Hydraulic Mining Sediment Impacts on American River Channel Morphology and Flood Stages

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2012 California Extreme Precipitation Symposium
June 26, 2012, UC Davis

Introduction

- Hydraulic gold mining generated 1.1 billion m^3 of *hydraulic mining sediment* (HMS) in the Sierra from 1853 to 1884.
  - 197 million m^3 in American River Basin
- The 1862 floods initiated HMS delivery to Sacramento Valley. Channel and floodplain aggradation continued to at least 1880. Legacy of HMS in LAR poorly documented & underestimated.
- Historical maps show changes but accurate maps don't go back to pristine conditions. Changes make paleohydrologic reconstructions problematic.
- Channel recovery complicated by engineering changes (dams, levees, bank protection, etc.).
- Stream-gauge records document stage changes in 20th century.

Lower American River (LAR) channels experienced deep aggradation due to a massive influx of hydraulic mining sediment (HMS) from 1862 to 1884. This converted deep, diverse river morphologies into shallow, braid-bar systems with low instable banks and low habitat diversity.

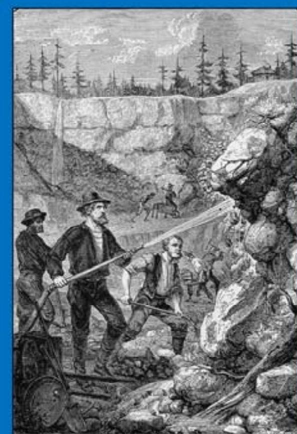
Subsequent channel recovery has been complicated by engineering changes (dams, levees & dredging). Enduring effects have been underestimated and so that the on-going recovery can be recognized. Channel recovery involved incision that re-exposed or created morphological elements, such as steps and pools, that increased aquatic habitat diversity. Channel widening is on-going where banks aren't hardened. Historical maps and USGS stream-gauge records provide information about channel recovery from the 1862 and subsequent floods.

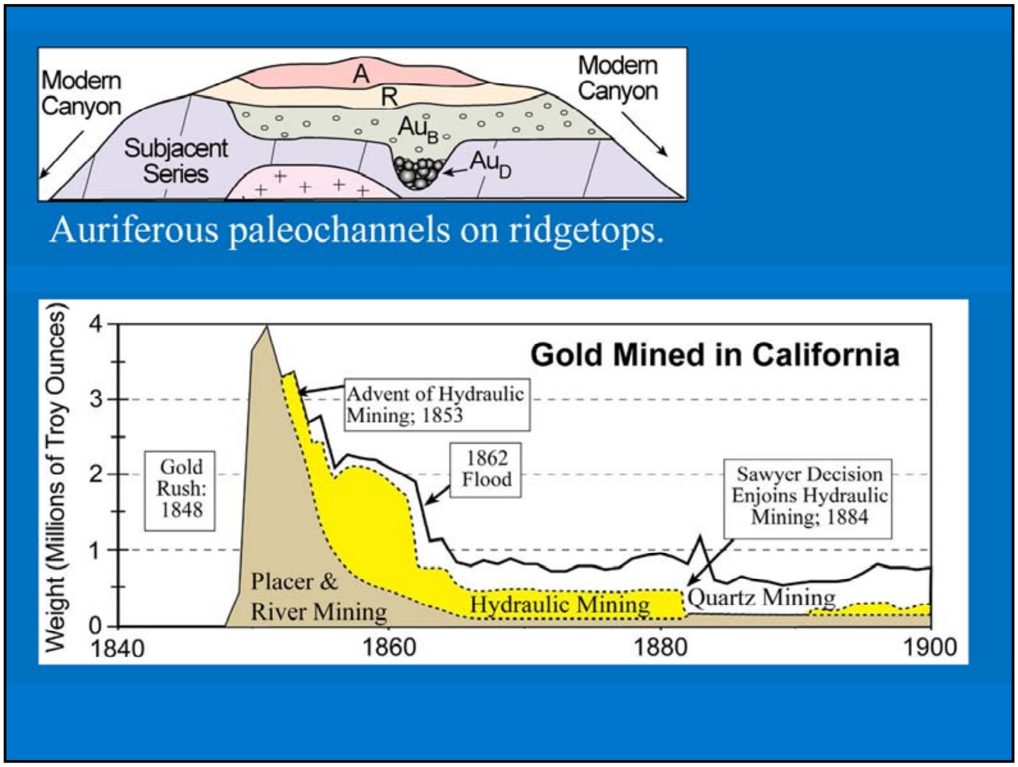
*) Historical maps are of relatively poor resolution and accuracy prior to mining, because the gold rush began shortly after settlement. Thus, evidence of pre-mining (pre-1862 flood) channel conditions is limited.

*) The discharge record from stream gauges in the 20th century has been studied previously, but a wealth of geomorphic information recorded about flow stage, width, depth, velocity, & other hydraulic variables has been neglected. The ability to reconstruct historical channel morphologies and flow environments and develop long-term process-response linkages for past events, can establish connections between extended sediment transport and channel morphological changes.

Objectives

- Review history of hydraulic mining sediment (HMS) production & delivery to lower American River (LAR)
- Employ historical maps & other historical data to describe pre-settlement channel conditions & subsequent changes.
- Examine historical USGS stage, discharge (Q), and suspended sediment (Q_s) data for changes in flow stage, channel morphology & sediment concentrations.
- Potential for *geomorphic change detection (GCD)*.





Top: Stratigraphy of gold-bearing Tertiary channels. A: andesitic volcanic cap; R: rhyolitic volcanic cap (not always present); Au_B: gold bearing bench gravels; Au_D: gold bearing deep gravels of ‘blue lead’. Volcanic cap was barren of gold and had to be removed. Deep gravels were rich but difficult to mine.

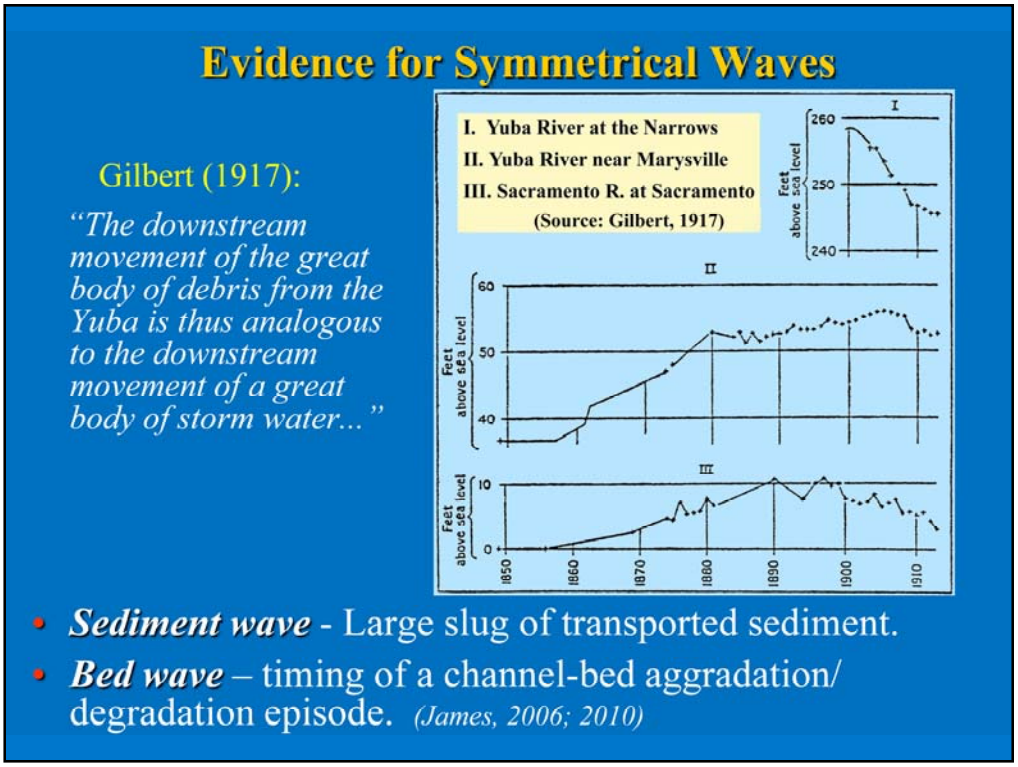
Bottom: Total gold mined in California. The highest yields occurred during the first few years of the gold rush when shallow placer mining produced millions of ounces of gold. After the advent of hydraulic mining in 1853 near Nevada City, this source of gold became dominant until it was enjoined in 1884. Hydraulic mining waned in the early 1860s as shallow bench gravels of Tertiary paleochannel system were exploited. Resurgence in 1870 resulted from introduction of TNT and hard-rock drift-mining technology to hydraulic mines allowing exploitation of deeper and coarser ‘blue lead’ deposits. Total production values from Loyd & Bane: ‘Gold Mining Activity in Calif.’ Subdivisions approximated.

19th Century HMS Production

Basin	Drainage Area (km^2)	Volume Produced (m^3 10^6)	Vol. yr^{-1} 31 years (m^3 10^6 yr^{-1})	Specific production (t km^{-2} yr^{-1})
Feather R.				
Yuba City	10,301	77	2.5	527
Yuba River	3,499	523	16.9	10,616
Bear Basin	1143	271	8.7	16,807
American	5,014	**197**	6.3	**2,783**
North Fork	900	**164**	**5.3**	**13,069**
Middle Fork	1,586	33	1.1	1,486

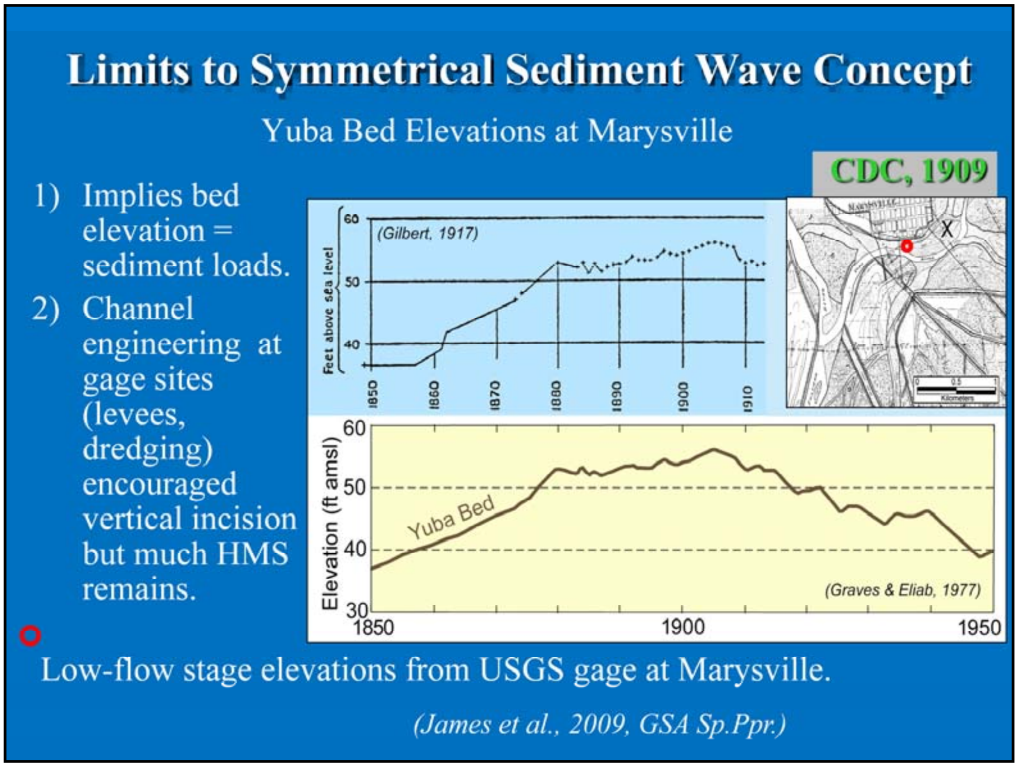
Data from Gilbert (1917)

As a whole, the American River basin received much less hydraulic mining sediment (HMS) than the Yuba or Bear Rivers. Only the North Fork American received amounts of sediment that were comparable on a per unit drainage area. The Middle and South Forks were not conducive to hydraulic mining due to thick volcanic caps over the Tertiary river gravels. The small amounts of HMS in the Middle and South Forks resulted in dilution of concentrations and lower specific yields to the lower American River (LAR) compared to the Yuba and Bear basins, where most studies of HMS have been concentrated. Nevertheless, sedimentation, flooding, and channel change were substantial in the LAR and should receive greater attention.



