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Channel incision on the lower American River, California, from streamflow gage records

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Abstract. Channel incision along the lower American River from 1905 to 1995 is investigated using channel cross-section plots and statistical analysis of stage-discharge data from two streamflow gages located at three sites. Channel incision lowered thalweg elevations at rates of up to 8.2 cm yr^{-1}, and flow stages decreased at rates of up to 4.3 cm yr^{-1} for periods lasting several decades. At a critical flood risk location in Sacramento, flow stages lowered 2 m from 1924 to 1970. Channel incision was the result of channel recovery from aggradation due to hydraulic gold-mining sediment and was exacerbated by sediment storage behind dams. Prolonged erosion and transport of historical alluvium in this river suggest that G. K. Gilbert's symmetrical sediment wave model is inappropriate for the lower American River and may not adequately allow for the importance of sediment storage and remobilization in fluvial systems.

Introduction

Channel morphological responses to sedimentation over time scales extending over a century or more are poorly understood. *Gilbert* [1917] advanced an influential theory of long-term fluvial response to episodic sedimentation that postulates the passage of sediment out of a basin as a sediment wave. Gilbert's model was based on responses of low-flow channel bed elevations to mining-derived sediment in channels draining the northern Sierra Nevada. Gilbert's time series of low-flow bed elevations of the Sacramento River below the American River confluence showed 3.1 m of bed aggradation from 1855 to 1890 and 2.4 m of degradation by 1914. Channel incision continued at this site until 1930, when the bed apparently returned to pre-mining base levels [*Graves and Eliab*, 1977]. Channel bed elevation changes were symmetrical in time, so if a sediment wave is assumed to have been synchronous with the bed changes [*Gilbert*, 1917], the resulting symmetrical wave implies that severe channel and floodplain aggradation was followed by the relatively rapid passage or stabilization of alluvium.

Rapid, complete passage of sediment through a fluvial system is not common in most watersheds, where temporal discontinuities characterize sediment transport and sediment delivery ratios tend to be less than 1.0 [*Walling*, 1983, 1988; *Madej*, 1995]. The empirical basis of the sediment wave model is biased because channel bed incision was encouraged by flow deepening induced by levees and terraces. Furthermore, the validity of the model has been questioned based on persistent storage and mobility of mining sediment in the nearby Bear River [*James*, 1989, 1991, 1993].

The lower American River near Sacramento is often assumed to have undergone aggradation then rapid degradation and sediment depletion or stabilization in phase with the channel bed changes documented on the Sacramento River. Evacuation or stabilization of historical alluvium is assumed in spite of large tracts of exposed historical sediment and evidence of ongoing erosion along the channels [*National Research Council* (*NRC*), 1995]. The present study examines channel cross-section and flow stage changes on the lower American River in order to evaluate the hypothesis that channel beds had stabilized by the 1940s as was implicitly predicted by Gilbert's model.

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Study Area and Background

The American River flows southwestward from the northern Sierra Nevada to its mouth at the confluence with the Sacramento River (Figure 1). The watershed covers an area of 4900 km^2 ranging in elevation from 10 m at Sacramento up to 3170 m on the Sierra crest. Floods have high peaks and arrive rapidly because prevailing maritime westerlies are lifted up steep, west facing slopes and generate intense precipitation in the upper basin, where steep, rocky canyons provide little natural storage. The upper basin is drained by three tributaries in a network of deep ravines: the North, Middle, and South Forks. These channels join above Folsom Dam, which regulates a drainage area of 4800 km^2 with a reservoir capacity of 1.2×10^9 m^3. The lower basin differs distinctly from the upper basin. Below Folsom Dam the river emerges onto an alluvial plain with high bluffs on the north side and low Quaternary terraces to the south. At the Sacramento River confluence, gradients are low, and the river historically flowed through a broad, swampy floodplain.

