

Decreasing sediment yields in northern California: vestiges of hydraulic gold-mining and reservoir trapping

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Abstract Suspended sediment loads in large rivers are increasing globally, but this trend has reversed in some basins due to dam construction, particularly in developed countries. Sediment loads in lower Sacramento Valley basins began decreasing by 1900 (as shown by G. K. Gilbert's classic 1917 study of hydraulic gold-mining debris), preceding most USA reductions by up to 50 years. From 1853 to 1884, hydraulic mining generated >3.7 billion tonnes of tailings with specific sediment productions up to $16\,807\text{ t km}^{-2}\text{ year}^{-1}$. Double-mass curves of post-1950 suspended sediment and runoff indicate decreasing sediment responses to streamflow in the lower Sacramento and Feather Rivers continued through the late 20th century. Independent evidence indicates that these reductions were caused by dam closures and the reduced availability of historical alluvium stored below the dams.

Key words historical alluvium; Sacramento Valley, California; suspended sediment; trends

INTRODUCTION

This study examines evidence of a decreasing trend in suspended sediment transport in the lower Sacramento River, a large river draining much of northern California, USA, and several of its main tributaries (Fig. 1). Decreasing sediment loads have been observed in many large

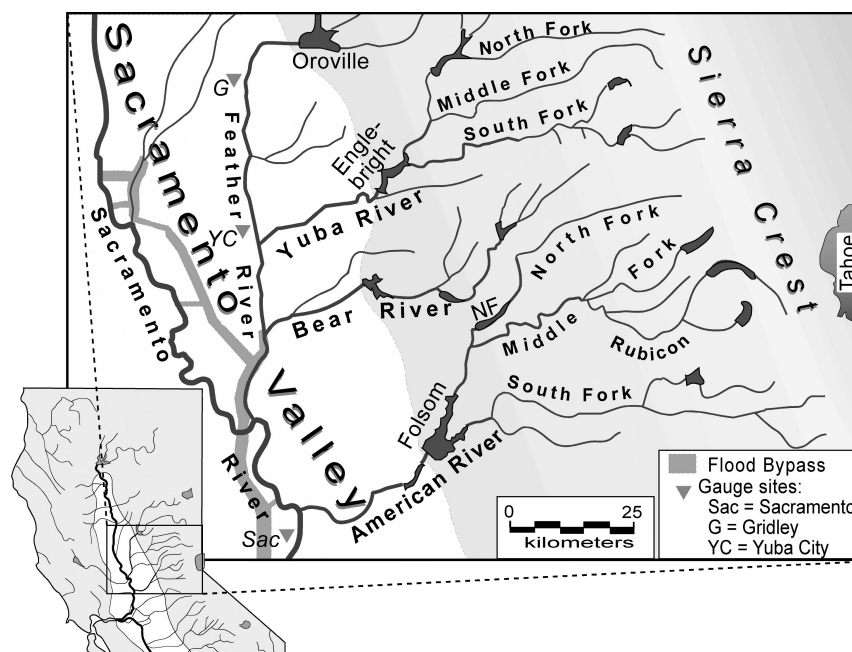


Fig. 1 Lower Sacramento Valley with major tributaries, reservoirs, and gauges.

rivers that were dammed in the mid-20th century, but reductions began early in the lower Sacramento Valley due to relaxation from episodic sedimentation by hydraulic mining from 1853 to 1884. Sediment deliveries were affected by extensive levee construction beginning in the 1860s, abrupt cessation of mining in 1884, and damming by the late 1960s of all large tributaries draining mining districts. The upper Sacramento River received far less historical sediment than the Yuba, Bear, and North Fork American Rivers that have large masses of mining sediment stored where they enter the Sacramento Valley.