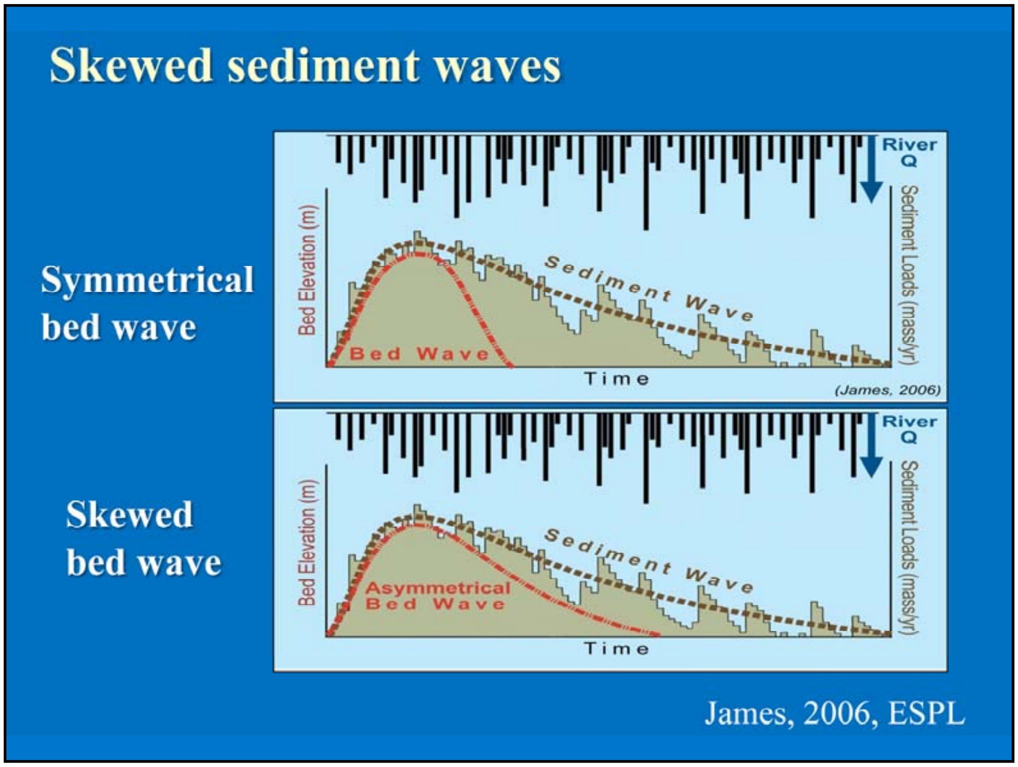
Gilbert's (1917; USGS Professional Paper 108) symmetrical sediment wave model. The rise of stages in the late 19th century represent aggradation due to HMS. The subsequent fall in stages is channel incision. The symmetry of the waning limb (shown later) indicates rapid bed recovery. Gilbert described the movement of HMS in terms analogous to the translation of a flood wave. This implied that channel-bed elevation changes are explicitly linked to sediment loadings. Several problems with this interpretation have been detailed in the literature. Of greatest importance here are the erroneous implications that HMS is now gone from the system or permanently stabilized, and that channels should be fully recovered; neither of which is true. This is not simply an academic or theoretical question, since HMS is highly contaminated with mercury (James et al., 2009, GSA Sp.Ppr).

Gilbert's symmetrical wave is based on bed elevations not sediment loads but it assumes the two are in phase. A distinction should be made between sediment waves (actual movement of sediment) and bed waves (the rise and fall of channel beds). Bed waves represent an aggradation-degradation episode, such as the HMS, legacy sediment along US eastern seaboard, deforestation episodes in prehistoric Europe, etc. Equating bed waves with sediment waves underestimates continued remobilization of reworked HMS. Bed waves may be symmetrical or skewed depending on local hydraulics, sediment supplies, and bed erodibility (armoring). They represent a time series plot of elevation changes at a site and do not include distance in their dimensionality. They do not necessarily propagate downstream in a progressive or systematic manner, but may be highly variable when sites are compared along a longitudinal transect. They respond to local hydraulic conditions, sediment loadings, bed erodibility (armoring), etc.

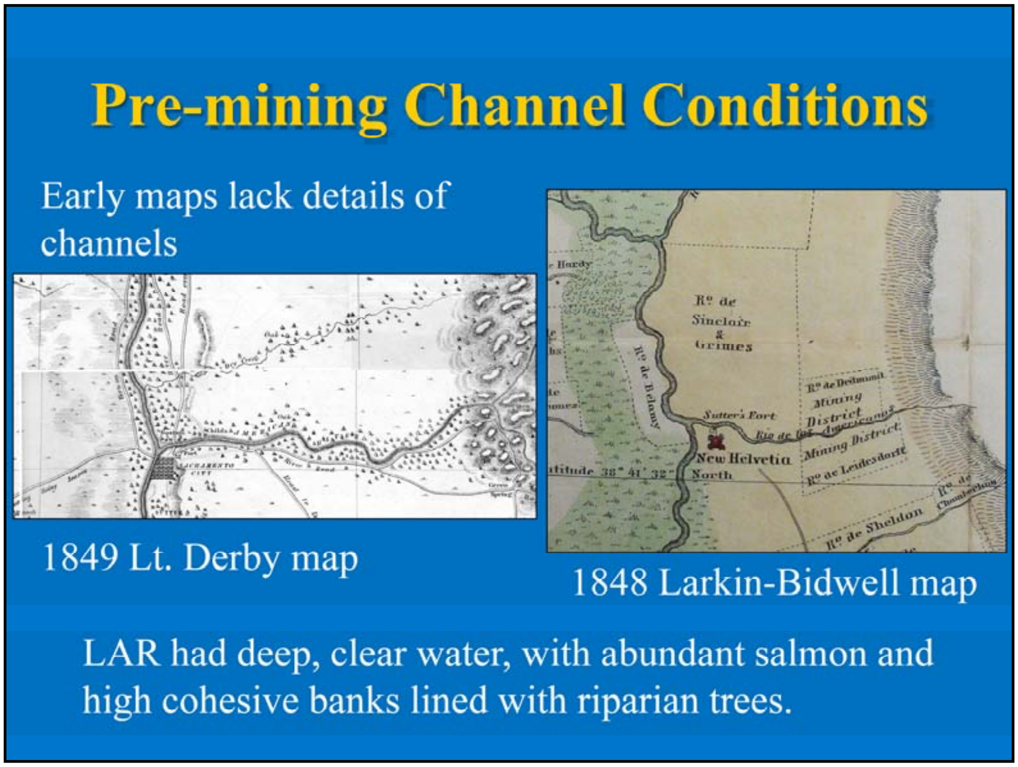


Stream gauge locations used by Gilbert were heavily engineered with levees and dredging that encouraged bed incision. Lowering of channel beds is a poor indicator of long-term sediment loads.

At-a-station (Lagrangian) view of reach-scale river processes. Gilbert's true genius in his 1917 treatise on HMS was in the integrated watershed approach he took to developing a sediment budget and tracking it from these large watersheds through the Valley, Delta, and Bay, through the Golden Gate (Eularian perspective). River science is culturally pre-determined to take a local-scale (Lagrangian) view of rivers, so the emphasis on Gilbert's findings has been on his at-a-station point data. This misses his genius entirely.



A right-skewed wave form is more accurate for most sediment waves that involve overbank storage. Both sediment and bed waves are at-a-point representations that vary from site to site and don't necessarily translate up or downstream. This is especially true of bed waves because bed scour and fill can vary greatly along longitudinal profiles.

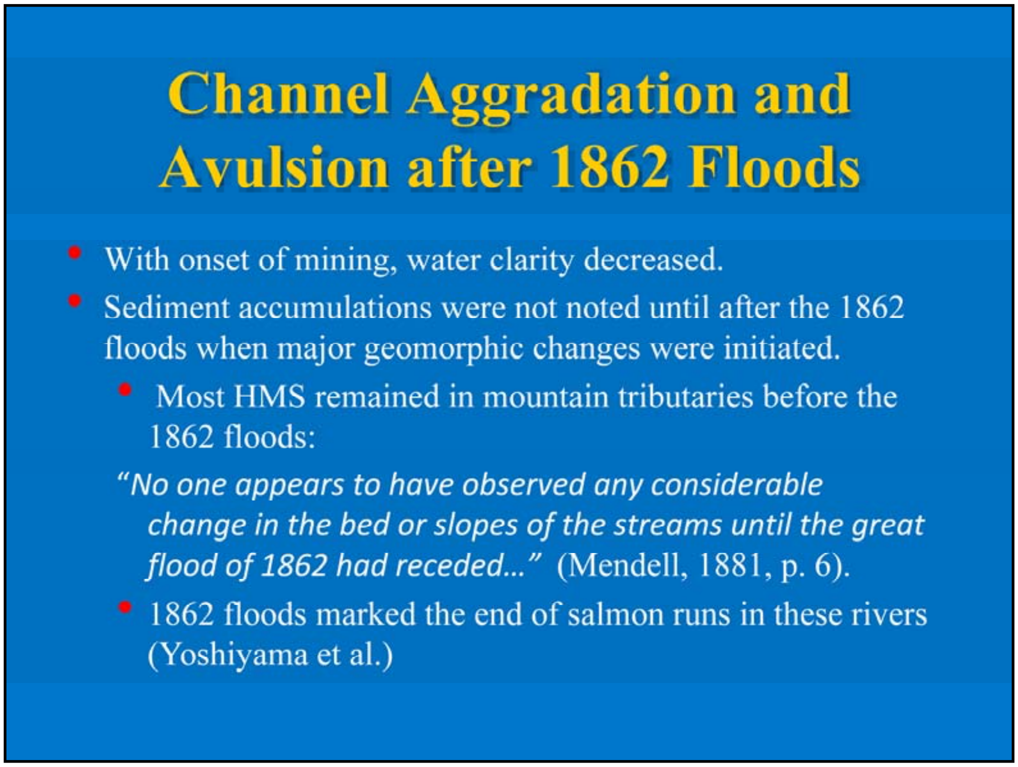


Early map lack details of river channels, especially tributaries such as the LAR that were only seasonally navigable.

"Map of the Valley of the Sacramento including the Gold Region" Tracing of Bidwell's map by Thomas Larkin.

As with Yuba and Bear Rivers, early accounts of river conditions indicate the LAR had relatively deep, clear water, with high cohesive banks lined with riparian trees. Salmon were plentiful.

A limit to studies of geomorphic change in Sierran rivers draining gold mining districts is the lack of pre-settlement survey data or measurements prior to disruption. Most pre-mining and initial change documentary evidence is qualitative written descriptions and sketch maps. This must be augmented with stratigraphic and sedimentological evidence.



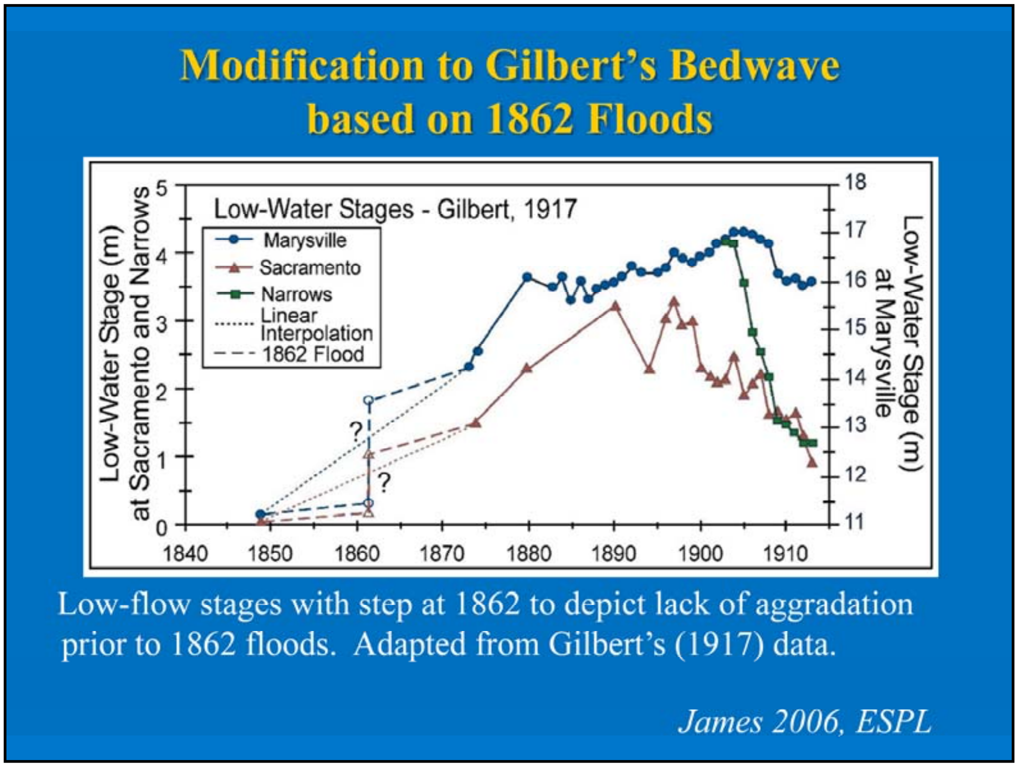
Although sedimentation in major rivers draining the mining districts began to increase from the mid-1850s onward, geomorphic impacts of this sediment were apparently minor until the great 1862 floods. These floods brought sediment down to main channels where subsequent moderate magnitude flows could rework them. In this way, the 1862 floods initiated geomorphic responses to HMS that governed morphogenesis through the 20th century and remain pervasive today.

