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Historical channel changes in the lower Yuba and Feather Rivers, California: Long-term effects of contrasting river-management strategies

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ABSTRACT

Hydraulic gold-mining tailings produced in the late nineteenth century in the Sierra Nevada foothills of California caused severe channel aggradation in the lower Feather and Yuba Rivers. Topographic and planimetric data from historical accounts, maps, topographic surveys, vertical sections, aerial photographs, and LiDAR (light detection and ranging) data reveal contrasting styles of channel change and floodplain evolution between these two rivers. For example, levee cross-channel spacings up to 4 km along the lower Yuba River contrast with spacings <2 km on the larger Feather River. More than a quarter billion cubic meters of hydraulic-mining sediment were stored along the lower Yuba River, and the wide levee spacing was intentionally maintained during design of the flood-control system to minimize delivery of sediment to navigable waters downstream. Consequently, the lower Yuba floodplain has a multithread high-water channel system with braiding indices >12 in some reaches. Some of the larger of these channels remain clearly visible on aerial photographs and LiDAR imagery in spite of intensive agricultural leveling. Narrow levee spacings on the Feather River were designed to encourage transport of mining sediment downstream and keep the channel clear for navigation. Levee spacings on the lower Feather River reached a minimum near the turn of the twentieth century, when floodplain widths were reduced at several constricted reaches to <250 m. Historical data indicate that the general channel location of the lower Yuba River had stabilized by the end of the nineteenth century, whereas substantial channel avulsions began later and continued into the twentieth century on the lower Feather River.

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The striking contrasts in channel change between the Yuba and Feather Rivers are due, at least in part, to different river-management strategies, although the Yuba River received much more sediment. Early river engineering of these channels represented the first efforts at integrated river-basin management west of the Mississippi, so the observed long-term effects are instructive. Modern river management should consider how the disturbance factors in these channels and the imprint of early river management affect the modern morphologic stability and sediment-production potential of the channel and floodplain.

INTRODUCTION

Human impacts have been pervasive on many rivers, and rivers with strong anthropogenic geomorphic imprints may be the rule rather than the exception. Several rivers that were highly influential to the foundations of modern fluvial geomorphology are recognized as vestiges of severe human alterations, including Brandywine River, Seneca Creek, Watts Branch, and Western Run in the mid-Atlantic Piedmont (Walter and Merritts, 2008), and the Yuba River of northern California (Gilbert, 1917). Reappraising the effectiveness of human impacts can undermine assumptions often made about reference reaches as stable design targets for restoration (Montgomery, 2008) and can contribute to answering the question of "what is natural" with regard to alluvial rivers (Graf, 1996).

Historical analyses can benefit river-restoration projects in several ways (Kondolf and Larson, 1995). Knowledge of past fluvial changes can be useful for designing, restoring, and maintaining a sustainable river (Gregory, 2006), because true restoration of a river to a previous condition requires knowledge of previous channel states. Knowledge of channel changes may also be crucial to anticipating future behavior. For example, the tendency for abandoned channels to be reoccupied during floods provides an additional incentive to recognize the recent history of alluvial floodplains (Petts, 1989; Kondolf and Larson, 1995).

Most instrumental and observational records of streams are limited in time and space, so historical records such as maps, vertical stratigraphic sections, and contemporary observations are valuable for reconstructing past channel conditions. Several reviews have been written about various methods of historical analysis that can be used to reconstruct changes in landform dimensions, erosion rates, and land use (Hooke and Kain, 1982; Trimble and Cooke, 1991), or more specifically, to reconstruct historical channel changes (Patrick et al., 1982; Gurnell et al., 2003) through the use of historical maps (Petts, 1989; Gilvear and Harrison, 1991; Kondolf and Larson, 1995) and aerial photography (Gilvear and Bryant, 2003; Hughes et al., 2006). With the development of geospatial processing tools for georeferencing digital maps and images—and their increasing ease of use—a greater degree of quantification and a higher level of precision can now be obtained by co-registering sets of historical maps and images made at different scales and projections. The success of these methods varies with the level of precision of the original maps or images and the availability of ground-control points or other reference points common to precise spatial data. Even where map registrations are insufficiently accurate for making measurements, much can be learned from qualitative assessments of historical cartographic or remotely sensed records.

