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Excerpts by L. Allan James

GEOMORPHOLOGY OF THE LOWER AMERICAN

Geomorphology of the lower American River is relevant to flood hazard management through three issues: (1) stability of channel banks and levees, (2) possible on-going channel enlargement and increases in conveyance, and (3) sediment deliveries to weirs and the lower river. This section addresses the first two concerns by examining geomorphic stability of the lower American River, and presenting evidence of channel erosion from U.S. Geological Survey stream-flow measurements at the Fair Oaks gage.

Evaluations of potential temporal changes in flood conveyance in the lower American River must consider channel stability, which in turn is dependent on channel morphology and stratigraphy. Since both morphology and stratigraphy of the lower American are largely the result of extreme and persistent channel changes induced by human activities, analyses of channel stability should begin with an understanding of the nature of historical sedimentation and subsequent channel adjustments.

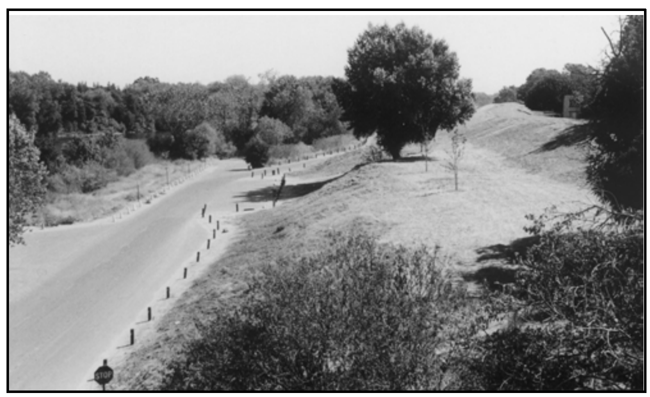
Historical Channel Changes

The channel geomorphic history over the last 130 years is one of great change. Mining sediment, dams, and levees caused perturbations to which the fluvial system is still adjusting. Channel stability is related to these extensive but undocumented changes due to both 19th century aggradation and engineering works. Yet, an analysis of the historical record of channel changes which could reveal instabilities has not been conducted. For example, two apparent 19th century channel diversions near downtown Sacramento, including a meander-bend cutoff near Sutter's Landing in 1862 and a northward diversion of the channel at its confluence with the Sacramento River (Bischofberger, 1975; Dillinger, 1991, map), are not mentioned in the geotechnical literature. These changes could represent channel shortening and steepening in critical reaches below Howe Avenue.

Mining Sediment

Hydraulic mining is a method of resource extraction invented in northern California in 1853 which uses pressurized water to move large volumes of sediment (Paul, 1947; James, 1994). Much hydraulic gold-mining sediment began to be delivered to main channels of northern Sierra rivers after 1861 when it began to cause channel aggradation (Mendell, 1881). The lower American River aggraded substantially during the primary hydraulic mining period (1861-1884) and later degraded as sediment loads decreased (Gilbert, 1917). Estimates of mining sediment stored along upper American River channels near the turn of the century were 20 to 25 million yd^3 in the North Fork, 10 to 15 million yd^3 in the Middle Fork, and none in the South Fork (Manson, 1882; Gilbert, 1917). Licensed hydraulic mining continued to produce sediment from 1893 through at least the 1930s. Few of the sediment detention structures required for licensing remain, so most of this sediment was delivered downstream until the North Fork Dam was built in 1939. Little mining sediment remains in the mountains other than sediment stored behind North Fork Dam (RCE, 1993) and Folsom Dam, although a low gravel terrace remains on the North Fork above Lake Clementine (behind North Fork Dam).