Two major perturbations led to a cycle of aggradation and degradation along the lower American River: nineteenth-century hydraulic gold-mining sediment production, and construction of dams and levees. Hydraulic gold mining began in 1853, and by 1862, sediment deliveries to main channels were causing severe channel aggradation [*U.S. Congress*, 1881; *Gilbert*, 1917]. Volumes of mining sediment produced in the upper American Basin by 1881 were estimated to be 15–19 × 10^6 m^3 in the North Fork, 8–11 × 10^6 m^3 in the Middle Fork, and zero in the South Fork [*U.S. Congress*, 1882; *Gilbert*, 1917]. Sediment storage along the lower American River in 1879 was estimated to range between 1.5 and 9 m in depth and was assumed to be increasing annually [*U.S. Congress*, 1881].

Hydraulic mining was enjoined in 1884, but large volumes of stored sediment continued to be reworked by floods. Licensed

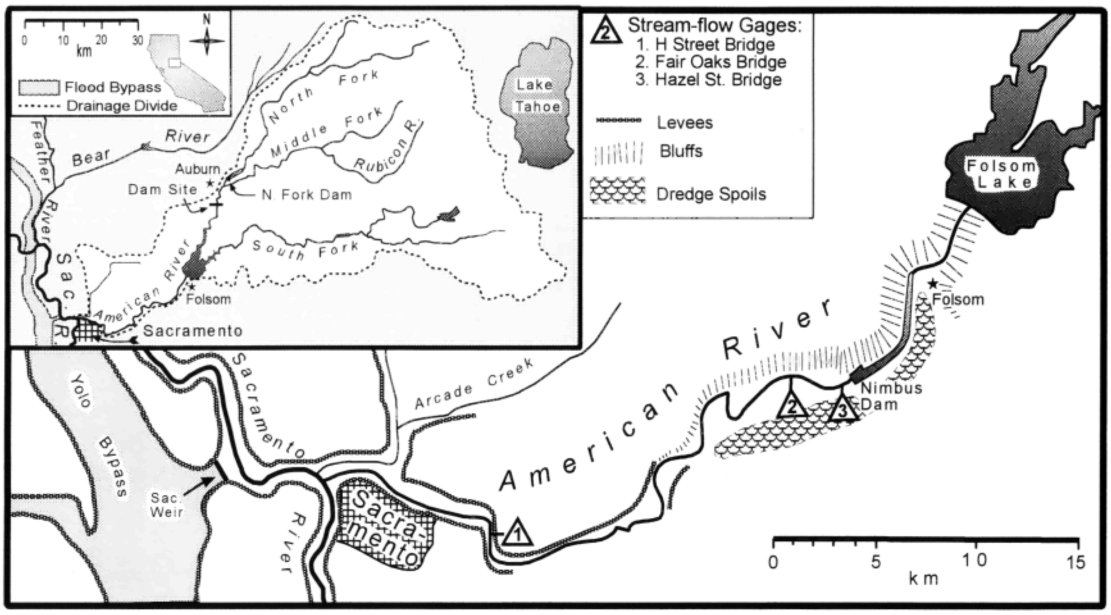

Figure 1. American River basin (inset) and lower American River showing streamflow gage sites.

mining resumed in 1893 at a much-reduced scale and continued until World War II. Most of the sediment produced during this later period was assumed to be stored in the mountains behind small sediment detention dams. Main channels below the mines adjusted to the decrease in sediment loads by degrading [*Gilbert*, 1917]. Geomorphic interpretations of this history are complicated by engineering developments in the basin. Dams have arrested downvalley transport of sediment and decreased the magnitude and frequency of flooding in the lower American River. Furthermore, commercial gravel extractions from the channel were apparently extensive, which commonly exacerbates channel incision below dams [*Kondolf*, 1995]. Dam closures often result in channel incision and enlargement downstream [*Williams and Wolman*, 1984], although response rates vary and may include periods of local aggradation. For example, closure of Oroville Dam on the nearby Feather River in 1968 caused complex channel changes downstream at least through 1975 [*Porterfield et al.*, 1978].