Most HMS remained in mountain tributaries before the 1862 floods:

"No one appears to have observed any considerable change in the bed or slopes of the streams until the great flood of 1862 had receded. Placer mining had been prosecuted by thousands of miners for thirteen years, and the gulches and water courses of the foot-hills had been receiving deposits of gravel and sand all these years . . . In all these years there had been no great flood. The prolonged and excessive high water of 1862 brought down such masses of material that they could not escape observation." (Mendell, 1881, p. 6).

Yoshiyama et al.:

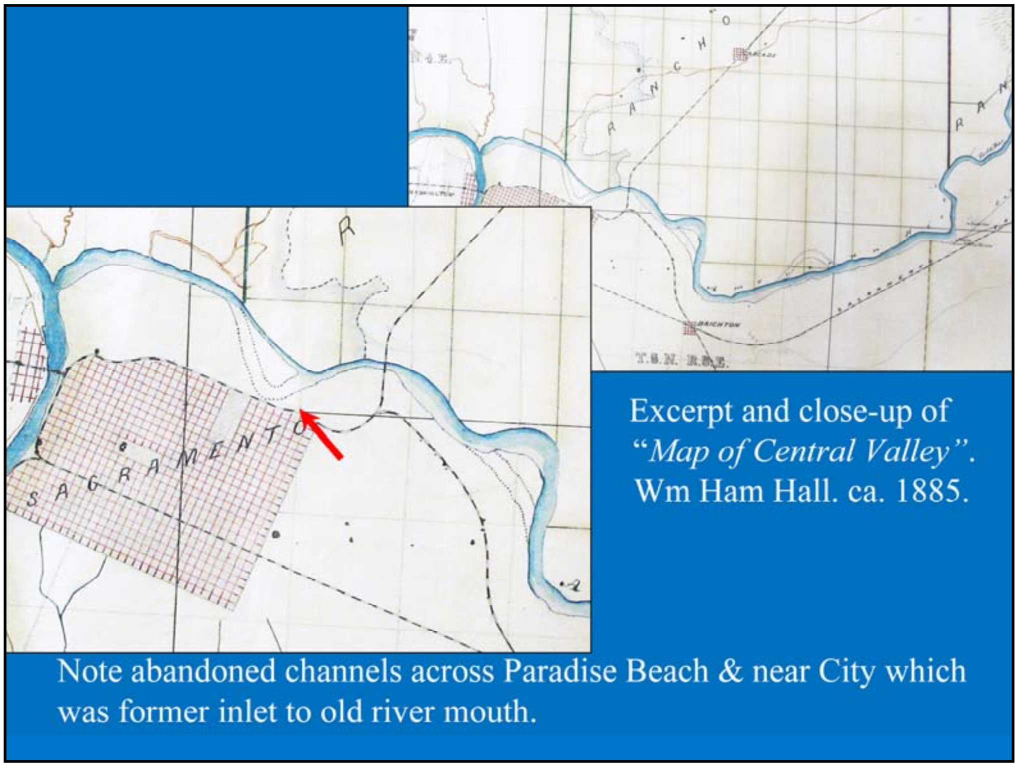
[p.119] "…according to the California Fish Commission, "It is the testimony of all the pioneer miners that every tributary of the Sacramento, at the commencement of mining, was, in the season, filled with this fish, …A few salmon continued to enter the Feather, Yuba, Bear, and American Rivers until the floods of the Winter of 1860–1, which covered the gravel bottoms of all those streams with mining sediment…" (CFC 1880, p 3).



Redrafted time-series plots of low-flow stage data at three stream gauges in the lower Sacramento Valley (data from Gilbert 1917).

The lack of data between ca. 1849 and 1874 resulted in a smoothed rise of channel beds for the Yuba and Sacramento Rivers.

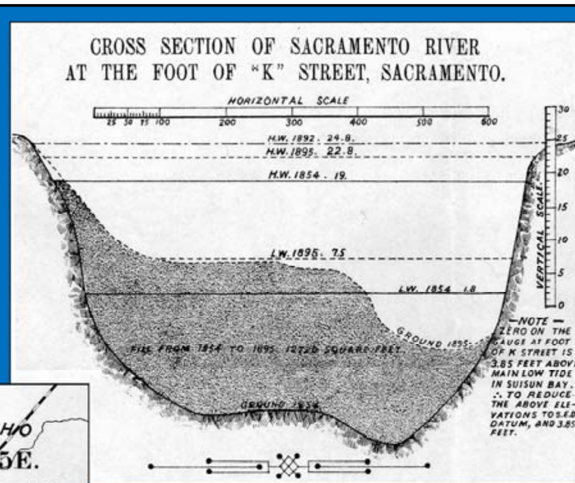
Assuming that bed aggradation prior to 1862 was minor, and that substantial aggradation occurred in 1862, a step is inserted in the plot to better approximate the bed waves at these locations based on Mendell's (1881) observation that most mining sediment remained in small mountain tributaries prior to the 1862 floods.



One of earliest planimetrically accurate maps of LAR. Some abandoned channels (e.g., Paradise Beach) can be traced on a highly accurate 1907 map. The eastern portion of the lowermost abandoned channel probably corresponds to the channel leading to the old river mouth. It corresponds to a slough on the 1907 CDC map that leads to the probable location of the old river confluence ~1/2 mile south of the modern mouth.

Excerpt of Map of Central Valley. Wm Ham Hall; ca. 1885. Photograph of large map from Grays Bend to Court land at California State Archives. Listed as "ca. 1880s."

- Inset cross sections show channel fill between 1854 and 1895 below site of old river mouth.

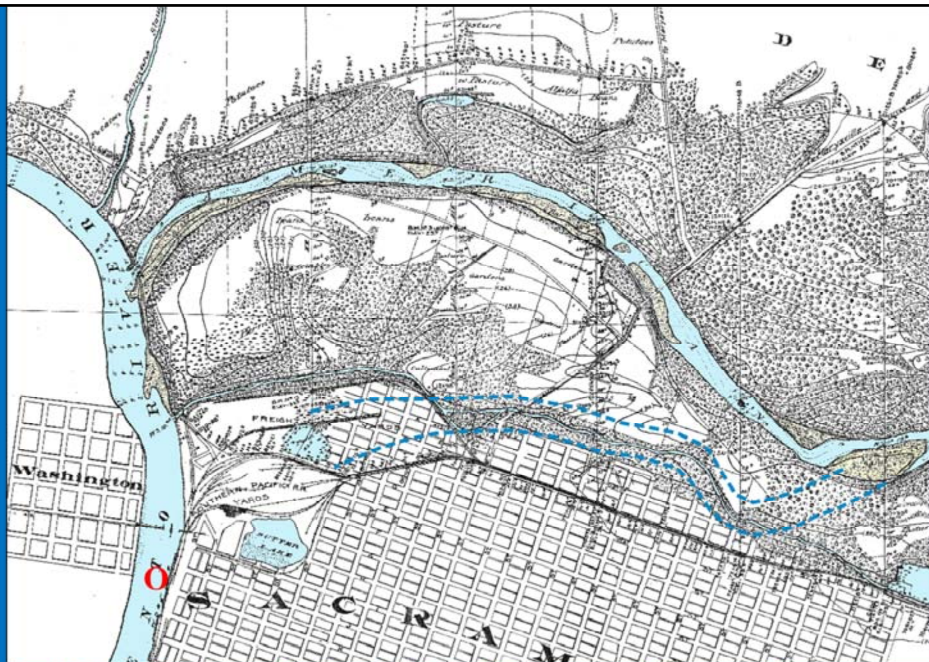


1898 small scale map of Sacramento and San Joaquin Rivers with Sac. R. low flow water depths for 1854 & 1895 (circled)

Map shows channel mean depths at low-flows measured by Major Heuer in 1895 and by Com. Wilkes in 1841. Mean depths generally decreased; from 5.5 to 2.3 m (18-7.5 ft) at the cross section site.

1898 "Map B. Map of a Portion of the Sacramento and San Joaquin Rivers and Tributaries Showing low water depths at different periods."

Office of Commissioner of Public Works, California.

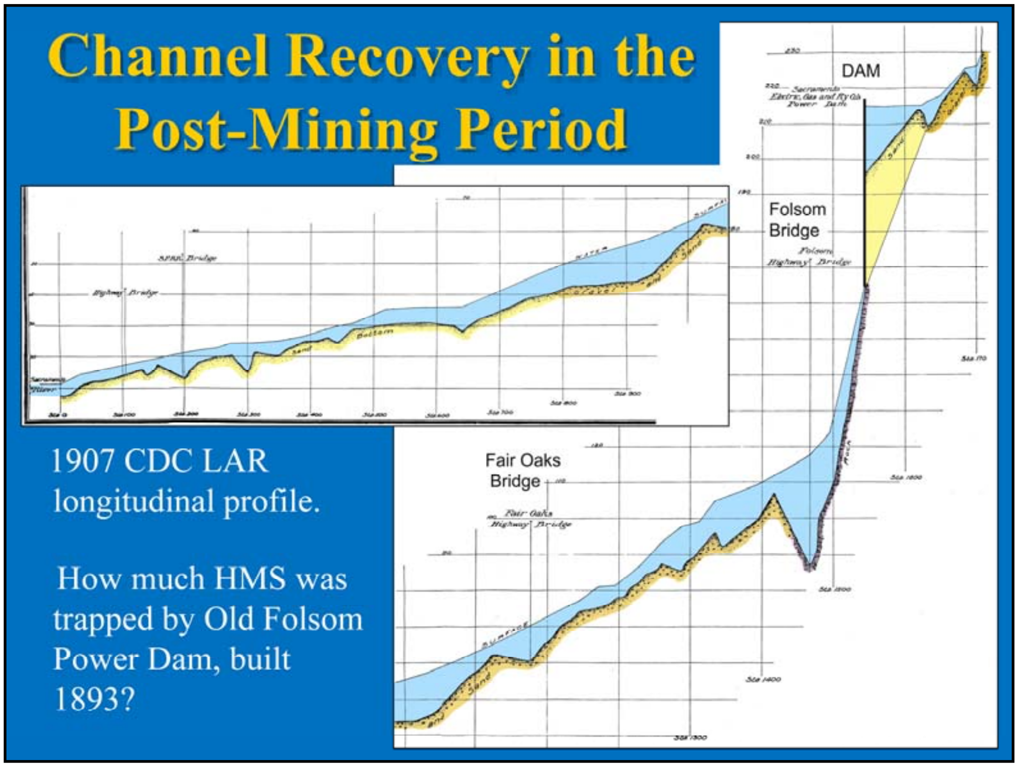


Calif. Debris Commission (CDC, 1907) map with pre-mining channel added (dashed blue line). Old channel filled by c.1871.

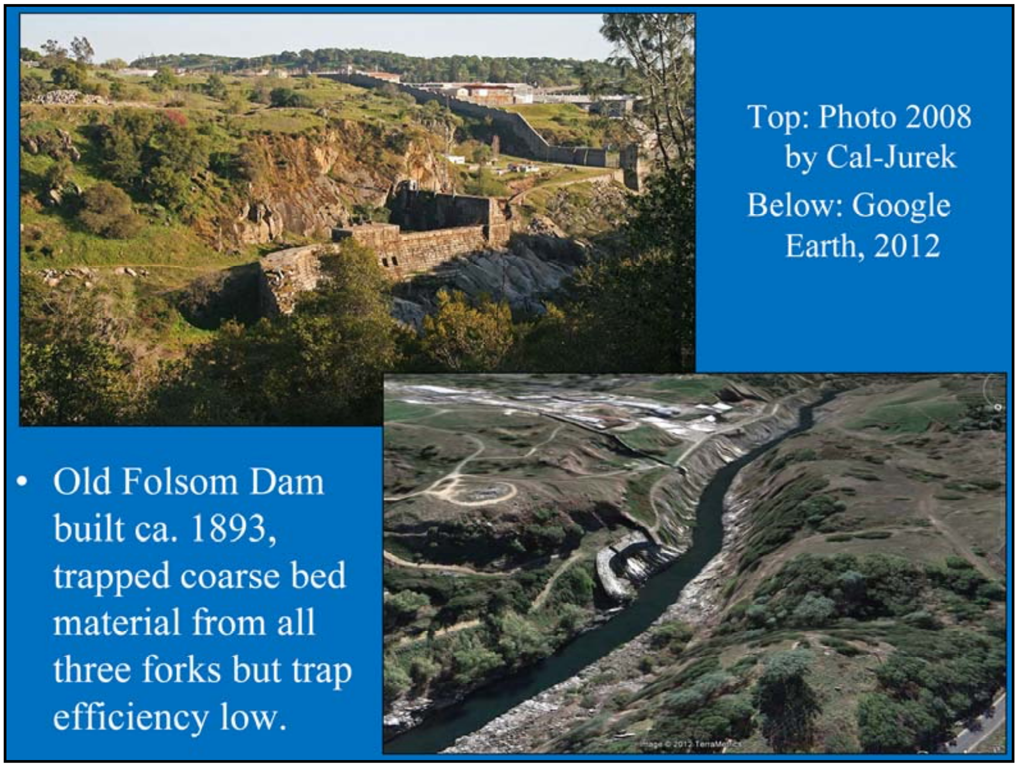
I.N. Hoag’s 1881 testimony in Federal Court: <u>People vs. Gold Run Ditch and Mining Company</u>. Hoag operated the ferry across the Sacramento River 1850-53 and had been there for 30 years crossing the river almost daily. He describes a change in the river mouth to about ½ mile north of it’s present position. He also describes substantial changes in water quality delivered by the American and shallowing of the American River at its mouth from 30 to only 4 or 5 ft after the 1850s. He notes that the old channel filled with sand and ‘slickens’: ‘Where I fixed a depth of the American river at thirty feet, at low water in the Sacramento now there is four or five feet of this sediment above water.”

