

# Shelf record of climatic changes in flood magnitude and frequency, north-coastal California

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## ABSTRACT

**Continental-shelf deposits off the Eel River, north-coastal California, document a recent increase in the magnitude and frequency of major hydrologic floods ( $\geq 10$  yr recurrence interval). The shelf record reveals a sudden, three-fold increase in sedimentation rate ca. 1954 and a concomitant increase in the frequency of preserved flood beds. Comparison of sedimentary and river-discharge records reveals that major floods after ca. 1950 had a more pronounced effect on coastal sediment delivery and accumulation offshore than previous recorded events of similar magnitude, and that stratigraphic preservation of flood events is highly dependent on flood frequency and net sedimentation rate. We contend that this change in marine sedimentation is a response to documented climatic phenomena that have increased the frequency of major floods throughout the western United States during the past half century, together with intrabasinal impacts of extreme floods in 1955 and 1964. Anthropogenic increase in watershed-sediment production is a probable secondary factor.**

**Keywords:** northern California, climatology, floods, marine sediments, geochronology.

## INTRODUCTION

Growing interest in the response of the terrestrial hydrologic cycle to climate variability on decadal to millennial time scales has led to increasing use of estuarine and shallow-marine sedimentary deposits as natural recording systems (e.g., Ingram et al., 1986). The value of sedimentary strata in environmental retrospection, while promising, rests on stratigraphic fidelity, i.e., the degree to which depositional events are accurately preserved in the face of physical and biological processes that tend to modify or destroy the record (Wheatcroft, 1990). In this regard case studies that compare instrumentation and high-resolution sedimentary records play a pivotal role in quantifying the response of estuarine and marine sedimentation to climatic variations in continental hydrology on multiple temporal and spatial scales (e.g., Soutar and Crill, 1977).

In considering the impact of short-period climate variability on fluvial-marine sedimentary systems, two questions come to mind: (1) what magnitude and frequency of an event (or combination of events) are most geomorphically effective over the long term? (2) Does the marine sedimentary record faithfully archive hydrologic phenomena? An observation in fluvial geomorphology is that floods of similar magnitude and frequency sometimes pro-

duce dissimilar results, which limits the predictive skill of river-discharge statistics in quantifying geomorphic change (Costa and O'Connor, 1995). In contrast, it has become dogma in marine sedimentology that the stratigraphic effectiveness (i.e., event-deposit thickness) of storms and floods is directly related to event magnitude (Dott, 1983). These opposing views pose unfortunate barriers to the understanding of how fluvial-marine systems respond to climate variability and thus recognition of hydrologic manifestations in the marine record. Such knowledge is timely in light of the increasing rainstorm intensity for the coming decades (Fowler and Hennessy, 1995), particularly when considering the major role of short-period climate change in modulating river-sediment flux (Inman and Jenkins, 1999).

In this paper we compare river discharge and sedimentary records for the Eel River and shelf, a well-characterized system in northern California, to examine links between hydroclimatology, coastal sediment delivery, and marine sedimentation. Our results shed new light on the sensitivity of fluvial-marine systems to flood magnitude and frequency, as well as preservation of hydrologic signatures in the marine record.

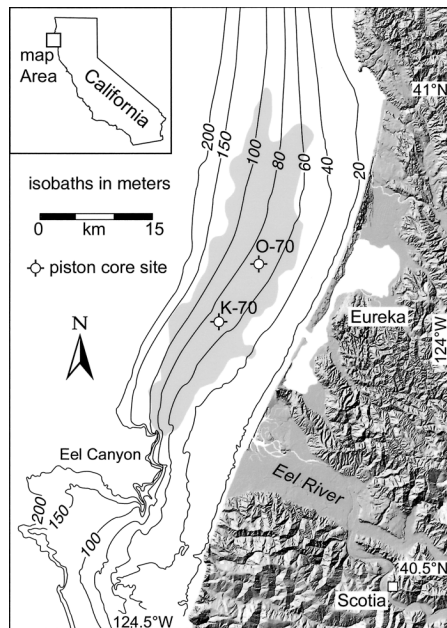
## SETTING AND METHODS

Streamflow in California's north coast region is dominated by intense, short-duration