The global sediment flux to lowland rivers is of the order of 24 Gt year⁻¹ including bedload (Savitsky, 2003) and causes a 1% decrease in reservoir capacity per year at an estimated annual cost of \$6 billion (Walling, 1997). Large uncertainties remain in estimates of the global flux of suspended sediment due to the dearth of uniform long-term instrumental records and temporal trends in suspended sediment at individual gauges. Accelerated erosion by human activities has greatly increased sediment production while dams have decreased yields during the period of instrumental records, but these changes have varied greatly in time and space (Walling, 1997). Vörösmarty *et al.* (1997) calculate that the 633 largest reservoirs trap approximately 16% of the global suspended sediment budget, and that all reservoirs may trap more than 25% of global suspended-sediment loads. Systematic temporal changes in large river sediment loadings are so pervasive that Walling & Fang (2003) found statistically significant trends—both positive and negative—in approximately half of the 145 major river long-term sediment records they examined.

Interpretations of extensive sediment-discharge records require an understanding of the magnitude and timing of human impacts on sediment production and retention behind reservoirs (Walling & Fang, 2003; Vörösmarty *et al.*, 2003). Recognition of trends and associated processes is needed if sediment records are to be used for future projections, past reconstructions, or calibration of simulation models. The growing importance of long-established gauges also calls for an understanding of sediment processes in those instrumented basins. Hence, past and present characteristics of basins that have long sediment-concentration records should be carefully evaluated.

Due to the importance of historical sediment in the region, the Sacramento River has a relatively long record of suspended sediment measurements. Interpretation of this record is easily confounded, however, by an exceptional history of sediment production and storage, extensive levee construction, and regulation of all large tributaries by reservoirs. This study examines evidence of temporal trends in sediment fluxes in the lower Sacramento and Feather Rivers and factors influencing those changes. These trends are placed in the context of channel adjustments to extreme hydrogeomorphic changes in the basins.

RECORDS OF SEDIMENT FLUX AND CHANNEL ADJUSTMENTS

Suspended sediment data and methods

Daily suspended sediment and runoff data from US Geological Survey (USGS, 2003) gauging stations are used to show trends in sediment production and transport. Data from five gauges (Table 1) provided instrumental records of suspended sediment concentrations and corresponding water discharges from as far back as 1957. These data were used by the USGS to calculate daily sediment fluxes and mean daily runoff (USGS, 2003). The runoff data have few missing values, but occasional periods of missing sediment concentrations required the USGS to empirically estimate daily loads from discharge. Uniform data-collection

Table 1 Stream gauges cited in this report.

Gauge name	ID	Basin area, km ²	Water years
Deer Creek near Smartsville	11-4185.00	219	1974–1979
Feather River at Gridley	11-4071.50	9521	1965–1992
Feather River at Yuba City	11-4077.00	10 293	1964–1976
Sacramento River at Sacramento	11-4475.00	60 885	1957–1979
Sacramento River at Freeport	11-4476.50	~61 000	1979–1989

methods utilized by the USGS (Edwards & Glysson, 1999), enhance the reproducibility and interpretability of analyses derived from these data. Double-mass curves are used here to isolate long-term trends by removing the seasonal and inter-annual variability in sediment loads associated with discharge fluctuations. Walling (1997) and Walling & Fang (2003) used this method with cumulative mean annual values of specific sediment yield and runoff. Here, cumulative values are calculated from mean daily data and are on the order of 365 times larger than values drawn from mean annual data.

The suspended sediment record for the lower Sacramento River is derived by combining data from two gauge sites. Measurements were made at the Sacramento gauge from water years 1957–1980, after which the gauge moved approximately 17 km downstream to Freeport where another 10 years of data were collected. No large tributaries enter between the two gauge sites.

