 years after the 1964 flood, however, the river had not returned to pre-flood width, which suggests that channel recovery required decades to complete. A long recovery time is unusual given that the Eel River is located in an area with a ‘‘superhumid’’ climate and has an exceptionally high sediment yield. This long recovery time may reflect highly seasonal precipitation and runoff, which are concentrated in 3–5 months each winter. In contrast to the main stem of the Eel River, the dominant effects of floods on the tributaries of the Eel River were rapid aggradation of channel bed and valley floor followed by immediate downcutting. Dendrogeomorphic data, aerial photographs, and field observations indicate that thick wedges of gravel, derived largely from hillslope failures in upper reaches of the tributaries, are deposited at and immediately upstream of the mouths of tributaries as the stage of the Eel River exceeded that of the tributaries during major floods. In the waning stages of the flood, the tributaries cut through the gravel at a rate equal to the lowering of the Eel and generated unpaired terraces and nickpoints. The complete process of deposition and incision can occur within a few days of peak discharge. Although reworking of some sediment on the valley floor may continue for years after large floods, channel morphology in the tributaries appears to be a product of infrequent, high

* Corresponding author. Current address: 1450 Joanie Court, Reno, NV 89509, USA.
E-mail address: sloan@scs.unr.edu (J. Sloan).

PII: S0169-555X(00)00037-4

magnitude events. The morphology of the tributary channel also appears to be greatly influenced by the frequency and magnitude of mass wasting in headwater areas of small basins.

Keywords: floods; gravel deposits; erosion; channel geometry; Eel River; recovery

1. Introduction

The relationships between discharge, sediment transport, and channel form have been recognized for centuries as critical factors in the design of stable canals (Ackers, 1972). Nonetheless, application of these relationships to natural channels has proved problematic. The documentation of the discharges that are responsible for shaping and maintaining channel form has become a fundamental question in geomorphology. Two important issues have recently led to a renewed interest in identifying the relationships among flood magnitude, frequency, and channel form in any given geological setting. First, restoring and maintaining the structure and function of riparian ecosystems has become a national and international topic of concern (National Research Council, 1992; Naiman et al., 1993; Tellman et al., 1993; Kentula, 1997). Although the number of stream restoration programs in the U.S. and Europe has increased dramatically within the past decade, the overall success of these projects has been inconsistent. Many have been ineffective or have completely failed (Frissel and Nawa, 1992; O'Neil and Fitch, 1992). Although the shortcomings of these projects result from a variety of factors, the lack of understanding of how the design flood (e.g., the 50- or 100-year event) will affect channel form is an important problem.

Second, natural streamflows are increasingly disrupted by water storage and diversion structures, particularly in arid climates and mountainous terrains. It is generally accepted that alterations in water discharge and sediment size and load can lead to changes in channel capacity, pattern, and planimetric configuration (Williams and Wolman, 1984). Given that the geomorphic setting provides the framework for aquatic and riparian ecosystems, these changes can lead to alterations in the composition, density, and successional patterns of biological communities (Gregory et al., 1991; Kondolf and Mitcheli, 1995). Thus, it has been recognized that a determination of the flows that control the characteristics and dimensions of a channel (known as the dominant discharge) is essential to minimize or avoid the impacts of the regulation of flow (Andrews and Nankervis, 1995).

A realistic perception of the relations between floods and system morphology requires a detailed analysis of geomorphic work, recovery time, event ordering, and the recurrence intervals of events capable of entraining bed and bank materials. Geomorphic work is usually estimated in one of two ways. Wolman and Miller (1960) suggested that work done by a river is revealed by the amount of sediment it transports during any given flow. They concluded that in most watersheds, much of the geomorphic work (i.e., much of the sediment transport) is conducted by the sum of rather ordinary events that occur at least once every 5–10 years. Although major floods may carry many times the load of ordinary events (Stewart and LaMarche, 1967; Scott and Gravlee, 1968), they occur so infrequently that the amount of sediment transported is relatively minor when considered on a long-term basis. Many investigators (e.g., Pickup and Warner, 1976; Baker, 1977; Newson, 1980) have evaluated the Wolman–Miller model and found it applicable to most rivers with adequate flow and sediment gaging records. The impact of rare, high magnitude floods, however, may be more important in smaller watersheds in arid climate where rivers carry coarse-grained bedload and have flashy hydrologic regimes (Baker, 1977).

Perhaps a more applicable method of estimating geomorphic work is to assess how extreme precipitation and floods impact form and stability of landforms within the watershed, including slope and valley features. Wolman and Gerson (1978) defined this type of work as geomorphic effectiveness. Implicit in this perception is that major floods may be able to affect the form of the landscape and the changes that are produced may be either long-lived or may be erased quickly as the system reverts to its pre-flood condition. Thus, geomorphic effectiveness is related to the time needed to obscure the impacts of the event on the landscape; a factor called recovery time by Wolman and Gerson (1978). Recovery can be defined in several different ways including the reconstruction of floodplains (Hack and Goodlett, 1960; Schumm and Lichty, 1963), or the return of channel width, hydraulic geometry, bed elevation, or sediment loads to approximate pre-flood conditions (Kelsey, 1980; Newson, 1980; Lisle, 1982; Osterkamp and Costa, 1987; Pitlick, 1993). Geomorphic effectiveness and system recovery are conceptually simple and intuitively appealing concepts. They become complicated, however, because an individual basin with constant physical and biological properties can experience different geomorphic responses in successive floods of similar magnitude (Newson, 1980; Beven, 1981; Kochel et al., 1987; Kochel, 1988), a phenomenon referred to as event ordering by Beven (1981). This indicates that effectiveness is partly controlled by factors other than flood magnitude and basin physiography. The most important parameter seems to be recovery time; specifically, whether the event occurs before the system has fully recovered from the effects of the previous event. The healing interval is generally thought to be climatically controlled. In humid areas, recovery times usually are short (Costa, 1974; Wolman and Gerson, 1978), whereas arid and semi-arid regions usually have much longer recovery times (Wolman and Gerson, 1978; Harvey, 1984).

This paper examines a part of the Eel River and five of its tributaries to document the responses to and recovery from major floods in 1955 and 1964 and to the moderate flood of 1997. Although the term ''recovery'' may be defined in a variety of ways, we use the definition of Wolman and Gerson (1978). For rivers in humid climates such as the Eel River, they predicted a ''relatively rapid recovery of vegetation and hence reconstruction of channel characteristics prevailing prior to the high-magnitude event.'' The study focuses on: (1) the occurrence and timing of changes to channel width, of bed erosion and deposition, and of removal of vegetation along the Eel River and selected tributaries during the floods, and (2) the recovery of the channel landforms to their pre-flood form after the floods. It also at-

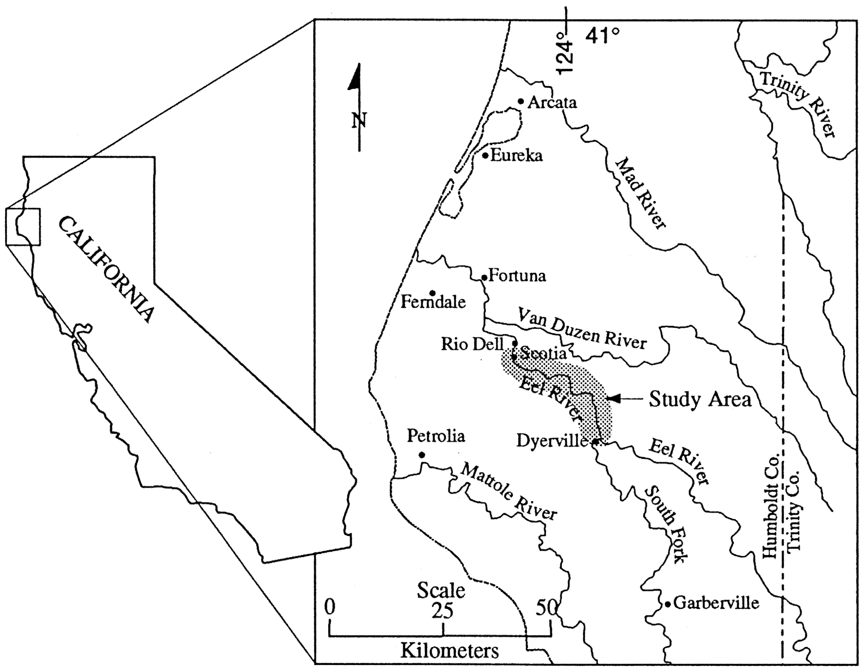

Fig. 1. Location of the Eel River and study area in northern California.

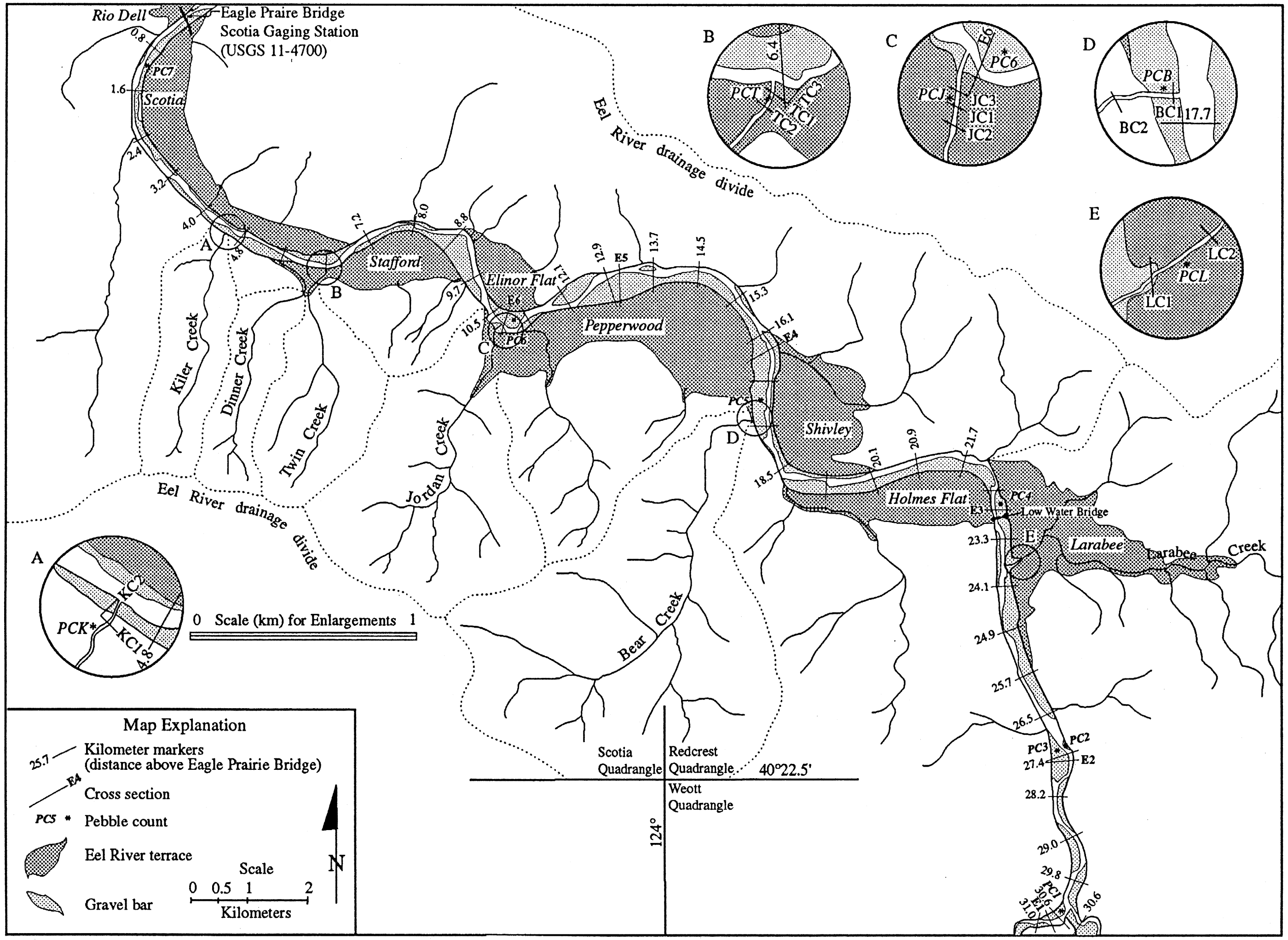

Fig. 2. Location of sample sites, cross-sections, kilometer markers, Eel River terraces, tributaries, and basins. In the upper reaches of the study area, between 25.7 and 31 km, the river flows through a straight, narrow, steep valley. Downstream, the valley widens and the river meanders through the valley forming terraces on the inside of meander bends with bedrock cliffs on the outside. California Highway 101 and the Avenue of the Giants (not shown on map) roughly parallel the Eel River to the south and west. The Pacific Northwestern Railroad (not shown on map) closely parallels the Eel River to the north and east. Names within the shaded terrace areas (for example, Pepperwood and Shively) are names of communities.

tempts to distinguish the different processes and timing of response and recovery between the main Eel River and the tributaries. The intent was to obtain insights into the factors controlling channel recovery and assess the implications of the results in the context of current knowledge of dominant discharge.