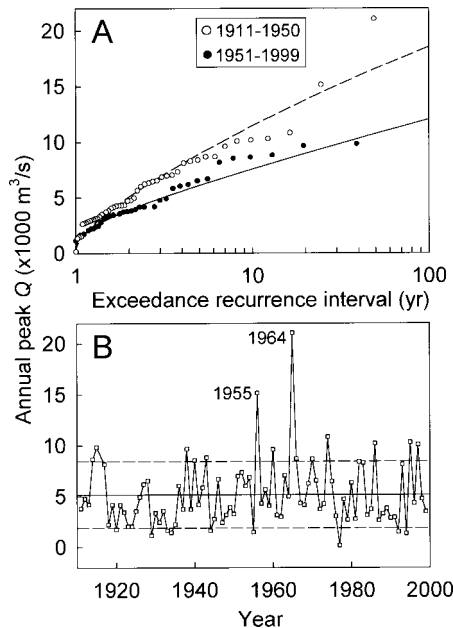
(3–6 days) rainstorms in winter, with peak flows that rank among the highest on record for the western United States (Hirschboeck, 1987). Factors including steep, mountainous, and geologically unstable terrain and limited flood-plain storage engender enormous suspended-sediment discharges to the coastal ocean during floods (Wheatcroft et al., 1997). Regionally, the unregulated Eel River (Fig. 1) has the largest mean annual sediment load at  $15\text{--}24 \times 10^6$  t/yr and is the largest point source of terrigenous sediment to the conterminous U.S. Pacific coast (Meade et al., 1990). The oceanic dispersal and fate of this material have been investigated through flood-response studies of major events in 1995 and 1997 (Sommerfield et al., 1999; Wheatcroft and Borgeld, 2000). This research has shown that oceanic flood deposits are packaged into distinctive sediment beds on the shelf that are unique to flood-producing rainstorms and that have potential to document paleohydrologic phenomena in the Eel River watershed.

To investigate the occurrence and significance of paleoflood deposition on centennial to millennial time scales, piston cores were collected on the Eel River shelf (Fig. 1) during oceanographic cruises in 1995–1998 as part of the STRATAFORM project (Nittrouer, 1999). Flood beds were identified from split cores on the basis of visual, X-ray radiographic, and grain-size characteristics following standard

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**Figure 1.** Bathymetric and shaded-relief topographic map of Eel River mouth and adjacent shelf showing locations of sediment cores and river gauge at Scotia, California. Footprint of mud deposit created by major floods in 1995 and 1997 is depicted by shaded area on shelf (Wheatcroft and Borgeld, 2000).



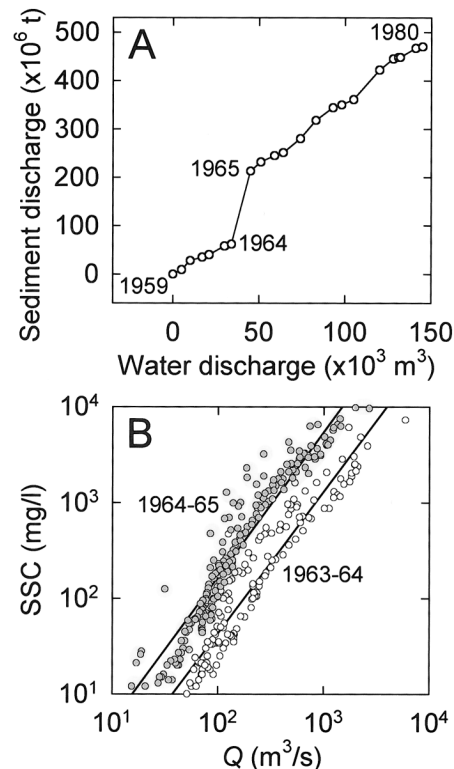
**Figure 2.** A: Frequency plot of annual peak discharges ( $Q$ ) for Eel River at Scotia (U.S. Geological Survey Station 11477000) during 1911–1999 showing marked increase in flood frequency after ca. 1950. Annual peak-flow values (circles) and Log Pearson III model curve fits to data series are shown. B: Same data set plotted as time series. Solid reference line is series mean (5160  $m^3/s$ ); upper and lower dashed lines are one standard deviation of mean.

methods (Sommerfield and Nittrouer, 1999; Drake, 1999). Down-core profiles of sand, silt, and clay concentration were generated by using a Coulter Multisizer II and a Sedigraph Model 5100 ET. Profiles of  $^{137}Cs$  activity measured via gamma spectroscopy provided age control for the upper sediment column through the identification of depth intervals corresponding to the onset of (ca. 1954) and peak (ca. 1964) fallout of  $^{137}Cs$  derived from atomic weapons testing. Older deposits were dated on the basis of  $^{14}C$  dates of articulated bivalve mollusks analyzed by accelerator mass spectrometry (AMS). Conventional  $^{14}C$  dates were calibrated and converted to calendar years A.D. following standard procedures and using a  $\Delta R$  value of 600 yr (Stuiver and Reimer, 1993). Linear sedimentation rates were determined from age versus depth relationships using the  $^{137}Cs$  and  $^{14}C$  control points and porosity-normalized depth intervals.