In the lower American River, mining sediment deposits were estimated to have varied between 5 and 30 feet in depth across almost ten square miles (Mendell, 1881; Manson, 1882), and mining sediment may dominate the active sediment. Field visits in 1994 located much historical sediment stored along the lower American River. Based on the mineralogy of pebbles (James, 1991b) much of this sediment was produced by hydraulic mining. A left bank historical terrace 4 m high (RM 21) of erodible unconsolidated sand and gravel is representative of historical deposits in the lower American River from river mile 15 to 22 (Photo 1 & 2). The high terrace of historical sediment on the left bank at Watt Avenue (Photo 3), extends laterally beneath the levees on both sides of the river and downstream below H Street through an area of critical bank erosion potential.



Channel instability may arise from the morphologic changes induced by historical aggradation. Erosion of historic sediment could be relevant to conveyance in two ways: (1) eroded sediment may fill channels or produce bedforms and other roughness elements during floods, thereby reducing conveyance and raising flow stages, or (2) increased channel capacities could improve flood conveyance. In addition, many levees are built on stratified mining sediment with high lateral hydraulic conductivities. Seepage beneath levees was observed in 1986 and is a substantial problem (RCE, 1993).

Geomorphic mapping is needed to identify where banks and levee foundations are composed of relatively erodible and permeable historic sediment. Two recent reports classified bank stratigraphy along the lower American as Pleistocene or Recent (Holocene) without distinguishing between prehistoric Holocene and historical sediment (WET, 1991; RCE, 1993). No mapping of long-term historical channel changes or field descriptions of present historical deposits has been attempted in the lower river. Nor has the condition of the pre-mining channel been considered, other than base level changes.

Bank and Lateral Stability

It was pointed out earlier in the Geotechnical Analysis section of the 1991 AWRI that banks and levees were structurally stable at flows up to 115,000 cfs, but would fail due to seepage or overtopping at higher flows. The 1991 AWRI was based largely on a geotechnical perspective, neglecting geomorphic processes. Three recent reports have introduced the geomorphic perspective (WET, 1991; WRC-Swanson, 1992; RCE, 1993). Based on historic aerial photographs and field evidence, consultants for SAFCA (WRC-Swanson, 1992) concluded that bank erosion potential is high, and that sustained bank erosion since 1955 can be attributed to Folsom Dam closure and levee construction. Consultants for the District (WET, 1991; RCE, 1993) identified lateral instability and seepage failures as serious concerns, although the District does not believe that the bank erosion problem goes beyond what can be treated by standard maintenance practices (Sadoff, 1992). Bank stability was evaluated (RCE, 1993) based on stream power which was highest in steep upper reaches below Folsom where channels were presumed stable due to resistant strata in the bed and right banks. The Committee has identified extensive deposits of historical sediment on the left bank of these reaches, however, that could be prone to erosion. In the lower reaches, stream powers were high between RM 5 and RM 6, corroborating other findings that the bends below Howe Avenue are vulnerable to bank erosion. Comparisons of aerial photographs from 1968 and 1986, indicated that channel migration rates at five critical sites (RM 12.5 to 20.1) averaged 4.8 ft/yr and ranged between 1.1 to 8.0 ft/yr (WET, 1991). Migration rates as high as 13.9 ft/yr at other sites were not deemed critical due to the channel distance from a 50' buffer around toes of levee slopes. These migration rates do not include substantial channel changes from the 1965 flood which caused an avulsion near river mile 15.

Agreement on the potential for lateral channel migration is important not only to bank stability, but also to channel enlargement. Lateral planation in meandering alluvial channels can maintain a natural equilibrium system, but with the down-valley sediment supply cut off by dams, eroded bank material may not be entirely replaced and erosion could result in net channel enlargement over time.

Channel Lowering and Enlargement

Questions relevant to channel stability and potential changes in conveyance in the lower American include the degree and timing of aggradation and degradation, whether channels have returned to pre-settlement base levels, and whether channel enlargement continues. Dam closures are often associated with channel erosion downstream (Williams and Wolman, 1984), although responses to dams may be complex and may include periods of local aggradation. For example, closure of Oroville Dam in 1968 caused complex channel changes downstream on the Feather River at least through 1975 (Porterfield and others, 1978). It has also been argued that the lower American has been degrading in recent decades, encouraged by closure of Folsom Dam and levee construction in the 1950s (WRC-Swanson, 1992), although little evidence has been cited.