A sand bar 100 ft wide form along the west bank of the Sacramento R.

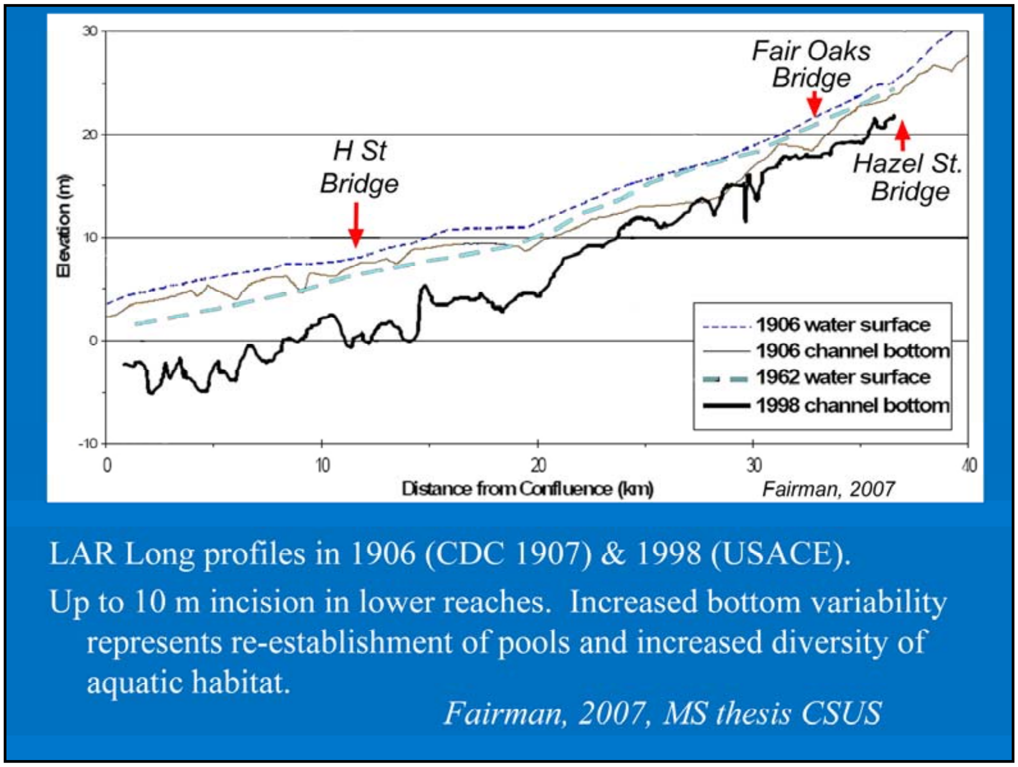
Prior to relocation (ca. 1870) the LAR channel mouth had been immediately upstream of the streamflow gauge that was used to document Gilbert’s sediment wave.



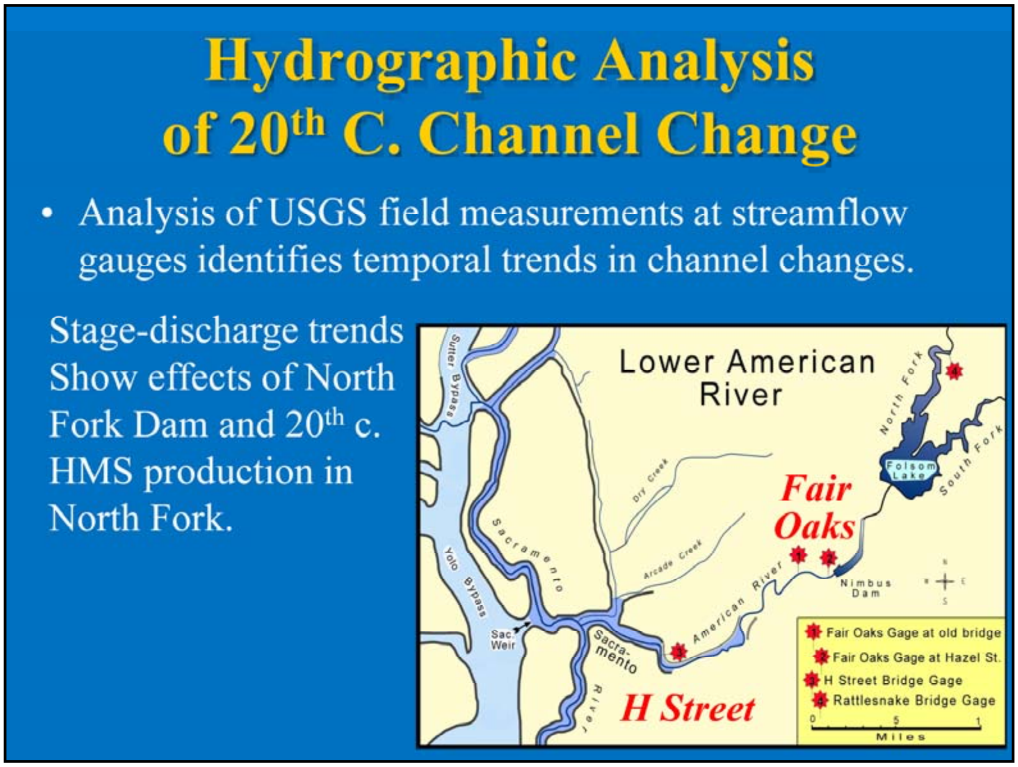
Longitudinal profile from 1906 CDC (1907) survey of LAR. Old Folsom Dam clearly stored substantial amounts of coarse bed material but it is not known if the dam was occasionally sluiced to empty the sediment. Stage-discharge relationships downstream (to be discussed) indicate that perturbations in the North Fork were translated downstream where channels responded. This suggests that sediment was not permanently trapped behind Old Folsom Dam.



Remnants of Old Folsom Dam stand below the modern dam in a steep, narrow canyon. The limited reservoir capacity in this canyon indicate a small trap efficiency, although coarse bed material could be detained.

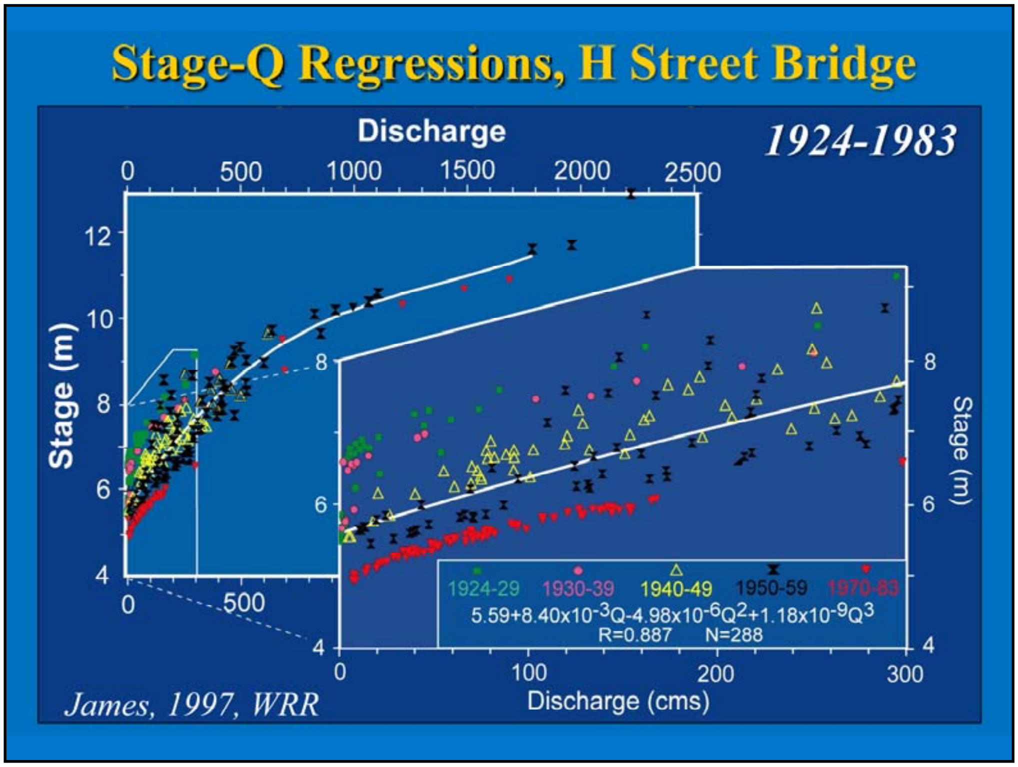


Comparison of longitudinal profiles from 1906 (CDC 1907) and USACE (1998) shows degree of channel incision over much of the recovery period. Note thick wedge of sediment (presumably HMS) removed in lower reaches. Incision was ~7 m at H Street, but much less (1 to 3 m) at upper reaches near Fair Oaks and Hazel St. bridges. Graphic adapted from D. Fairman, 2007, MS in Geology at CSUS.

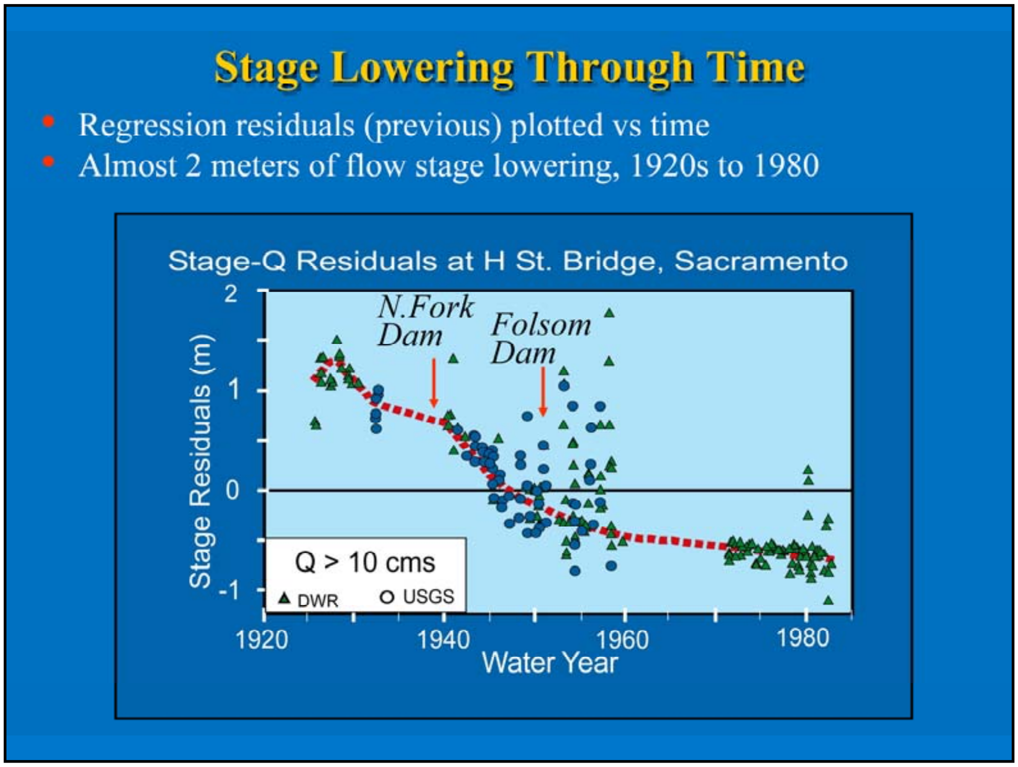


Analysis of data from USGS field measurements at streamflow gauges can be used to identify temporal trends in channel changes. These analyses include stage-discharge, cross sections, and hydraulic geometry, but they are mostly concerned with changes in stage. The general procedure for stage-discharge analysis is to develop univariate statistical regressions, compute regression residuals from that relationship, and plot the residuals against time. The same procedure can be used with at-a-station hydraulic geometry variables such as width, mean depth, and mean velocity.