Until North Fork Dam was built in 1939 to detain hydraulic mine tailings, sediment was freely delivered downstream to the lower American River. North Fork Dam (capacity, 18×10^6 m^3; drainage area, 888 km^2), was highly effective in storing 5×10^6 m^3 of sediment (primarily bed material) since its closure in 1939 [*Resource Consultants and Engineers, Inc.* (*RCE*), 1993]. Recent degradation of the lower American River has been attributed to Folsom Dam which was closed in 1956 [*WRC-Environmental/Swanson & Associates* (*WRC*), 1992]. Few tributaries enter the American River below Folsom Dam, and none enter from mountainous basins, so little sediment has been supplied downvalley to the study area since Folsom Dam was closed in 1956. Folsom Dam also lowered the frequency of large floods below the dam [*NRC*, 1995].

Concern over channel stability and morphologic changes along the lower American River was spurred recently by debate over the need for a proposed dam upstream near Auburn. Opponents have argued that safe flood conveyance through the lower American River system was greater than that estimated by the U.S. Army Corps of Engineers (USACE) owing to channel degradation since the 1960s. Channel cross sections used by the USACE for initial flood stage modeling were surveyed in the 1960s [*USACE*, 1991; cf. *NRC*, 1995]. In response to these criticisms, recent studies of morphological change examined lateral migration using aerial photographs and longitudinal profile changes based on topographic maps. Aerial photographs indicated rapid lateral erosion rates and bank instability on the lower American River [*Water Engineering and Technology, Inc.* (*WET*), 1991; *WRC*, 1992; *RCE*, 1993].

Although studies of channel incision using topographic maps are limited in temporal and vertical resolution, they constrain the magnitude and timing of channel adjustments. Comparisons of topographic maps surveyed in 1906 [*California Debris Commission*, 1907] with later maps showed that bed incision through the H Street reach from 1906 to 1957 ranged from 3 to 5.5 m [*RCE*, 1993]. More recent maps of the first 7 km above the Sacramento River confluence showed that channel degradation from 1957 to 1987 averaged 5.5 m and was attributed to removal of hydraulic mining sediment [*WET*, 1991; cf. *WRC*, 1992]. Based on map and field evidence, thalweg incision was considered to be ongoing at some locations, including the H Street gage site, but no longer occurring in the upper reaches below Nimbus Dam where the channel rests on resistant Plio-cene-Pleistocene strata [*WET*, 1991; *RCE*, 1993; *USACE et al.*, 1995]. Incision into resistant alluvium under similar conditions on the nearby Bear River, however, resulted in an episode of rapid channel degradation [*James*, 1991], so renewed incision into resistant strata should not be ruled out. The present study documents historical changes in channel bed elevation and flow stage by examining channel cross sections and stage-discharge relationships at three sites on the lower American River.

Methods Used to Identify Historical Channel Changes

Archived U.S. Geological Survey (USGS) and California Department of Water Resources (CDWR) streamflow measurements at two gages were used to develop channel cross sections at four sites and stage-discharge relationships for

Table 1. Gage and Cross-Section Locations With Periods Analyzed

Gage Name and Period	USGS Gage Number	Site and Period: Gage	Site and Period: Cross Section
Sacramento	11-4470.00*	H Street bridge, 1924–1982	H St. bridge, 1941–1982
Fair Oaks	11-4465.00	Fair Oaks bridge, 1905–1957; gage moved to below Hazel Street, 1958–1994	Fair Oaks bridge [cf. *NRC*, 1995]; cable established below bridge, 1930–1957; cable moved to below Hazel St., 1958–1992

USGS, U.S. Geological Survey; NRC, National Research Council.
*California Department of Water Resources number A07140.

three river reaches (Figure 1; Table 1). The streamflow gage located farthest downstream on the American River is at the H Street bridge 10 km upstream from the Sacramento confluence. This site is critical to flood conveyance owing to a sharp bend, narrow floodway, and high stream powers during floods [*RCE*, 1993]. Levees along this reach are built on terraces apparently composed of historical sediment contemporaneous with mining-induced aggradation [*NRC*, 1995]. The Fair Oaks gage was established in 1905 at the Fair Oaks bridge 34 km upstream from the Sacramento River confluence. After 1930, many current measurements were made from a cable 90 m downstream of the Fair Oaks bridge. In 1958 the gage and cable were moved 3.5 km upstream to their present site below Nimbus Dam, hereinafter referred to as the Hazel Street site.