Knowing the nature of channel morphologies on the lower Yuba and Feather Rivers prior to Anglo-European settlement, and the subsequent changes that occurred from hydraulic mining, is crucial to the recognition of how these channels were adjusted to former equilibrium conditions and how they now differ from those conditions. These reconstructions are not motivated by the desire to restore channels to presettlement channel forms because pre-mining water and sediment discharge regimes have been so drastically changed by dams, levees, and channelization that full restoration is not plausible—if full restoration is defined as a return to a pristine past condition (National Research Council, 1992). Knowledge of past channel forms and subsequent changes to these anthropogenically disturbed rivers serves several purposes, including an understanding of rates of passive recovery or the long-term consequences of structural changes. Also of immediate importance is knowledge of the locations of former positions of channels that may underlie modern levees and compromise their integrity by allowing underseepage or bank erosion during floods.

Much can be learned by assessing the results of early river-management policies in these rivers. A valid critique of the modern river-restoration movement has been the lack of postproject assessments (Kondolf and Micheli, 1995; Bernhardt et al., 2005). A substantial effort was made to control the Yuba and Feather Rivers during and after the mining period, but little study has been made of these changes from a river-management perspective. Beginning as early as the 1880s, flood-control efforts sought to maintain wide cross-channel levee spacings in the non-navigable Yuba River to encourage deposition of hydraulic-mining sediment, and to construct levees with narrow spacings along the navigable Feather River to encourage self-scouring of the channels. This manipulation of levee spacings to control sediment storage and transport is an early example of attempts to stabilize a large river system following human impacts, and it provides an opportunity to assess the outcome of diverse river rehabilitation methods.

This paper contrasts the resulting channel morphologies of the lower Yuba and Feather Rivers. Both systems underwent severe morphological changes and continue to store large volumes of hydraulic-mining sediment, but the spatial patterns and processes of sediment redistribution and morphologic change are distinctly different. These morphological and sedimentologic adjustments remain relevant to river management in the region. Ongoing engineering changes to these rivers, such as major levee setback projects on the Bear and Feather Rivers, represent modern river-management efforts to reduce flood risks as residential developments encroach on flood-prone lands. Moreover, mercury toxicity of the mining sediment has recently been recognized as an important issue with the mining sediment (May et al., 2000; Hunerlach et al., 2004). Most of the historic sediment stored in both rivers is between levees and may be available for reworking.

The lower Yuba and Feather Rivers were severely altered by the arrival of sediment produced in the mountains by hydraulic gold mining. In addition to the rapid aggradation of channels, drastic engineering measures were taken to protect these rivers during the late nineteenth and early twentieth centuries. The history of hydraulic gold mining from its advent in 1853 to its cessation following an injunction in 1884 is covered elsewhere (May, 1970; Kelley, 1954, 1959, 1989; Greenland, 2001), as are discussions of its impact on rivers and floodplains (Gilbert, 1917; James, 1989, 1994; James and Singer, 2008; Singer et al., 2008). This paper documents the nature and timing of channel changes in the lower Yuba and Feather Rivers from hydraulic-mining sedimentation and river engineering works. It provides documentary and field evidence of the changes and puts them into the context of river-management strategies. The results are part of an ongoing study of hydraulic-mining sediment stored along the lower Yuba and Feather Rivers.

STUDY AREA: HYDRAULIC-GOLD-MINING SEDIMENTATION

The Feather River Basin heads in the northern Sierra Nevada and flows out onto the Sacramento Valley (Fig. 1). The basin includes the Yuba River and the Bear River, which join the Feather above its confluence with the Sacramento River. The mining districts are located on high ridges in the foothills of the Sierra Nevada and consist of rugged terrain with deep, narrow canyons. This study is concerned with the lower Feather River below the Yuba confluence and the lower Yuba River from the mountain front to the Feather River. The Feather River has a drainage area of 10,300 km^2 (3974 mi^2) directly above the Yuba River confluence, and the Yuba River has a drainage area of 3470 km^2 (1340 mi^2) at the U.S. Geological Survey stream gauge above Marysville (no. 11421000).