#### CONTINENTAL RECORD OF FLOODS

Magnitude and frequency analysis of U.S. Geological Survey discharge data for the Eel River at Scotia (1911–1999) reveals that the past half century in northern California has been particularly flood prone, with direct implications to coastal sediment delivery. Since 1950, major floods (i.e.,  $\geq 10$  yr recurrence interval) were more than two times more frequent than during the previous 40 yr (Fig. 2), an increase observed throughout the western United States (Aguado et al., 1992; Inman and

Jenkins, 1999; Ely et al., 1994). Floods have a disproportionate impact on sediment transport in the Eel River watershed; rating-curve estimates indicate that the 10 highest annual peak-flow events alone delivered to the coast a mass of sediment equivalent to  $\sim 40\%$  of the cumulative 90 year suspended load (Sommerfield et al., 1999). Of particular importance is the 1964 flood, characterized by a 21 300  $m^3/s$  peak discharge at Scotia, California (Fig. 2), and a 3 day sediment load of 116 t,  $\sim 1.2$  times the cumulative sediment load of the previous 8 yr (Brown and Ritter, 1971). Geomorphic impacts of the 1955 and 1964 floods are well documented and include immediate and subsequent streamside debris slides and earthflow landslides (Kelsey, 1980; Sloan et al., 2001), a dramatic increase ( $\leq 3$  m) in streambed elevations (Waananen et al., 1971; Hofmann and Rantz, 1963), and marked increases in subsequent suspended-sediment loads (Fig. 3). Both of these floods occurred during La Niña years (e.g., Dracup and Kahya, 1994) with westerly storm tracks centered over northern California. Beyond the instrumentation record, geologic evidence of extreme paleofloods in northern California is provided by alluvial records of events ca. 1600, 1750, 1862, 1881, and 1890 (Helley and LaMarche, 1973).

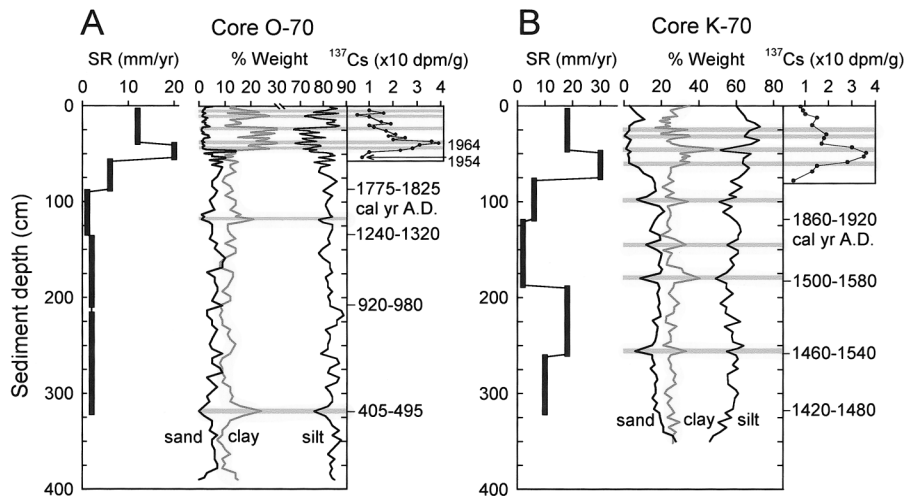


**Figure 3.** A: Cumulative suspended-sediment and water discharge for Eel River at Scotia during 1959–1980 (U.S. Geological Survey data). Cumulative sediment discharge is product of daily mean water discharge ( $Q$ ) and daily mean suspended-sediment concentration (SSC). B: Marked increase in cumulative sediment discharge triggered by 1964 flood was caused by widespread channel infilling, which increased SSC per unit  $Q$  in subsequent years.