Vertical Incision

Vertical changes on the lower American River have been the subject of several investigations. Gilbert's (1917) time series of Sacramento River bed elevations just below the American River confluence shows 10 feet of bed aggradation from 1855 to 1890, and about 8 feet of degradation by 1914. These responses to hydraulic mining sediment indicate that the lower American also must have experienced substantial channel-bed aggradation and degradation. Recent studies of historical incision, based primarily on California Debris Commission (CDC, 1907) and subsequent topographic maps (1955 and 1987), identify 10 to 20 feet of degradation in the lower river from 1906 to 1986 and conclude that thalweg incision is on-going at some locations (WET, 1991; WRC-Swanson, 1992; RCE, 1993). Ten channel cross-sections, resurveyed between 1987 and 1993, showed no systematic change (RCE, 1993), but these surveys were not separated by any major flood events. At some sites the channel bed rests on resistant pre-mining strata, and removal of historical sediment from the bed is complete at these sites (RCE, 1993). Incision of resistant Pleistocene strata can result in sustained channel degradation, however, as on the nearby Bear River in response to a 1955 flood (James, 1991a).

Thalweg profiles indicate that most channel degradation between RM 6 and RM 11 was complete by 1955, but that considerable incision occurred between 1955 and 1987 from RM 6 to the mouth and between RM 11 and RM 14 (RCE, 1993). Channel incision of about 20 feet and considerable channel enlargement had occurred in the lower American by 1960 (Olmsted and Davis, 1961). Changes in thalweg profiles on 1957 and 1987 maps indicate an average of about 18 feet incision between RM 2 and 3 (WET, 1991).

Bed stability was modelled using Corps design 100-year hydrographs and the Parker bedload transport equation based on the median bed material size (D_{50}) and Shields entrainment criteria (RCE, 1993). Most simulated channel-beds experienced no scour, and maximum bed elevation change under the worst scenario was less than 2 feet (at RM 7). Based on the model, it was concluded that channel beds throughout the lower American River should be stable under relatively large and infrequent events.

Channel Enlargement

Vertical incision is only one form of channel erosion, and vertical stability would not preclude channel enlargement by erosion of sediment stored along channel margins. It is common in aggraded systems for channels to respond initially to decreased sediment loads by incising vertically, and later to widen out; particularly when channel top widths are confined by levees or terraces. For example, it has been shown experimentally that knickpoint retreat is often followed by lateral migration and bank erosion (Schumm, 1973; Schumm, Mosley, and Weaver, 1987).

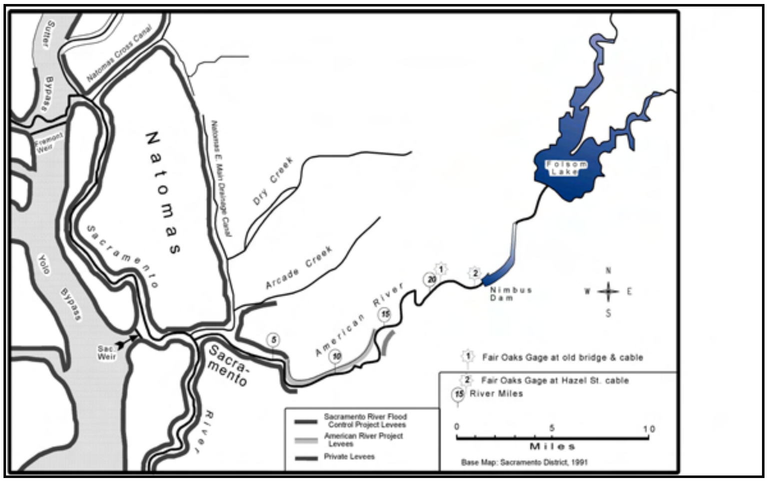
Following vertical regrading of the lower American channel profile, a period of channel enlargement by bank and berm erosion and lateral migration cannot be ruled out. In fact, due to surplus energy from decreased sediment loads and decreased channel capacities from levees and historical deposits, and due to observed channel erosion and lack of sediment replacement from above Folsom Dam, on-going net channel erosion could be expected for the lower American River. In spite of these reasons to suspect channel enlargement and the ramifications to channel conveyance and environmental concerns along the Parkway, evidence of channel change in the lower American River has not been adequately studied.

