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Climate Change and the Episodicity of Sediment Flux of Small California Rivers

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ABSTRACT

We studied the streamflow and sediment flux characteristics of the 20 largest streams entering the Pacific Ocean along the central and southern California coast, extending for 750 km from Monterey Bay to just south of the U.S./Mexico border. Drainage basins ranged in area from 120 to 10,800 km^2, with headwater elevations ranging from 460 to 3770 m. Annual streamflow ranged from 0 to a maximum of 1×10^9 m^3/yr for the Santa Clara River in 1969, with an associated suspended sediment flux of 46×10^6 ton. Trend analyses confirm that El Niño/Southern Oscillation–induced climate changes recur on a multidecadal time scale in general agreement with the Pacific/North American climate pattern: a dry climate extending from 1944 to about 1968 and a wet climate extending from about 1969 to the present. The dry period is characterized by consistently low annual river sediment flux. The wet period has a mean annual suspended sediment flux about five times greater, caused by strong El Niño events that produce floods with an average recurrence of ca. 5 yr. The sediment flux of the rivers during the three major flood years averages 27 times greater than the annual flux during the previous dry climate. The effects of climate change are superimposed on erodibility associated with basin geology. The sediment yield of the faulted, overturned Cenozoic sediments of the Transverse Ranges is many times greater than that of the Coast Ranges and Peninsular Ranges. Thus, the abrupt transition from dry climate to wet climate in 1969 brought a suspended sediment flux of 100 million tons to the ocean edge of the Santa Barbara Channel from the rivers of the Transverse Range, an amount greater than their total flux during the preceding 25-yr dry period. These alternating dry to wet decadal scale changes in climate are natural cycles that have profound effects on fluvial morphology, engineering structures, and the supply of sediment and associated agricultural chemicals to the ocean.

Introduction

The importance of large rivers in transporting the denudation products of the continents to the sea has been known since Lyell (1873) described the flux of sediment into the Bay of Bengal from the Ganges and Brahmaputra Rivers. Since then, the contributions from large rivers have been updated and summarized in many studies (e.g., Garrels and Mackenzie 1971; Inman and Brush 1973; Milliman and Meade 1983; Meade 1996), with estimates of the total flux of particulate solids to the ocean of ca. 16×10^9 ton/yr. The importance of small rivers to the global budget of sediment was first documented by Milliman and Syvitski (1992). They showed that small rivers (drainage basin <10,000 km^2) cover only 20% of the land area, but their large number results in their collectively contributing much more sediment than previously estimated, increasing the total flux of particulate solids by rivers to ca. 20×10^9 ton/yr.

Sediment yield increases with the relief of the drainage basin and with decrease in basin size, factors that enhance the sediment flux of small rivers along mountainous coasts (Schumm and Hadley 1961; Inman and Nordstrom 1971; Dickinson 1988). Climate, rainfall, and type of geological formation are also well-known factors in determining sediment yield. Maximum yield occurs for basins in temperate climates that receive an annual rainfall of ca. 25–50 cm and decreases for precipitation

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rates either above or below this maximum (Langbein and Schumm 1958; Inman et al. 1963; Schumm 1977). As a consequence, central and southern California coastal basins, with a temperate climate (mean annual temperatures at the coast of 15°–19°C) and annual rainfall along the coast ranging from about 25 to 65 cm, have high sediment yields.

Human intervention in natural processes is accelerating erosion rates, perhaps by a factor of about two on a global scale (Milliman and Syvitski 1992; Vitousek et al. 1997). Significant anthropogenic effects began as early as 9000 yr ago with deforestation and the spread of agriculture from the "Fertile Crescent" (e.g., Heun et al. 1997). Human intervention has accelerated in this century with increased deforestation, expansion of mechanized agriculture, proliferation of dams (Inman and Jenkins 1984; Inman 1985; Meade et al. 1990; Meade 1996), and, since World War II, with extensive urbanization of coastal lands, particularly in central and southern California (Inman and Brush 1973). Urbanization decreases erosion locally but accelerates streambed erosion in response to the greater frequency and magnitude of peak streamflow caused by runoff from impervious urban surfaces (e.g., Schick 1995; Trimble 1997). Also, environmentally persistent organochlorine residues such as DDT and PCBs are transported in stream runoff and are primarily associated with fine minerals and organic material (Chiou et al. 1983) moving with the suspended sediment (Pereira et al. 1996). Monitoring of organochlorine residues in coastal rivers (e.g., Cross et al. 1992) and lagoons (e.g., P. M. Masters and D. L. Inman, unpublished data) of southern and central California shows that these compounds continue to erode from nonpoint sources (e.g., Rasmussen 1996) long after their use was discontinued.

The effects of changing climate and sea level rise have been studied extensively on a glacial-interglacial time scale (e.g., Hay 1994; O'Brien et al. 1995) and, during the Holocene, on a millennial scale (e.g., Bond et al. 1997; Campbell et al. 1998). Here, we address El Niño/Southern Oscillation (ENSO)–induced climate changes that occur on decadal time scales of one-quarter to one-half century, and the impact these changes have on the yield of basin sediment and the sediment flux of rivers along the coast of central and southern California.

Procedure

This study is based on the streamflow and sediment flux characteristics of the 20 largest streams entering the Pacific Ocean along the central and southern California coast, draining an area of 60,300 km^2 and extending for 750 km from Monterey Bay (lat. 37°N) to just south of the U.S./Mexico border (lat. 32°N; fig. 1). The river drainage basins ranged in area from 120 to 10,800 km^2, with headwater elevations ranging from 460 to 3770 m. The coastal climate is Mediterranean, with dry summers and winter rainfall along the coast of ca. 25–65 cm/yr with accumulation of snow at the higher elevations.

Almost all streams in this study have one or more dams or other water retention structures, and sand and gravel mining occurs on many. Several streams in the Los Angeles area have been altered by diversion facilities and contain extensive sections channelized with cement and/or rock, particularly in their lower reaches near the sea. We follow a drainage basin classification, modified from Brownlie and Taylor (1981), where the basins are designated as natural, moderately developed, and extensively developed. Moderately developed (*M*) basins are those with one or more water retention structures, mostly on secondary streams. Extensively developed (*E*) basins have either major water retention/diversion structures with large-scale channelization or, alternatively, have dams that intercept more than 50% of the drainage area. The only natural (*N*) basin is Calleguas Creek, and it has extensive agricultural development that modifies its overland flow. Sweetwater River drainage area is natural to the gage station at an elevation of 1030 m, but the downstream 85% of the area is highly developed with two dams. The basins are designated as *M*, *E*, and *N* in table 1.

Measurements of streamflow and suspended sediment flux were obtained from the U.S. Geological Survey (USGS; U.S. Geological Survey 1999) database on the Internet. The gage stations were located on USGS Hydrologic Unit Map-1978, State of California; the gage station closest to the coast was identified; and the area above the gage station entered in table 1. Annual streamflow was tabulated for each of the coastal gage stations of the 20 rivers. Data gaps in the coastal stations were filled using the method of hydrographic comparisons with upstream stations to generate flow-rating curves (e.g., Porterfield 1972). Gaps in the USGS measurements of suspended sediment flux were filled using sediment-rating curves developed from the measured values of streamflow and sediment flux (e.g., Porterfield 1972; Brownlie and Taylor 1981; Inman and Masters 1991). The cumulative monthly flow volume (Q_i, m^3/mo) and the cumulative monthly suspended sediment flux (J_i, ton/mo) were correlated with a best-fit power function $J_i = aQ_i^b$, where a and