#### MARINE SEDIMENTARY RECORD

The piston cores provide a marine record of flood activity in the Eel watershed for the past 1500–1600 yr and exhibit three properties that signify an increase in sediment delivery to the coast beginning ca. 1950: (1) a three-fold increase in shelf sedimentation rate, (2) increases in the concentrations of clay and decreases in the concentrations of silt and/or sand, and (3) an increase in the frequency of well-preserved flood beds. Sedimentation rates computed from  $^{14}C$  age versus depth relationships are variable at 1–5 mm/yr from A.D. 405–495 to ca. 1954 at site O-70 and 2–18 mm/yr from A.D. 1420–1480 to ca. 1954 at site K-70 (Fig. 4). Sedimentation rates based on  $^{137}Cs$  activity profiles at both sites increased suddenly ca. 1954 to 20 mm/yr and 30 mm/yr at sites O-70 and K-70, respectively. Rates at both sites decreased after 1964 but remained higher than pre-1954 rates.

Flood-event beds, 2–3 cm thick, are readily distinguished from adjacent sediments by visual and measured properties, including pale brown color, low bulk density, basal contact with underlying strata, high clay content (20–



**Figure 4.** Grain-size profiles and  $^{137}\text{Cs}$  and  $^{14}\text{C}$  chronologies for shelf cores revealing change in sedimentation conditions after ca. 1950. Onset and peak  $^{137}\text{Cs}$  activities are presumed consistent with calendar years 1954 and 1964, respectively. Increase in clay-rich flood beds (shaded), decrease in sand content, and increase in sedimentation rate at 1954  $^{137}\text{Cs}$  reference depth (40 cm in O-70, 63 cm in K-70) together evince increase in suspended-sediment delivery to and accumulation on Eel River shelf.

40 wt%), and low to negligible sand content (<1–5 wt%) (Fig. 4). Detailed studies of Eel River flood deposition have shown that, whereas fine silts and clays are transported to mid-shelf sites during and shortly after rainstorms, coarse silts and fine sands are supplied from the inner shelf via wave resuspension during comparatively dry oceanic storms (Drake, 1999; Wheatcroft and Borgeld, 2000). Accordingly, the observed downcore decrease in silt and sand content after 1954, in association with the increase in total sedimentation rate, is a dilution effect brought about by an increase in flood deposition and burial of clay-rich beds. Inspection of other cores from sites north and south of the river mouth indicates that this sedimentological change is widespread yet most apparent where sedimentation rates are  $\geq 4$  mm/yr (Sommerfield and Nittrouer, 1999).

Good correspondence between preserved flood beds and major floods in 1955, 1964, 1974, 1986, and 1995 indicates that flood frequency was faithfully recorded in shelf deposits after 1954 (Fig. 4). However, bed thickness does not correlate directly with flood peak-flow magnitude; the extreme nature of the 1964 event is not apparent from its corresponding deposit offshore. Variable transport and depositional conditions in the coastal ocean during floods are undoubtedly responsible for this observation (Wheatcroft and Borgeld, 2000). Older flood layers are more difficult to recognize on X-ray radiographs owing to bioturbation, yet are resolvable from the characteristic grain-size signature (Fig. 4). On the basis of interpolated  $^{14}\text{C}$  dates, it is possible that three of the paleofloods between ca. 1600 and 1890 identified by Helley and LaMarche (1973) are recorded in core K-70.

Deeper paleoflood beds evince previously unreported events ca. A.D. 1440–1540 (K-70 and O-70) and A.D. 405–495 (O-70). In view of the proximity of the two shelf sites, the higher frequency of pre-1950 flood beds at K-70 is in all likelihood a result of preferential preservation rather than preferential deposition.

## DISCUSSION

We attribute the recent increase in sediment accumulation offshore of the Eel River to two principal factors: (1) multidecadal changes in flood hydroclimatology and (2) intrabasinal geomorphic changes triggered by the 1955 and 1964 floods. In addition, there is evidence to suggest that land-use practices in the watershed have elevated suspended-sediment loads, yet another consideration. First and foremost, it is important to point out that the Eel River peak-flow record (Fig. 2) since 1950 mirrors an upward trend in extreme rainfall events and floods throughout the western United States as documented by long-term precipitation and streamflow time series (Aguado et al., 1992; Kunkel et al., 1999). These hydrologic changes have been attributed to variations in the strength and position of Pacific pressure cells, trajectories of westerly rainstorm tracks over the western United States, and related atmospheric anomalies (Cayan and Peterson, 1989; Ely et al., 1994). Climatic variability of this scale has been invoked to decipher paleoflood stratigraphies that indicate a steady increase in the frequency of extreme floods since ca. 500 yr B.P. and earlier flood epochs ca. 1000 yr B.P. and from 4800 to 3600 yr B.P. (Ely et al., 1993; Knox, 2000). Because northern California rainfall and streamflow are driven by westerly storms

originating in the North Pacific, and given the close coupling of Eel River floods and massive depositional events on the adjacent shelf, we consider increasing flood frequency to be the primary forcing factor for the change in sedimentation after 1950.