2. Study area

2.1. Geographic and geologic setting

The Eel River basin encompasses an area of about 8300 km^2 in northern California. From its headwaters, it flows northwest through the Coast Ranges for nearly 250 km before reaching the Pacific Ocean about 19 km south of Eureka (Fig. 1). Scott Dam, built in 1921 in the upper part of the watershed, created Lake Pillsbury, the only reservoir on the river.

The northern Coast Ranges are underlain by Upper Cretaceous, Lower Tertiary, and Upper Pliocene marine sandstone, mudstone, graywacke, and conglomerate that contain large masses of ultramafic rock, most of which have been altered to serpentine (California Division of Mines and Geology, 1962; Norris and Webb, 1990). The combined effects of high seasonal rainfall, easily eroded bedrock, and high relief make this area one of the most rapidly eroding landscapes in the United States (Judson and Ritter, 1964; Ritter, 1967; Brown and Ritter, 1971). Excluding rivers with glacial or active volcanic sources, the Eel River has the greatest mean annual suspended load (23 million tons (21 million metric tonnes) per year) of any basin its size in the U.S. (Brown and Ritter, 1971; Norris and Webb, 1990).

The Eel River basin lies in the tectonically active region of the Mendocino Triple Junction. Uplift, which began in the late Miocene and continues to the present, has generated northwest-trending folds and faults (Brown and Ritter, 1971). Dated stream terraces document uplift rates of about 4 m per 1000 years at Scotia Bluffs at the north end of the study area (Norris and Webb, 1990). This high rate of uplift affects the rate of incision and the formation of terraces along the Eel River (Merrits et al., 1994).

This study focuses on a 31-km reach of the Eel River between Scotia and the confluence of the South Fork of the Eel River (Fig. 1). This reach was selected for investigation because: (1) A nearly continuous discharge record has been collected at a USGS gaging station at Scotia from 1910 to the present and can be used to characterize the magnitude and frequency of flooding. (2) The area was significantly affected by major floods in 1955 and 1964 (Hofmann and Rantz, 1963; California Department of Water Resources, 1964; Helley and LaMarche, 1968, 1973; Waananen et al., 1971) and by moderate floods in 1938, 1960, 1974, 1986, 1995, and 1997. (3) Aerial photographic coverage of the area is available for every 3–7 years from 1954 to 1996, tightly bracketing the two largest floods on record in 1955 and 1964.

Within the study area, the Eel River alternates between straight, narrow reaches constrained within steep bedrock valleys and reaches with wide valleys and terraces on the inside of meanders (Fig. 2). Terraces vary from about 9 to 23.5 m above the channel and were historically covered with redwood forests. The terraces, however, were largely cleared for farmland, and until the 1950s and 1960s, sustained small communities.

Of the many tributaries to the Eel River in the study area, five were selected as representative for detailed study (Fig. 2 and Table 1). Kiler and Twin Creeks have small, elongate basins, high gradients, and responded differently to the 1955 and 1964 floods. Jordan and Bear Creeks have larger, pear-shaped basins with lower gradients. The mouths are within the Humboldt Redwoods State Park on rela-

Table 1
Comparison of basins in study area

Basin	Basin size (km^2)	Channel gradient (m/km)
Kiler Creek	4.1	185
Dinner Creek	3.5	181
Twin Creek	5.5	156
Jordan Creek	12.3	115
Bear Creek	22.2	66
Larabee Creek	231	12
Eel River in study area	410	0.8
Eel River overall	8288	

tively undisturbed land. Larabee Creek has the largest basin and lowest gradient.

2.2. Regional climatic setting

Climate along the northern California coast is moderate with uniform annual temperatures averaging 12.6°C, fog, and prevailing west to northwest winds. Precipitation averages about 123 cm/year at the Scotia station and is distinctly seasonal; about 75% occurs between the months of November and March. About 83% of annual runoff occurs during the same period (U.S. Geological Survey, 1997). This seasonal precipitation and runoff greatly influence the timing and characteristics of floods. During some winters, an atmospheric high-pressure cell, which normally is situated over northern California allowing cold fronts moving inland from the northwest to dump snow on the Coast Mountains, moves westward over the Pacific Ocean. This shift in the location of the atmospheric high-pressure allows massive low-pressure systems to develop over the ocean and feed a succession of warm, moist storms, which move inland from the southwest and generate large quantities of precipitation (Hirschboeck, 1988). The largest floods of record, including those of 1955, 1964, and the more moderate flood of 1997, occurred when these atmospheric conditions prevailed and large quantities of rain fell on existing snow and saturated soils.

Flooding in 1955 was the result of almost continuous rainfall from December 17 to 27, which melted accumulated snow at elevations up to 3048 m (Goodridge, 1996). The maximum 8-day total rainfall exceeded 102 cm and was reported at Honeydew in the Mattole River basin immediately to the south of the Eel River. High temperatures and wind velocities accompanied the storm (Hofmann and Rantz, 1963). Precipitation during the storm totaled 40 cm at the Scotia station where peak discharges were measured at 15,317 m^3/s on December 23, 1955 (Figs. 3 and 4). Nine years later, to the day, December 23, 1964, a larger flood occurred on the Eel River. The 1964 flood was generated by meteorological conditions similar to those occurring in 1955. Prolonged precipitation on a heavy snowpack from December 19 to 24 resulted in higher than ever recorded rainfall on every major stream in northern California including the Eel River. The greatest 6-day rainfall for the Eel River basin was 80.5 cm at Branscomb, about 60 km south east of the study area (Goodridge, 1996). The peak discharge at Scotia for the event reached 21,291 m^3/s, 39% higher than the 1955 flood (Figs. 3 and 4). This is similar to the peak discharges recorded on the Mississippi River north of St. Louis, MO, during the floods of 1993

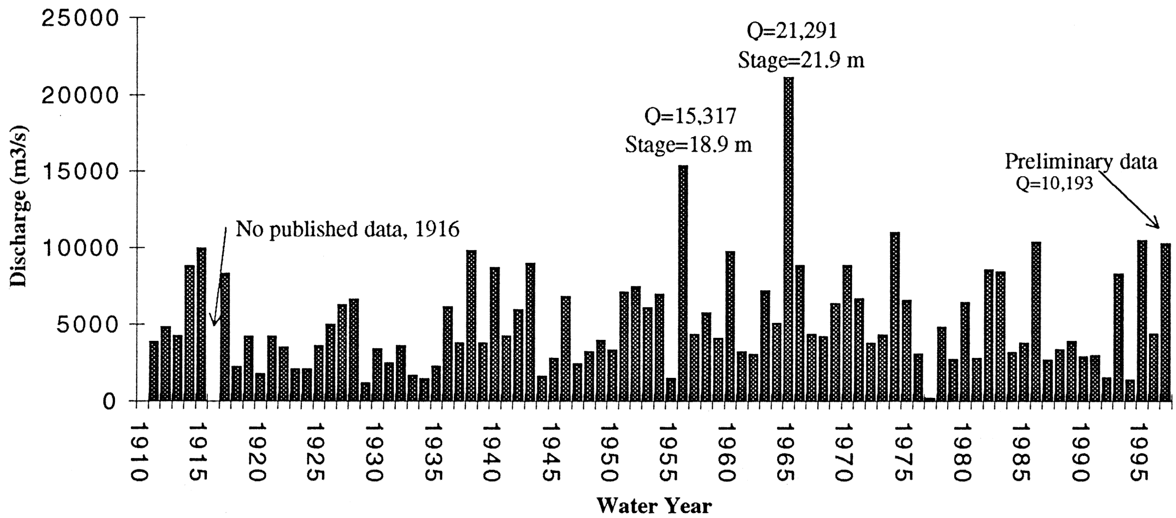

Fig. 3. Peak discharge for each recorded water year at the Scotia Gaging Station, Eagle Prairie Bridge (U.S. Geological Survey station number 11477000). Prepared from data provided by the U.S. Geological Survey (Robert Meyer, written communication, 1998).

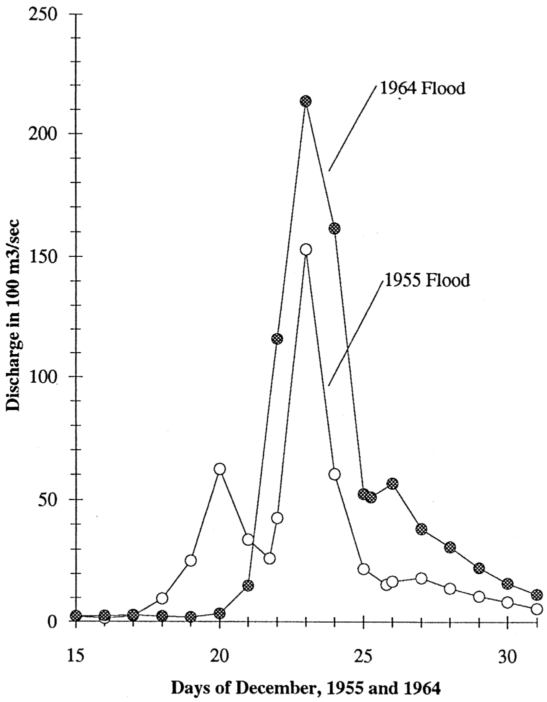

Fig. 4. Flood hydrographs for the 1955 (Hofmann and Rantz, 1963) and 1964 floods (Waananen et al., 1971). The 1964 flood exceeded the 1955 flood by 5974 m^3/s at peak discharge and lasted about 24 h longer.

(Mount, 1995), but from a basin only about 1.5% of the size.

Recent analyses by the U.S. Geological Survey (Robert Meyer, written communication, 1998) classify the 1964 and 1955 floods as having recurrence intervals of about 200 and 50 years, respectively. Preliminary data from the U.S. Geological Survey indicates that the peak discharge during the 1997 flood was 10,193 m^3/s, which represents a recurrence interval of 12–15 years. Before the 1955 flood, the greatest known flood occurred in the winter of 1861 and 1862, and was estimated to be about the same magnitude as the 1955 flood (Hofmann and Rantz, 1963).

3. Methods

Changes in channel and valley morphology during and after the 1955, 1964, and 1997 floods were determined by combining field studies with an interpretation of aerial photography and historical documents. Topographic cross-sections were surveyed at right angles to the valley floor at six locations across the Eel River and 12 locations on tributaries in 1996 (Fig. 2, Sloan, 1997). Three of the tributary cross-sections were resurveyed in June and October 1997. The locations of the cross-sections on the Eel River were chosen to illustrate the topographic relations between the channel, terrace levels, and steep banks. Cross-sections across the tributaries were within 0.5 km of the mouth, where most erosional and depositional changes occurred during floods. Longitudinal profiles of terrace surfaces were surveyed along Jordan and Bear Creeks to document spatial variations in the topographic relations of surfaces along the valley floor (Fig. 5). All surveys were measured with an Electronic Distance Meter (EDM).