Suspended sediment double-mass curves

Suspended sediment responses to stream flow on the Feather and Sacramento Rivers steadily declined in the second half of the 20th century as is shown by the progressive lowering of slopes on double-mass curves. At the Sacramento gauge, no change in sediment flux rates with runoff was apparent in 1980, suggesting that the change in gauge site had little effect on sediment responses to discharge (Fig. 2). Sediment responses decrease gradually, however, throughout the period from 1957 to 1989. Events such as the 1965 and 1986 floods and the 1978 high flows following a severe drought, appear as brief sediment-flux events that are minor when compared to the long-term trend at this site. The sediment flux during the record 1986 flood was less than that of the 1965 flood indicating a decreased response in sediment to runoff. Although the mean daily discharge of the 1986 flood was 16% greater than the 1965 flood at this gauge, it produced less than half the maximum mean daily sediment flux ($3.3 \text{ t day}^{-1} \text{ km}^{-2}$) as the 1965 flood ($7.8 \text{ t day}^{-1} \text{ km}^{-2}$). In fact, the four largest mean daily sediment fluxes on the Sacramento River for the 32-year period of record at the Sacramento and Freeport gauge sites were in 1965 and the fifth largest flux was in 1963. Singer & Dunne (2001) examined 17 years (1963–1979) of annual sediment discharge data from the Sacramento gauge and found no statistically significant evidence of a temporal trend over that period. While the double-mass analysis presented here does not constitute a significance test, the gradual long-term reduction in sediment responses to runoff shown by double-mass curve analysis together with the limited loads carried by the 1986 flood suggest that this longer record has a trend.

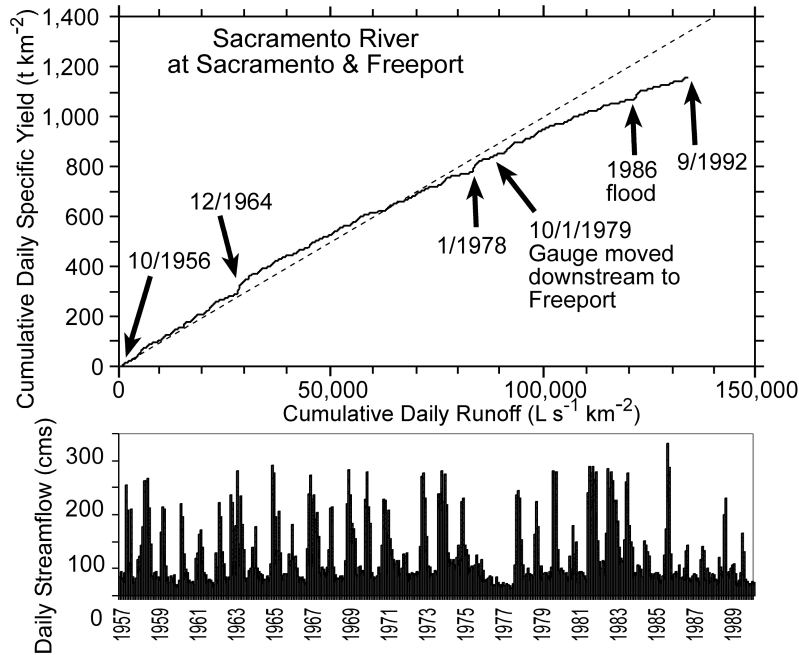


Fig. 2 Double-mass curve showing decreasing suspended sediment responses to discharge. Reference line (dashed) represents sediment flux of one t per 100 l s^{-1} . Hydrograph shows annual floods and floods of record in water years 1965 and 1986.

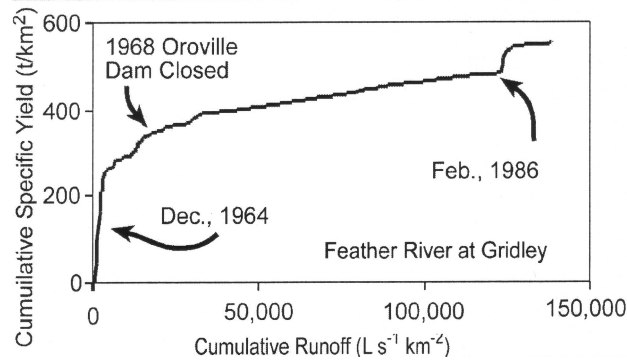


Fig. 3 Double-mass curve of mean daily suspended sediment and runoff for Feather River at Gridley. The December 1964 flood is a major sediment event; subsequent flux rates, including the record 1986 flood, are much lower.