Channel Changes at Stream-flow Gages

The nature of channel erosion since closure of Folsom Dam has been examined primarily by using topographic maps and air photos with limited temporal and spatial resolutions (WRC-Swanson, 1992; RCE, 1993). To enhance the channel-change database, the Committee examined high resolution U.S. Geological Survey cross-section measurements the Fair Oaks gage (11446500).

These analyses are based on only a few sites associated with various lacations of Fair Oaks gages and soundings, so caution should be exercised before extrapolating results up- or down-stream.

Channel changes are demonstrated by channel cross-section plots and stage-discharge regression analysis. Data were derived from stream-flow measurement records (U.S.G.S. archives). Cross-section plots were derived from depth soundings at three locations (Figure 2.4): the old Fair Oaks bridge (1913-1950), a cable about 300 feet below the bridge (1930-1957), and a cable 2.2 miles upstream below Hazel Street (1958-1994). All sections are from bridges or



cables to control the longitudinal position. Numerous plots reproduced sections during stable periods indicating high accuracy of the procedure. For the sake of brevity only five cross-sections at one site are presented here.

Channel morphological changes are rarely related to changes in flood stages in a simple manner. For example, channel deepening may not result in lower stages of overbank floods if meander-belt flows develop turbulence at channel crossings (Ervine and others, 1993). Thus, an independent analysis of stage-discharge relationships was conducted to evaluate temporal changes in stage at the two gage sites: the old Fair Oaks bridge and Hazel Street gage sites. Stage integrates morphologic and hydraulic factors providing an indicator of flow conveyance. Stage data represent gage readings at the time of discharge measurements (not rating curves), corrected for gage datum changes.

Flow stage is strongly related to discharge, so stage was statistically regressed on discharge to control for these effects. A third-order polynomial provided the best-fit model at both sites. Extreme discharge events were eliminated from regressions (Q-Range, Table 2.7) to emphasize changes within the inner channel rather than over-bank characteristics that can be dominated by roughness elements. The regressions provide an objective estimate of the stage of a given discharge. Plots of residuals (errors in the predicted stage) against time reveal temporal changes in stages of flows up to moderate magnitude floods. These methods and some limitations to their morphologic interpretation (*e.g.*, changes in roughness and energy gradient) are explained elsewhere (Knighton, 1974; James, 1991a).

Table 1. Stage-Discharge Data.

Location	Total N	Model N	Model Years	Q Range	R^2
Bridge	528	497	1905-58	$500 < Q < 20,000$	0.85
Stage = $67.5 + 7.18 \cdot 10^{-4} Q - 2.00 \cdot 10^{-8} Q^2 + 2.30 \cdot 10^{-13} Q^3$					
Hazel St.	454	413	1958-94	$Q < 15,000$	0.74
Stage = $76.1 + 1.52 \cdot 10^{-3} Q - 1.66 \cdot 10^{-7} Q^2 + 7.05 \cdot 10^{-12} Q^3$					