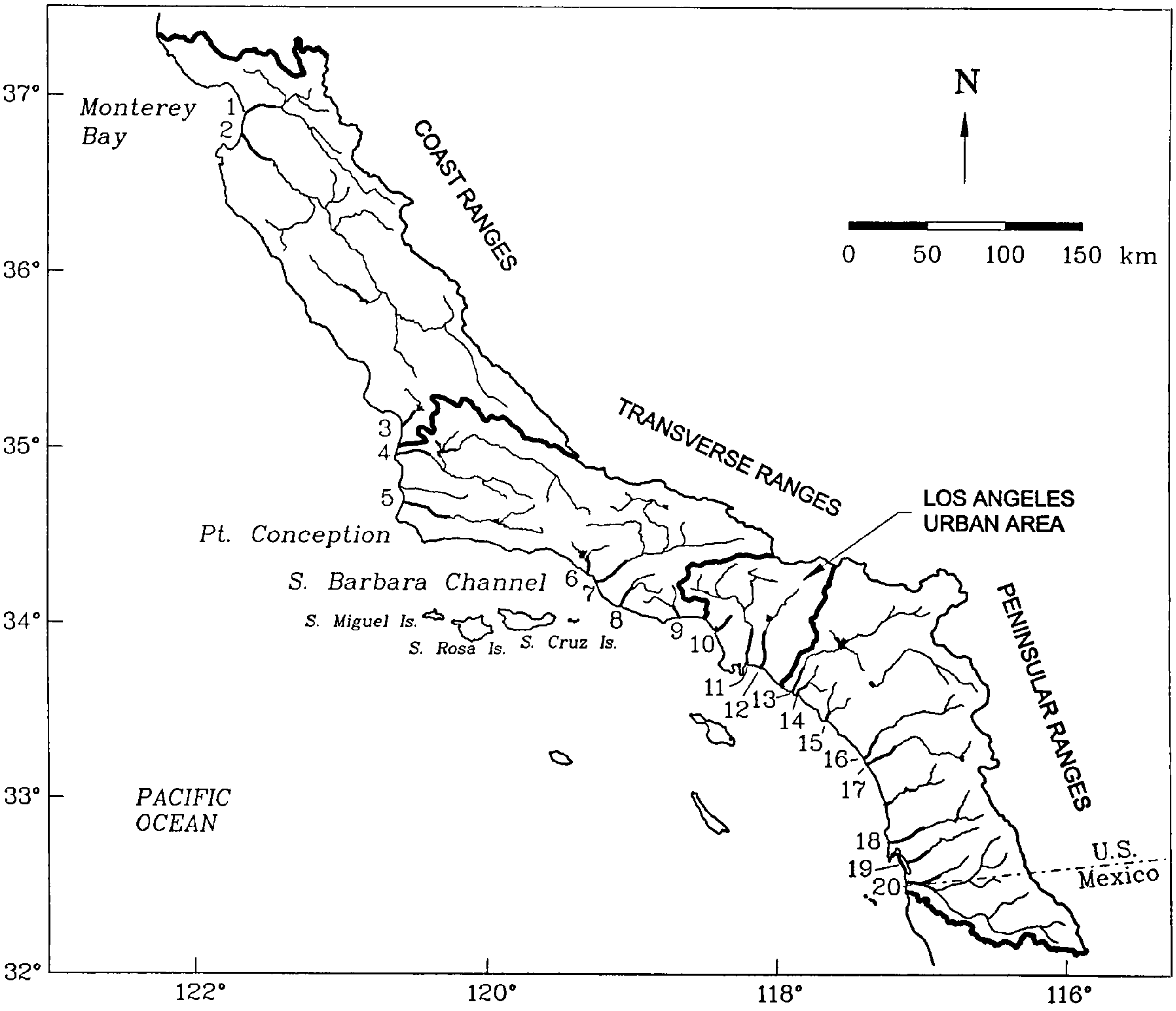

Figure 1. Location map for the rivers, basins, and provinces analyzed in this study. The rivers are numbered *1–20* and are listed in table 1.

b are derived constants. Data gaps in sediment flux were filled by applying monthly streamflow data to the rating curve. The monthly values of Q_i and J_i were then summed over the water year to provide the annual values of streamflow (Q, m^3/yr) and suspended sediment flux (J, ton/yr). The annual data for streamflow and sediment flux of the 20 rivers are tabulated for the period 1940–1995 in Inman et al. (1998).

The sediment fluxes recorded and used here are for the flux of suspended load material measured or assumed to occur within the streamflow from ca. 10 cm above the bed to the surface of the flow. This suspended load includes the wash load of silt and clay sized material and some sand, usually fine sand. Estimates of the coarser bedload material are not included in these suspended load estimates. The bedload, together with estimates of the total sediment flux (suspended and bedload), is discussed under "Bedload, Suspended Load, and Total Load."

Suspended sediment measurements began in the Santa Clara and Santa Ana Rivers in water year 1968. During the 27 yr from 1969 to 1995, there were 146 year-long measurements of suspended sediment flux in the 15 rivers (*A* and *C* in table 1). Thus, 36% of the data tabulated for these rivers is from USGS measurements and 64% is based on sediment-rating curves. Streams with the most suspended sediment measurements were Santa Ana (18 yr), Santa Clara (16 yr), San Juan Creek (16 yr),

Table 1. River and Basin Statistics

River	Basin class[a]	Gage station	Station number	Drainage area[b] (km^2)	Headwater elevation (m)	Period of record	Rating procedure/surrogate[c]	Interdecadal break[d]
1. Pajaro (36.8°N)	*M*	Chittenden	11159000	2550[e]	1720	1949–1995	*A*/none	1968/1969
2. Salinas (36.7°N)	*M*	Spreckels	11152500	10,760	1920	1929–1995	*A*/none	1968/1969
3. Arroyo Grande (35.1°N)	*E*	Arroyo Grande	11141500	264	930	1939–1995	*B*/Lopez Creek	…
4. Santa Maria (35.0°N)	*E*	Guadalupe	11141000	4510	2460	1940–1995	*A*/none	…
5. Santa Ynez (34.7°N)	*M*	Lompoc	11133500	2050	2240	1906–1995	*B*/San Antonio	1968/1969
6. Ventura (34.2°N)	*M*	Ventura	11118500	487	1970	1929–1995	*A*/none	1968/1969
7. Santa Clara (34.2°N)	*M*	Montalvo	11114000	4130	2900	1927–1995	*A*/none	1968/1969
8. Calleguas Creek (34.1°N)	*N*	Camarillo	11106550	642	1230	1968–1995	*A*/none	1968/1969
9. Malibu Creek (34.1°N)	*M*	Crater Camp	11105500	272	930	1931–1995	*A*/none	1968/1969
10. Ballona Creek (34.0°N)	*E*	Culver City	11103500	232	460	1928–1995	*B*/Topanga Creek	1968/1969
11. Los Angeles (33.8°N)	*E*	Long Beach	11103000	2140	2340	1929–1995	*A*/none	1968/1969
12. San Gabriel (33.7°N)	*E*	Spring Street	11088000	1610	3300	1936–1995	*B*/Los Angeles	1968/1969
13. Santa Ana (33.6°N)	*E*	Santa Ana	11078000	4400	3770	1923–1995	*A*/none	1968/1969
14. San Diego Creek (33.6°N)	*E*	Campus Drive	11048555	306	580	1977–1995	*A*/none[f]	1968/1969
15. San Juan Creek (33.5°N)	*M*	San Juan Capistrano	11046550	303	1870	1969–1995	*A*/none	1968/1969
16. Santa Margarita (33.2°N)	*M*	Ysidora	11046000	1920	2230	1923–1995	*A*/none	1968/1969
17. San Luis Rey (33.2°N)	*M*	Oceanside	11042000	1440	2140	1912–1995	*C*/none	1977/1978
18. San Diego (32.8°N)	*E*	Santee	11022500	976	2140	1912–1995	*A*/none[g]	1977/1978
19. Sweetwater (32.6°N)	*N*/*E*[h]	Descanso	11015000	118	1730	1905–1995	*B*/San Diego	1977/1978
20. Tijuana (32.5°N)	*E*	Nestor	11013500	4390	1060	1936–1995	*C*/none	1977/1978

[a] *M*, *E*, *N* = moderately developed, extensively developed, and natural, respectively; refer to "Procedure."

[b] Area above gage station.

[c] Sediment-rating procedure: *A* = monthly values summed by water year; *B* = monthly values using surrogates summed by water year; *C* = annual values per Brownlie and Taylor (1981). See Inman et al. (1998) for details.

[d] Indicates water year of the dry to wet climate break; ellipses indicate indeterminate break.

[e] Sediment-rating curve developed from 1952–1992 monitoring data at Chittenden, with streamflow and drainage area from the sum of Gilroy (Pajaro River) and Hollister (San Benito River).

[f] Sediment-rating curve developed from 1972–1985 monitoring data at Culver Drive (11048500), with streamflow from Campus Drive.