The ages of trees growing on the margins of active channels give an estimate of the time necessary for revegetation after floods. To determine the age of a tree, an incremental tree coring device was

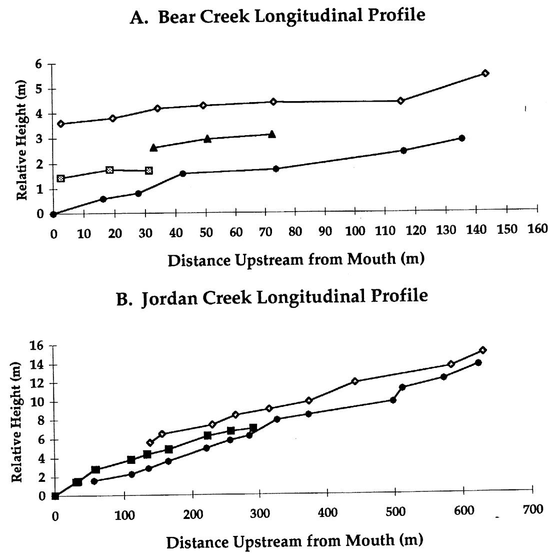

Fig. 5. Longitudinal profiles on Bear Creek (A) and Jordan Creek (B) measured in the summer of 1996. The surfaces delineated with closed circles represent the channel bed. Higher surfaces represent gravel terraces that tend to converge with the channel bed upstream.

used to extract two, 4-mm diameter cylinders of wood at right angles to one another about 1–1.25 m above the ground. Tree cores were mounted, sanded to bring out the grain, and viewed under a binocular microscope to count tree rings.

Grain-size distribution of the terrace and channel deposits was determined at 28 sites. Sixteen samples were analyzed by standard sieving techniques (Folk, 1968). Statistical parameters regarding sediment size were calculated using a program entitled Granny (McLane, 1989). Gravel size at 12 sites were determined using pebble-counting techniques after the procedures of Wolman (1954). Sloan (1997) provides a more detailed description of sedimentology of the deposits, including the median, mean, and standard deviation for the intermediate dimension of the clasts.

Ten sets of aerial photographs at 3–7 year interval between 1954 and 1996 provide an exceptional historic record of the geomorphic changes along the Eel River and the mouths of its tributaries (Table 2). Changes in channel width and position were determined by mapping the active channel on aerial photographs and comparing photos of different years. The active channel was defined as the riverbed and its associated gravel bars discernible on aerial photographs. The boundary of the active channel was drawn at the break in slope between the nearly flat surface formed by the channel bed plus associated gravel bars, and the steeper banks of the terraces and bedrock cliffs. After the active channel was drawn, a composite map of the active channel in the study area was compiled for each set of photos. Compilation consisted of enlarging or reducing the active channel traces to a scale of 1:24,000 and projecting them onto mylar using a Vertical Sketchmaster. The composite drawing of each set of photos was then placed on the previous composite and comparisons of channel width were made at 41 sites, about every 0.8 km upstream from the Eagle Prairie Bridge (Fig. 2).

The resolution of the aerial photographs and accuracy of measurements and data transfer were evaluated in several ways to determine what magnitudes of change could be identified. Even on the smallest scale photos (1:34,800; 1992), two distinct railroad tracks, which are about 1.4 m apart, can be resolved in stereo. Therefore, features as small as 1.4 m can be identified in all cases.

The accuracy of the measurements of channel width was determined by comparing Eel River cross-sections surveyed in the field in 1996 with the trace of the active channel compiled on the 1996 aerial photographs. The difference between widths determined in the field and from aerial photographs averaged 11 m and ranged from 1 to 23 m, at cross-sections E6 and E2, respectively. Twenty-three meters represent only a 7% error on cross-section E2. Combining the precise resolution of the aerial photographs with the uncertainty involved in transferring data from photographs of different scales, we consider a change in channel width of 24 m (1 mm at 1:24,000 scale) to be a conservative estimate of what can be determined accurately and reproducibly.

The average daily discharge at the Scotia gaging station for the date of each set of photographs indicates that all photographs were taken when the river was at similar rates of low flow. None were taken during floods. Recorded stage for aerial photographs taken on 6/5/96 and 8/14/63 (Table 2) indicate that the difference between the lowest and one of the highest stages for photo sets is 0.7 m. This similarity in water stage minimizes the errors involved in determining changes in channel width (riverbed plus the associated gravel bars) by comparing sets of aerial photographs.

Table 2
Aerial photograph coverage

Date	Approximate scale	Source	Discharge (m^3/s)[a]	Available stage (m)
7/27/54	1:24,000	Humboldt[b]	6.7	
6/26/60	1:14,500	Humboldt	25.8	
8/14/63	1:13,920	Humboldt	5.8	2.4
6/14/66	1:13,780	Humboldt	15.7	
5/7/74	1:13,390	Humboldt	113.5	
6/17/81[c]	1:29,000	Humboldt	14.9	
5/6/84	1:34,800	WAC[d]	118.1	
6/18/88	1:33,950	WAC	24.5	
4/1/92	1:34,800	WAC	107.3	
6/5/96	1:26,750	WAC	98.2	3.1

[a] Discharge at time of aerial photograph.
[b] Humboldt County Public Works Department, Eureka, CA.
[c] Available photographs did not cover entire study area.
[d] WAC, 5200 Conger Street, Eugene, OR.

Aerial photographs also allowed assessment of the changes in vegetation caused by the floods along the Eel River and its tributaries and the regrowth of plant communities as the river recovered from floods. Locations showing extensive geomorphic and vegetative changes were selected as sites for stream-cross-sections and tree cores. The different scales of aerial photographs allow different sizes of vegetation to be identified. Vegetation of about the same diameter as the distance between rails (1.4 m) is visible on the 1992, 1:34,800 photos. Vegetation with a diameter half this size can be seen on the largest scale photos (1:13,390; 1974).

Aerial photographs covering the Dinner and Twin Creek basins in 1954, 1960, 1963, and 1974 were examined to identify hillslope failures or sites of mass wasting that may have contributed sediment to the tributary valleys during or after flooding.

Nearly continuous discharge records are available from U.S. Geological Survey gaging station 11477000, which was established on the Eagle Prairie Bridge between Scotia and Rio Dell in 1910. Gaging information from this station was used to plot maximum annual discharge and to estimate the low-water streambed elevations. Discharge and stage height were obtained from the U.S. Geological Survey (Robert Meyer, written communication, 1998). Low-water streambed elevation above the gage datum at the Scotia station was calculated to assess the changes in channel bed during and after floods. Hickey (1969) defined the low-water elevations of the streambed as ''the mean elevations of the low-flow channel'' and calculated the elevations using the Discharge Measurement Notes recorded each month at the station. He subtracted the average depth of water from the gage height during low-flow periods to obtain the average elevation of the streambed with reference to gage datum. Hickey's data covered 1910–1965. Using the same method, data were extended to 1995 for this study (Fig. 6).

4. Response and recovery of tributaries

The geomorphic effects of floods on tributaries and the timing and nature of recovery from floods were studied by interpreting aerial photographs from 1954 to 1996, together with field observations and measurements made in 1996 and 1997.

4.1. Observations from aerial photographs

Although Twin and Dinner Creeks are similar in size and gradient (Table 1), they responded very differently to the 1955 and 1964 floods. Before the 1955 flood, tributary valleys within the study area were characterized by dense riparian vegetation, which is easily distinguished on aerial photographs from the surrounding redwoods (Fig. 7A). No hillslope failures were observed within the basins of Twin or Dinner Creeks on the 1954 photos. On the 1960 aerial photographs, hillslope failures totaling about 84,000 m^2 (about 2.4% of basin) were present from about 1.6 m upstream of the mouth of Dinner

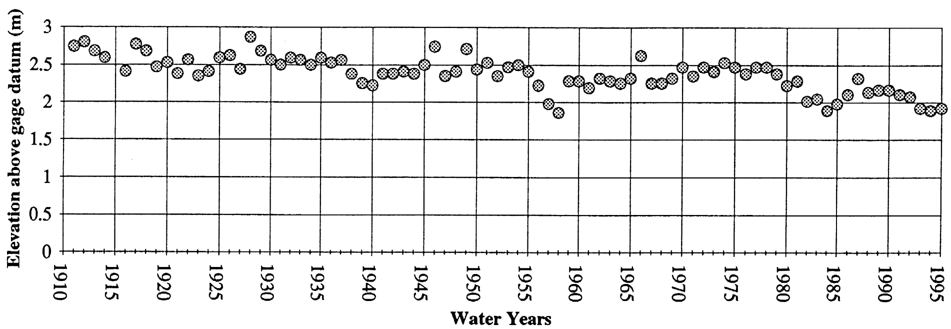

Fig. 6. Annual low-water streambed elevation at the Scotia Gaging Station, Eagle Prairie Bridge. Method of plotting after Hickey (1969). Elevation steadily decreases about 0.8 m during period of record. Irregular fluctuations apparently do not correlate to years with high peak discharge (Fig. 3).

Creek to its headwaters. Each hillslope failure extended to the valley floor. A large (30,000 m^2), noticeably deep, landslide was evident about 1.7 km upstream of the mouth. Downstream of slope failures, nearly all riparian vegetation was removed across the valley floor (Fig. 7B). The creek itself can be seen as a narrow channel meandering through the light colored gravel deposits. Although the exact timing and cause of these hillslope failures are uncertain, they likely formed as a result of heavy rainfall during the 1955 flood.

In contrast, Twin Creek appeared less affected by the 1955 flood (Fig. 7B). Four small hillslope failures totaling about 11,100 m^2 (about 0.2% of basin) were observed on 1960 photos at the headwaters of the Twin Creek basin. No changes in valley shape or vegetation, however, could be detected on aerial photographs (Fig. 7B). The difference in response between Twin and Dinner Creeks to the 1955 flood may occur because of the size of the hillslope failures and the distance from the mouth of the creek. On Twin Creek, sediments may have been stored at the base of hillslopes as debris fans between the 1955 and 1964 floods.