Fair Oaks Gage near Old Bridge

Cross-section plots (1913 to 1950) at the Fair Oaks bridge indicate channel-bed scour and fill with net thalweg erosion of about 8 feet (Figure 2.5). Channel morphology is controlled by bridge piers and the right bank bluff. A deep left bank fill narrowed the channel by about 20 feet toward the end of the period suggesting that constriction by the bridge is not the dominant reason for erosion. A cable was installed about 300 feet below the bridge in 1930, where cross-section plots indicate about 5 feet of thalweg erosion from 1944 to 1952 followed by about 2 feet of fill by 1957 when the cable was moved. Deepening and narrowing of cross-sections at this site suggest that erosion at the bridge extended through the reach. Channel deepening and narrowing at this bridge site follows the general response observed elsewhere where channels incised through hydraulic mining sediment (James, 1991a).

[Data graphics are missing; no figs 2.5 - 2.8 in excerpts]

Stage-discharge relationships at the bridge site indicate a systematic grouping by period with occasional changes in flow stages (Figure 2.6). Temporal patterns of flood stage changes are illustrated by a time series plot of regression residuals (Figure 2.7). Flow stages at the old Fair Oaks gage rose slightly from 1905 to 1912, lowered about 2 feet by 1920, rose about 2½ feet in the late 1930s, and dropped about 3½ feet by 1950 to about 1½ foot below the mean for the period. The rapid incision during the 1940s may represent a response to decreased sediment yields following closure of North Fork Dam in 1939.

Fair Oaks Gage at Hazel Street

In 1957, the gage and cable were moved 2.2 miles upstream to the present Hazel Street site below Nimbus Dam. From 1958 to 1994 the channel at this location experienced episodes of thalweg deepening and bar deposition followed by stable periods lasting several years, and about 9 feet of net thalweg degradation. The 1965 flood scoured the thalweg about 10 feet, but the channel partly refilled from 1965 to 1973 and was colonized by willows. From 1973 to 1986, the channel bed was stable, but the 1986 flood lowered the thalweg about three feet and widened the channel considerably.

Analysis of flood stages at the Hazel Street site from 1958 to 1994 displays two periods of relative stability (Figure 2.8). Stage-discharge regression residuals reveal progressive lowering of flow stages at this site (Figure 2.7). The 1965 scour event had no effect on flow stages, presumably due to rapid refilling and increased vegetational roughness of the channel. From 1967 to 1970, however, flow stages rapidly lowered about 2 feet. Sustained incision over the period 1958 to 1994, during which time flow stages dropped about 2 feet, suggests a long-term tendency for channel degradation and a mobile bed at this site. The close proximity of Nimbus Dam upstream severely limits replacement of eroded bed sediment, resulting in net degradation.

Thalweg incision at the two gage sites was about 8 feet (1913-1950) and 9 feet (1958-1994), respectively. Although net stage lowering for the two periods was only about 1 3/4 feet and 2½ feet, respectively, large rapid fluctuations characterize these changes. This evidence of rapid erosion at gages lends credence to a hypothesis of continued channel deepening and enlargement in the upper reaches. If the gage sites are representative of other sections, the conclusion that extreme floods would cause little incision on the lower American River (RCE, 1993) could underestimate the potential for channel down-cutting.

Geomorphic Summary

Bank stability is a serious consideration to conveyance of high flows in the lower American River. Although there is little agreement on the hazard that bank erosion, lateral migration, or bed incision poses to levee stability is contested, all parties appear to agree that a program of channel monitoring and maintenance will be required. The belief that historical sediment in channels of the Sacramento Valley is now stable is based largely on evidence of elevations derived from topographic maps and numerical simulations of channel bed erosion. Thalweg elevations indicate base level adjustments have decelerated, but on-going vertical adjustments should not be ruled out. Nor would stabilization of long profiles necessarily indicate an end to channel bank erosion, lateral migration, enlargement, or instability.