Hydraulic gold mining in the northern Sierra Nevada foothills produced 1.1 billion cubic meters of sediment (Table 1). Approximately 38% (~400 10^6 m^3) of the total hydraulic-mining sediment produced was stored in piedmont deposits of the Yuba and Bear Rivers and the lower Feather River (Table 2). The immense deposit in the lower Yuba River alone represents 24% of the hydraulic-mining sediment produced from 1853 to 1884. These low-lying, unconsolidated deposits reside below all dams and reservoirs and are largely between modern levees. Thus, they are subject to erosion and transport down-valley to the flood bypasses and Sacramento–San Joaquin Delta, where flood hazards are great (Mount and Twiss, 2005; Singer, 2007; Singer et al., 2008).

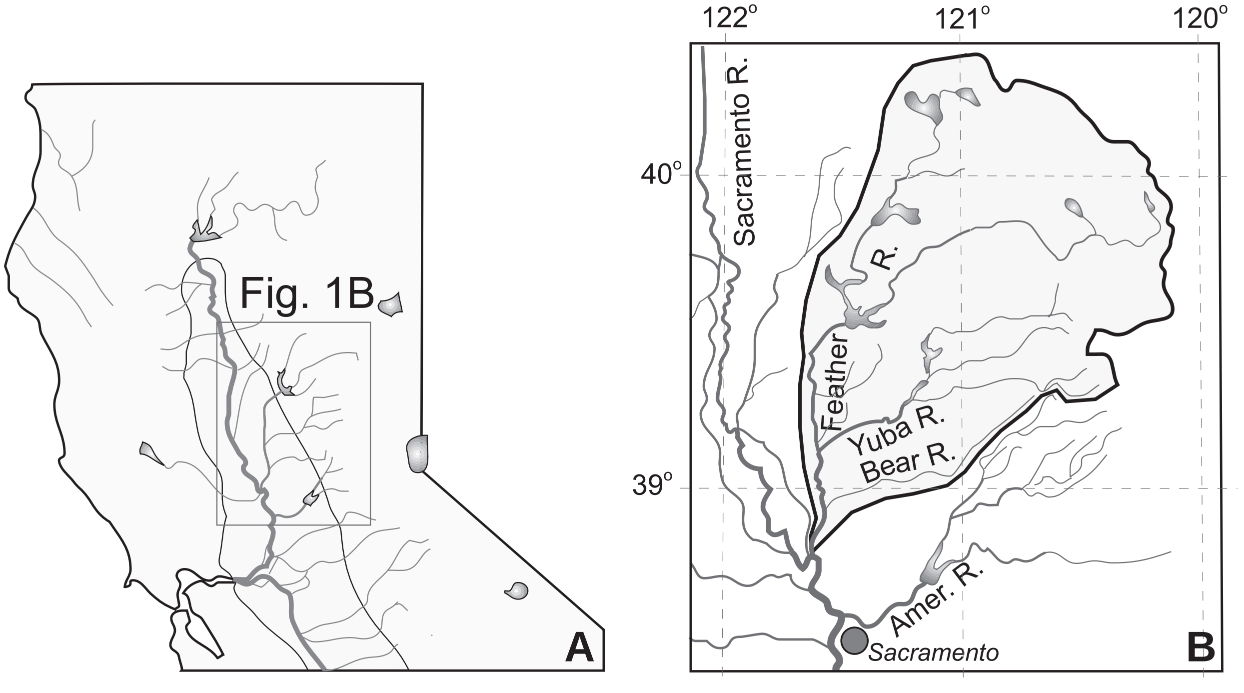

Figure 1. Map of Feather River Basin in northern California. (A) Region straddles the northwestern Sierra Nevada and southeastern Sacramento Valley. (B) Feather River Basin with Yuba and Bear sub-basins. Most hydraulic mines were near 121°W longitude in Yuba and Bear basins.