In the 1966 photos, after the 1964 flood, vegetation had been removed from the lower reaches of Twin Creek and gravel deposited along the valley floor (Fig. 7C). Although 1966 aerial photographs only cover about half of the Twin Creek basin and 1974 photographs only covered about 90% of the basin, many small hillslope failures totaling about 13,500 m^2 were observed between 1.4 and 2.8 km

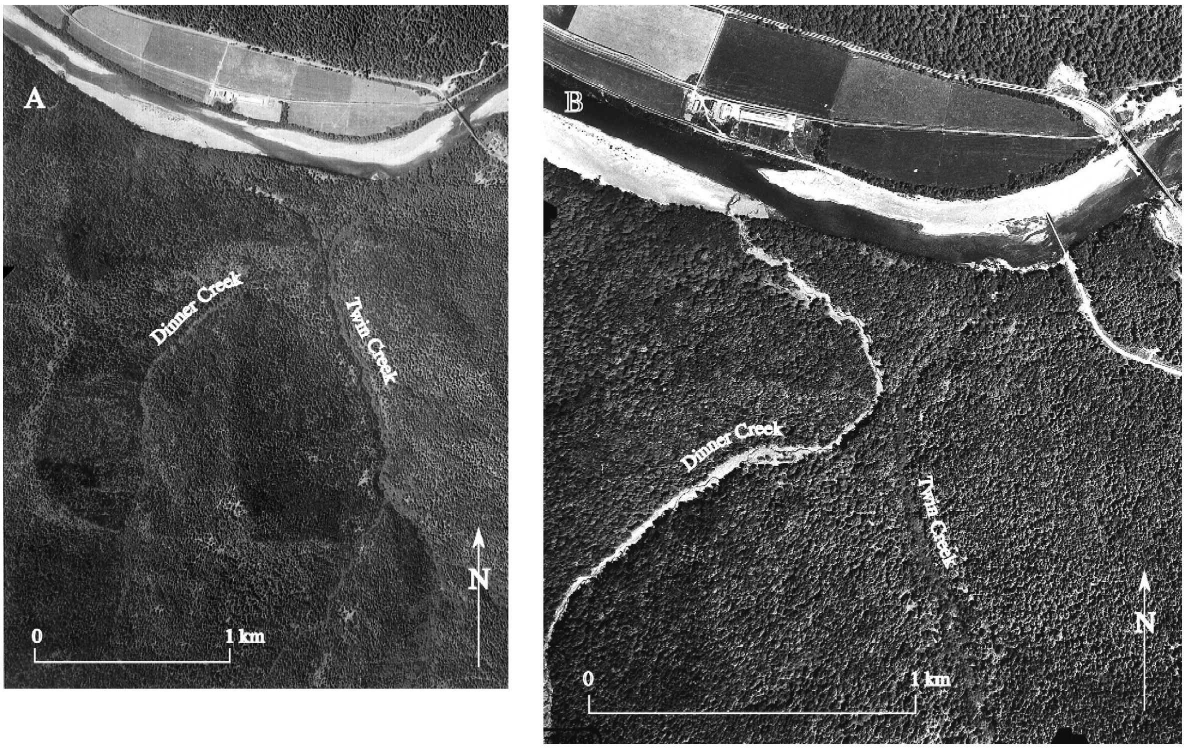

Fig. 7. (A) Dinner and Twin Creeks before the 1955 flood (1954 photograph). Riparian vegetation obscures the valley floors of both creeks. (B) Dinner and Twin Creeks after the 1955 flood (1960 photograph). Riparian vegetation has been removed and new gravel deposited along Dinner Creek. In contrast, Twin Creek appears to be unaffected by the 1955 flood. Hillslope failures were identified on the 1960 photos upstream in the Dinner Creek basin but not in Twin Creek basin. (C) Dinner and Twin Creeks after the 1964 flood (1966 photograph). Riparian vegetation has been removed and gravel deposits are visible in both Creeks. Hillslope failures were identified on the 1966 photos in both basins.

Fig. 7 (*continued*).

upstream of the mouth of Twin Creek on the 1974 photos. The valley floor downstream and upstream of the hillslope failures was devoid of vegetation suggesting that more hillslope failures were present in the headwaters of the basin outside the aerial photographic coverage. In the Dinner Creek basin, at least one hillslope failure about 1.5 km upstream of the mouth was reactivated and enlarged to about 15,800 m^2 from its pre-1964 flood size of 5580 m^2. It is likely that reactivation and enlargement of the hillslope failure were the result of heavy rainfall during the 1964 flood.

A hillslope failure occurred during the 1997 flood in a 0.75 km^2 basin south of the community of Stafford. The debris flow removed houses from foundations and destroyed vegetation.

The 1960 and 1963 aerial photographs show that vegetation was not re-established along the tributaries between the 1955 and 1964 floods. Revegetation of the tributaries was first visible on the 1981 photos. Vegetation density and size appear to increase steadily on the 1984–1996 photos, which show riparian vegetation about as extensive as in 1954. Dendrochronologic data support observations from aerial photos. The oldest trees cored on a tributary are 20 years old, and were found on Kiler and Larabee Creeks. They began growing in the mid-1970s.

The 1997 flood also significantly affected vegetation on the tributaries. Smaller vegetation (herbaceous plants, vines, and shrubs) was removed, mostly scoured out by the flood but some may have been

Fig. 8. New gravel deposits 4 days after the 1997 peak discharge on the Eel River. (A) At this location (about 0.2 km upstream of cross-section, Fig. 9B), at least five new terrace levels exist on Twin Creek, which are interpreted to have formed as the thalweg switched back and forth across the valley while incising into new gravel deposits. An abandoned channel (arrow) indicates that the creek flowed at a higher level and in a slightly different direction only a few days earlier. Lack of slackwater deposits indicates that the Eel River did not back up to this location. Trees that appear to be growing from the upper level are tops of trees covered by about 5 m of new sediment. (B) Kiler Creek (about 10 m downstream of cross-section, Fig. 9A), with five or six terrace levels in new gravel deposits. Slackwater deposits cap gravel in background (arrow).

buried by gravel deposits. Some trees were removed, and others were buried by gravel (Fig. 8). Some trees that were buried by 1997 gravel deposits were partially re-exposed by subsequent erosion within the same flood event.

4.2. Field observations during 1996

Topographic cross-sections measured in 1996 across downstream reaches of the tributaries show multiple terrace levels, which were generally un-

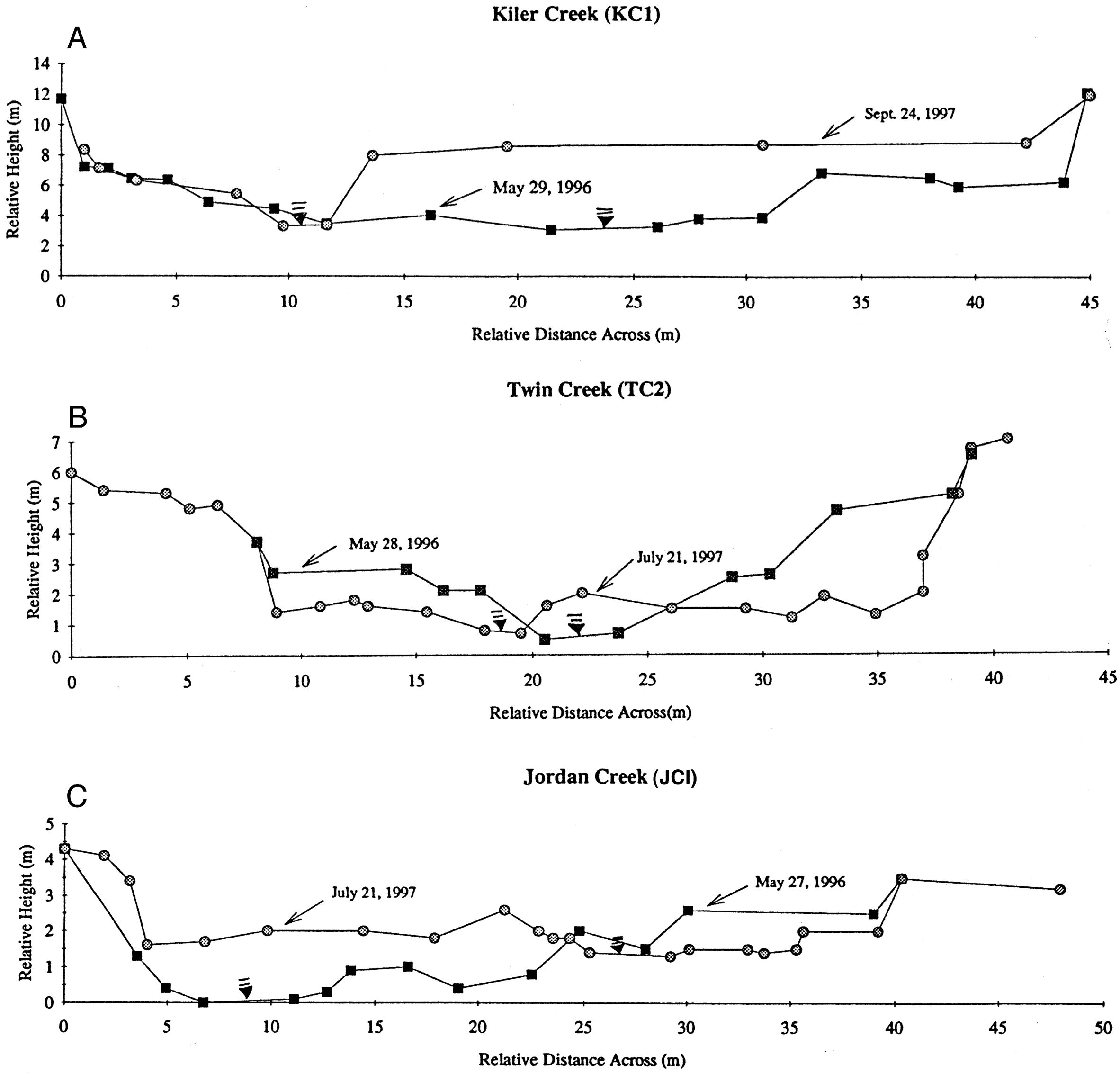

Fig. 9. Comparison of cross-sections measured in 1996 and 1997 across Kiler, Twin, and Jordan Creeks (see Fig. 2 for locations). (A) Almost 5.5 m of new sediment exists at Kiler Creek after the 1997 flood and the channel eroded to about the same elevation as 1996. Though it was impossible to make exact measurements immediately after the 1997 flood, it appears that much of the channel incising through new sediments took place in a matter of days. (B) The cross-sections on Twin Creek suggest that during the 1997 flood, a period of scour of the existing gravels occurred in the tributary valley, followed by deposition of at least 2 m of gravel (at 22 m), followed by more scour to form the new valley shape. The channel elevation in 1997 is about the same as in 1996. (C) In contrast to Twin and Kiler Creeks, the elevation of the channel bed on Jordan Creek is almost 1.5 m higher in 1997 than in 1996.

paired across the valley floors (Fig. 9). Longitudinal profiles along the channel bed and selected terrace treads on Jordan and Bear Creeks show that the terrace surfaces converge and the number of terrace levels decreases upstream (Fig. 5).

Terraces on tributaries are composed primarily of gravel that is locally interbedded with fine to medium sand. Gravel clasts are predominantly rounded sandstone and range from less than 1 to 40 cm in diameter. Median intermediate clast diameter on the surface of selected terraces decreases with elevation above the 1996 channel bed. One or two lenses of light brown to gray, fine to medium sand are interbedded in gravel deposits. A representative stratigraphic section on Bear Creek, about 0.3 km upstream of the mouth, illustrates this relationship of interbedded sand and gravel. The lowest exposed unit consisted of a clast-supported, moderately imbricated gravel, with a medium-to-coarse sand matrix. The base of this unit was not exposed in the 1996 channel, so only a minimum thickness of 0.7 m could be determined. This gravel was overlain by a light brown to olive gray, moderately well sorted, fine-to-medium sand which was, at most, 0.7-m thick and thinned and pinched out up valley. An overlying 0.6 m-thick gravel was similar to the basal gravel. A thin (10–12 cm) discontinuous lens of sand was present near the top of this unit. The lower and upper sands are similar in grain-size to a slackwater deposit collected in January of 1997. This similarity and sand lenses that thin and pinch out upstream along the tributaries suggest that they are also slackwater deposits. Bedrock or incised Eel River terrace deposits are only exposed in a few places near the mouths of tributaries.

4.3. Field observations after the 1997 flood

Observations made within 4 days after peak discharge of the 1997 flood provide important insight into how tributaries in the study area respond to floods. Thick sequences of gravel were deposited at the mouths of tributaries during the 1997 flood. At Twin and Kiler Creek, about 5 m of new gravel was exposed 4 days after peak discharge on the Eel River (Figs. 8 and 9). At the mouth of Jordan Creek, newly deposited gravel was at least 1–3-m thick (Fig. 9) and extended upstream more than 0.75 km. Exposed gravel deposits at the mouth of Larabee Creek were estimated to be at least 1–2-m thick. At the time of observation, the mouth of Bear Creek was clogged with log debris that covered any new gravel deposited.