Second, we hypothesize that by charging the fluvial system with sediment, the extreme floods of 1955 and 1964 indirectly increased event-specific yields of subsequent lower magnitude floods. This positive feedback mechanism is necessary to explain the sudden increase in shelf sedimentation rate after 1954 (in response to the 1955 event) and, as a consequence, the higher frequency of flood beds preserved in the uppermost sediment column. Because the preservation potential of sedimentary-event beds increases directly with net accumulation rate below the biologically active layer (Wheatcroft, 1990), the increase in sedimentation rate after 1950 presumably enhanced stratigraphic archival of subsequent floods. While the persistence of this feedback is unknown, the shelf sedimentation rate record (Fig. 4) as well as watershed observations (Sloan et al., 2001) suggest that the river may have yet to fully recover from the 1955 and 1964 flood events.

In consideration of potential anthropogenic influences on coastal sediment delivery, timber harvesting and cattle grazing have occurred in the Eel watershed for more than 100 yr; the intensity of commercial logging increased significantly in the late 1940s. These activities can substantially increase sediment yields through excess erosion associated with soil compaction, unpaved logging roads, and clear cuts, and through initiation or reactivation of landslides on steeper, logged slopes (Montgomery et al., 2000). Recent studies of the South Fork Eel River and Van Duzen River tributaries suggest that anthropogenic sediment production may account for ~23%–45% of the load in those subbasins (U.S. Environmental Protection Agency, 1999a, 1999b). Because the South Fork Eel and Van Duzen Rivers have been most heavily affected by human activities, we assume that the excess sediment yield of the unstudied parts of the greater watershed will be similar or lower. Consequently, we conclude that anthropogenic sediment production in the entire Eel River basin may account for a maximum of ~33% of the total sediment load reaching the coast. Although this is not a trivial amount of material, it is clearly too small to account for the three-fold increase in sedimentation rate measured on the shelf. Unfortunately, because the climatic and anthropogenic influences on river-sediment discharge are coeval, and because the gauge record is biased by an extreme event (Fig. 3), it is not possible to elucidate an anthropogenic impact on the shelf record.

## CONCLUSIONS

Comparison of river discharge and sedimentary records for the Eel River system suggests that sediment accumulation on the continental shelf has increased primarily due to an increase in the magnitude and frequency of hydrologic floods since ca. 1950. In contrast to classical models of event sedimentation, our findings suggest that presence of hydrologic signatures in shallow-marine deposits is perhaps more dependent on flood frequency than on magnitude, inasmuch as frequent depositional events increase net sedimentation rates and the preservation potential of flood-produced strata. Accordingly, it can be conjectured that climatic periods characterized by frequent floods of moderate scale are more apt to be recorded in bioturbated marine deposits than periods of infrequent, more extreme events. This conclusion is relevant to paleoenvironmental analysis based on sedimentary records, given the natural tendency for large floods to be clustered through time (Ely et al., 1993). One final implication speaks to challenges in elucidating natural and anthropogenic influences on fluvial-marine sedimentation. Although historical increases in sedimentation rate are often attributable to land-use activities (e.g., van Geen et al., 1999), climate variability may be a contributing, if not the chief, factor in some cases. Increasing use of geologic observations to deduce rapid climate change (Schimmelmann et al., 1998; Knox, 2000) demands that these issues be addressed for the full range of sedimentary systems.

## ACKNOWLEDGMENTS

This research was supported by Office of Naval Research grant N00014-99-1-0047. We thank J. Kravitz, C. Nittrouer, and the National Ocean Sciences Accelerator Mass Spectrometry Facility, Woods Hole, Massachusetts.

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Manuscript received August 28, 2001

Revised manuscript received December 20, 2001

Manuscript accepted December 20, 2001

Printed in USA