TABLE 1. SEDIMENT PRODUCTION BY HYDRAULIC GOLD MINING IN SIERRA NEVADA, CALIFORNIA

River basin	Volume (10^6 m^3)	Production (%)
Yuba River	523	49.0
Bear River	271	25.4
Feather River	76.5	7.2
Subtotal	871	81.6
American River	197	18.4
Total	1067	100

Note: Data from Gilbert (1917).

TABLE 2. HYDRAULIC-GOLD-MINING SEDIMENT STORAGE IN THE SIERRA NEVADA PIEDMONT

	1879–1880	1914	1985	Total production (%)
Lower Yuba River		253		24
Lower Feather River, Oroville to Yuba City	14.0	19.1		1.8
Lower Feather River below Yuba confluence	24.6			2.3
Bear River*	27.5		106	9.9
			Total:	38%

Note: Storage volume in lower Bear River was revised upward by coring (James, 1989). All values are in millions of cubic meters. Data from Gilbert (1917).

Most sediment produced in small watersheds is commonly stored close to the source of production, and its distant delivery is usually a small proportion of the sediment produced (Roehl, 1962; Walling, 1983; Novotny and Chesters, 1989). An exceptional feature of Feather River Basin sediment-delivery ratios is that initial sediment storage near the source did not dominate. Most storage occurred tens of kilometers downstream of the source, where gradients decrease along the margin of the Sacramento Valley. Most mines in the Yuba Basin dumped sediment into extremely steep, narrow canyons, where it was quickly and efficiently delivered downstream to alluvial fans and basins in the valley. (Exceptions include Shady, Spring, and Scotchman Creeks, where moderately large deposits remain near the mines.) The high sediment loads overwhelmed the transport capacity of valley channels and caused major geomorphic adjustments such as channel aggradation and avulsions. Engineering efforts to control sedimentation and flooding—including leveeing, channelization, and bank protection—contributed to morphological changes on these rivers and altered patterns of sedimentation. Construction of levees during the mining period was largely uncoordinated, and the history and characteristics of early levees is not well known. By the 1880s, river-management policies began to emerge that encouraged coordination of flood-control efforts (James and Singer, 2008). The strategies employed in the Feather and Yuba Rivers were strikingly different and encouraged contrasts between the floodplain geomorphology of the two rivers.

Methods

The evidence used in this paper to document channel changes over the past 150 yr consists of historical documents, recent maps and geospatial data, and field observations made in 2006 and 2007. The historical evidence is derived from field observations by contemporary experts and from historical maps and aerial photographs, which are compared with modern spatial data including digital orthophoto quarter quads (DOQQs) and LiDAR (light detection and ranging) and sonar topographic data. Numerous historical maps and aerial photographs of channels were visually inspected for channel features and conditions. Selected maps and images were georeferenced to 1999 DOQQs or to a modern geographic information system (GIS) map of section lines of the Public Land Survey System (PLSS, 2001) using ArcGIS 9.2 software. Most rectifications achieved reasonably small root mean square (rms) errors with 10 to 29 evenly spaced ground-control points using a second-order polynomial transformation (Table 3). The earliest of the rectified maps (Von Schmidt, 1859) is not sufficiently accurate to allow length or area measurements to be made of channel dimensions or planform changes, but it provides dates of pre-mining channel positions and islands shown on later, more accurate maps. It also allows first-order comparisons to be made of channels through time. Channel boundaries were digitized on-screen from the historic maps and were overlain on more recent maps and images to identify channel positions and features.