[g] Sediment-rating curve developed from 1984 monitoring data at Fashion Valley (11023000).

[h] Natural to gage station at elevation 1030 m; downstream 85% of basin extensively developed.

and Ventura River (14 yr). The USGS estimates that errors in measurement of suspended sediment flux could range from ca. ±5% to ±20%, depending on type of sediment load (e.g., Guy and Norman 1970); while statistical errors in our calculations using rating-curve procedures are ca. ±20% (Inman et al. 1998). Thus, assuming that the measurement errors are ±15% and that the statistical errors are ±20%, an overall error of ca. ±35% could occur for the worst-case scenario in data that are calculated from rating curves.

Delineating Climate Trends

Visual representation of rainfall and streamflow over time invariably produces confused, noisy time histories, and the occurrence of climate change is not easily detected. However, trends become more apparent when the data are expressed in terms of cumulative residuals, Q_n, taken as the continued cumulative sum of departures of annual values of a time series, Q_i, from their long-term mean values $\overline{Q}$, such that $Q_n = \sum_o^n (Q_i - \overline{Q})$, where n is the sequential value of a time series of N yr. This method was first used by Hurst (1951, 1957) to determine the storage capacity of reservoirs on the Nile River, where the range between the maximum and minimum of the cumulative residual gives the needed deficit or credit storage capacity necessary for runs of excessively dry or wet years. The Hurst method has since been widely used to show trends in natural phenomena such as rainfall (e.g., Flick 1993), riverflow (Riehl and Meitin 1979), river sediment flux (Inman and Jenkins 1997), and turbulent flow intensity (Van Atta and Helland 1977).

We use the Hurst method to determine the periods of ENSO-induced climate change reflected in the discharge of rivers. When the streamflow and sediment flux are plotted as cumulative residuals versus time for the 68-yr period 1928–1995, all of the 20 rivers displayed a clear change from wet to dry climate in 1944, as shown in figure 2 by three representative rivers. Note that periods of low sediment flux, representing dry climate, appear as intervals of decreasing residual (negative slope), while high sediment flux (wet periods) are represented by intervals of increasing residual (positive slope). Within the remaining 52-yr period (1944–1995), 18 of the 20 rivers showed a uniform dry period lasting for ca. 25 yr from 1944 to 1968, followed by a wet period characterized by episodic floods during the 27-yr period from 1969 to the end of the database in 1995. This wet period is still continuing through water year 1998. It is likely that the indeterminate climate breaks on two of the rivers (Santa Maria River and Arroyo Grande Creek; table 1) are caused by retention and release of water from the relatively large dams on these streams.

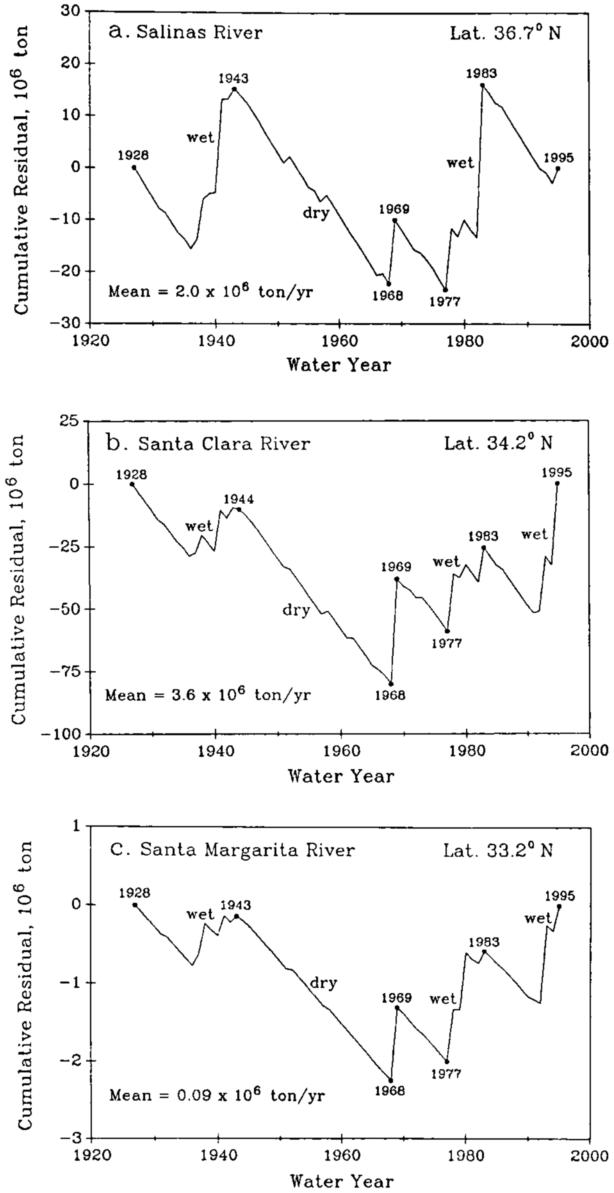

Figure 2. Cumulative residuals of annual suspended sediment flux for Salinas, Santa Clara, and Santa Margarita Rivers, showing the change from dry to wet climate following the floods of 1969. (Data from Inman et al. 1998, apps. B and C.)

Typical cumulative residuals for rivers with large sediment flux, intermediate fluxes, and intermediate fluxes with large dams are shown in figure 3. Rivers with large and intermediate sediment flux (fig. 3*a*, *b*) all show a dry to wet climate change at 1968/1969. The cumulative residuals in figure 3*c*

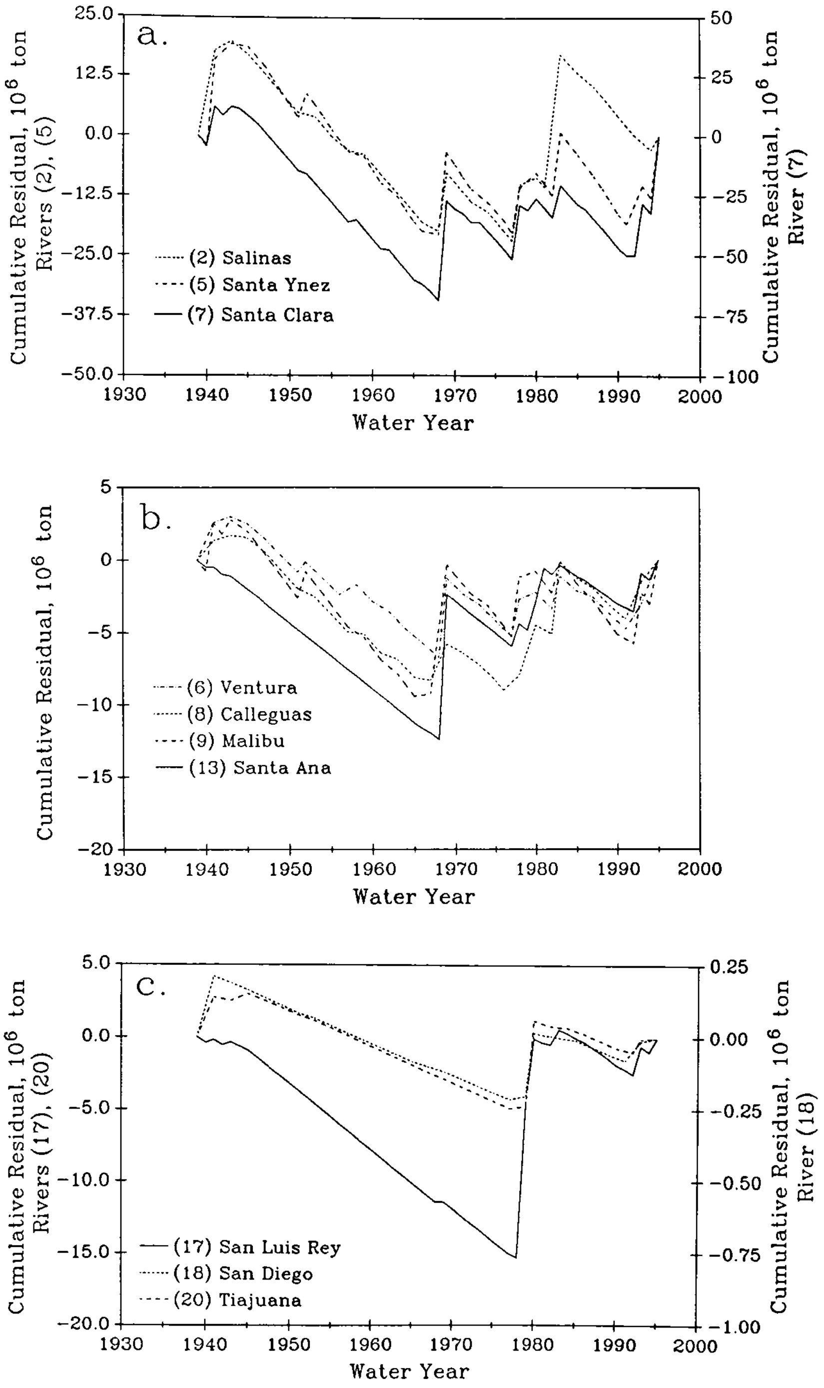

Figure 3. Typical cumulative residuals showing trends for the central and southern California rivers. *a*, Rivers with large sediment flux. *b*, Rivers with intermediate sediment flux and with dams on secondary streams or of low sediment storage. *c*, Rivers with low to intermediate sediment flux and with high sediment storage. Period of record is 1940–1995. (Data from Inman et al. 1998, app. C.)