Plots of discharge-measurement data from fixed positions at bridges or cables were used to demonstrate changes in channel cross sections. Cross sections at the Fair Oaks bridge (1913–1950) were plotted by the author and presented elsewhere [*NRC*, 1995]. For the present report, cross sections were plotted at two additional sites: the Hazel Street cable and H Street bridge. Stage-discharge relationships were analyzed to evaluate temporal changes in flow stage. Stage-discharge data include all available measurements other than flows at H Street known to be affected by backwater, or extremely low or high flows. Extreme discharges were eliminated from analysis because regression models were less reliable for the tails of distributions and the emphasis of this analysis is on regression residuals. Flow stage was regressed on discharge using a third-order polynomial at all three sites, and regression residuals were plotted as time series to reveal temporal changes in flow stage. These methods and limitations to morphologic interpretations drawn from them are discussed elsewhere [*Knighton*, 1974; *James*, 1991]. Flow stage responds not only to channel bed elevation but also to changes in width, roughness, and energy gradients. Cross section plots provide independent indicators of channel morphologic change that allow verification that stage responded to channel form.

Results

Representative channel cross sections at the H Street bridge from 1941 to 1982 (Figure 2) show that the mean position of the channel bed lowered 1 m from 1941 to 1954 and another 1 m by 1980. Stage was related to discharge at this site in a nonlinear manner during the period of record (Figure 3), and stages (controlled for discharge) lowered 2 m (Figure 4a). Flow stages were relatively high in the late 1920s through the 1930s but began to drop in the 1940s and displayed increasing variability in the 1950s. Increased stage variability in the 1950s may be due, in part, to backwater effects, although known backwater-influenced data points were removed from the analysis. Stage variability resulted primarily from channel bed deposition and erosion, as is shown by detailed cross-section plots (not shown). Whether these stage variations and bed changes represent persistent aggradation or ephemeral passage of dunes cannot be determined with available data. Nevertheless, they indicate high sediment mobility through the reach, perhaps due to disturbances caused by an extreme 1951 flood, dam

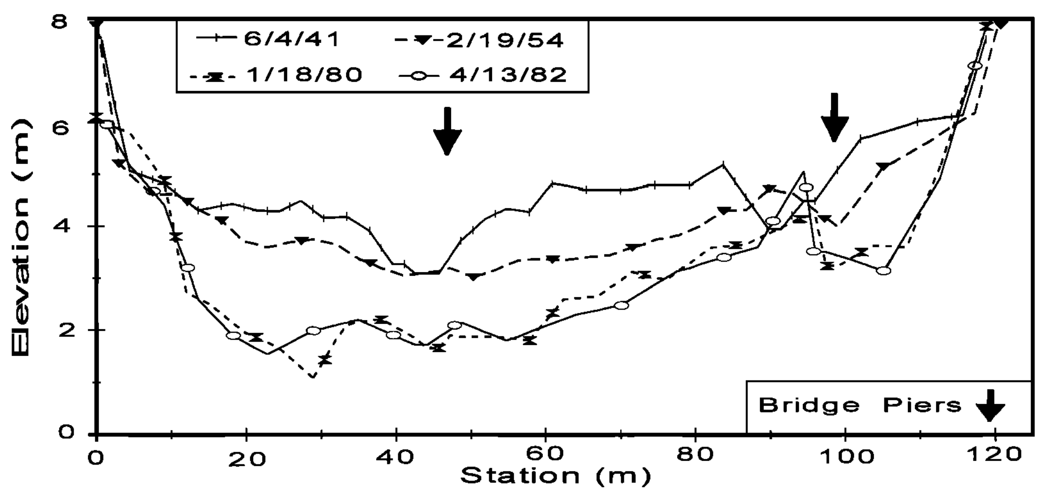

Figure 2. Channel cross sections at upstream side of H Street bridge (1941–1982). The channel bed lowered more than 2 m in this period. (Data from U.S. Geological Survey and California Department of Water Resources.)