Channel morphology and bed elevations respond to a variety of forcing functions that are integrated by fluxes in water and sediment at the stream gauge. The results of this analysis were compared with the timing of dam closures and active hydraulic mining in the mountains to test the hypothesis that channels responded directly to such identifiable perturbations, perhaps with a lag period. After 1893, licensed hydraulic mining was permitted and some HMS was generated. Production values for the North Fork were estimated from published CDC license data. In most cases, the timing of downstream channel change is not simply related to a single event but in some cases the patterns suggest causal relationships.

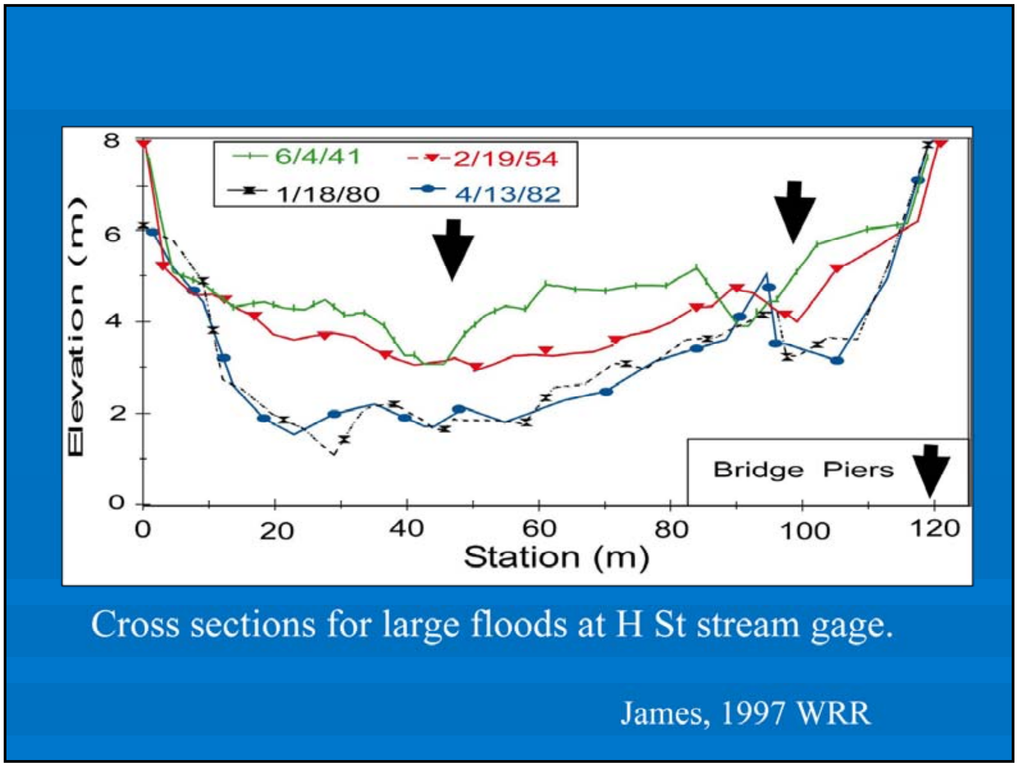


Stage-discharge relationships at H-Street bridge (1924-1983). (Upper left) Scatter around regression line showing high early stages compared to variable later. (Lower right) Close-up of discharges less than 300 m^3s^{-1} showing that stages dropped more than 2 m at the H St gauge from 1924 to 1983.

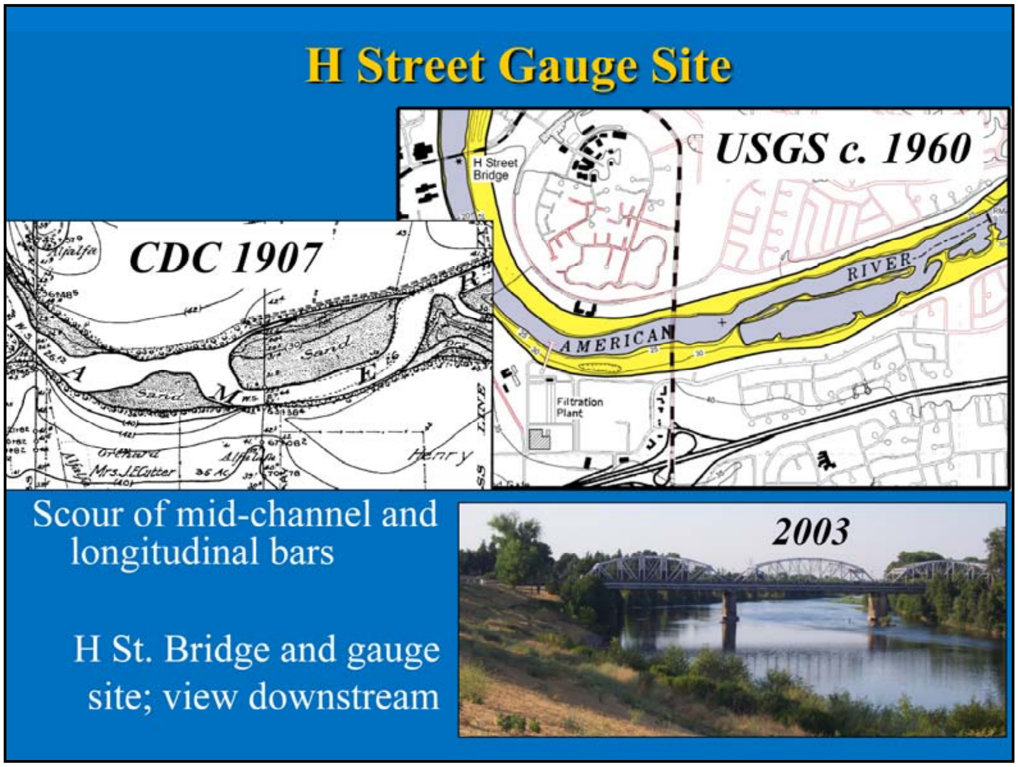


Time series of stage-discharge regression residuals at the H-Street stream gauge (at CSUS) showing rapid lowering (1940-1955) and highly variable stages in the 1950s. Lowering of low-flow stages are assumed to represent channel-bed lowering. The site is beyond the tidal range. While lower stages may be a response to decreased roughness, there is no mention in the carefully maintained field notes of structural changes or removal of vegetation at the site. Such a change would require recalibration of the gauge and would be carefully noted in gage records. Closure of the NF Dam in 1939 appears to be synchronous with the onset of this incision episode. Although Old Folsom Dam had been in place since 1893 and presumably trapped coarse bed material, it had a low trap efficiency and may have been sluiced regularly to maximize storage. This evidence may indicate that sediment from the North Fork was driving sediment budgets in the LAR until closure of NF Dam.

Changes in longitudinal profiles from 1906 to 1998 indicate lowering throughout the lower river of about 7 meters in that period (previous figure). Thus, this 2-m change was apparently part of a longer-term adjustment with other periods of incision not shown here. Presumably, much of the 7 m of incision occurred early in the period and this episode was a renewed period of incision to a new equilibrium level.

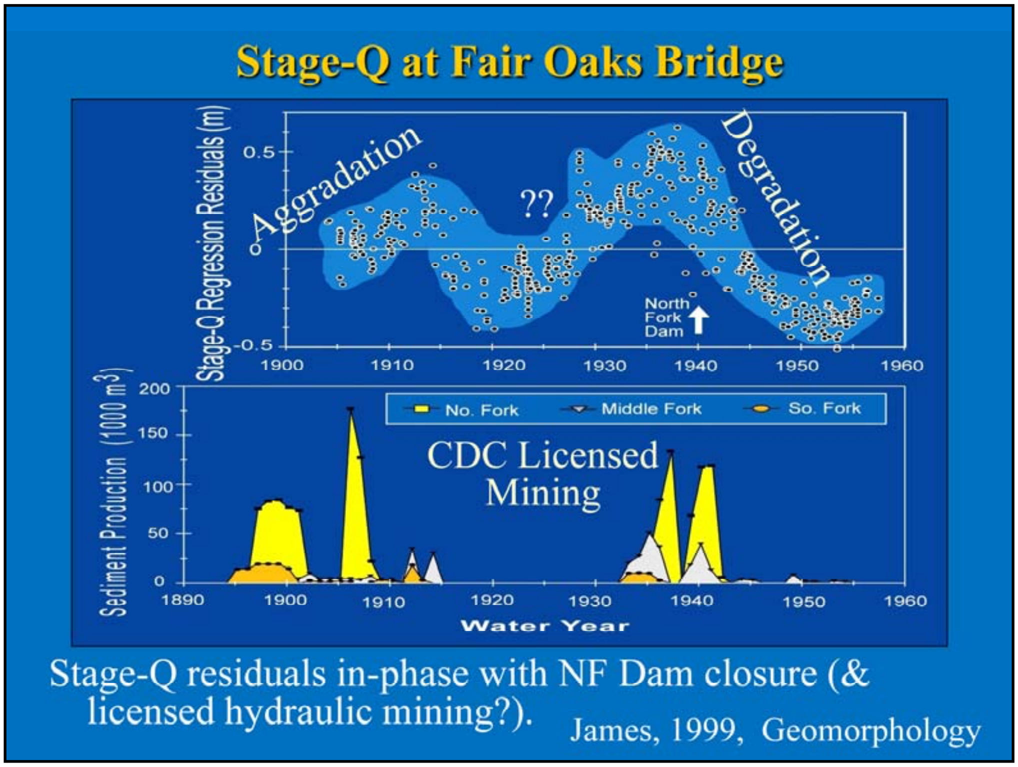


Cross sections developed from data collected by sounding for current velocity measurements during floods at the H Street gage by USGS hydrographers using a relative elevation (not meters asl). The 2 m drop in stages shown earlier is corroborated by ~2 m lowering of the channel bed between 1941 to 1982. Lowering appears to extend across the entire bed and is not confined to the thalweg.



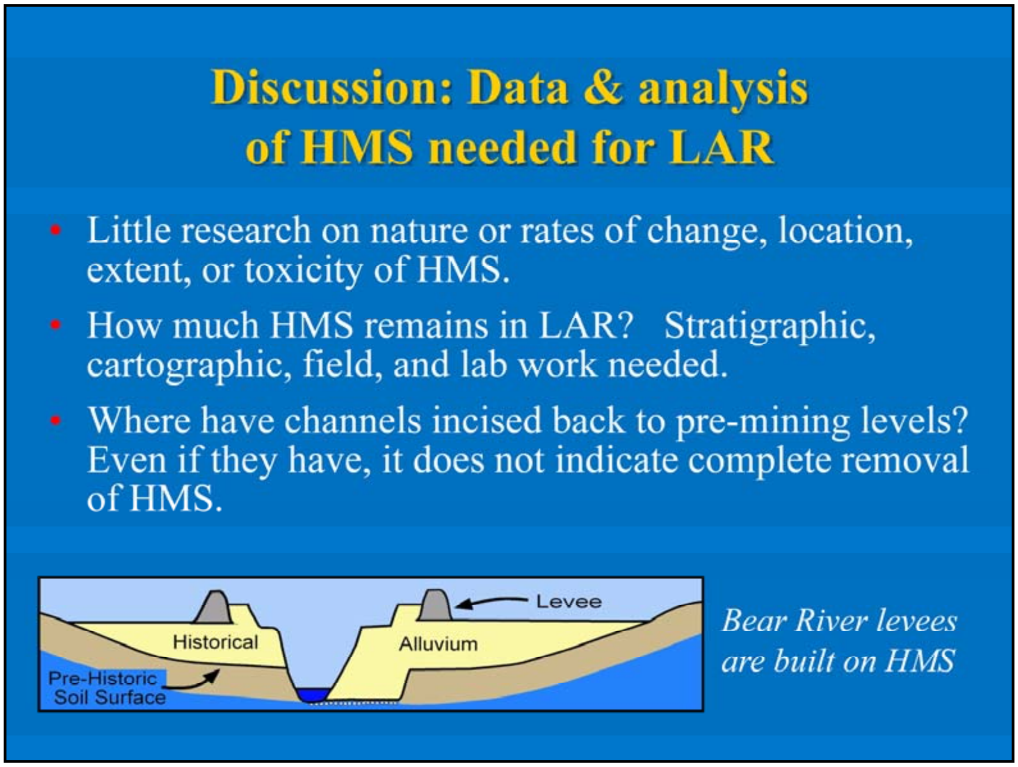
Two meters of stage lowering is a significant reduction in flood risk at any location. The **H Street Gauge is located at a critical bend in the LAR as the river approaches the City of Sacramento adjacent to the CSUS campus, which compounds the implications of lowered stages.**

Scour of mid-channel and longitudinal bars between 1906 and 1960. In addition to vertical incision, comparison of topographic maps indicates that extensive mid-channel bars have been scoured from within the channel. This conforms with the cross-section evidence at the bridge that suggests incision was not confined to the thalweg but extended across the channel.