suggest that the climate change from dry to wet for the San Luis Rey, San Diego, and Tijuana Rivers occurred following the floods of 1978 and 1980, rather than 1969. These rivers have relatively low streamflow and dams with large storage capacity. These dams were nearly empty in 1969, and that year's flood was only sufficient to fill them. Thus, significant downstream flooding below the dams was delayed until 1978 for the San Luis Rey River and 1980 for the San Diego and Tijuana Rivers. However, there is a latitudinal difference in the focus of El Niño storm intensity. For example, during 1969, the storms were more intense in the latitude of the Transverse Range, whereas 1980 storms tended to be more intense to the south, and 1983 storms were most intense in central California, as discussed later under "Episodic Events."

The periods of multidecadal climate change found in these California rivers are in general agreement with the interdecadal Pacific/North America (PNA) climate pattern that is linked to ENSO cycles, with the dry/wet shift occurring between 1968 and 1977 (Bjerkness 1969; Wallace and Gutzler 1981; Douglas et al. 1982; White and Cayan 1998). Generally, the decadal scale oscillations in the wet climate portions of the PNA involve a flurry of strong and unusually persistent El Niño events (Goddard and Graham 1997). These strong, long-lived El Niño events signal a greater than normal streamflow in the southwestern United States (e.g., Cayan and Peterson 1989; Cayan and Webb 1992; Ely et al. 1994), as also was found in this study. In contrast, the opposite dry phase of the PNA involves a period of relatively few, weak El Niño events. This La Niña–dominated portion of the PNA is characterized by a dry climate in central and southern California (Inman and Jenkins 1997; Zhang et al. 1997).

The dry climate is reflected in years with no measurable streamflow on some southern California rivers. During the 1944–1968 dry period, there were 2.3 yr of no flow per river draining the Transverse Ranges (six rivers) and 5.8 yr per river draining the Peninsular Ranges (eight rivers). During the wet period, the number of no-flow years per river decreased to ca. 1 yr per river draining these ranges (Inman et al. 1998).

Climate Trends and Sediment Yield

The streamflow and sediment flux data for the 20 rivers were separated into several sets based on the delineated climate trends: a 25-yr dry period (1944–1968), a 27-yr wet period (1969–1995), and a 52-yr period spanning the dry and wet periods (1944–1995). The mean values of annual streamflow, suspended sediment flux, and sediment yield for these data sets are entered in table 2. The net yield of suspended sediment ([ton/yr]/ha) is taken as the mean annual suspended sediment flux (ton/yr) during the period, divided by the area of the drainage basin (ha) upstream from the gaging station (table 1), where 100 ha = 1 km^2. The net yield of suspended sediment is based on material that passes the gaging station in suspension. It is the gross yield of sediment caused by soil erosion of basin lands minus the local bedload and the material retained in dams, valley fill (colluvium and alluvium), and stream channels.

Inspection of table 2 shows significant differences between the streamflow, sediment flux, and sediment yield for the two periods. The mean annual streamflow during the wet period, summed for all rivers, exceeds that during the dry by a factor of about three. The mean annual suspended sediment flux, summed for all rivers, during the wet period exceeds that during the dry by a factor of about five. However, there is little systematic relation between the sediment flux of these 20 rivers and their streamflow or drainage area. For example, the Santa Clara River, with the highest sediment flux, ranks third in streamflow and fifth in area; the Santa Ynez River, with the second highest sediment flux, ranks fifth in streamflow and eighth in area.

Geological Provinces

When the 16 largest rivers in terms of drainage area (>300 km^2) are aligned in a south-to-north sequence (fig. 4), it becomes clear that there is a pronounced latitudinal difference in the yield of suspended sediment of these coastal drainage basins. The four rivers in the vicinity of Point Conception have sediment yields about an order of magnitude greater than those to the north or south.

The areas of the drainage basins for these four rivers (Santa Ynez, Ventura, Santa Clara, and Calleguas Creek) are intermediate among the 20 rivers (ranking eighth, fourteenth, fifth, and thirteenth, respectively), as are their headwater elevations (ranking sixth, tenth, third, and fifteenth). There is a gradual increase in annual rainfall from south to north, with a notable increase for these river basins associated with the orographic effect of the Transverse Ranges on El Niño storms. However, the basins of the Transverse Ranges are most distinctive in their geology and type of country rock (e.g., Rice et al. 1976; Norris and Webb 1990; Luyendyk 1991; Hey 1998). The basins lie within and between structurally complex east/west trending folds and thrust faults with appreciable vertical slip and overturned beds. The formations are predominantly relatively unconsolidated and easily eroded Cenozoic sediments of Pliocene through Eocene age. In contrast, the Peninsular Range to the south and the Coast Ranges to the north are older, more resistant Mesozoic formations, including intrusive igneous

Table 2. Streamflow, Suspended Sediment Flux, and Yield by Dry/Wet Period

	Mean annual streamflow[a] (10^6 m^3/yr)			Mean annual suspended sediment flux[a] (10^6 ton/yr)			Annual net yield[b] ([ton/yr]/ha)		
River	Total (1944–1995)	Dry (1944–1968)	Wet (1969–1995)	Total (1944–1995)	Dry (1944–1968)	Wet (1969–1995)	Total (1944–1995)	Dry (1944–1968)	Wet (1969–1995)
1. Pajaro	79.1	56.9	99.6	.056	.027	.083	.22	.10	.33
2. Salinas	311.	191	422	1.70	.487	2.82	1.58	.45	2.62
3. Arroyo Grande	16.7	13.1	20.0	.299	.258	.336	11.3	9.8	12.8
4. Santa Maria	23.3	16.7	29.5	.524	.367	.670	1.2	.8	1.5
5. Santa Ynez	96.5	49.4	140	2.35	1.12	3.49	11.5	5.5	17.1
6. Ventura	52.6	29.6	73.8	.521	.191	.827	10.7	3.9	17.0
7. Santa Clara	173	74.5	265	3.83	.82	6.61	9.3	2.0	16.0
8. Calleguas Creek	23.6	14.8	31.8	.621	.229	.983	9.7	3.6	15.3
9. Malibu Creek	21.6	12.5	30.0	.722	.270	1.14	26.5	9.9	41.9
10. Ballona Creek	46.1	31.9	59.2	.014	.0076	.019	.6	.33	.82
11. Los Angeles	236	121	342	.243	.071	.403	1.1	.33	1.9
12. San Gabriel	100	34.5	161	.052	.0068	.094	.32	.042	.59
13. Santa Ana	60.8	6.95	111	.495	.023	.933	1.1	.05	2.1
14. San Diego Creek	29.1	15.7	41.4	.107	.051	.159	3.5	1.7	5.2
15. San Juan Creek	14.3	2.11	25.5	.051	.00076	.097	1.7	.025	3.2
16. Santa Margarita	33.0	8.47	55.7	.095	.0083	.176	.50	.04	.92
17. San Luis Rey	44.1	3.98	81.3	.426	.015	.876	3.0	.10	6.1
18. San Diego River	13.7	3.94	22.7	.010	.0013	.017	.10	.01	.18
19. Sweetwater	7.42	2.67	11.8	.0043	.00085	.0075	.36	.07	.63
20. Tijuana	28.9	8.32	48.0	.206	.049	.351	.47	.11	.80
Total	1411	698.0	2071	12.33	4.00	20.09			

[a] Streamflow and suspended sediment flux averaged from annual values (Inman et al. 1998, app. C).