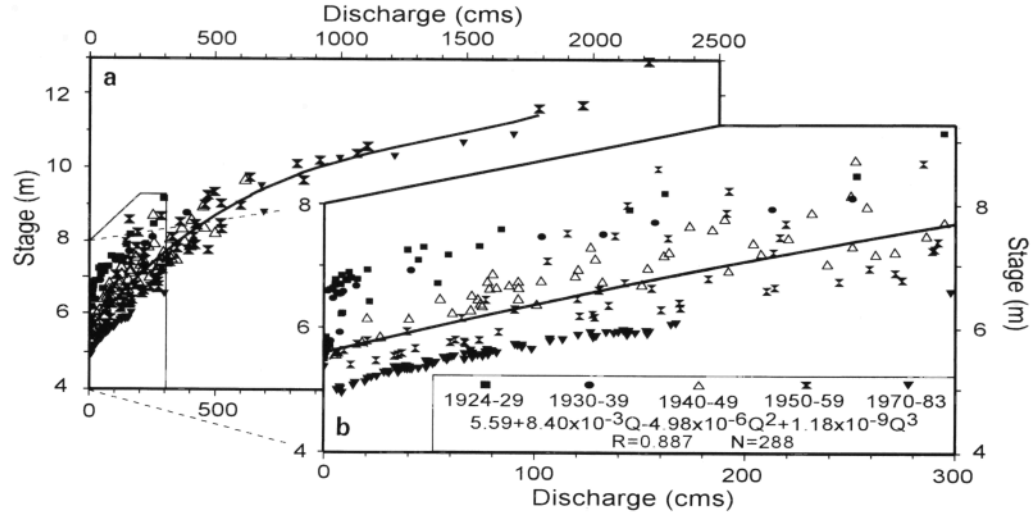

Figure 3. Stage-discharge relationships at H Street bridge (1924–1983). (a) Scatter around regression line, showing high early stages compared to later. (b) Close-up of discharges less than 300 m^3 s^{-1} showing lowering of stages through time.

construction, dredging, or gravel mining upstream, or by passage of mining sediment from the mountains prior to closure of the North Fork Dam. By 1970, stages had lowered 2 m from 1924 and 0.7 m from 1950, representing stage-lowering rates of 4.3 cm yr^{-1} for the entire period and 3.5 cm yr^{-1} for the latter period.

Cross sections at the Fair Oaks bridge (1913–1950) indicate the channel bed scoured with net thalweg erosion of 2.4 m at a rate of 6.5 cm yr^{-1} [*NRC*, 1995]. Cross sections from the cable below the Fair Oaks bridge show 2 m of thalweg incision from 1944 to 1952 followed by 0.8 m of aggradation from 1952 to 1957 (not shown). Deepening and narrowing of cross sec-