Field reconnaissance mapping of river-bank stratigraphy was conducted in the summers of 2006 and 2007 to identify the depths and locations of hydraulic-mining sediment and collect sediment samples. Generalized stratigraphic sections were measured using a total station or hand level to show the relative thickness of major alluvial units, especially contacts between historical sediment and the underlying presettlement alluvium. Stratigraphic and sedimentological evidence at four selected stream-bank exposures is used in this paper to demonstrate the magnitude and character of sedimentation associated with channel changes. Total mercury concentrations of the fine fraction (<63 µm) of sediment samples were determined via cold vapor

TABLE 3. MAP GEOREFERENCING STATISTICS

Map	Original scale	GCPs (N)	RMSE (m)	Transform
1859N Von Schmidt	1:63,400	29	43.7	2d order poly
1859S Von Schmidt	1:63,400	20	45.8	2d order poly
1881 Mendell	NA	23	27.5	2d order poly
1906 CDC map of Yuba	1:9,600	avg ~12	avg ~12	2d order poly
1909 CDC map of Feather*	1:9,600	NA	NA	NA

*Feather River map registration performed by California Department of Water Resources.

GCPs—ground-control points; NA—not applicable; RMSE—root mean square errors; CDC—California Debris Commission; poly—polynomial.

atomic fluorescence spectroscopy to test field designations of historical and prehistorical alluvial units. Maps of historical deposits generated from digital soil maps were also consulted for evidence of former channel positions and alluviation.

CONTRASTING RIVER-MANAGEMENT STRATEGIES AND CHANNEL MORPHOLOGIES

Levees, dams, and channelization ultimately caused substantial channel changes in these rivers. Early policies of river management that sought to control mining sediment along the Yuba and Feather Rivers went through a period of evolution in which the emphasis shifted from small dams to levees and channelization. On the non-navigable Yuba and Bear Rivers, the goal was to sequester mining sediment and reduce sediment deliveries to the navigable waters of the Feather and Sacramento Rivers downstream. Initial attempts to detain sediment with dams in the piedmont failed. A brush and rock dam 1.8 m (6 ft) high on the Bear River failed within a year (Mendell, 1881) after impounding 735,000 m^3 of sediment from 1880 to 1881 (Mendell, 1882). A brush dam on the lower Yuba River built in 1880 failed the following year. Barrier No. 1, a gravel and stone dam, was constructed on the lower Yuba River in 1904, raised a total height of 4.2 m, and held 1,292,000 m^3 of sediment before failing in 1907 (Gilbert, 1917). The Daguerre Point Dam, built a few km below the Barrier Dam in 1910, persisted, but it provided too little sediment storage too late to encourage a policy of using dams to control sediment on these large rivers. Contemporary dam technology was simply not yet up to such a task.

Failure of the early dams led to an increased emphasis on channelization and levees to protect the Feather and Sacramento Rivers from flooding and sedimentation. This strategy included spacing levees widely in the lower Yuba River to encourage sediment retention and employing narrow levee spacings on the Feather River to encourage channel scour. By 1906, levee spacings in the Yuba River were as great as 4.1 km above Marysville but narrowed to a 640-m constriction at Marysville 1 km above the Yuba-Feather confluence (Fig. 2). No substantial change in the outer levee spacings has occurred along the Yuba River since 1906. To compensate for the widely spaced levees, main channel margins along the lower Yuba were armored with riprap to protect banks from erosion, and boulder wing dams to constrict flow widths within the main channel. Thus, the main Yuba channel was designed to convey water and scour sediment, but high lateral connectivity with a broad floodplain encouraged overbank deposition on floodplains and in high-water channels.

Levee spacings along the Feather River are much narrower than those along the Yuba River. By 1909, levee encroachment along much of the Feather River had reduced cross-channel spacings to dangerously small widths. At several points, levees