A similar statistical regression of stage on discharge was performed for streamflow data at the USGS Fair Oaks gauge. Analysis of regression residuals indicates a strong temporal relationship that presumably represents raising and lowering of the channel bed. Initial raised stages at Fair Oaks gauge at the beginning of the 20th century appear to respond in phase with early CDC licensed mining. Later cycle of raised stages begins between 1925 and 1930, before the second series of licenses begins ~1932. Degradation after 1940 is synchronous with closure of North Fork Dam and coincides with the onset of accelerated incision downstream at H St.

At least 300,000 m^3 of sediment was produced in the North Fork American Basin between 1907 and 1908 which was followed by a decade of increased flow stages on the order of 30 cm at the Fair Oaks gage site. The lack of hydraulic mining for two decades after 1910 corresponds with a decade of incision followed by more than a decade of aggradation. The lack of large floods in the 1930s may account for aggradation in this period.



•Little research has been conducted on the nature and rates of channel change, the location and extent of HMS, or the chemical toxicity of those deposits.

• In the Yuba and Feather Rivers, we have developed DEMs from 1906 and 1909 CDC maps that, when combined with LiDAR and bathymetric data, allow us to perform volumetric change detection surveys.

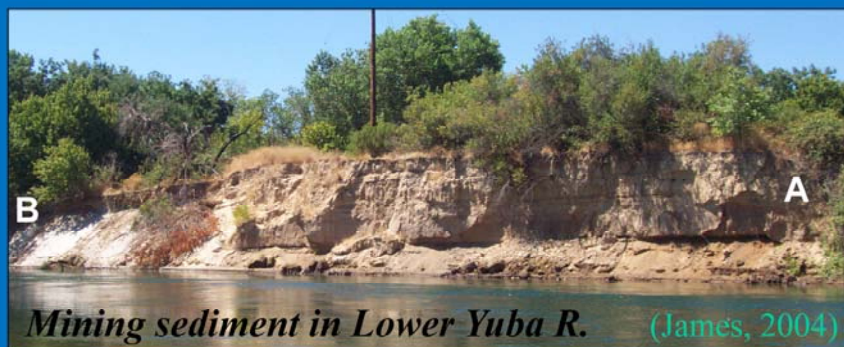
Cut:

•Paleohydrologic reconstructions for floods such as the 1862 events are common due to their importance to flood risk assessment and flood frequency analysis. Reconstructions of peak Q, three-day volumes, etc. for the 1862, however, have been elusive due to the drastic changes in stage and channel morphology that occurred during the event and further changes later.

•Lack of pre-settlement survey data or measurements prior to disruption applies to this issue. No base data.

•Can document geomorphic changes but quantitative comparisons with pristine conditions not possible.

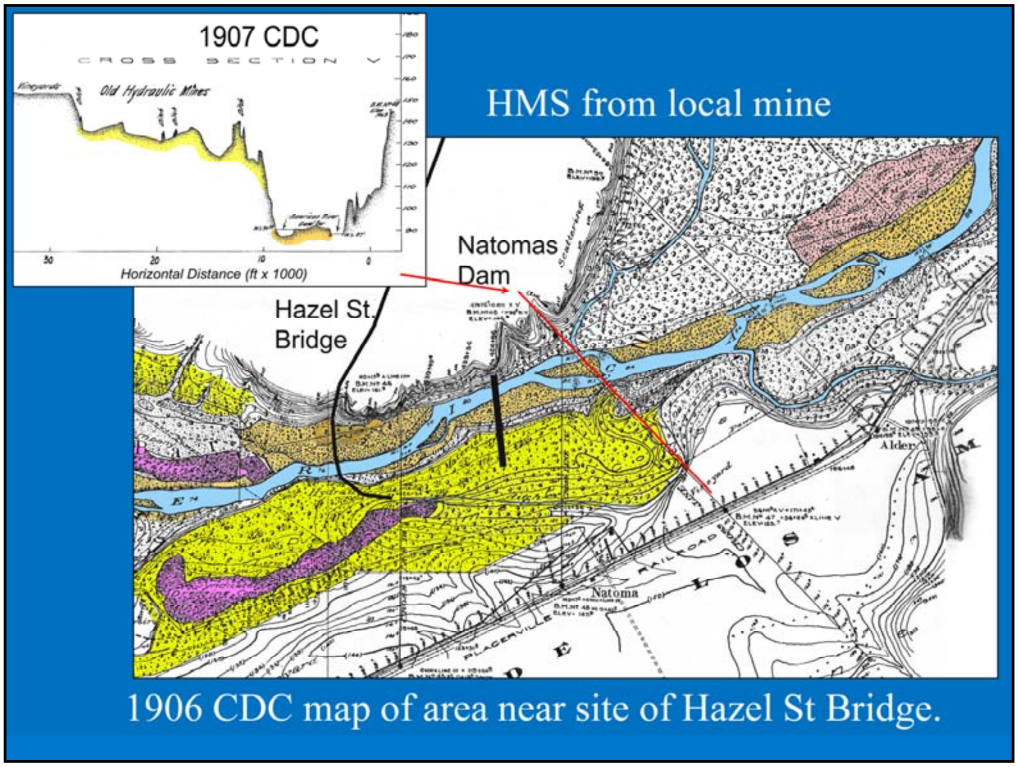
- Vast HMS deposits along lower Yuba River are being actively reworked.
- Lowering of local base level by breaching of Shanghai Shoals may accelerate erosion of this sediment.
- Studies of LAR HMS deposits are needed to understand magnitude and dynamics of legacy HMS.



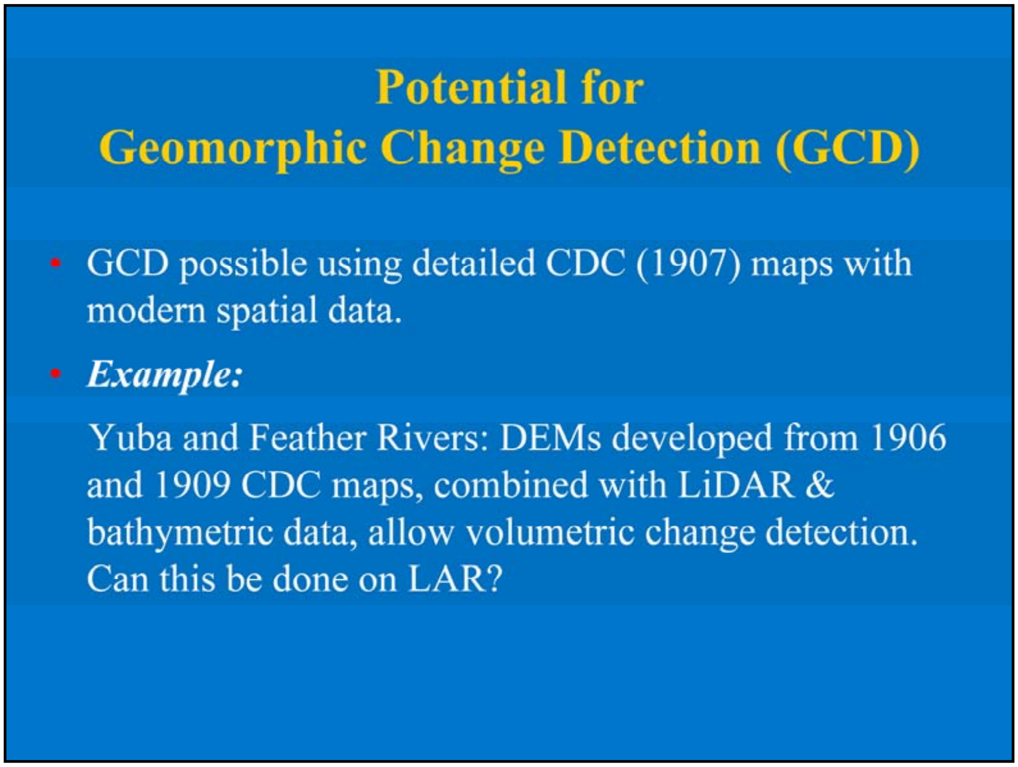
Extensive study in the Yuba and Bear Rivers indicates tremendous storage of HMS remains. Deposits downstream in Sutter Bypass indicate on-going remobilization of this Hg-rich sediment.

- Alluvial stream banks near Fair Oaks gage appear to be composed of a high proportion of HMS.
- Needs to be confirmed by fingerprinting (Hg; Zr/Ni).
- Could be derived from mountain mines or locally.

NRC, 1995. Photos by A. James



1906 CDC map of area near site of Hazel St Bridge. Hazel Street, bridge, dam and labels added. The yellow pattern on south side is labeled 'Hydraulic Material' . Corresponding Cross Section V across this zone labels the area as 'Old Hydraulic Mine'.



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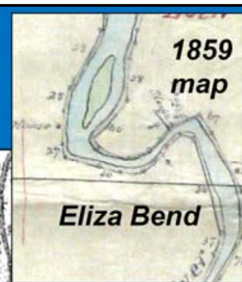
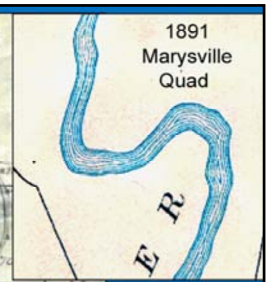
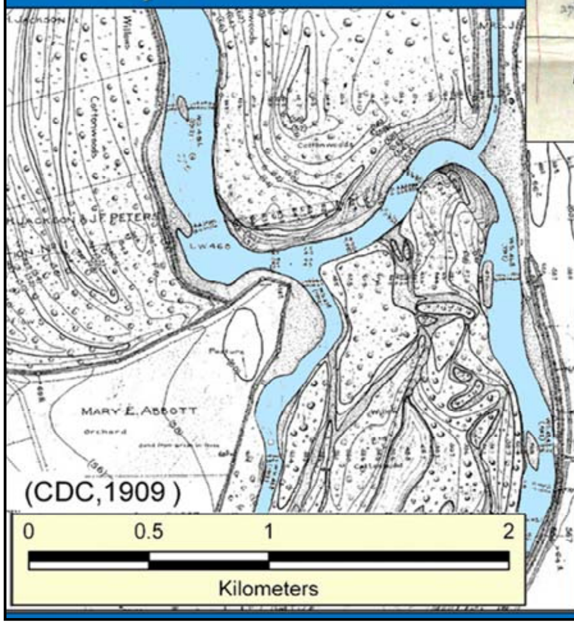
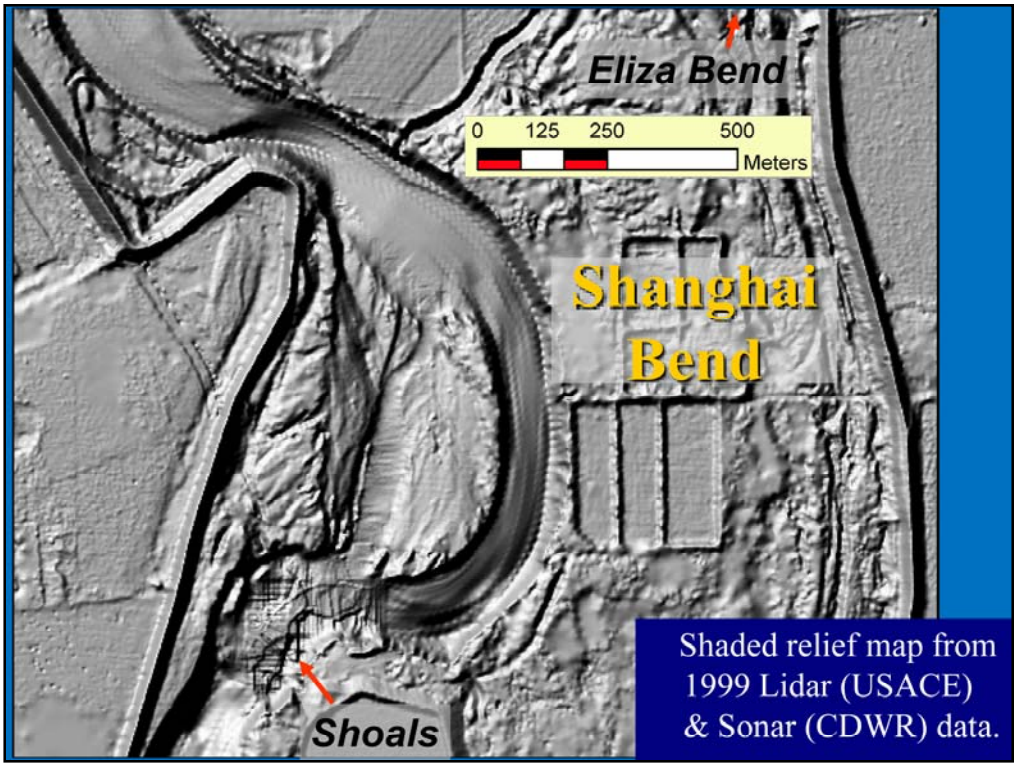
GCD – Shanghai Bend, Feather River