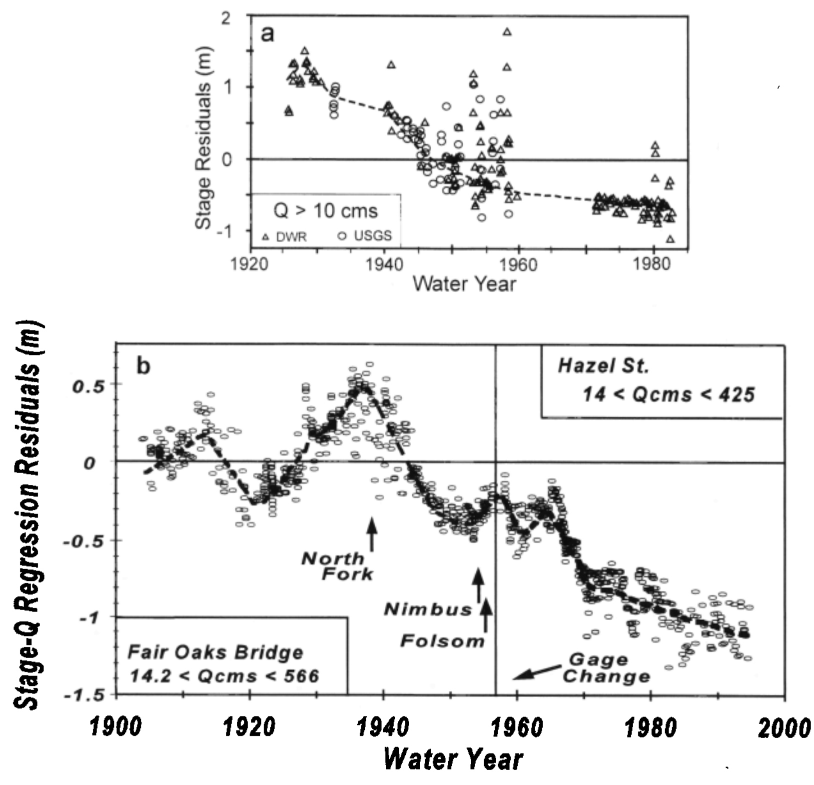

Figure 4. Time series of stage-discharge regression residuals. (a) H Street gage residuals showing rapid lowering (1940–1955) and highly variable stages in the 1950s. (b) Residuals for Fair Oaks gage. Two episodes of rising and then lowering stages at the Fair Oaks bridge are shown at left. Times of dam closures are shown by arrows. Hazel Street residuals (at right) were reduced uniformly 0.7 m to match the old bridge series. (Figure 4b adapted with permission from *NRC* [1995]. Copyright 1995 by the National Academy of Sciences. Courtesy of the National Academy Press, Washington, D. C.)

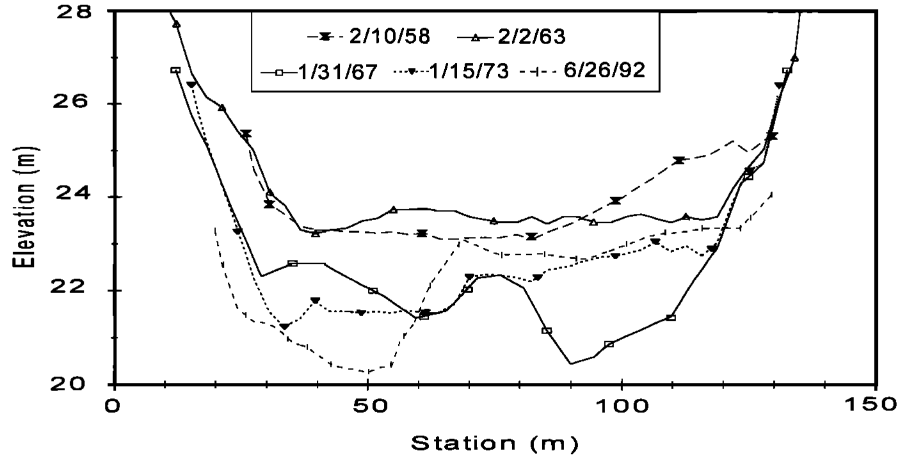

Figure 5. Hazel Street cross sections showing active channel erosion.

tions at the cable show that erosion extended from the bridge through the reach and conform with decreased width/depth ratios during incision through hydraulic mining sediment in the Bear River [*James*, 1991]. Flow stages lowered through time, as is shown by stage-discharge regression residuals (Figure 4b). Net stage lowering at the Fair Oaks bridge from 1905 to 1957 was only 0.6 m (1.2 cm yr^{-1}), but rapid changes occurred before and after an aggradation period from 1920 through the 1930s. Rapid stage lowering during the 1940s corresponded with channel incision, as is shown by cross-section plots at the cable and bridge.