Each of these new gravel deposits had already been deeply incised by tributaries within 4 days after peak discharge on the Eel River (Figs. 8 and 9), which indicates rapid downcutting at the mouths of tributary channels. Incision generated new unpaired terraces within the tributary valleys, which resemble terraces surveyed in the summer of 1996. The new terraces were likely created as the tributary channel eroded through the recent gravel deposits and migrated from one side of the valley to the other in response to lowering of the base level as the Eel River receded. For example, as many as five new terrace levels were observed on Kiler and Twin Creeks (Fig. 8).

Resurveys of the 1996 tributary cross-sections on Kiler, Twin, and Jordan Creeks during the summer and fall of 1997 illustrate that large amounts of new gravel were deposited during the 1997 flood and were almost immediately incised. Channel beds in Kiler and Twin Creeks eroded to about the same elevations as they were in 1996, whereas Jordan Creek did not erode as deeply as the 1996 level. At Jordan Creek, at least 3 m of gravel were deposited in the channel, but the creek had incised through only about 1.5 m (Fig. 9). On all three tributaries, the thalweg was in a different location in 1997 than in 1996. Comparison of the summer 1997 cross-sections with visual observations made in January 1997 indicate that almost all downcutting occurred within 4 days after peak discharge of the Eel River.

Sandy sediments resembling slackwater deposits capped gravel deposits on the studied tributaries after the 1997 flood. Sandy deposits were also observed adjacent to the Eel River after the 1997 flood where water backed up onto roads leading down to the River. A sample collected on the terrace at Shively at km marker 17.7 is composed of fine, poorly sorted sand, similar to samples collected in 1996 and interpreted as slackwater deposits produced from previous floods. This supports the interpretation that sand lenses interbedded in older gravel deposits are slackwater deposits.

5. Response and recovery of the Eel River

The analysis of the response and recovery of the Eel River to flooding focused on changes in channel width and elevation of the channel bed from 1954 to 1996 using aerial photographs and gaging station measurements. The dominant geomorphic response of the Eel River was widening during floods and narrowing after floods. Widening was measured at 7 of the 41 sites between the 1954 and 1960 photos (Fig. 10) which bracket the 1955 flood. Extensive widening was measured at km markers 12.9 (17% increase in width) and 16.9 (26%). Similarly, widening was measured at 15 of the 41 sites between 1963 and 1966 photos, which bracket the 1964 flood (Fig. 10). Extensive widening was observed at km markers 8.8 (80%), 9.7 (57%), 12.1 (55%), 16.1 (40%), and 16.9 (28%). Widening presumably resulted from erosion during the respective floods. The only major widening not associated with the 1955 or 1964 floods was at km marker 18.5 (71%) between 1974 and 1984 and at km marker 14.5 (76%) between 1992 and 1996, which could be the results of the 1974 and 1995 floods. The only major channel narrowing resulting from floods was at km marker 13.7 after the 1955 flood and is primarily from the straightening of a meander during the flood.

The percentage of locations that indicate widening, narrowing, and less than 25 m of change document the relative importance of widening and narrowing during and after floods (Fig. 11). By considering only the type of change occurring at each marker, the magnitude of change was eliminated, which prevents a large measurement of widening from overshadowing a smaller measurement of narrowing. Based on comparison of the type of change for each set of photos, widening is dominant when comparing photo sets that bracket the 1955 and 1964 floods and narrowing is generally dominant when comparing photo sets between and after floods (Fig. 11).

With one exception, channel width after the 1955 flood had not returned to pre-flood conditions before the 1964 flood at sites that exhibited more than 25 m of channel change. Similarly, none of the sites that exhibited more than 25 m of channel widening during the 1964 flood had returned to pre-flood conditions by 1996, more than 30 years after the event.

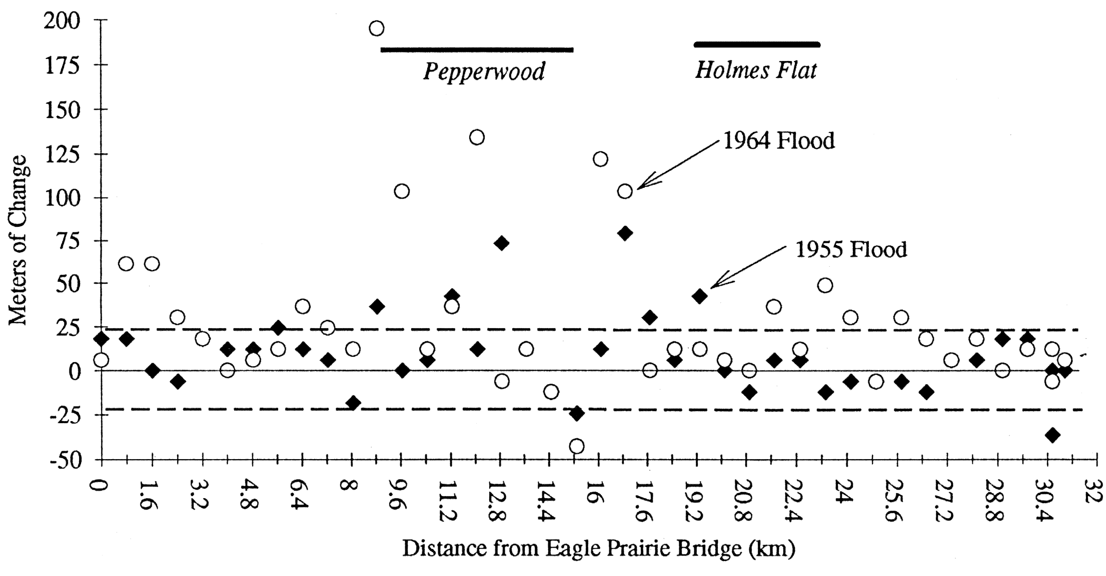

Fig. 10. Changes in channel widths between photo sets bracketing the 1955 and 1964 floods. Points above the zero line represent widening and points below the zero line represent narrowing. Changes in width between 24 and −24 m (dashed lines) were considered insignificant in this study (see Section 3). The dominant process of change during floods is channel widening. Most widening occurred by erosion of the Pepperwood terrace between 10.5 and 16.9 km upstream from Scotia.

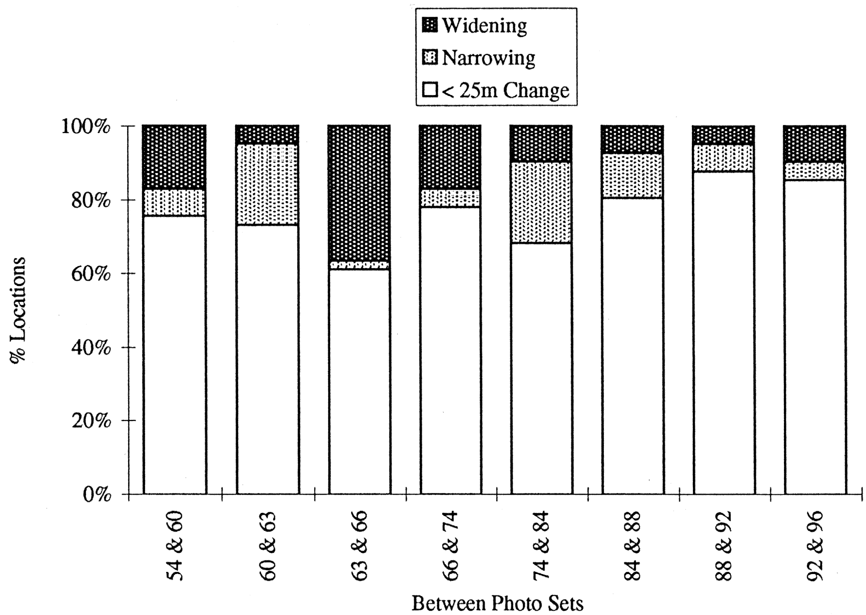

Fig. 11. Percent of locations (km markers) showing widening, narrowing, or less than 25 m of change in channel width between photo sets. Widening is more extensive than narrowing when comparing photographs bracketing the 1955 and 1964 floods, and narrowing is more extensive than widening in most of the comparisons between and after the floods, during the period of recovery.

Changes in the elevation of channel bed related to flooding or recovery from flooding proved difficult to quantify at closely spaced intervals along the river. The most reliable data were obtained at the Scotia gaging station. Here, low-water stages were used to assess long-term changes in the elevation of the channel bed by updating the results presented by Hickey (1969). Elevation of the streambed at the Scotia gaging station decreased about 0.8 m in 85 years (Fig. 6). Short-term variations in the elevation of the streambed do not appear to correlate with floods but may result from minor measurement errors or periodic migration of gravel bars beneath the Eagle Prairie Bridge. In either case, floods do not appear to be an important factor.

Local, long-term incision was observed on aerial photographs near cross-section E5 (Figs. 2 and 12). After the 1955 flood, a large, flat, gravel surface

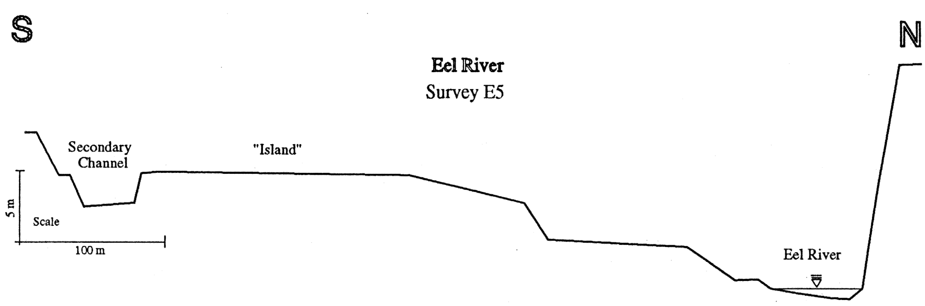

Fig. 12. Cross-section looking downstream across the Eel River measured in October 1996 (see Fig. 2 for location). A secondary channel on the south side of the valley now separates the island from the bank. Downcutting of the thalweg of the Eel River since the 1955 flood created an island, which remains above water in all but the largest winter floods.

extended from the south bank toward the thalweg in the area of cross-section E5. In subsequent aerial photographs, the Eel River appears to have incised into the bed material along the north side of the channel, and a secondary channel had cut into the gravel surface on the south side. The net result was the formation of an island (Fig. 12), which, in 1996, had 12-year-old cottonwood trees on the surface.

The Eel River exhibited a continued phase of aggradation after the 1964 flood, near the low-water bridge from Holmes Flat immediately downstream of the confluence of Larabee Creek (Fig. 2). When Pacific Lumber constructed the bridge in 1937, the bridge was about 6 m above the riverbed (Humboldt County Department of Public Works, 1996). When purchased by Humboldt County in 1959, the bridge was at essentially the same height above the riverbed. Although no measurements are available, County records indicate significant aggradation since at least 1969. An August 1987 photograph (Humboldt County Department of Public Works, 1996) indicates the channel bed was between 1 and 2 m below the bridge. In the summer of 1996, the channel bed was less than 0.5 m below the top of the bridge and in the summer of 1997, the channel had to be dredged to allow water to flow beneath the bridge.

Aerial photographs indicate the 1964 flood had a much greater impact on riparian vegetation than did the 1955 flood. Although inundated during the 1955 flood, gravel bars and banks along the Eel River had similar species of riparian vegetation in the 1954 and 1960 photos. The only exceptions are two places near Shively where vegetation was removed from the east bank downstream of the confluence of Larabee Creek. In contrast, the 1966 photos, after the 1964 flood, show much less riparian vegetation than do the 1963 photos. Vegetation was removed in several places along both banks of the Eel River and from terraces by the 1964 flood. Removal of riparian vegetation was particularly notable near Stafford (between km marker 7.2 and 8.0), Pepperwood (at km marker 13.7 and between km markers 15.3 and 16.1), and Shively (between km markers 16.9 and 17.7, Fig. 2).