A similar pattern of long-term decreasing sediment flux rates was revealed at the Gridley and Yuba City gauges on the Feather River below the Oroville Dam and above the Yuba River confluence at Marysville (Table 1). The double-mass curve for the Gridley gauge (Fig. 3) shows a pronounced sediment response to the 1965 flood that was equally apparent at the Yuba City gauge approximately 30 km downstream. In a 30-day period ending in January 1965 the flood carried 250 t km^{-2} at the Gridley gauge and almost 150 t km^{-2} at Yuba City. This comprised 45% of the entire suspended load over the 28-year period at the Gridley gauge and almost 20% of the entire load for the 12-year period at Yuba City. Closure of Oroville Dam in 1968 did not immediately lower sediment responses, presumably due to production of sediment from local channel storage during moderate-magnitude floods and

lack of large floods until 1986. The 1986 flood, the flood of record at many gauges in this region, carried much less sediment at Gridley than the 1965 flood. At the Gridley gauge, the 1986 flood ($4130 \text{ m}^3 \text{ s}^{-1}$) had essentially the same magnitude as the 1965 flood ($4220 \text{ m}^3 \text{ s}^{-1}$) due to flood storage in Oroville Reservoir, but the mean daily sediment concentration on the day of peak flow was almost three orders of magnitude less in 1986 (456 mg l^{-1}) than in 1965 ($345\,000 \text{ mg l}^{-1}$). This subdued sediment response to the 1986 flood was presumably due to trapping of sediment in Oroville Reservoir and reduction of erodible sediment below the dam.

The variability of suspended sediment with discharge after 1968 was also reduced at the Gridley gauge. A power function was fit to the suspended sediment and discharge data and regression residuals from this long-term rating curve were calculated. Positive residuals largely correspond to the rising limbs of hydrographs at this gauge indicating the occurrence of a “first-flush” during floods. When plotted against time, the largest positive residuals cluster prior to 1968 (Fig. 4). Subsequent reduction of the first-flush response shows that supplies of sediment easily eroded during the rising limb were greatly reduced after closure of the Oroville Dam. These supplies may include both mountain sources above the dam and historical alluvium in the lower river, but they suggest an important change in the timing and sources of sediment following dam closure.

Few small tributaries in the region have long records of suspended sediment. Deer Creek, a small Yuba River tributary, is a small basin in the heart of the mining districts for which a short record of daily suspended sediment discharges is available. Deer Creek is unique in that it not only received large volumes of mining sediment, but also remained relatively unregulated by reservoirs below areas of extensive mining. The Deer Creek double-mass curve for suspended sediment and runoff for the six-year period 1974 to 1979 shows a high sensitivity of sediment transport to two runoff events (Fig. 5). High flows in 1974 and 1978 were not large runoff events, but they generated high proportions of the total sediment load for this period. Sensitivity of sediment transport to runoff in Deer Creek is also reflected by the close relationship between daily runoff and daily suspended sediment in the sediment rating curve (Fig. 6). This is characteristic of a transport-limited system with abundant erodible sediment. In sediment-starved basins, sediment-discharge relationships tend to be weak due to dominance of intermittent hillslope processes as sediment production mechanisms.