Evidence from two Fair Oaks gage sites indicates substantial local channel-bed scour. From 1913 to 1958, flow stages at the Fair Oaks bridge changed considerably showing two periods of increasing stages and two of decreasing stages, interpreted as periods of agradation and degradation, respectively. There was a net lowering of flow stages by almost 2 feet for this period, presumably due to erosion of historical sediment. From 1958 too 1994 flow stages at Hazel Street also lowered about 2 feet. If these sites are representative of the lower river as a whole, further channel incision may be anticipated.

Given historical aggradation, cessation of sediment deliveries since dam construction, and evidence of erosion, the potential for net erosional tendencies in the lower river cannot be rejected. A sediment budget deficit exists in the lower river as dams arrest sediment deliveries from up-stream while erosion removes sediment, and this deficit results in net erosion. The hypothesis that channel erosion and enlargement have resulted in increased channel conveyance over the last two decades should be tested further using hydraulic models. Analysis of stage-discharge time series provides empirical support for the hypothesis that channel stages of moderate magnitude floods have lowered by a modest amount at two locations over two different periods, but more information is needed to substantiate these results and extend them to other locations downstream.

Geomorphic Recommendations

Given the critical nature of flood hazards in Sacramento and extensive 19th century channel changes, three areas of study are recommended regarding the geomorphology of the lower American River: (1) on-going monitoring of channel changes, (2) historical reconstruction of channel changes, and (3) geomorphic mapping. Recent and on-going channel changes should be documented and monitored following large flood events by monumenting and repeating channel cross-section surveys, and by registering air photos.

Study of long-term historical changes should include consultation of early historical records to establish pre-settlement channel conditions that could establish a base line for changes to the fluvial regime which was presumably in equilibrium with long-term flow conditions. In addition, historical changes should be documented through historical and field methods. For example, CalTrans bridge surveys could be collected and repeated, and CDC records of 20th century hydraulic mining sediment production could be tabulated.

Vast tracts of erodible historical sediment stored in the lower river should be studied and mapped. In the upper reaches they are relevant to channel enlargement and sediment production, while in the lower reaches they are relevant to bank and levee stability and seepage. Mapping will reveal spatial patterns and allow more accurate interpolation between geotechnical sample points. As pointed out in the Geotechnical Analysis section, implementation of risk and uncertainty analysis in the lower American River will require appraisals of channel and levee stability (USACE, 1994). Assignment of PNP and PFP elevation for levees should be based in part on knowledge of lower American River stratigraphy with an emphasis on the spatial pattern of historical sediment and former channels.

Additional Citations:

James, L.A. 1994. "Channel changes wrought by gold mining: Northern Sierra Nevada, California." *Proc. American Water Resources Association; Symposium, Jackson Hole, WY. June, 1994.* In Marston, R.A. and Hasfurther, V. (ed.), Effects of Human-Induced Changes on Hydrologic Systems.

Mendell, Col. G.H. 1881. "Protection of the navigable waters of California from injury from the debris of mines." *House Document 76, 46th Congress, 3rd Session.*

Paul, Rodman W. 1947. California Gold: The Beginning of Mining in the Far West. Lincoln: University of Nebraska Press. 380 pp.

Figure Captions

Fig. 2.5 - Representative channel cross-section plots at the Fair Oaks Bridge showing about 8 feet of thalweg degradation between 1913 and 1950.

Fig. 2.6 - Stage-discharge relationship from the Fair Oaks gage at the bridge and early cable site. Several distinct periods of high and low stages can be identified.

Fig. 2.7 - Stage-discharge regression residuals for the Fair Oaks gage. Left side is from Fair Oaks bridge site (see Figure 2.6) and shows two periods of low stages and two of high stages interpreted as degradation and aggradation, respectively. Right side is from Hazel Street site (see Figure 2.8) and shows a short period of rapid stage lowering interpreted as in response to channel degradation. Joining of the two series is approximate.

Fig. 2.8 - Stage-discharge relationship from the Fair Oaks gage at the Hazel Street cable site. Several distinct periods of high and low stages can be identified.