New growth on the banks of the Eel River after the 1964 flood was first observed on the 1974 aerial photographs. Tree cores confirm the observations from aerial photographs. The oldest trees on banks and terraces, where vegetation had been removed, are 25 years old, which suggests that they began growing in the early 1970s.

6. Discussion

The lasting impacts of catastrophic floods on fluvial landscapes, or geomorphic effectiveness as defined by Wolman and Gerson (1978), is a function of the magnitude of flood-initiated erosion and deposition, and the subsequent recovery of the river to the form and process rates that characterized it before the flood. The nature and magnitude of geomorphic alterations during rare, high magnitude flooding have been studied extensively, and are thought to be strongly influenced by climate (Baker, 1977; Wolman and Gerson, 1978; Kochel, 1988). Substantial variability, however, exists within any one climatic regime (Hack and Goodlett, 1960; Schumm and Lichty, 1963; Stewart and LaMarche, 1967; Baker, 1977; Moss and Kochel, 1978; Kochel et al., 1982; Kochel, 1988). In an analysis of the literature through the mid-1980s, Kochel (1988) argued that the magnitude of landform modification during a flood is spatially variable and is dependent on the complex interplay between the drainage basin and channel. Within any given climatic region, the most important effects on landscapes are in high gradient, coarse-grained channels in headwater areas, particularly those characterized by abundant bedload (Kochel, 1988).

The data collected in this study are consistent with previous studies in that the nature of the geomorphic impacts of the 1955, 1964, and 1997 floods differ greatly between the larger main stem of the Eel River and the smaller tributaries. The geomorphic effects on tributaries were characterized by extreme changes in channel and valley morphology and channel position. In contrast, the predominant impact along the Eel River was channel widening by localized bank erosion.

It seems reasonable to suggest that bedload size and channel gradients can be used to explain the differences in response of the Eel River and its tributaries. The tributaries generally have coarser bedload material, higher basin relief ratios, and steeper channel gradients than the main stem of the Eel River. Equally important is the proximity of the tributary channels to the sites of mass wasting that provide an abundance of coarse-grained debris.

6.1. Geomorphic effectiveness of major floods on the lower Eel River

The primary response to flooding along the Eel River was localized channel widening. The uneven distribution of channel widening within the study area indicates that some reaches are more prone to erosion than others. Differences may reflect the nature of the bank, height of the bank above the channel, vegetation, and depth of flow during the floods. For example, most widening in 1955 and 1964 occurred between km markers 10.5 and 16.9 with the erosion of the terrace at Pepperwood (Figs. 2 and 10), which stands about 9 m above the channel. The area also underwent minor widening during the moderate 1997 flood (Sloan, 1997). This terrace was inundated in the 1955 and 1964 floods and was likely flooded by many of the more moderate winter floods since then. The community of Pepperwood and extensive farmlands stood on the terrace before the 1964 flood, and sustained extensive damage during the flood.

In contrast, the terrace at Holmes Flat, 3–4 km upstream of Pepperwood, did not undergo extensive channel widening during any of the recorded major floods despite its geomorphic similarity to the terrace at Pepperwood (Figs. 2 and 10). The banks at Holmes Flat are also composed of terrace deposits, and Holmes Flat was also cleared for farming. The terrace tread, however, stands about 15 m above the channel, 6-m higher than Pepperwood. Although the terrace at Holmes Flat was inundated in the 1955 and 1964 floods, it was flooded to a lesser depth than Pepperwood by at least 6 m because of the difference in elevation of the terraces. Holmes Flat was not inundated during the 1997 flood and has likely been flooded less frequently than Pepperwood since the 1964 flood. Given that critical shear stress, a measure of erosive capability, is proportional to the product of water depth and slope (Ritter et al., 1995), greater depths of flow over the terrace deposits may have allowed for more extensive erosion at Pepperwood. Additionally, more frequent inundation of the terrace deposits may have weakened the banks and made them more susceptible to erosion.

6.2. Recovery of the Eel River

Whereas the effects of major floods on fluvial landforms have been extensively studied, the rates of, mechanisms for, and controls on channel recovery have been examined much less frequently. Nonetheless, the recovery of fluvial systems varies as a function of (1) the frequency of flows capable of entraining and transporting bed and bank materials, (2) sediment loads within the channels, and (3) the rate of revegetation of valley and channel margins, the vegetation functioning as a trap that fosters the accretion of particles along the channel banks (Wolman and Gerson, 1978; Pitlick, 1988). In light of these controls, it follows that recovery varies as a function of geology, climate, and spatial scale.

After the 1955 and 1964 floods, channel widths tended to decrease on the Eel River (Fig. 11). Only one of the sites that showed more than 25 m of widening during floods, however, had returned to pre-flood widths more than 30 years later. Thus, recovery of channel widths is a relatively slow process along the lower Eel River and requires decades to occur.

Slow rates of recovery along the Eel River and its tributaries located in the ‘‘superhumid’’ climate of northern California seemingly contradicts the currently accepted concept of rapid recovery in humid environments. Long recovery times, however, have been suggested for other basins in northern California. Stewart and LaMarche (1967), for example, show that the channel and valley floor of Coffee Creek located within the Trinity River basin of northern California is the product of rare, catastrophic flooding. Similarly, Pitlick (1988) argues that the morphology of cobble and boulder rivers in steep terrains may be adjusted to rare events that are characterized by sediment transport conditions that extensively rework channel and valley systems. In these cases, the controls on recovery are related to the competence of flow after the floods.

Long rates of recovery within basins where bed and bank materials are frequently transported have been documented by Kelsey (1980) for the Van Duzen River, a major tributary to the Eel River downstream of the study area. The Van Duzen River had not recovered from the 1964 flood 15 years after the event (Kelsey, 1980), and local residents suggest that the river is continuing to aggrade in downstream reaches. Similarly, while recovery times along Redwood Creek, California, have been variable along the channel, downstream reaches will apparently require decades to recover from the 1964 flood (Madej and Ozaki, 1996; Ozaki and Madej, 1996). Yet, Redwood Creek exhibits exceptionally high sediment loads (Madej and Ozaki, 1996).

Although the 1955 and 1964 floods locally widened the Eel River, they appear to have had little effect on regional elevation of the channel bed. For example, the channel bed at the Scotia gaging station appears to have dropped progressively 0.8 m in 85 years (Fig. 6). Irregular short-term variations in the elevation of the streambed do not appear to correlate with major floods at the station.

Since the 1964 flood, local aggradation at Holmes Flat bridge downstream of Larabee Creek has been continuous. Although aerial photographs did not cover enough of the Larabee Creek basin or upstream tributaries to identify hillslope failures, evidence from other tributaries indicates that mass wasting during floods is common in the study area. Subsequent flushing of sediments into the Eel River after the 1964 flood could account for the aggradation at Holmes Flat bridge. The gravel accumulating at Holmes Flat bridge could be supplied by Larabee Creek or from the straight reach of the Eel River upstream of the Holmes Flat bridge (Fig. 2). The introduction of tributary sediments has been used to explain localized aggradation in other studies. For example, Kelsey (1980) argued that the influx of tributary sediment during floods is an important control on channel bed aggradation along the Van Duzen River immediately north of the Eel River basin.

Although further study could help identify the source of sediment, grain size data support the Larabee Creek source. The median size of gravel along the Eel River at Holmes Flat bridge is about 31 mm, which falls within the range of grain sizes found on two discontinuous terraces within Larabee Creek (17.6 and 50.9 mm). Additionally, sediments could be funneled into the area of Holmes Flat bridge from the straight, steep canyon of the Eel River upstream of Larabee Creek (Fig. 2). Flood waters emerging from the constraints of the narrow channel and entering the wider reach of the Larabee Creek delta likely slow down and deposit the gravel load near the crossing.

Localized downcutting along the Eel River is indicated at cross-section E5 (Fig. 12). Since the 1955 flood, an island has formed in this area from the downcutting of the Eel River. The island was heavily vegetated with large 12-year-old cottonwoods in the summer of 1996, and its surface consisted of a 1.5-m layer of moderately sorted, medium-grained sand, which overlay gravel. These factors suggest that the island is no longer inundated as deeply and frequently by floods because the Eel River has gradually incised since the gravel bar first appeared in the 1960 aerial photographs.

Primary controls on the rates of channel recovery are the frequency of post-flood flows that are capable of moving bed materials and the regrowth of riparian vegetation that can trap sediment along the channel banks (Baker, 1977; Wolman and Gerson, 1978). Lisle (1981) concluded that recovery of rivers in northern California and southern Oregon to the 1964 event was slower than might be predicted because precipitation and runoff are highly seasonal. Furthermore, the regrowth of riparian vegetation is hindered in north coastal California because the permeable, coarse-grained flood deposits rapidly lose soil moisture during the dry season (Lisle, 1981).

Greater removal of riparian vegetation during the 1964 flood compared to the 1955 flood may result from the higher stage and longer duration of the 1964 flood (Fig. 4). Vegetation had only begun to be re-established along the Eel River by the 1974 photos. Regrowth appears to have taken longer than the 2–3 years that is observed for many newly created flood surfaces (Scott et al., 1996), which is consistent with Lisle's (1981) argument that the slow regrowth of vegetation limits the rates of channel recovery. Thus, the seasonal nature of precipitation and runoff along with the coarse texture of the substrate may be a primary control on the rates of channel recovery.

6.3. Geomorphic effects of flooding on tributaries of the lower Eel River

In contrast to the Eel River, the examined tributaries underwent extensive and rapid aggradation and immediate downcutting during floods. These responses were similar among each of the basins and for each of the three floods examined. The one exception is Twin Creek, which was not greatly affected by the 1955 flood. Removal of riparian vegetation and reworking of gravel along most tributaries during the 1955 flood is in marked contrast to the lack of removal and reworking along Twin Creek (Fig. 7). This difference in response may be a function of the size of hillslope failures in respective drainage basins during the flood and the proximity to the mouths of the tributaries. Hillslope failures provided abundant coarse material and log debris to the tributaries during periods of high flow. In turn, transport of this material as bedload and suspended sediment likely contributed to the removal of vegetation along and in the channel.

Much of the material provided by hillslope failures appears to have been deposited in the lower reaches of the tributaries (Figs. 8 and 9). In 1996, gravel deposits with interbedded sand lenses were inset into much older Eel River terrace deposits and bedrock at the mouths of Twin and Bear Creeks. The sand lenses are interpreted to be slackwater deposits because they pinched out upstream and have a similar grain-size distribution as the slackwater sample collected on the terrace at Shively after the 1997 flood. The one or two sand lenses observed interbedded in gravel deposits in 1996 may be products of the 1955 and 1964 floods. Observations of similar slackwater deposits overlying gravel after the 1997 flood (Fig. 8) support the interpretation that these older lenses are slackwater sediments deposited during previous floods. Regardless of the time of deposition, the gravel and sand deposits demonstrate that extensive aggradation occurs within tributaries during floods.

At the mouths of the tributaries, downcutting of the tributary channel though the gravel was immediate, occurring during the waning stages of the 1997 flood. Further upstream, the effects were less dramatic, particularly with regard to channel incision. In successive sets of aerial photographs after the 1955 and 1964 floods, it was noted that incision was initiated at the tributary mouths and migrated progressively upstream. Nevertheless, most of the valley floor was reworked during the floods. Based on observations made immediately after the 1997 flood, it seems reasonable to assume that channel morphology was also completely modified during the 1955 and 1964 floods.

6.4. Proposed general evolution of Eel River tributaries during major floods

Based on observations in 1996 and after the 1997 flood, a general model describing the response of tributaries to floods is proposed. As warm rains fall on saturated soils of snow covered mountains, overland flow quickly accumulates in low-order, steep tributary channels. Initial flows in the tributary channels may carry small quantities of bedload or suspended sediment and likely scour existing gravel in the lower reaches of the tributary. Some riparian vegetation may be removed as its substrate is eroded. Heavy rainfall also generates hillslope failures in the steep, poorly consolidated bedrock of the tributary valleys, which contribute large quantities of sediment and log debris to the tributary channel. With increased bed and suspended load from hillslope failures, erosion of pre-flood gravel may decrease but removal of riparian vegetation could continue as gravel and debris further batter vegetation.