[b] Net yield is mean suspended sediment flux for period divided by drainage area above gage station; see table 1.

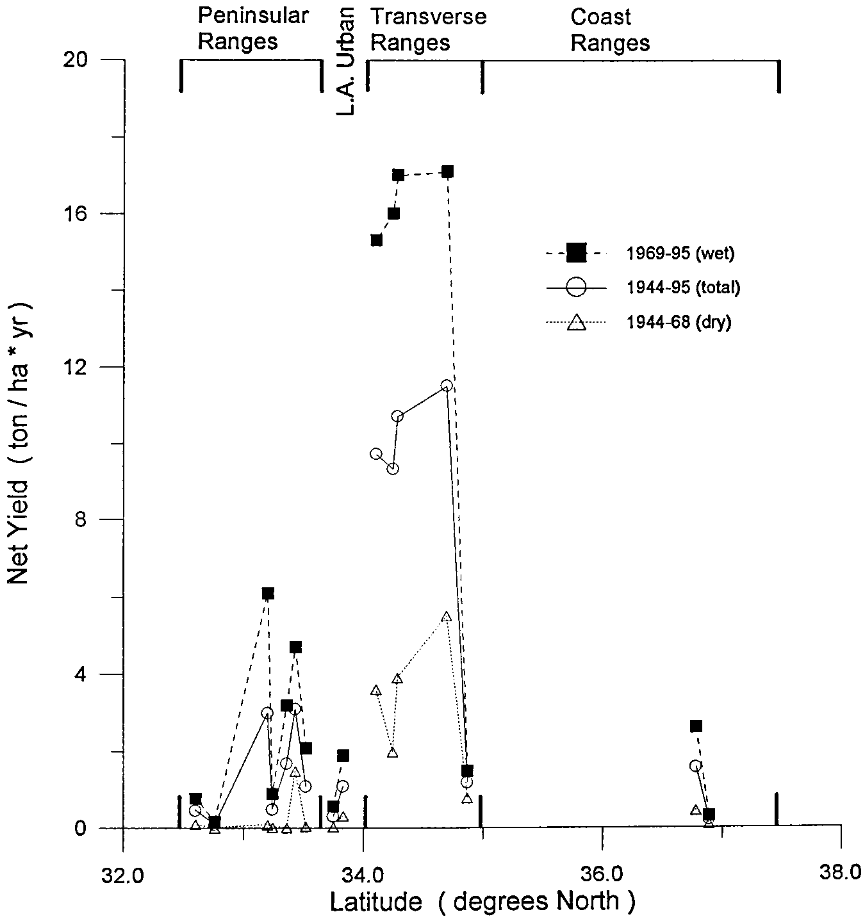

Figure 4. Net sediment yield versus latitude and province for basins of southern and central California rivers having drainage areas greater than 300 km^2. (Data from table 2.)

rocks. The Peninsular Range consists of Jurassic and Cretaceous plutonic, mostly granitic type rocks that are more resistant to erosion, with post-Cretaceous sediments forming only a thin veneer over the plutonic rocks. The southern Coast Ranges are elongate topographic features associated with the San Andreas fault zone, a major tectonic transform noted for its extensive strike slip and absence of dip slip. The Salinas River basin lies in a synclinal trough to the west of the San Andreas fault that is underlain by basement complexes of resistant metamorphic and plutonic rocks.

The variation in the yield of sediment with latitude (fig. 4) emphasizes the importance of geological factors in determining erosion along this mountainous collision coast. Accordingly, the coastal segments were grouped into three provinces corresponding to their geological setting: Southern Coast Ranges, Transverse Ranges, and Peninsular Ranges. A separate unit was added for the Los Angeles urban area with its extensively modified river channels. These provinces and their associated rivers, sediment fluxes, and net yields are listed in table 3.

The total sediment flux for each province is determined by prorating the net yield determined at the gage station (table 2) to cover the entire area of the basin and then summing the various basin fluxes. Where the gage network was incomplete, as was the case for some of the small, steep coastal areas, the appropriate net yield was estimated from that of adjacent basins or combinations of adjacent basins, as indicated in notes to table 3.

The data in table 3 show that the 20 streams in this study transport 4.0 × 10^6 ton/yr of suspended sediment during the dry period and 20.1 × 10^6 ton/yr during the wet period. When the net yield determined from these data, representing 72% of the total study area, is prorated over the entire 60,300 km^2 area of the study, the suspended sediment dis-

Table 3. Suspended Sediment Flux and Yield by Province

Province/river basin	Coast length (km)	Area (10^{3} km^{2})	Area covered by rating curves (%)	Flux from rating curve areas[a]			Flux prorated for total area[b]			Average net yield of province[c] ([ton/yr]/ha)		
				Total (1944–1995)	Dry (1944–1968)	Wet (1969–1995)	Total (1944–1995)	Dry (1944–1968)	Wet (1969–1995)	Total (1944–1995)	Dry (1944–1968)	Wet (1969–1995)
South Coast Ranges: 1–3	280	21.5	63	2.06	.772	3.24	7.43[d]	4.74[d]	9.91[d]	3.5	2.2	4.6
Transverse Ranges: 4–9	250	15.6	77	8.57	3.00	13.7	12.0[e]	4.23[e]	19.2[e]	7.7	2.7	12.3
Los Angeles urban area: 10–12	70	5.1	78	.309	.085	.516	.370	.106	.632	.73	.21	1.2
Peninsular Ranges: 13–20	150	18.1[f]	77	1.39	.149	2.62	1.86	.173	3.56	1.0	.10	2.0
Total coast: 1–20	750	60.3	72	12.3	4.01	20.1	21.7	9.25	33.3	3.6	1.5	5.5

Note. Refer to figure 1 and text.

[a] Suspended sediment flux to coast (10^{6} ton/yr); summed from table 2 for stream basins listed in col. 1.

[b] Suspended sediment flux to coast (10^{6} ton/yr); net yield from table 2 prorated over basin area and summed for basins listed in col. 1.

[c] Prorated data divided by province area.

[d] Net yield for Santa Cruz coast from Hicks and Inman (1987); Carmel/Big Sur coast prorated from basin 3.

[e] Net yield for Santa Ynez Mountains coast prorated from average of basins 5–9.

[f] The 18,100-km^{2} area is exclusive of the 2010 km^{2} area of the Elsinore closed basin.

charge to the sea increases to 9.25×10^6 ton/yr and 33.3×10^6/yr, respectively, for the two periods. In terms of coast length, this prorated discharge of suspended sediment to the sea becomes 12.3×10^3 (ton/km)/yr and 44.4×10^3 (ton/km)/yr for the dry and wet periods, respectively. The Transverse Ranges province, with one-quarter of the total area of the study, yields between one-half and three-quarters of the flux of suspended sediment to the ocean. The Los Angeles urban area has the lowest yield of the four provinces. In terms of geology, it is the northernmost part of the Peninsular Ranges and, although it receives more rainfall than the ranges to the south, its net yield is only ca. 20% of that of the Peninsular Ranges province. This low yield is apparently the result of the extensive hard cover of streets and river channels.