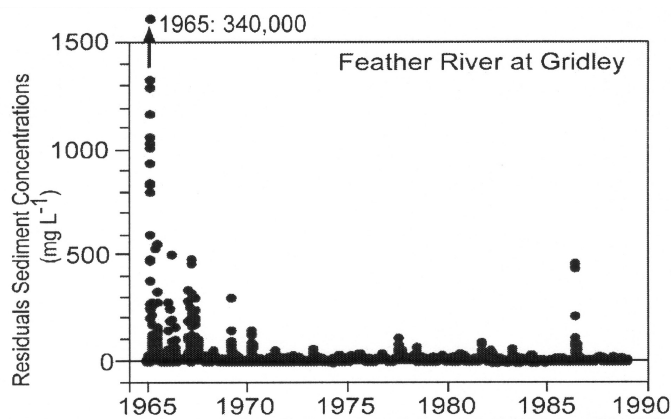


Fig. 4 Residuals from regression of daily mean suspended-sediment concentration on daily mean discharge for Feather River at Gridley, 1965 to 1988. Large positive residuals in 1960s indicate high loads on hydrograph rising limbs prior to Oroville Dam closure in 1968.

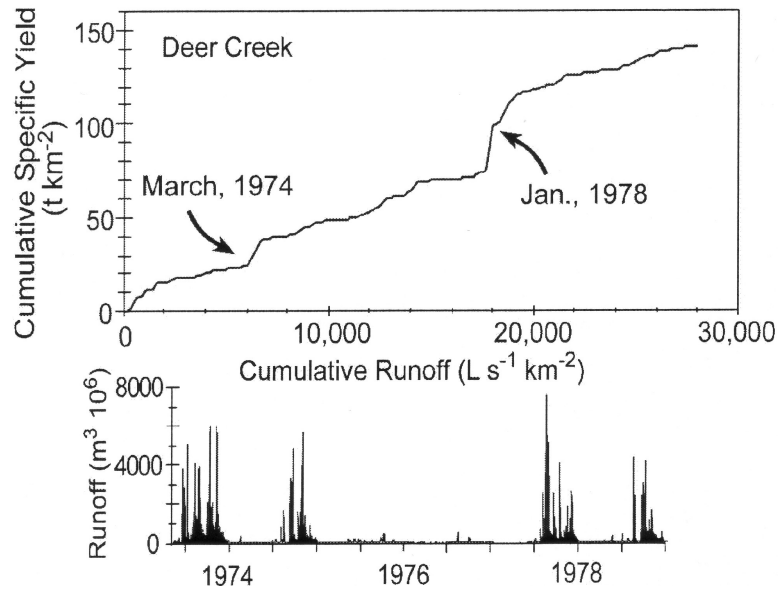


Fig. 5 Double-mass curve for Deer Creek, a small tributary to lower Yuba River that received much hydraulic mining sediment and has only minor regulation by dams.

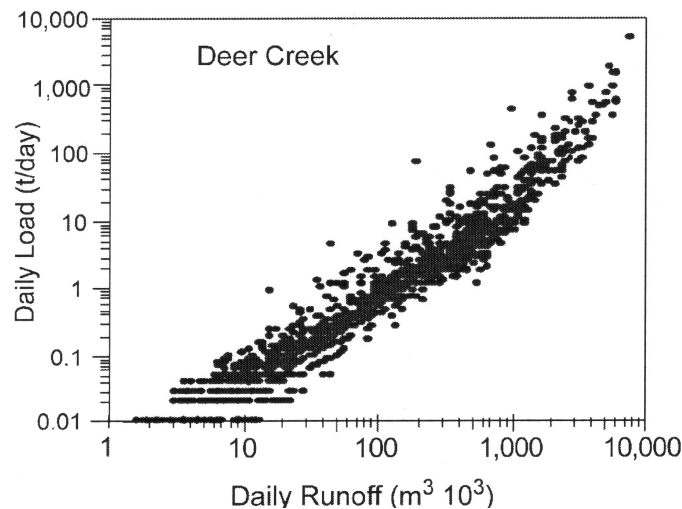


Fig. 6 Sediment rating curve for Deer Creek shows close relationship between mean daily discharge and daily suspended sediment load from 1974 to 1979.