Although the Eel River rises more slowly than the lower order tributaries, in a major flood the stage of the Eel River will eventually exceed that of the tributaries. At that point, the Eel River raises the base level for the tributary and effectively acts as a dam or a lake, abruptly slowing the flow velocity. With the sudden decrease in velocity, bedload and suspended sediments are deposited within the tributary valleys. These deposits form a wedge at the mouth of the tributaries and may bury vegetation that was not removed during the rising stage of the flood.

As the storm subsides, flow stage on the lower order tributaries drops rapidly whereas the Eel River may continue to rise above the waning stages of the tributaries. Eel River water that backs up into tributaries slows relative to the main channel and deposits suspended load. The resulting slackwater deposits consist of sand capping the gravel deposited in the tributaries during the rising phase of the flood.

During the waning phase of the flood, the stage of the Eel River recedes below the elevation of the newly deposited gravel and lowers the base level of the tributaries. Flow in the tributaries is also reduced, which decreases carrying capacity. With reduced sediment load, however, the flow is sufficient to incise the new, unconsolidated gravel deposits at the mouths of tributaries. As observed in January 1997, incision is rapid and essentially controlled by the rate of lowering of the Eel River. During this rapid incision into the new gravel, the tributary channel switches back and forth across the valley floor producing unpaired terrace levels (Fig. 8), which converge upstream. Comparison of the tributaries between January and September 1997 indicates that the vast majority of incision occurs within the first few days after the flood as the Eel River recedes.

This model is consistent with observations from aerial photographs and field observations in 1996 and 1997. The aerial photographs suggest the same series of events took place on the tributaries after the 1955 and 1964 floods. For example, in the 1960 aerial photographs, channels are observed to have incised into the newly deposited gravel along those tributaries that were affected by the 1955 flood. Similarly, incised channels and unpaired terraces were observed on the 1966 aerial photographs after the 1964 flood. Riparian vegetation appeared to be removed along the tributary valleys on the 1960 and 1966 photos. The timing of these events, however, cannot be precisely determined from aerial photographs because photos provide only an instantaneous snapshot of the area 5 years after the 1955 flood and 2 years after the 1964 flood. It is impossible to tell if the incision occurred immediately after the flood as observed in 1997 or if it took several years. What is visible on aerial photographs is consistent with the proposed model and could have occurred within days of the large floods.

Although the model is based primarily on field observation made only a few days after peak discharge on the Eel River in January 1997, field data in 1996 also support the model. Slackwater deposits such as those observed capping new gravel deposits in 1997 were also observed in gravel deposits in 1996. Unpaired gravel terraces, such as those found newly formed after the 1997 flood, were documented in the tributary valleys in 1996. Riparian trees were found at least partly buried by gravel in 1996. Although it was not possible to determine the timing of earlier events during field observations in 1996, each of these geomorphic processes and landforms could have been produced in one flood as was observed immediately after the 1997 flood.

The origin of the two sets of slackwater deposits seen interbedded with gravel on Twin and Bear Creeks in 1996 is uncertain. These could have formed in two distinct annual floods separated by several years or in a single, somewhat episodic flood. The first case would mean that not all gravel was scoured out during the rising phase of the flood on the tributary. Stages of floods in 1955, 1964, 1974, 1986, and 1995 were greater than the 1997 flood, so the Eel River would have generated slackwater deposits as it backed into tributaries in each of these events. Alternatively, both sets of slackwater deposits and gravel overlying them could have been generated by different episodes of a single flood. This case would require at least two pulses of high discharge from the tributaries and availability of sediment from hillslope failures during one storm. That is, the lowest gravel resulted from an early peak discharge. With decreased rainfall, discharge on the tributary decreased, and deposition was dominated by deposition of suspended sediment from the Eel River. Another episode of rainfall, possibly only a few hours or days later, would generate another peak discharge on the tributary and more gravel deposition, burying the first slackwater deposit. These processes could be repeated as long as the Eel River remained high and episodes of rainfall occurred. Episodic rainfall within a storm is documented by the hydrograph of the 1955 flood on the Eel River (Fig. 4). The flashy nature of the tributaries could allow for the stage of the tributaries to rise and fall several times during a storm.

6.5. *Recovery of tributaries*

Within the tributaries examined here, minor modification of the channel and valley floors occurred during the recovery period between each of the three events. These modifications included local aggradation of the valley floor, as evidenced by the burial of the basal root flares of trees, and minor channel cutting upstream of tributary mouths, as documented on aerial photographs. Although minor modifications occurred within the tributaries between floods, the valley floor topography is primarily the product of these rare, high magnitude floods.

Very little vegetation is observable along the tributaries on the 1974 photographs, 10 years after the 1964 event. New riparian growth is first visible on the 1981 air photos. This could reflect 10 years of downcutting progressively migrating upstream after the 1964 flood, particularly during substantial floods in water years 1966, 1970, and 1974 (Fig. 3), or by complete reworking of tributary deposits during these floods. Whereas massive deposition seems to be associated with major floods, the reworking of these valley floor sediments upstream from the mouth could have continued for more than 10 years after the 1955 and 1964 events. This conclusion is based on the assumption that the regrowth of riparian vegetation on newly formed deposits requires stable surfaces that allow plant germination and establishment. Aerial photographs show that new vegetation had not become established along the tributaries between the 1955 and 1964 floods.

The lag time between floods and regrowth of riparian vegetation is supported by tree ages. Trees apparently began to germinate on the surfaces of the tributary valleys around the mid-1970s. Water years 1975, 1976, and 1977 had relatively low annual peak discharges (Fig. 3). Thus, tree growth may have begun during this period of reduced flows because sediments on the upper geomorphic surfaces were not reworked during winter floods. Once established, trees were able to withstand subsequent moderate floods. Friedman et al. (1996) found a similar lag time after a major flood before vegetation became established on Plum Creek in the Colorado Piedmont Section of the Great Plains. They concluded that for 5–15 years after the flood, annual floods apparently would rework new surfaces that developed during and after the flood. Eventually, incision of the channel left terraces at sufficiently high levels that they were no longer flooded and could be revegetated.

To understand the geomorphic changes during the flood and recovery from the flood, most aggradation and degradation documented within the tributaries are associated with the few discrete flow events including the floods of 1955, 1964, and 1997. Whereas minor valley floor aggradation and channel bed degradation likely took place between floods, the overall morphology of the channel and valley bottom was created during the largest floods. It follows, then, that the channel forming discharges within these tributary basins are not the flows of low frequency and magnitude as has been suggested from many humid, temperate environments (Wolman and Miller, 1960). Rather, channel form is the product of infrequent, high magnitude floods. From 1964 to the present, the lower reaches of the five tributaries never attained a uniform longitudinal profile assumed to represent the equilibrium form. Instead, the channels were characterized by downcutting and by nickpoints commonly associated with disequilibrium. Moreover, the 1997 flood presumably re-initiated the process of channel adjustment. Two interpretations are possible.

First, the time between geomorphically effective floods, such as those of 1955, 1964, 1997, and perhaps others in between, is too short for the tributaries to recover before the next major event. The greater abundance of large to moderate floods after 1955 than before (Fig. 3) may indicate the crossing of a geomorphic threshold, and the tributaries may be in the process of readjusting to a new set of climatic conditions characterized by more frequent flooding. This suggestion is consistent with studies by Webb and Betancourt (1992) who argued that the frequency of atmospheric ''regimes'' that trigger major floods can change greatly on decadal time scales.

Alternatively, moderate floods on the tributaries are unable to rework and reshape the coarse gravel brought in by landslides. Thus, the morphology that is present at the end of major floods generally remains until the next large event. In this case, the channels never attain equilibrium characterized by smooth longitudinal stream channel profiles, devoid of nickpoints.

6.6. Influence of mass wasting on geomorphic effectiveness and recovery

Landform recovery is dependent on the ability of subsequent, low-to-moderate magnitude floods to entrain, transport, and redeposit sediment along the channel. This study, however, suggests that the magnitude of landform modification during the 1955 and 1964 events, and the slow rates of recovery after these floods, are influenced by mass wasting processes that provide a massive, instantaneous input of sediment and debris to the valley floor during floods. This provides the materials and conditions required for rapid aggradation and, as argued by Kochel (1988), can enhance erosional processes by providing cutting tools that are carried along by the high magnitude flows. Data collected from Redwood Creek by Madej and Ozaki (1996) suggest that the influx of sediment at a given point along the valley can overwhelm the transport capacity of the channel and create depositional reaches. Sediment within the zones are subsequently eroded and redeposited farther downvalley, the mass of sediment moving as a wave (Madej and Ozaki, 1996). Localized aggradation along the Eel River does not appear to be moving as a sediment wave. Nevertheless, long-term aggradation at Holmes Flat bridge suggests that materials reworked from lower order channels that have been extensively impacted by mass wasting could have been delivered to the Eel River and cause instabilities in the elevations of the channel beds. These instabilities may continue for years after the events and require decades to recover.

The perception that mass wasting is an important control on geomorphic effectiveness is not new. What is less commonly appreciated is that in areas characterized by steep slopes and frequent landslides, geomorphic effectiveness is strongly dependent on the frequency and magnitude of denudation. That is, the magnitude of landform modification and slow rates of recovery may have little to do with the frequency and magnitude of flooding and the competence of flows to perform geomorphic work, as is inherent in the concept of a dominant discharge. Rather, landform modification may depend more on the frequency and magnitude of mass wasting phenomena. This concept emphasizes the need to more fully understand process linkages between fluvial and hillslope systems, particularly in smaller drainage basins.

7. Conclusions

The dominant geomorphic change resulting from major floods on the lower Eel River in 1955 and 1964 was channel widening, specifically by the erosion of terraces. Widening, however, was not spatially uniform within the study area. Terraces at lower elevations relative to the Eel River channel were preferentially eroded probably because (1) greater depths of flow in major floods likely produced enough shear stress to erode the terrace banks, and (2) more frequent inundation by winter floods may have weakened the banks making them more susceptible to erosion.

Channel narrowing characterized the periods after the 1955 and 1964 floods. More than three decades after the 1964 flood, the sites that were widened more than 25 m have not returned to pre-flood widths. Channel recovery appears to be slower than would be predicted for a river in a ''superhumid'' climate such as the Pacific northwest. Slow recovery is likely because of the seasonality of precipitation and runoff, which predominantly occurs during a 5-month period each winter.

Floods appear to have had little effect on overall elevation of the channel bed on the Eel River. At the gaging station at the downstream end of the study area, the channel bed has progressively degraded during 85 years of record. Local aggradation of the channel bed occurred at one location where the river valley first widens abruptly from the upstream reach. This aggradation may be related to seasonal input of sediment from the tributary immediately upstream or to bedload carried by the straight, narrow reach of the Eel River upstream of the location.

The dominant geomorphic processes along Eel River tributaries during floods were deposition of gravel immediately upstream of the mouths followed by rapid incision. These processes were observed during the 1997 flood when 1–5 m of gravel were deposited at tributary mouths and incised within 4 days of peak discharge on the Eel River. This immediate deposition and incision occurs during the rising and falling stages of major floods. During the rising stage, water rapidly accumulates in the basins of lower-order tributaries. Initial flows may carry small quantities of bedload or suspended sediment and likely scour existing gravel in the lower reaches of the tributary. As more gravel and debris are introduced to the tributary channels by hillslope failures, bedload increases and erosion of pre-flood gravel may decrease. Eventually, the stage of the Eel River rises above that of the tributaries, abruptly slowing the flow in the tributaries, which results in deposition of debris and gravel at the mouths. As the Eel River continues to rise, it backs up into the tributary valleys and deposits suspended sediments as slackwater deposits. During the falling stage of a flood, lowering of the Eel River lowers the base level of the tributaries and causes them to incise the newly deposited gravel at a rate equal to the lowering of the Eel River.