Episodic Events

When the three major sediment flux events are tabulated and grouped by climate period (table 4), it is apparent that, in all cases, the major event during the wet period is also the major event for the entire period. This is also true for the three major events and their sequences, except for the three streams with the largest dams relative to their size (Arroyo Grande Creek, Santa Maria River, and Tijuana River), where the second or third largest events differ in years of occurrence. Table 4 also shows that the years having major sediment flux events tend to cluster. Water years 1952 and 1958 were the most common years for higher flow during the dry period, while 1969, 1978, 1980, 1983, 1993, and 1995 were common years for floods during the wet period, with the largest clusters at 1969 and 1983. The major cluster of intense sediment flux events in 1969 that followed the long period of low transport during the period of dry climate emphasizes the abruptness and magnitude of the change in sediment-transport regime associated with the multidecadal climate change. Since 1969 and 1983 were major events on all rivers, the suspended sediment flux and associated sediment yields for these two water years are also listed in table 4. Comparison of the sums in tables 2 and 4 shows that the sediment fluxes during the 1969 and 1983 floods exceeded the average annual flux during the dry period by factors of 31 and 22, respectively. The average sediment flux during the three major

Table 4. Years of Highest Flux/Yield of Suspended Sediment

	Three major events[a]			1969 water year		1983 water year	
River	Total (1944–1995)	Dry (1944–1968)	Wet (1969–1995)	Suspended sediment flux[c]	Net yield[d]	Suspended sediment flux[e]	Net yield[f]
1. Pajaro	83, 69, 95	58, 52, 56	83, 69, 95	.389	7.1	1.03	18.7
2. Salinas	83, 69, 78	58, 52, 67	83, 69, 78	14.4	13.4	31.7	29.5
3. Arroyo Grande	83, 58, 67	58, 67, 52	83, 95, 93	.521	19.7	1.96	74.2
4. Santa Maria	69, 83, 58	58, 52, 67	69, 83, 95	5.23[b]	11.6	4.34	9.6
5. Santa Ynez	69, 83, 95	52, 67, 58	69, 83, 95	20.04	99.7	16.3	79.7
6. Ventura	69, 95, 78	58, 52, 44	69, 95, 78	6.03[b]	124.	2.95	60.6
7. Santa Clara	69, 95, 78	58, 62, 44	69, 95, 78	45.8[b]	111.	17.4	42.1
8. Calleguas Creek	83, 69, 80	58, 62, 44	83, 69, 80	5.68[b]	88.5	3.77	58.7
9. Malibu Creek	69, 78, 93	52, 66, 58	69, 78, 93	9.88	363.	2.87[b]	106.
10. Ballona Creek	83, 80, 78	52, 62, 67	83, 80, 78	.0352	1.5	.0526	2.3
11. Los Angeles	69, 83, 78	66, 44, 52	69, 83, 78	1.62	7.5	1.56	7.3
12. San Gabriel	83, 80, 69	44, 67, 47	83, 80, 69	.183	1.1	.512	3.2
13. Santa Ana	69, 93, 80	67, 66, 58	69, 93, 80	10.5[b]	6.6	1.10[b]	4.5
14. San Diego Creek	83, 80, 93	67, 66, 58	83, 80, 93	.356	11.6	.493[b]	10.4
15. San Juan Creek	80, 78, 93	67, 66, 58	80, 78, 93	.287	9.4	.209[b]	6.1
16. Santa Margarita	93, 69, 80	52, 58, 44	93, 69, 80	1.04[b]	2.0	1.32	1.4
17. San Luis Rey	79, 80, 93	44, 45, 67	79, 80, 93	.468[b]	.4	1.32	9.2
18. San Diego R.	80, 93, 95	52, 66, 58	80, 93, 95	.00743	.1	.0196	.2
19. Sweetwater	83, 80, 93	52, 58, 67	83, 80, 93	.00821	.7	.0547	4.6
20. Tijuana	80, 93, 44	44, 52, 45	80, 93, 95	.0181	.04	.358	.8
Total				122.5		89.3	

Note. Data from Inman et al. (1998, app. C).

[a] By magnitude, highest flux year first.

[b] Suspended sediment flux measured by USGS; other data from rating curves.

[c] 10^6 ton.

[d] (Ton/yr)/ha.

[e] 10^6 ton.

[f] (Ton/yr)/ha.

events on all rivers listed in table 4 exceeded the average annual flux for the dry period by a factor of 27.

Comparison of the suspended sediment flux for 1969 (table 4) with the flux during the dry period (table 2) shows that the suspended sediment brought to the coast by the flood of 1969 equaled or exceeded that for the entire preceding 25-yr dry period in 12 out of the 20 rivers. The only exceptions are rivers with large dams and/or small drainage areas. The cumulative transport of the six rivers (4–9, table 4) draining the Transverse Ranges during the 1969 flood exceeded the sum of their average annual transport during the dry period by a factor of 31, while the storm-generated transport on the Santa Clara River alone exceeded the total transport during the previous 25 yr by a factor of 2.2. These comparisons show that the flood of 1969, following a protracted 25-yr dry period with low runoff, was a "first flush" event (Clean Water Act 1990; EPA/NOAA 1993) for fine sediment and associated contaminants in most of these river basins.

Because of its high sediment yield, the Transverse Ranges province provides the major contribution of sediment discharge to the sea along the central and southern California coast. In 1969, the streams from the Transverse Ranges (4–9; table 4) discharged 93 million tons of suspended sediment into the ocean, 76% of the discharge of all 20 rivers. When we include the smaller streams in this high-yield province, the total discharge is even greater. For example, the suspended sediment flux from San Antonio Creek (between the Santa Maria and Santa Ynez Rivers) was calculated for 1969 from the U.S. Geological Survey (1998, 1999) measurements and found to be 0.72 million tons. The sediment flux from the many small, ungaged, streams draining the Santa Ynez Mountains coast of the Santa Barbara Channel was determined by prorating the average of the net yields of the five adjacent streams (5–9, table 4) and was found to be 157 ton/ha for 1969. This net yield multiplied by the 970 km^2 drainage area of the Santa Ynez Mountains coast gives a total suspended sediment flux of 15.2 million tons for the 110-km-long Santa Ynez Mountains coast during 1969. The collective flux of suspended sediment load from streams draining the Transverse Range in 1969, rounded to the nearest million tons, is 109 million tons. As is shown later, ca. 100 million tons of this suspended sediment converges on the waters of the Santa Barbara Channel.

Bedload, Suspended Load, and Total Load

The above discussions pertain to the suspended sediment transport by streams, which is determined from the depth-integrated measurements of suspended load and stream velocity. The total load transport also includes the bedload, which is the material transported in and above the bed by traction and saltation. Whereas the estimates of suspended sediment flux are reasonably accurate and easily obtained, the bedload is difficult to measure directly and is often inferred from material retained in river deltas and debris basins (e.g., Langbein and Schumm 1958; Guy 1970; Guy and Norman 1970). Once the river discharges into the sea, there are significant differences in the transport paths of the suspended and bedload sediment. Most of the fine suspended sediment moves with the river water and flows out over the sea as a spreading turbid plume, and the sediment, which is subject to flocculation and ingestion by organisms, is eventually deposited in deeper water (e.g., Gorsline et al. 1984). The coarser bedload material remains nearer to the river mouth as a submerged sand delta and is later transported along the shore by waves and currents to nourish the downcoast beaches. The few reliable measurements of bedload indicate that it is ca. ≤10% of the total load in large rivers but, in smaller, mountainous streams, may be considerably more (Richards 1982, p. 106; Meade et al. 1990). Kroll and Porterfield (1969) and Kroll (1975) estimated bedload as the difference between the total load transport calculated by the modified Einstein procedure (Colby and Hembree 1955) and the measured suspended sediment flux. They found that the percentage of bedload to total load varied with streamflow and ranged from ca. 10% to 39% in the Santa Maria and Santa Ana Rivers and up to 73% in San Juan Creek. Using the same procedure, Williams (1979) found that bedload was ca. 6% of the total load for the Santa Clara River over the period 1968–1975 and that, for these water years, 55% of the total sediment transport occurred in a 2-d period and 92% occurred in less than 2 mo. Considering the size of these rivers and their relatively high sand content, it appears reasonable to assume that, for rivers with drainage basins greater than ca. 500 km^2, the percentage of bedload relative to the total load is ca. 10% and that for smaller streams it is ca. 15% or more.