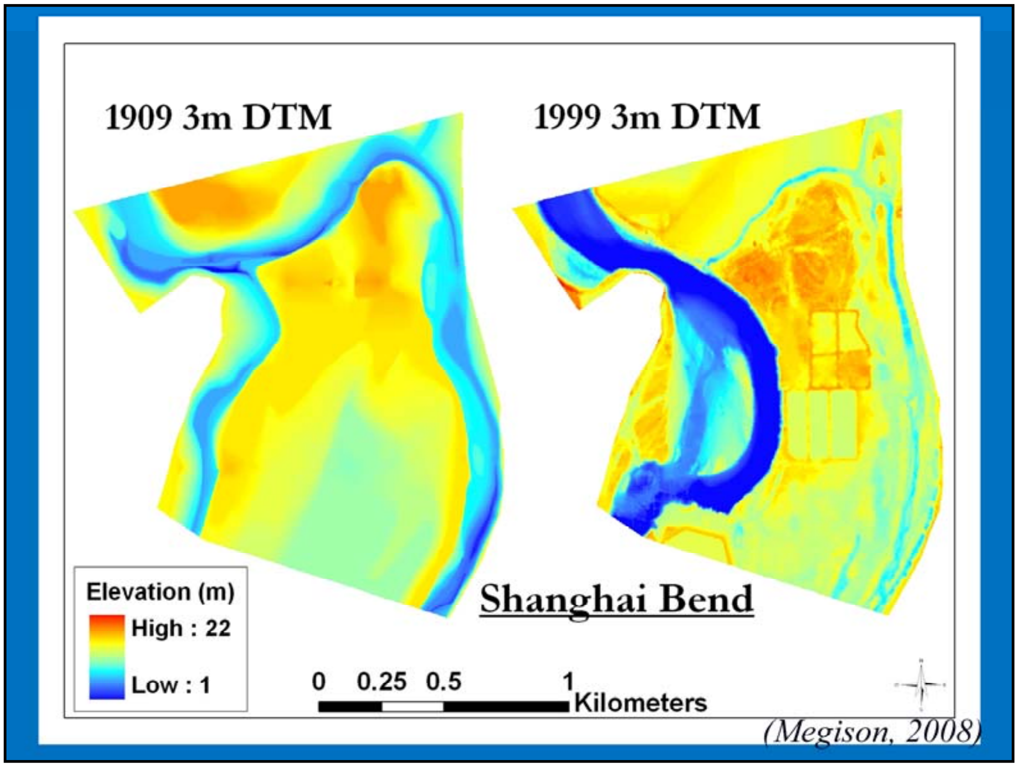






- Pre-mining Feather R. channel flowed NE into Eliza Bend (above).
- Cutoff channel shown as "dredged" on 1906 CDC map.
- Left: 1909 CDC map shows incipient meanders.


Eliza Bend
0 125 250 500
Meters
Shanghai Bend
Shoals
Shaded relief map from 1999 Lidar (USACE) & Sonar (CDWR) data.


1909 3m DTM
1999 3m DTM
Elevation (m)
High : 22
Low : 1
Shanghai Bend
0 0.25 0.5 1
Kilometers
(Megison, 2008)

Differencing DEMs (GCD) 1909-1999

$\Delta E_{ij} = DEM99_{ij} - DEM09_{ij}$

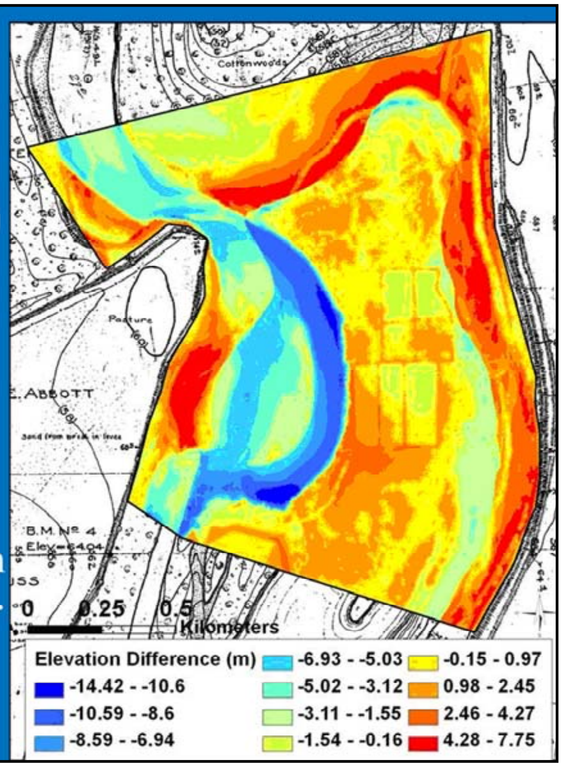
$\Delta E_{ij} > 0$: Deposition

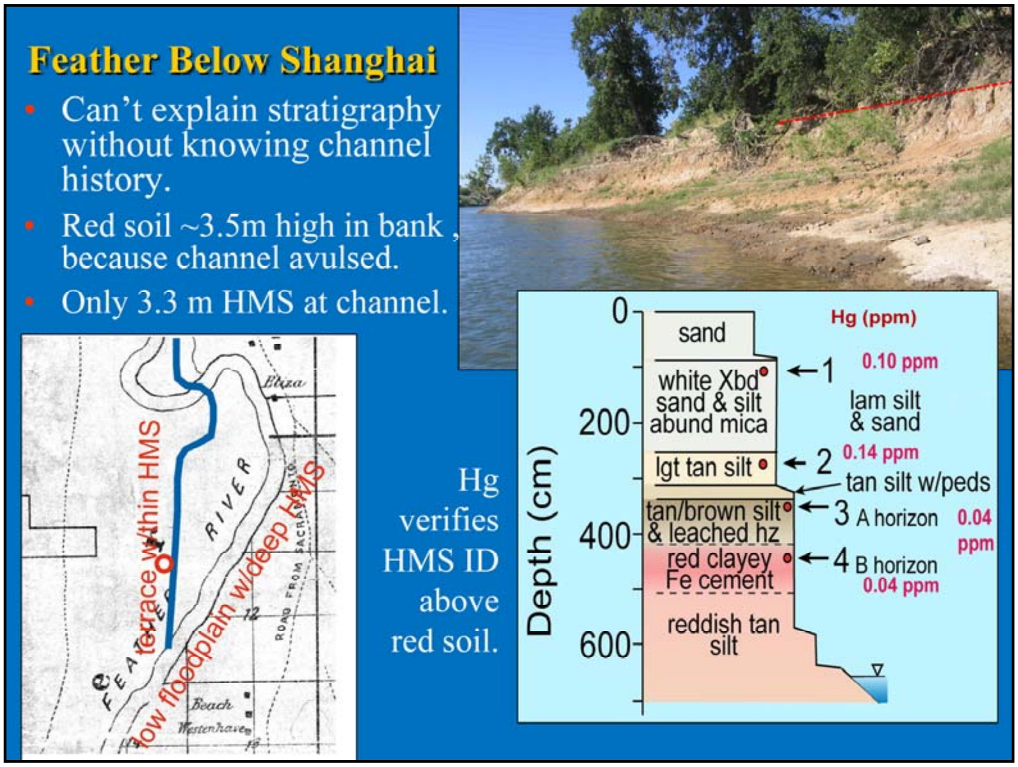
$\Delta E_{ij} < 0$: Erosion

Range:

- Up to 14 m channel incision where thalweg cuts natural levee
- Deposition up to 7.7 m in filled channels & ditches.

(Megison, 2008; James et al., 2009)

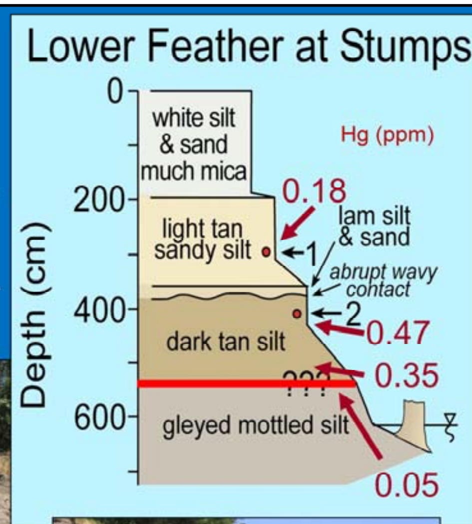


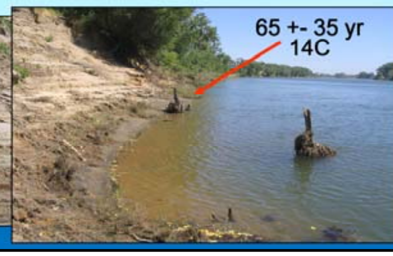

Feather Below Shanghai
• Can't explain stratigraphy without knowing channel history.
• Red soil ~3.5m high in bank , because channel avulsed.
• Only 3.3 m HMS at channel.
terrace within HMS
low floodplain w/deep HMS
RIVER
Eliza
Beach
Hg verifies HMS ID above red soil.
Depth (cm)
0
200
400
600
Hg (ppm)
sand
white Xbd sand & silt abund mica
1
0.10 ppm
lam silt & sand
lgt tan silt
2
0.14 ppm
tan silt w/peds
tan/brown silt & leached hz
3 A horizon
0.04 ppm
red clayey Fe cement
4 B horizon
0.04 ppm
reddish tan silt

- In contrast, Feather R. bed above Shanghai is still above pre-mining base level.
- Hg shows HMS ~5.5 m thick.
- Stumps rooted in pre-mining soil at base of HMS exposure.

^{14}C: 65 +- 35 yr

~**1885** +-35





- Shanghai Shoals knickpoint breached in January, 2012.
- HMS stored upstream likely to be remobilized.
- Channels upstream could be destabilized.

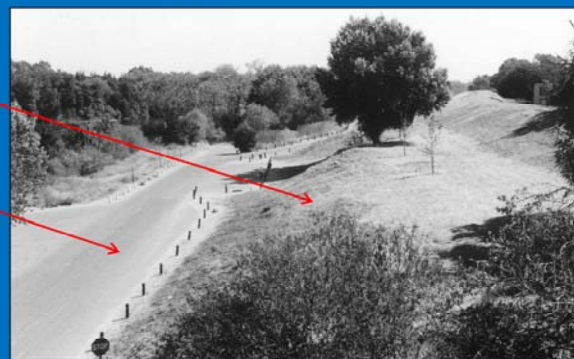
- Mapping & stratigraphy of LAR HMS needs to be done.

Yuba R. near Feather R. confluence

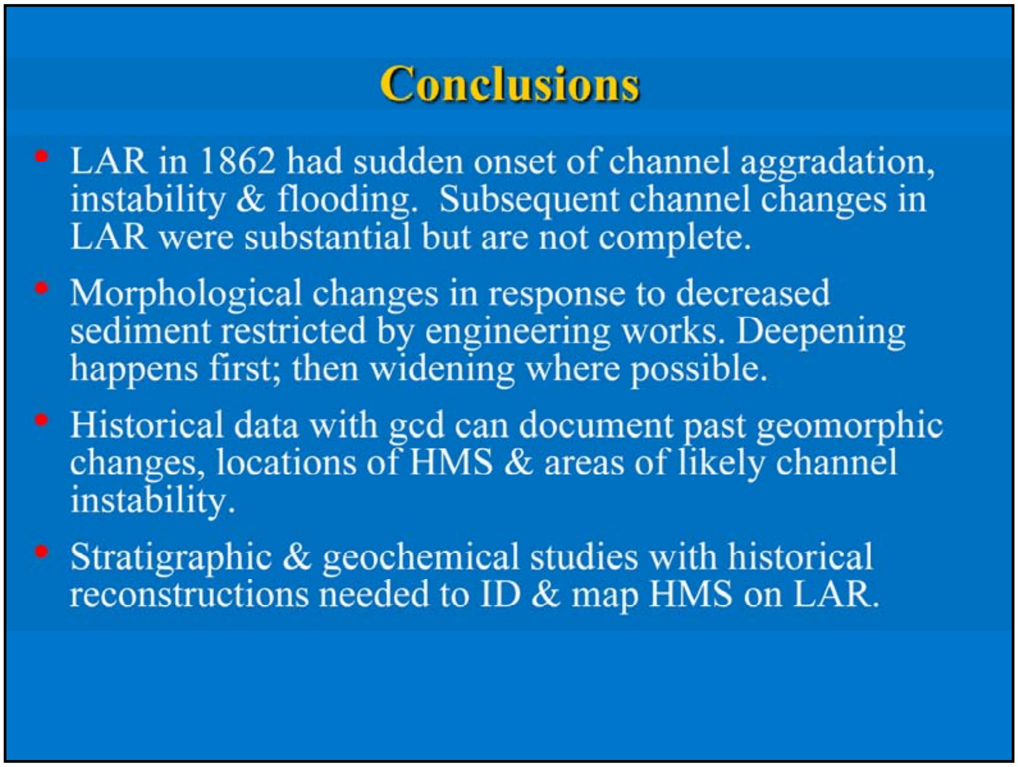
- HMS deposits in the Sacramento Valley form terraces. They need to be identified by their mineralogical (quartz) and geochemical (Hg) signatures. This has not been done in the LAR.