It is difficult to statistically test the available suspended sediment data for the significance of temporal trends caused by reservoir trapping. Extensive records of sediment data are not available for the Yuba, Bear, and American Rivers that received the most mining sediment. Sediment data collected at the Feather River gauges did not begin until three or four years prior to closure of Oroville Dam and include the large 1965 flood in the pre-dam period. The Sacramento River gauge at Sacramento integrates sediment trapping by numerous dams constructed over an extended period, so it is not possible to isolate the effects of one dam. Independent evidence, however, indicates regional channel deepening and enlargement associated with substantial sediment production that supports the interpretations of a decreasing trend in sediment loads.

Stage lowering as evidence of sediment production

Stage–discharge relationships developed from archival USGS hydrographic records provide an independent test for trends, push the observational database back another 50 years, and expand the spatial resolution of observations to locations where suspended sediment data are not available. Changes in channel morphology and sediment production can be inferred from the lowering of flow stages through the examination of channel cross-sections and hydraulic geometry (James, 1999). Stage–discharge statistical regressions presented in previous studies document the timing of flow-stage lowering at several foothill gauges. For example, substantial flood-stage reductions were documented at three streamgauge sites on the lower American River including almost 2 m of flood-stage lowering at a critical bend in Sacramento (NRC, 1995; James, 1997). Stage lowering at these sites was shown to correspond to local channel incision and enlargement and the timing was related to closure of the North Fork Dam upstream. Similarly, at a site on the lower Bear River, flow stages decreased about 2 m from the early 1950s to 1970 (James, 1991). The timing of incision at this site was not related to the enlargement of Camp Far West Reservoir upstream in 1963 as hypothesized, but was delayed because the channel had avulsed onto an armoured layer in the 1870s.

DISCUSSION: SPATIAL AND TEMPORAL PATTERNS OF SEDIMENT LOADS

Sediment from the mountain areas is now prevented from reaching the Sacramento Valley by large dams, but below the dams are large repositories of historical sediment. Clearly, these storage sites were actively producing sediment during the 20th century. Important questions to be addressed are the extent to which these sources continued to supply sediment during the late 20th century, their present importance, and systematic trends. Singer & Dunne (2001) analysed gauge data on the Sacramento River using a time-series analysis of daily suspended sediment records for the period from 1948 to 1979. They constructed a sediment budget using six gauges on the main river and an additional gauge on each of four major tributaries including the Feather River. Their budget identifies zones of increasing and decreasing sediment loads that define a distinct spatial pattern of sediment production in the Sacramento Valley. The greatest erosion occurred in the lower Sacramento River between the mouth of the Feather River and the Sacramento gauge where aggradation by historical mining sediment from the Yuba, Bear, and American Rivers was most severe. Erosion there is consistent with an interpretation of long-term readjustments to hydraulic mining sedimentation. Singer & Dunne (2001) emphasize the importance of failed levee banks and bed erosion as sediment sources and cite evidence of 42 cm of bed incision in the Sacramento River above the Feather River between 1965 and 1979. Additional (perhaps the dominant) sediment sources to the Feather River and lower Sacramento below the Feather confluence are historical alluvium stored in terraces along the Yuba, Bear, lower Feather, and lower American Rivers. More study is needed of sediment production by channels widening and eroding these terraces.

Mining sediment deposits, levee construction, and dams

Sediment budgets in the lower Sacramento Valley cannot be fully appreciated without an understanding of the massive sediment deposits remaining along the east margin of the

Table 2 Nineteenth century mining sediment produced (1853–1884).