Although there are no direct measurements of total load transport on these rivers, there are measurements of the size distribution of the sediments and estimates of total load. For example, the hydrograph for the 1969 flood on the Santa Clara River shows two major streamflow events 1 mo apart. The first was on January 25, with a daily streamflow rate of 2100 m^3/s, followed by another, on February 25, at 2610 m^3/s (U.S. Geological Survey 1999). Williams (1979) lists two "instantaneous" measurements of streamflow and suspended sediment characteristics for the January 25 event at 10:15 and 17:25, with streamflows of 4620 m^3/s and 1590 m^3/s, and suspended sediment fluxes of 422 ton/s and 113 ton/s, respectively. During the peak flood flow (January 25, 10:15) the suspended load had a solids concentration of 91 g/L and consisted of 9% sand, 51% silt, and 40% clay-sized particles (fig. 5). Later in the day (17:25), the concentration had dropped to 71 g/L and the size distribution had changed to 22% sand, 46% silt, and 32% clay. The median diameter of the suspended load at 10:15 and 17:25 was 12 μm and 16 μm, respectively. There was no bedload sample available, but surficial bed material at that station several years later was found to be all sand with a median diameter of 890 μm. For the 1969 flood year, Williams estimated the total transport of sediment to be 48.4 million tons, of which bedload was ca. 5%. Alexander et al. (1996) showed that, during the flood of 1983, the suspended load of the Santa Clara River was 62% sand, 24% silt, and 14% clay-sized materials with a median diameter of 95 μm. The surficial bed material was all sand with a median diameter of 270 μm (fig. 5). There was a higher percentage of fine material in suspension in 1969 than in 1983 because the former was a first-flush event for fine material following a protracted dry period with little or no high streamflow. Figure 5 suggests that the heavy load of fine sediment carried by the 1969 flood had accumulated as stream and valley fill during the preceding dry climate and was abruptly eroded from the drainage basin during the onset of flooding. This suspended flood load included much of the fine sand component of the bed material, leaving a coarse residual on the bed. Much less fine material was available for subsequent flood events, such as 1983, so that their suspended load was coarser and closer in size to the bed material. Initial fining of the suspended sediment load and coarsening of the bed material during floods was observed and studied during the experimental flood on the Colorado River in 1996 (Rubin et al. 1998).

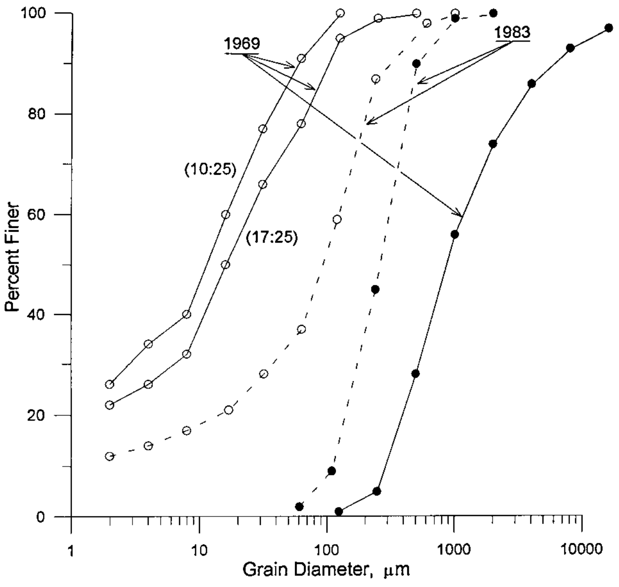

Figure 5. Size distribution of suspended load (*open dot*) and surficial bed material (*closed dot*) in the Santa Clara River at Montalvo gage station on January 25, 1969 (Williams 1979; bed sample composite of 1971, 1975), and March 2, 1983 (Alexander et al. 1996). *10:25* and *17:25* indicate sampling time on January 25, 1969.

Soil Erosion and Sediment Yield

The sediment yield derived from the suspended sediment flux of the rivers (table 2) was compared (table 5) with soil erosion measurements obtained from the database of the National Resources Inventory (NRI) of the U.S. Department of Agriculture. This database utilizes the Revised Universal Soil Loss Equation described by Renard et al. (1997). The database tabulates soil losses and estimated annual sheet and rill erosion for nonfederal agricultural lands, including cropland (cultivated and noncultivated), pastureland, and rangeland. The sums of the erosion of agricultural lands listed in the NRI survey ending in 1992 are listed in table 5 (col. 4).

In order to obtain a yield rate from soil erosion that is comparable to that based on the sediment flux in rivers, it was necessary to estimate an erosion rate for the unreported nonagricultural (federal) land in the basin. We assumed that the NRI erosion rate for rangeland in the same basin would be a sensible estimate for the remaining land in the basin. These rates are listed in table 5 (col. 5). Accordingly, the estimates for the remaining nonagricultural land, based on the erosion rate for rangeland, were calculated and are listed in column 6 of table 5. The total erosion for the basin is taken as the sum of the erosion of agricultural and nonagricultural land. Table 5 includes data from all basins in this study for which the boundaries of the USGS and the USDA-NRI survey coincided without overlap and/or were not mostly urban.

Table 5. Estimated Soil Erosion, USDA-NRI 1987–1992 Survey

River basin	Area[a] (km^2)	Agricultural land (%)	Agricultural land erosion[b] (ton/yr)	Rangeland Soil Erosion Rate[c] ([ton/yr]/ha)	Nonagricultural land erosion[d] (ton/yr)	Total basin erosion[e] (10^6 ton/yr)	Basin-wide gross yield[f] ([ton/yr]/ha)	Sediment delivery ratio[g] (%)
1. Pajaro	3464	69	1160	5.2	558	1.72	5.0	7
2. Salinas	8400	51	3860	7.6	3150	7.01	8.3	...
Estrella	2490	63	2040	7.0	640	2.68	10.8	...
(Combined)	10,890	54	5900	...	3790	9.70	8.9	29
5. Santa Ynez	2640	38	1670	18.8	3060	4.73	17.9	95
6. Ventura	917	40	1240	24.6	1360	2.60	28.4	60
7. Santa Clara	3730	26	1480	16.1	4440	5.92	15.9	115
8. Calleguas Creek	940	60	530	13.0	480	1.02	10.8	142
13. Santa Ana	3630	28	654	8.1	2108	2.76	7.6	29
14. San Diego Creek	281	12[h]	14	4.0	31[i]	.045	4.1[j]	127
16. Santa Margarita	2566	77	998	4.9	296	1.29	5.0	18

Note. Data for agricultural lands from the U.S. Department of Agriculture (USDA), Davis, California.

[a] Total area of basin from USDA database.

[b] Sum of erosion from cropland cultivated and uncultivated, pastureland, and rangeland.

[c] Value of soil erosion rate for rangeland listed in USDA database.

[d] Nonagricultural land taken as basin area minus agricultural land; erosion rate assumed to be equal to that for rangeland.

[e] Sum of cols. 4 and 6.

[f] Col. 7 divided by col. 2.

[g] Net yield for 1969–1995 (table 2) divided by gross yield (this table).

[h] Basin is 61% urban, 12% agricultural, 27% nonagricultural.

[i] Based on 27% nonagricultural land.

[j] Excluding 61% urban land (i.e., 39% of 281 km^2 = 110 km^2).

Continuity of sediment transfer from basin erosion to the sediment flux in rivers is not expected to be high, particularly for larger basins where sediment storage may occur on many different spatial and time scales (e.g., Schumm 1977; Richards 1982; Meade et al. 1990; Meade 1996; Allison et al. 1998). A measure of the continuity is given by the "sediment delivery ratio" (Roehl 1962), the percentage of the total basin soil erosion (here taken as the gross yield in table 5) transported to the sea as river sediment flux (here taken as the net yield in table 2).

Table 5 shows that the sediment delivery ranges from 7% to 142%, with the highest ratios for basins (6–8, table 5) in the Transverse Ranges and San Diego Creek (basin 14) in the Peninsular Ranges. San Diego Creek basin has the smallest area, which in part accounts for the higher delivery ratio (e.g., Richards 1982). However, it is unusual for basins as large as the others (~900–4000 km^2) to have delivery ratios of 100% and above. This could be explained as follows. Assume that soil erosion in terms of a gross yield G applies everywhere in the basin except to the stream channel and its closely adjacent valley fill, whereas the sediment delivery to the ocean is based on the sediment flux measured at a coastal gage station and expressed in terms of a net yield N. Then consider the following conditions: (1) In the long term, valley fill and stream cutting nearly balance, and $N \leq G$; (2) during dry climate, there is valley fill with little stream cutting, and $N \ll G$; (3) during wet climate, stream cutting exceeds valley fill, and $N \geq G$.

It is suggested that conditions 1, 2, and 3 are representative of the erosion, transport, and depositional patterns in our 20 basins for the total, dry, and wet climate periods respectively. Delivery ratios (table 5) calculated from net yields for total, dry, and wet periods (table 2) give N and G limits in agreement with these conditions (assuming gross yield does not vary widely from that for the wet period). Further, it is known that there is exceptional stream cutting associated with the high runoff in the wet period (e.g., Stow and Chang 1987; Chang and Stow 1989; Trimble 1997).