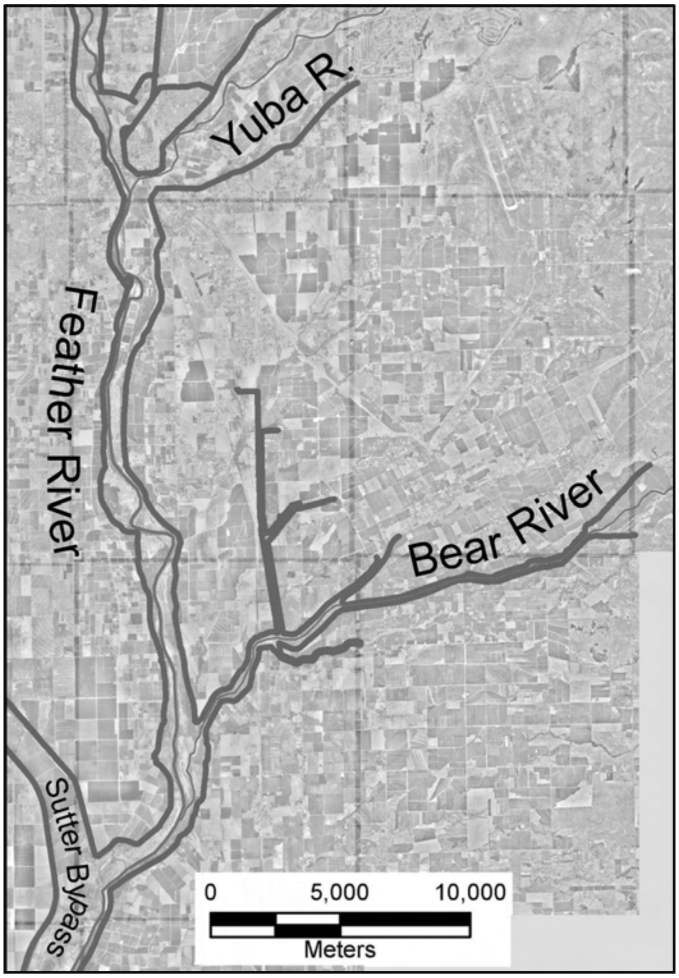

Figure 2. Levee cross-channel spacings with narrow Feather River floodway, wide Yuba River floodway, and narrow constriction at Yuba mouth. Digitized from 1999 digital orthophoto quarter quads (DOQQs).

constricted the width of the floodway to <2.5 times low-flow channel widths (Fig. 3). Levee spacings below Shanghai and Star Bends and at Star Bend in 1909 were on the order of only 240 m apart, not much wider than the low-flow channel (Fig. 4). These constrictions probably caused backwater effects during large floods, but they had been widened by 1999. Owing to frequent levee failures before the 1930s, the U.S. Army Corps of Engineers had set back many of the levees by 1940 (Eckbo, Dean and Williams, 2006). An extensive Feather River levee setback project was recently completed above the Bear River confluence, and another is currently under way in the reach above Star Bend. Downstream, near the confluence of the Feather and Sacramento Rivers, levee positions along the left bank did not change substantially between 1909 and 1999, but in 1909 a Southern Pacific Railroad embankment along the right bank constrained widths of moderate-magnitude floods to <250 m. High flood stages evidently flowed through the embankment into the Sutter Basin through a series of crevasses that are described later in this paper.

HISTORICAL CHANNEL TRANSFORMATIONS

Responses of the lower Feather and Yuba Rivers to the rapid influx of hydraulic-mining sediment varied owing to contrasts in water- and sediment-discharge regimes, geomorphology, and flood-control measures of the two rivers. Deep burial near the Yuba River fan apex graded downstream to broad, shallower deposits on the order of 5 m deep near Marysville (California Debris Commission [CDC], 1906). The lower Feather River deposits were constrained laterally by levees and—unlike in the Yuba River—two major post-1909 channel avulsions occurred. This section examines the historical record of channel changes. It begins with pre-mining conditions and then examines changes in a geographic sequence progressing from the Yuba River fan area downstream to the mouth of the Feather River.