Basin	Drainage area (km ²)	Volume produced ^A (m ³ 10 ⁶)	Vol. year ⁻¹ 31 years (m ³ 10 ⁶ year ⁻¹)	Denudation		Mass Produced @ $\rho = 2.2^B$		
				(mm)	(mm year ⁻¹)	(Mt)	Mass year ⁻¹ (Mt year ⁻¹)	Spec. prod. (t km ⁻² year ⁻¹)
Feather River at Yuba City	10301	77	2.5	7.4	0.2	168	5.4	527
Yuba River	3499	523	16.9	149.6	4.8	1151	37.1	10616
North Yuba ^C	1351	165	5.3	122.4	5.3	364	11.7	8685
Middle Yuba	536	109	3.5	203.7	6.6	240	7.7	15192
South Yuba	988	165	5.3	167.2	5.4	363	11.7	11794
Deer Creek	233	29	0.9	126.4	4.1	65	2.1	8968
Bear Basin	1143	271	8.7	236.8	7.6	596	19.2	16807
American	5014	197	6.3	39.2	1.3	433	14.0	2783
North Fork	900	164	5.3	181.7	5.9	360	11.6	13069
Middle Fork	<u>1586</u>	<u>33</u>	<u>1.1</u>	20.9	0.7	<u>73</u>	<u>2.4</u>	1486
Totals:	25437	1663	53.7	65.4	2.1	3659	118.0	4640

^A Production volumes from Benyaurd *et al.* (1891) multiplied by 1.51 as recommended by Gilbert (1917).

^B $\rho = 2.2 \text{ g cm}^{-3}$ is a conservative approximation of densities of bedrock materials mined.

^C North Yuba above South Yuba confluence not including South or Middle Yuba.

Sacramento Valley. Hydraulic mining was associated with rapid sediment production and resulted in dramatic sedimentation along the Yuba, Bear, and North Fork American Rivers (Gilbert, 1917; James, 1999). Volumes and masses of sediment produced by 19th century hydraulic mining are given in Table 2. Volumes were derived from Benyaurd *et al.* (1891) adjusted using a coefficient of 1.51 based on Gilbert's (1917) surveys of mine-pits exhumed in regolith and consolidated rock—cemented conglomerates with a late Tertiary volcanic overburden. Volumes were converted to mass using a density of 2.2 g cm^{-3} . Mining sediment was produced for 31 years at an average rate of 118 Mt year^{-1} , equivalent to 0.6% of the modern global annual suspended sediment yield delivered to lowland rivers (approx. 20 Gt year^{-1}). However, only a fraction of the sediment produced was delivered to the lower Sacramento River and much was stored in the mountains and in low-gradient fans along the margin of the Sacramento Valley. Upland denudation in these large basins during the mining period was as high as 237 and 214 mm at rates of 7.6 and 6.6 mm year^{-1} for the Bear River and Middle Yuba Basins, respectively (Table 2).

Most of the mining sediment remains in terraces in the mountains and deep flood plain deposits along the lower reaches of the rivers where they enter the Sacramento Valley. These historical deposits continue to be reworked, although dams prevent much of the sediment from being delivered to the Sacramento River. Levees isolate large volumes of the historical alluvium, but they also deepen flows and facilitate erosion of historical alluvium stored in terrace and channel-margin deposits (Fig. 7). Deep deposits of stratified sands and silts along these rivers are highly erodible and continue to be reworked (Fig. 8). For example, repeated topographic surveys on the lower Bear River in 1985 and 1989 documented 82 m^2 of net cross-section enlargement by the 1986 flood representing $82\,000 \text{ m}^3 \text{ km}^{-1}$ of sediment supplied to the lower Sacramento from this reach below all dams (James, 1993). Scour down to the pre-mining surface was indicated by exhumed tree stumps, and additional historical alluvium remaining on the left channel margin indicates that the channel capacity has not yet been restored at this site.