Channel cross-section plots at the Hazel Street cable indicate that the thalweg shifted twice from side to side, deepened episodically between stable periods, and lowered 2.8 m overall from 1958 to 1992 (8.2 cm yr^{-1}; see Figure 5). The thalweg scoured 3.2 m in response to a 1965 flood but refilled by 1973 as the thalweg shifted to the left bank. The channel then stabilized until 1986, when the bed lowered 1.0 m and widened by eroding the left bank. Subsequently, the left bank was artificially rebuilt and riprapped, and the channel was stable until at least 1992. In accordance with the cross sections, stage-lowering episodes of 0.6 m from 1965 to 1970 (12 cm yr^{-1}) and of 0.2 m in the 1980s were separated by a stable period in the 1970s (Figure 4b). Overall, stages lowered 0.9 m from 1958 to 1994 (2.5 cm yr^{-1}) at this site, mostly in the late 1960s, a decade after closure of the Nimbus and Folsom Dams.

Discussion and Conclusions

Channel bed elevations and flow stages lowered at all three study sites. Channel incision at H Street from 1924 through the 1930s corresponded with aggradation at the Fair Oaks bridge and suggests that sediment deliveries to the Fair Oaks site had not reached the lower reaches of the river. Rapid degradation at the H Street site from 1940 through the 1950s was in phase with degradation at the Fair Oaks bridge, where stages lowered 1.1 m in this period. These changes may have been responses to (1) high sediment loads through the 1930s from transport of stored and contemporary mining sediment, (2) absence of large floods in the 1930s, (3) construction of North Fork Dam in 1939, and (4) large floods in the early 1940s.

Readjustments of lower American River channels to perturbations caused by hydraulic mining and dams are relevant to flood hazards in the Sacramento metropolitan region [*NRC*, 1995]. Lowering of flow stages by 2 m (1924–1982) at the H Street site is particularly important to the evaluation of flood hydraulics and hazards given the nature of the location. Stage-discharge relationships in recent years should be examined further to see if flood conveyance has changed.

The strong temporal correspondence at all three sites between lowering of bed elevations and stages indicates that flow stages responded primarily to channel aggradation and degradation rather than to changes in roughness elements or energy gradients. Although minor channel widening occurred at both Fair Oaks sites, this did not correspond in time with the major episodes of stage lowering. Thus stage lowering at all sites is attributed primarily to erosion of bed alluvium, presumably historical mining sediment. Erosion accelerated sharply in 1940 in response to sediment trapping by the North Fork Dam. Gravel aggregate extractions probably contributed to channel erosion, but the pronounced incision from 1940 to 1945, prior to peak post–World War II urban development, indicates that dam closure dominated the process.

The timing of sediment storage and transport on the lower American River, a type locale of *Gilbert*'s [1917] classic sediment transport model, is relevant to general concepts of long-term sediment transport and storage. Channel degradation after 1940 is in contrast to postulated stabilization of channel beds throughout the region based on *Gilbert*'s [1917] symmetrical wave concept and observations on the nearby Sacramento River [*Graves and Eliab*, 1977]. Closure of the North Fork Dam in 1939 had a pervasive impact on channel erosion downstream because the dam detained 5.0 × 10^6 m^3 of sediment from 1939 to 1993, probably mostly in its early years [*REC*, 1993]. The dam controls only 18% of the American River drainage area, and its basin is dominated by rocky, glaciated terrain, presumably with low natural sediment production rates. Yet the North Fork received from 58 to 70% of the nineteenth-century hydraulic mining sediment produced in the basin [*U.S. Congress*, 1882]. Preliminary analysis of archived licensed mining records indicates that the North Fork also received large volumes of hydraulic mining sediment in the twentieth century. Either twentieth-century mining sediment production caused much more aggradation on the lower river than previously has been assumed, or storage and transport of nineteenth-century mining sediment was maintained until at least the 1940s. The latter interpretation would indicate that the symmetrical sediment wave model is inappropriate in fluvial systems where sediment is stored in sites with the potential for long-term residence and protracted releases through time. Either interpretation indicates that channel morphology along the lower American River did not stabilize as early as predictions based on a single sediment wave.

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