Summary and Discussion

The flow and sediment flux of the streams of central and southern California record the effects of decadal scale climate changes, with a dry climate from 1944 to 1968 followed by a wet climate from 1969 to 1995 and extending into the present (fig. 3). These climate changes are in general agreement with the PNA pattern that has been shown to influence climate and coastal fisheries. The dry to wet climate pattern changes with latitude, with Alaska and California tending to be out of phase with Washington and Oregon (Latif and Barnett 1994, 1996; Cayan 1996; Zhang et al. 1997; Barnett et al. 1999). The PNA effect also influences the coastal fishing for anchovy and salmon (Baumgartner et al. 1992; Holmgren-Urba and Baumgartner 1993; Mantua et al. 1997).

The wet period of PNA involves flurries of strong El Niño events accompanied by severe storms and extensive runoff along the coast of central and southern California. The mean sediment flux of the rivers during the wet period exceeds that during the dry period by a factor of about five when summed for all rivers. Within the wet period, strong El Niño events with a series of cluster storms occur every 3–7 yr, and the average sediment flux caused by the three largest of these events is 27 times greater than that during the preceding dry period.

The type of country rock and its tectonic setting were found to be important factors in determining the rate of sediment yield of the basins. The Transverse Ranges province, with its thrust-faulted, overturned formations of Cenozoic sediments, provided by far the greatest yield of sediment (fig. 4; table 3). This province, with one-quarter of the total area, yields over one-half the measured sediment flux of all rivers. The prorated net yield calculated from table 3 for the 15,600 km^2 Transverse Ranges province was 2.7 (ton/yr)/ha for the dry period and 12.3 (ton/yr)/ha for the wet period. In contrast, the Los Angeles urban area, with its hard covered streets and river channels, has the lowest yield of 0.21 and 1.2 (ton/yr)/ha for the dry and wet periods, respectively.

The most remarkable aspect of the dry to wet climate fluctuation was the abruptness of the change and the magnitude of the sediment flux that occurred. The sediment transported to the sea by the Santa Clara and Ventura Rivers during the single 1969 flood year exceeded the total transport of these rivers during the preceding 25-yr dry period. In fact, the 1969 sediment transport for most of the 20 rivers exceeded or equaled the total flux during the dry period.

In this regard, it is of interest to consider the magnitude of the sediment transported from the many high-yield basins whose sediment discharges converge on and enter the waters of the Santa Barbara Channel. The discharge from the Santa Clara and Ventura Rivers and Calleguas Creek, as well as that from the many small streams draining the Santa Ynez Mountains (fig. 6), all enter the channel waters directly. Bowen and Inman (1966) found that

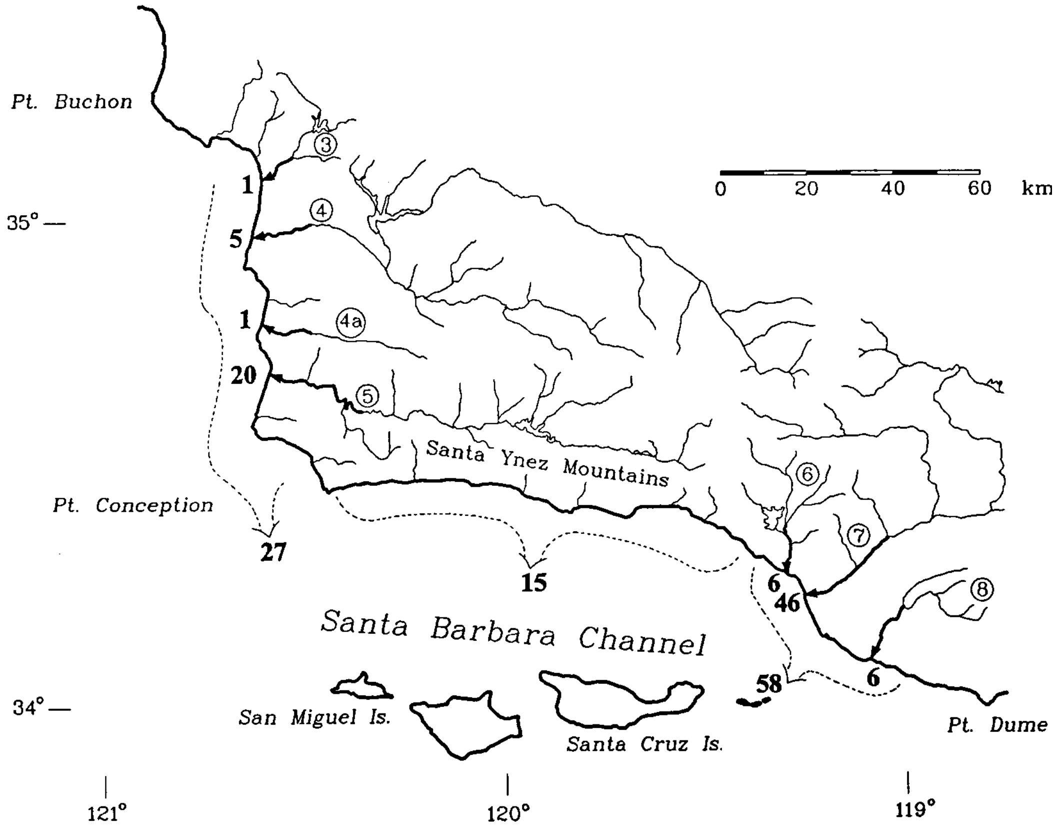

Figure 6. Suspended sediment flux (millions of tons) entering the waters of the Santa Barbara Channel from streams draining the Transverse Ranges during the flood of 1969. Streams identified by number in table 1; *4a* is San Antonio Creek.

much of the sand from the rivers draining the Transverse Range north of Point Conception is transported to the south and around Point Conception. In addition, subsequent satellite imagery (e.g., Thornton 1981; B. M. Hickey and N. B. Kachel, unpublished data) shows that there is conspicuous river pluming from the four streams north of Point Conception and that the turbid material is carried south to the Santa Barbara Channel area by the California Current.

The collective flux of suspended sediment load entering Santa Barbara Channel in 1969 was 100 million tons (fig. 6). This total flux includes sediment discharges from streams 3–8 (table 4), plus San Antonio Creek and the many small streams of the Santa Ynez Mountains coast (see "Episodic Events"). The total of 100 million tons is suspended sediment load. Four of these streams (table 4) with 63% of the suspended sediment flux were measured directly by USGS and not subject to statistical error from the rating curves. Assuming that the unmeasured bedload is 10%–15% of the total load gives a total load transport of sediment into the Santa Barbara Channel in 1969 of ca. 115 million tons.

The 1969 flood, following 25 yr of low runoff, was a first-flush event for fine sediment in these river basins, and the proportion of fine sediment in the suspended load is significantly larger than in subsequent floods. For the Santa Clara River, the fine material (silt and clay <62 μm) was ca. 85% of the suspended sediment load for 1969, in contrast to 35% for 1983 (fig. 5). This means that in 1969, ca. 39 million of the 46 million tons of suspended sediment flux of the Santa Clara River was fine material. Other rivers draining the Transverse Range are smaller, indicating that the overall percentage of fine material would be lower for the range as a whole. Assuming that fine material (<62 μm) averages 65% of the suspended sediment for all of the rivers draining the range, ca. 65 million tons of fine sediment entered the ocean edge of the Santa Barbara Channel in 1969.

This flux of fine sediment also entrained soil organic material and associated agricultural chemicals, including pesticides and fertilizers (Chiou et al. 1983; Cross et al. 1992). For certain organochlorine pesticides, peak usage occurred during the dry period of 1944–1969. For example, DDT production and usage peaked during the 1960s (Study of Critical Environmental Problems 1970), and the applications to agricultural lands over the 25 yr of low runoff were available to the first-flush events of January and February 1969. Agricultural soil brought to the sea by rivers during the floods of 1969 likely contributed to the high concentrations of DDT residues subsequently measured in the zooplankton (McClure and Barrett 1972), fish (Cox 1972), and seabirds (Anderson et al. 1975) of the Southern California Bight.

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