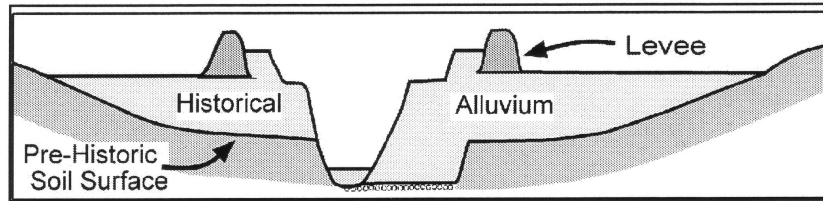


Fig. 7 Typical relationship between pre-mining surface, historical alluvium, and levees in major tributaries from mining districts in Sacramento Valley. Vertically exaggerated.

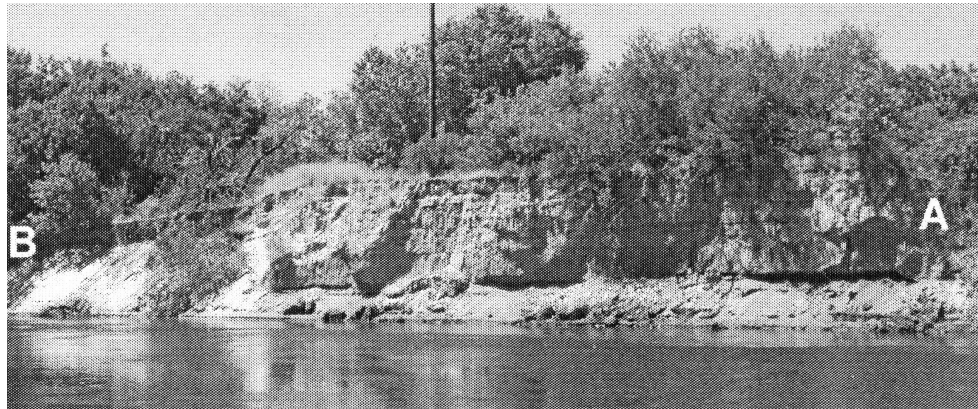


Fig. 8 Exposure of erodible historical alluvium in right bank of lower Yuba River above railroad bridge near Feather River confluence. (A) Stratified silts in vertical face undercut at base by sand layer. (B) Upper layer of clean white sand wasting down face of exposure.

CONCLUSION

Understanding the long-term sediment dynamics in the lower Sacramento basin requires an appreciation for the extensive deposits of erodible historical alluvium in major tributaries of the Sierra foothills. Channels along the margins of the Sacramento Valley incised and enlarged in the 20th century in response to reduced sediment loads after mining stopped and dams were constructed. This widespread erosion represents a tremendous flux of sediment from storage. Double-mass curves provide evidence of decreasing sediment fluxes for a given discharge from the mid- to late-20th century. Stage-discharge relationships and other evidence of channel incision and enlargement indicate that much of the sediment production came from channel erosion. While field evidence indicates that erosion of historical alluvium in the lower Sacramento Valley continues, the double-mass curves suggest that available supplies are decreasing. The relative importance of sediment production from historical alluvium in the lower Sacramento River system should be systematically quantified.

The on-going reworking of historical alluvium in the lower Sacramento Valley has important implications to the longevity of episodic sedimentation events. Much of the vertical adjustment in these channels occurred rapidly (Gilbert, 1917), but after initially incising, the channels have continued to widen during large floods, except where prevented by levees or other channel-protection measures. Gilbert's (1917) symmetrical wave model implies a relatively short-lived sediment response followed by rapid stabilization and reduction of sediment loads to pre-sedimentation levels. Use of the wave model to infer sediment yields is based on the conflation of low-flow channel-bed elevations with sediment

loads, however, and does not stand up to scrutiny in the lower Sacramento Valley where it was initially conceived. If future global sediment fluxes are projected on the basis of this assumed wave symmetry, they will likely underestimate long-term sediment discharges following episodic sedimentation events. When sediment production exceeds channel capacities to the extent that large sediment volumes are stored in floodplain and terrace deposits, elevated sediment yields may persist for centuries.

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