HMS storage…
here?

or here?



Terrace at right and stream bank at left near Howe Avenue. View upstream. NRC, 1995. Photo by A. James



HMS transport to Sacramento Valley was inevitable. Lack of large floods between 1853 (hydraulicking) and the 1862 floods minimized mitigation & preparedness, however. The sudden onset in 1862 of channel aggradation in the LAR, instability & flooding had tragic consequences. Subsequent channel changes in the LAR were substantial. Channel morphological changes & sediment transport have been mutually adjusting in period of recovery in conjunction with engineering works (dams, levees & dredging). Deepening tends to happen first and is largely completed in the lower river. Channel deepening was in response to decreases in available sediment due to depletion of stored HMS in the lowflow channel and trapping of sediment behind dams in the mountains.

Historical data provide much info about geomorphic changes, sed. transport & locations of HMS. This needs to be coupled with stratigraphic/geochemical studies to ID & map HMS. Little of this work has been done on LAR. Given high Hg concentrations, this needs immediate attention.

Acknowledgements

- National Research Council provided funds for photocopying hydrographic records and CDC maps back in 1995.
- USACE provided LiDAR data for Yuba & Feather R.
- Cal.DWR provided SONAR data: Yuba & Feather R.
- Generations of hydrographers are thanked for risking life and limb suspended on a cable cart over flood waters to collect hydrographic data. Field surveyers of the Hall and CDC mapping expeditions endured the briars and brambles of the LAR to produce historical records of this river.
- Gary Estes' patient and diligent organization made this meeting possible and allowed me time to develop new material and integrate it with earlier work.

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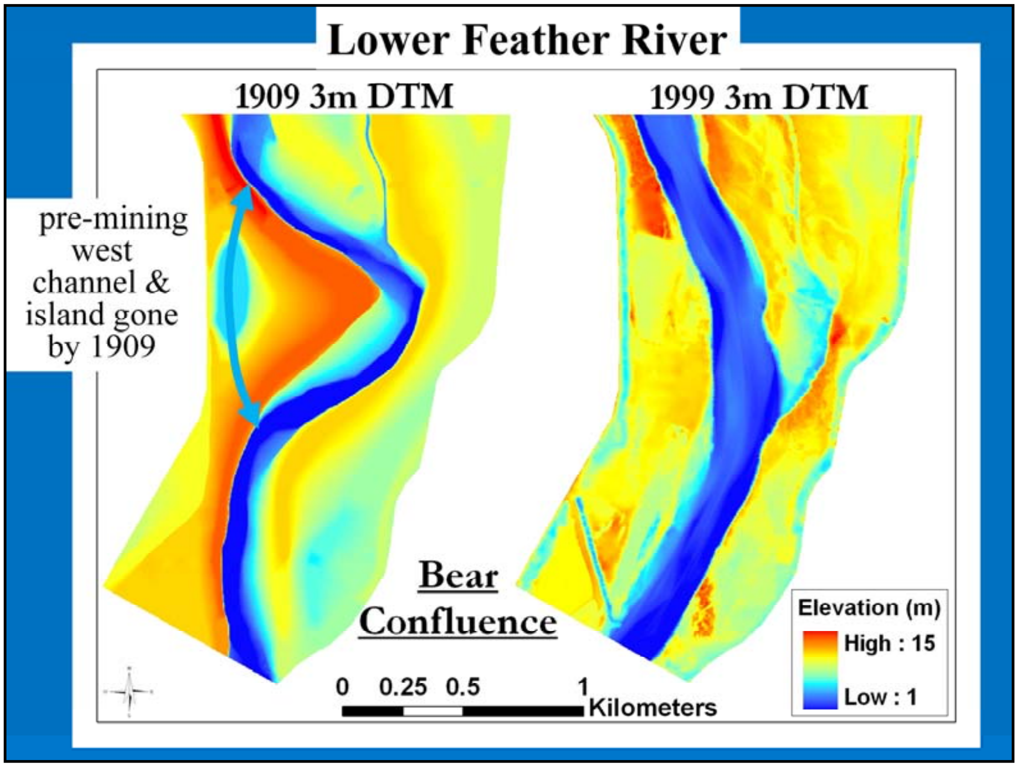
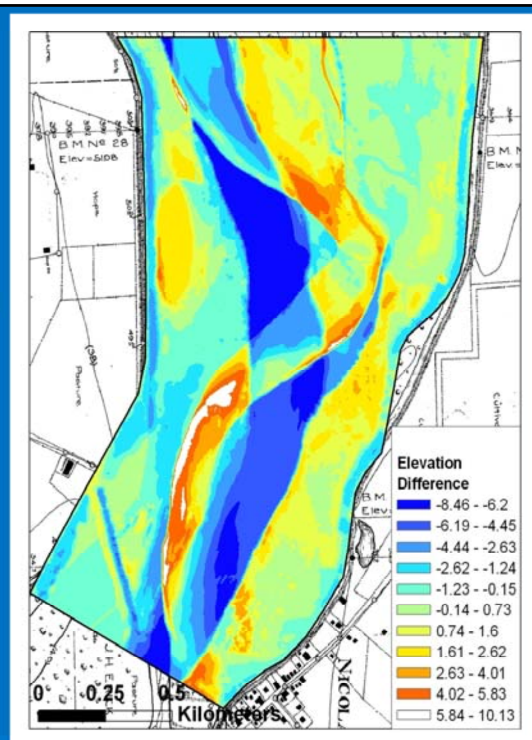


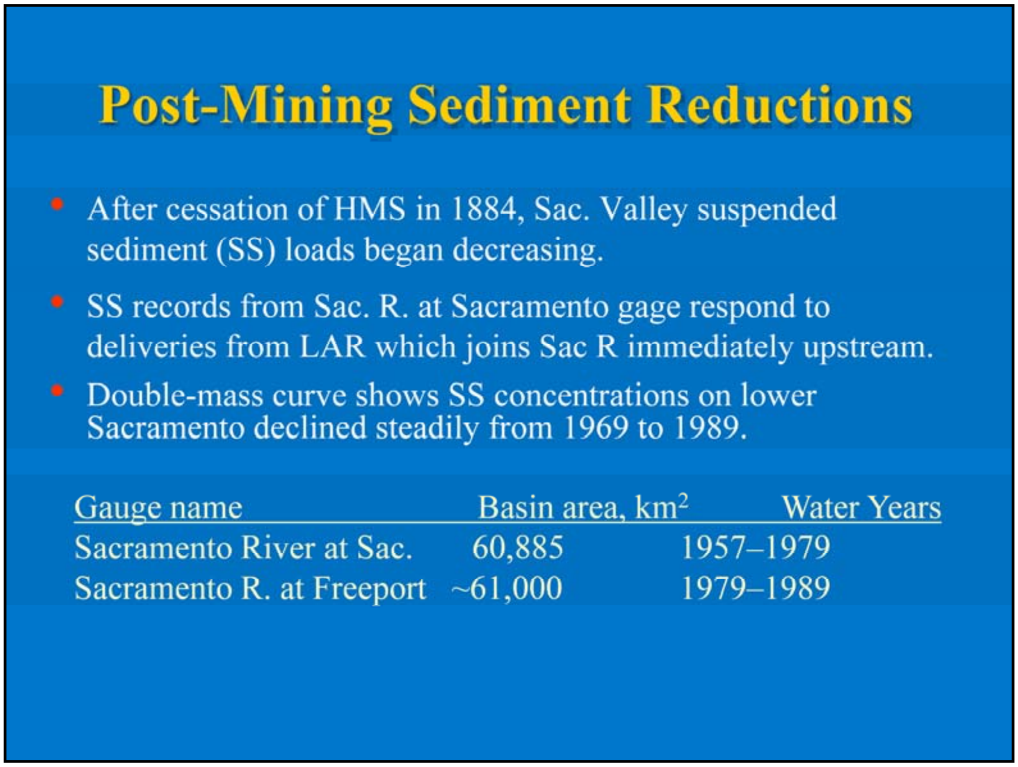
Lower Feather River
1909 3m DTM
1999 3m DTM
pre-mining west channel & island gone by 1909
Bear Confluence
Elevation (m)
High : 15
Low : 1
0 0.25 0.5 1 Kilometers

Differencing DEMs

*Volume Change (m^3) = Mean Elevation Change * Area*



Elevation Difference



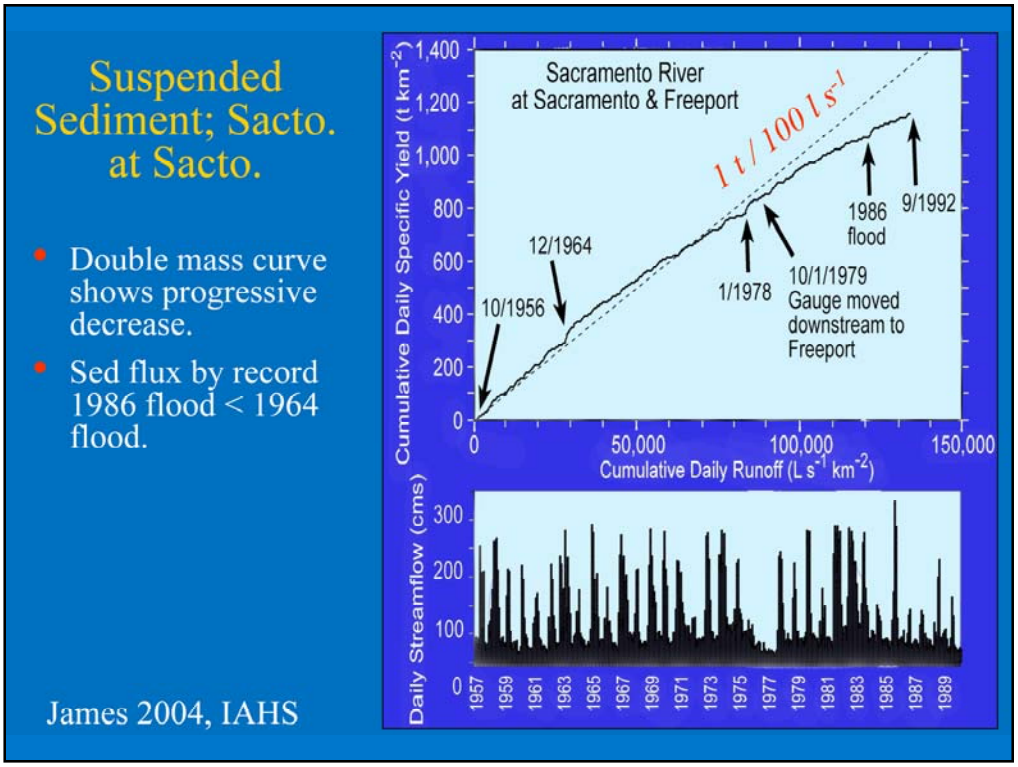
Suspended sediment loads in large global rivers have been increasing on average, although those with dams have been responding reversed this trend. Due to the cessation of hydraulic mining and decreasing amounts of HMS in these rivers, sediment loads in Sac. Valley began decreasing by 1900, *preceding global average of rivers by ~50 years.* Thus, these rivers provide case studies of what to expect as major global rivers adjust to dams constructed in the mid-twentieth century.

Hydraulic gold-mining production ended 1884

Levees encouraged channel incision and isolated large lowland deposits

Dams later arrested downstream deliveries

Suspended sediment (SS) records from the Sacramento River at Sacramento gauge



Double-mass curves indicate on-going decreases in suspended sediment production & transport. Corroborates independent evidence of flow stage lowering & channel erosion with armoring below dams. Interpretation: sediment loads have been decreasing throughout post-dam period because down-valley sediment deliveries have been trapped in Folsom Reservoir, the repository of readily available HMS and other sediment is being depleted, and increasingly large floods are required to mobilize sediment stored in armored or high deposits.

Largest sediment-transport days were in 1960s; highest days were in 1964 flood.

Four of the five largest sediment-transport days were in 1960s; four of the highest were in the 1964 flood. Sediment concentrations during the period of record occurred in the 1960s prior to closure of Oroville Dam. Could Oroville be driving sediment concentrations this far down in the system?