The massive deposition of gravel in the tributary valleys and the immediate downcutting into those sediments occur during large floods such as in 1997. Although reworking of sediments may continue for 10 or more years after large floods, channel morphology at the mouths of tributaries is essentially a product of infrequent, high magnitude floods.

One tributary was not significantly affected by the 1955 flood, while others were. The lack of response may result from the absence of large hillslope failures in the tributary basin. The influence of mass wasting processes on geomorphic effectiveness is striking where hillslope failures are common. In this study area, the magnitude of landform modification during floods and the unusually slow rate of recovery may be the result of the frequency and magnitude of mass wasting phenomena. This argument suggests that the dominant discharge along many channels that are characterized by periodic, intense flooding are likely dependent on the frequency and magnitude of slope failure.

Acknowledgements

We would like to thank the people who provided access to properties and files that made this study possible, including the Humboldt Redwood State Park and Pacific Lumber. In particular, we thank Patrick Vaughn and Ken Anderson with the California Parks Department, Eureka, CA. Richard Stein at the Humboldt County Public Works Department, Eureka, CA, allowed access to aerial photographs and files. Geologists at the U.S. Geological Survey Office in Ukiah, CA, particularly Greg Susich, Jim Gibbons, and Mike Webster, allowed us to examine their files and provided data that would have taken us an eternity to get otherwise. Kris Pizaro at the Nevada Bureau of Mines and Geology helped to digitize photographs. Finally, we thank Craig Kochel and Dusty Ritter for reviewing early drafts of the manuscript and Jack Vitek and Dick Marston for thorough and constructive reviews of the submitted manuscript.

References

Ackers, P., 1972. Rever regime: research and application. J. Inst. Water Eng. 26, 257–281.

Andrews, E.D., Nankervis, J.M., 1995. Effective discharge and the design of channel maintenance flows for gravel-bed rivers. In: Costa, J.E., Miller, A.J., Potter, K.W., Wilcock, P.R. (Eds.), Natural and Anthropogenic Influences in Fluvial Geomorphology, The Wolman Volume. American Geophysical Union, Washington, DC.

Baker, V.R., 1977. Stream-channel response to floods, with examples from central Texas. Geol. Soc. Am. Bull. 88, 1057–1071.

Beven, K., 1981. The effect of ordering on the geomorphic effectiveness of hydrologic events. IAHS-AISH Publ. 132, 510–526.

Brown III, W.M., Ritter, J.R., 1971. Sediment transport and turbidity in the Eel River Basin, California. U.S. Geological Survey Water Supply Paper 1986.

California Department of Water Resources, 1964. North coastal area investigation. State of California, The Resources Agency, Department of Water Resources, Bulletin no. 136.

California Division of Mines and Geology, 1962. Redding sheet, geologic map of California. State of California, Resources Agency, Department of Conservation, Sacramento, CA.

Costa, J.E., 1974. Response and recovery of a Piedmont watershed from tropical storm Agnes, June 1972. Water Resour. Res. 10, 106–112.

Folk, R.L., 1968. Petrology of Sedimentary Rocks. Hemphill's, Austin, TX.

Friedman, J.M., Osterkamp, W.R., Lewis Jr., W.M., 1996. The role of vegetation and bed-level fluctuations in the process of channel narrowing. Geomorphology 14, 341–351.

Frissel, C.A., Nawa, R.K., 1992. Incidence and causes of physical failure of artificial habitat structures in streams of western Oregon and Washington. North Am. J. Fish. Manage. 12, 182–197.

Goodridge, J.D., 1996. Historic Rainstorms in California. California Department of Water Resources, California.

Gregory, S.V., Swanson, F.J., Mckee, W.A., Cummins, K.W., 1991. An ecosystem perspective of riparian zones. Bioscience 41, 540–551.

Hack, J.T., Goodlett, J.C., 1960. Geomorphology and forest ecology of a mountain region in the central Appalacians. U.S. Geological Survey Professional Paper 347.

Harvey, A.M., 1984. Geomorphic response to an extreme flood: a case from southeast Spain. Earth Surf. Processes 9, 267–279.

Helley, E.J., LaMarche Jr., V.C., 1968. December 1964, a 400-year flood in northern California. U.S. Geological Survey Professional Paper 600D, pp. D34–D37.

Helley, E.J., LaMarche Jr., V.C., 1973. Historical flood information for northern California Streams from geological and botanical evidence. U.S. Geological Survey Professional Paper 485-E.

Hickey, J.J., 1969. Variations in low-water streambed elevations in selected stream-gaging stations in northwestern California. U.S. Geological Survey Water Supply Paper 1879-E.

Hirschboeck, K.K., 1988. Flood hydroclimatology. In: Baker, V.R., Kochel, R.C., Patton, P.C. (Eds.), Flood Geomorphology. Wiley, New York, pp. 27–49.

Hofmann, W., Rantz, S.E., 1963. Floods of December 1955–1956 in far western states. U.S. Geological Survey Water Supply Paper 1650.

Humboldt County Department of Public Works, 1996. Eureka, CA.

Judson, S., Ritter, D.F., 1964. Rates of regional denudation in the United States. J. Geophys. Res. 69, 3395–3401.

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. Am. Bull., Part I 91, 190–195, Part II on microfilm.

Kentula, M.E., 1997. A step toward a landscape approach in riparian restoration. Restor. Ecol. 5, 204.

Kochel, R.C., 1988. Geomorphic impact of large floods: review and new perspectives on magnitude and frequency. In: Baker, V.R., Kochel, R.C., Patton, P.C. (Eds.), Flood Geomorphology. Wiley, New York, pp. 169–187.

Kochel, R.C., Baker, V.R., Patton, P.C., 1982. Paleohydrology of southwestern Texas. Water Resour. Res. 18, 1165–1183.

Kochel, R.C., Ritter, D.F., Miller, J., 1987. Role of tree dams in the construction of pseudo-terraces and variable geomorphic response to floods in Little River valley, Virginia. Geology 15, 718–721.

Kondolf, G.M., Mitcheli, E.R., 1995. Evaluating stream restoration projects. Environ. Manage. 19, 1–15.

Lisle, T.E., 1981. The recovery of aggraded stream channels at gaging stations in northern California and southern Oregon. IAHS-AISH Publ. 132, 189–211.

Lisle, T.E., 1982. Effects of aggradation and degradation on pool-riffle morphology in natural gravel channels, northwestern California. Water Resour. Res. 18, 1643–1651.

Madej, M.A., Ozaki, V., 1996. Channel response to sediment wave propagation and movement, Redwood Creek, California, USA. Earth Surf. Processes Landforms 21, 911–927.

McLane, M., 1989. Granny Software User's Manual. Self Published, Littleton, CO.

Merrits, D.J., Vincent, K.R., Wohl, E.L., 1994. Long river profiles, tectonism, and eustacy: a guide to interpreting fluvial terraces. J. Geophys. Res. 99 (B7), 14031–14050.

Moss, J.H., Kochel, R.C., 1978. Unexpected geomorphic effects of the hurricane Anges storm and flood, Conestoga drainage basin, southeastern Pennsylvania. J. Geol. 86, 1–11.

Mount, J.F., 1995. California Rivers and Streams; The Conflict Between Fluvial Process and Land Use. University of California Press, Berkeley, CA.

Naiman, R.J., DeCamps, H., Pollock, M., 1993. The role of riparian corridors in maintaining regional biodiversity. Ecol. Appl. 3, 209–212.

National Research Council, 1992. Restoration of Aquatic Ecosystems. National Academy Press, Washington, D.C.

Newson, M.D., 1980. The geomorphic effectiveness of floods — a contribution stimulated by two recent event in mid-Wales. Earth Surf. Processes 5, 106–112.

Norris, R.M., Webb, R.W., 1990. Geology of California. Wiley, New York.

O'Neil, J., Fitch, L., 1992. Performance audit of instream habitat structures constructed during the period 1982–1990, in southwestern Alberta. Abstracts for American Fisheries Society Meeting, September 1992, Rapid City, South Dakota.

Osterkamp, W.R., Costa, J.E., 1987. Changes accompanying an extraordinary flood on a sand-bed stream. In: Mayer, L., Nash, D. (Eds.), Catastrophic Flooding, Binghamton Symposia in Geomorphology: International Series. Allen and Unwin, London, UK, pp. 201–224.

Ozaki, V.L., Madej, M.A., 1996. Long-term channel response to large floods and sedimentation. In: LeBlance, J. (Ed.), Proceedings of the Conference on Coast Redwood Forest Ecology and Management, June 18–20. Humboldt State University, Arcata, CA.

Pickup, G., Warner, R.F., 1976. Effects of hydrologic regime on magnitude and frequency of dominant discharge. J. Hydrol. 29 (1–2), 51–75.

Pitlick, J., 1988. The geomorphic effects of large floods on rivers in Colorado and California. Eos, Trans. Am. Geophys. Union 69 (16), p. 348.

Pitlick, J., 1993. Response and recovery of a subalpine stream following a catastrophic flood. Geol. Soc. Am. Bull. 105, 657–670.

Ritter, D.F., 1967. Rates of denudation. J. Geol. Educ. 15 (4), 154–159.

Ritter, D.F., Kochel, R.C., Miller, J.R., 1995. Process Geomorphology. 3rd edn. William C. Brown Publishers, Dubuque, IA.

Schumm, S.A., Lichty, R.W., 1963. Channel widening and flood–plain construction along Cimarron River in southwestern Kansas. U.S. Geological Survey Professional Paper 352-D.

Scott, K.M., Gravlee Jr., G.C., 1968. Flood surge on the Rubicon River, California — hydrology, hydraulics, and boulder transport. U.S. Geological Survey Professional Paper 422-M.

Scott, M.L., Jonathan, M.F., Auble, G.T., 1996. Fluvial process and the establishment of bottomland trees. Geomorphology 14, 229–327.

Sloan, J., 1997. Response and recovery of the Eel River, California to floods in 1955, 1964, and 1997. Master's Thesis, University of Nevada, Reno.

Stewart, J.H., LaMarche, V.C., 1967. Erosion and deposition produced by the flood of December 1964 on Coffee Creek, Trinity County California. U.S. Geological Survey Professional Paper 422-K.

Tellman, B., Cortner, H.J., Wallace, M.G., DeBano, L.F., Hamre, R.H., 1993. Riparian management: common threads and shared interests. A Western Regional Conference on River Management Strategies. Albuquerque, New Mexico. USDA Forest Service, Rocky Mountain Research Station, Gen. Tech. Rep. RM-226.

U.S. Geological Survey, 1997. water.wr.usgs.gov/data_95.html, April 28.

Waananen, A.O., Harris, D.D., Williams, R.C., 1971. Floods of December 1964, and January 1965 in the far western states.

U.S. Geological Survey Water Supply Paper 1866-A and 1866-B.

Webb, R.H., Betancourt, J.L., 1992. Climatic variability and flood frequency of the Santa Cruz River, Pima County, Arizona. U.S. Geological Survey Water-Supply Paper 2379.

Williams, G.P., Wolman, M.G., 1984. Downstream effects of dams on alluvial rivers. U.S. Geological Survey Professional Paper 1286.

Wolman, M.G., 1954. A method of sampling coarse river-bed material. Trans. Am. Geophys. Union 35 (6), 951–956.

Wolman, M.G., Gerson, R., 1978. Relative scales of time and effectiveness of climate in watershed geomorphology. Earth Surf. Processes 3, 189–208.

Wolman, M.G., Miller, J.P., 1960. Magnitude and frequency of forces in geomorphic processes. J. Geol. 68, 54–74.