Pre-Mining Channel Conditions

Early descriptions of the Yuba and Feather Rivers prior to the onset of mining sediment are limited because of the fervor caused by the gold rush during pioneering settlement and the brief period from the late 1840s to 1861, before rapid sedimentation began to alter the river. Maps and descriptions by contemporaries allow some reconstructions of the nature of channel conditions at the time of settlement. For example, G.K. Gilbert interviewed an early resident on the Yuba River who remembered the presence of low terraces or banks (“bottom lands”) up to the Barrier Dam but not on the Feather. He remembered bedrock outcrops in the Yuba channel bed above the Barrier Dam (near the present location of Daguerre Point Dam):

> Dr. C. E. Stone, 77, lived at Long Bar up the Yuba and ‘practiced’ in the region before the sixties. There were bottom lands along the Yuba, cultivated and dwelt on, up to above Daguire Point and nearly to site of dam. Half mile above dam first bedrock in river. A cascade at Narrows near Sucker Flat and considerable fall below. There were also high benches. Recalls no bottom land on the Feather. (Gilbert, 24 August 1905, Book no. 3499, p. 18)

Pre-mining channels in the Sacramento Valley were described as having high, steep banks with dark, fertile soils on low adjacent surfaces (Hall, 1880). Bottomlands were described by contemporaries as having dark soils, presumably representing floodplains in frequent lateral connectivity with the river.

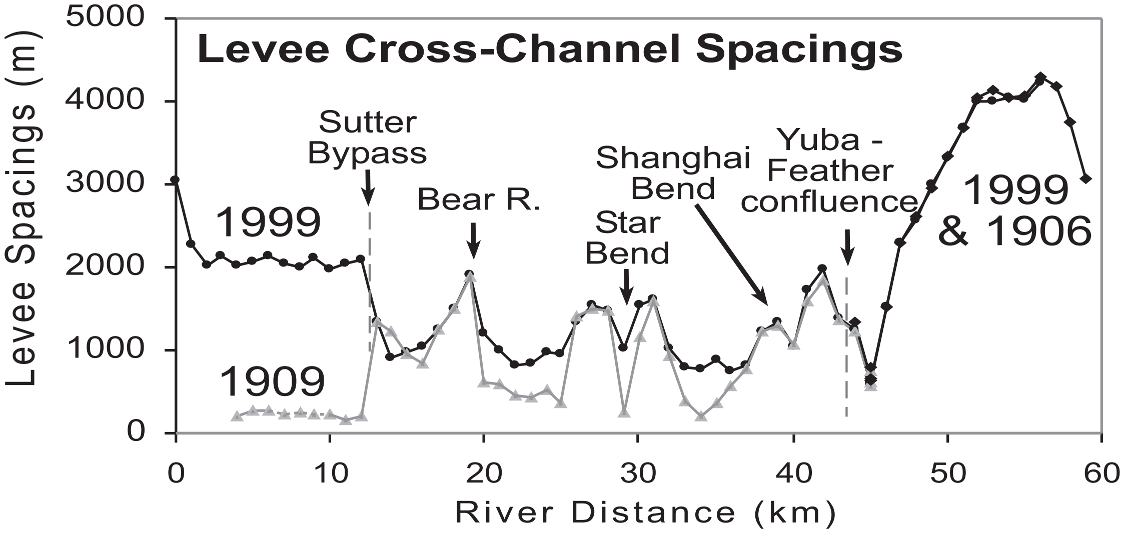

Figure 3. Levee cross-channel spacings in 1999 in comparison with 1909 (Feather River) and 1906 (Yuba River). Measured from 1999 DOQQs and California Debris Commission (CDC) 1906 and 1912 maps.

An early detailed (1:63,400) map produced from a survey by Von Schmidt (1859) is interpreted as representing the planimetry of pre-mining channels (Fig. 5), because hydraulic-mining sediment did not begin to be delivered to the valley in appreciable quantities until the 1861–1862 floods (Mendell, 1881). This and several other early maps (e.g., Gibbes, 1852) show the Yuba River joining the Feather River at an upstream, oblique angle, indicating that this unusual obliquity predated historical sedimentation influences. Likewise, downstream along the Feather River, the 1859 map shows the highly sinuous Elisa (aka Eliza) Bend near the present location of Shanghai Bend and an island upstream that persisted until the twentieth century. This large meander

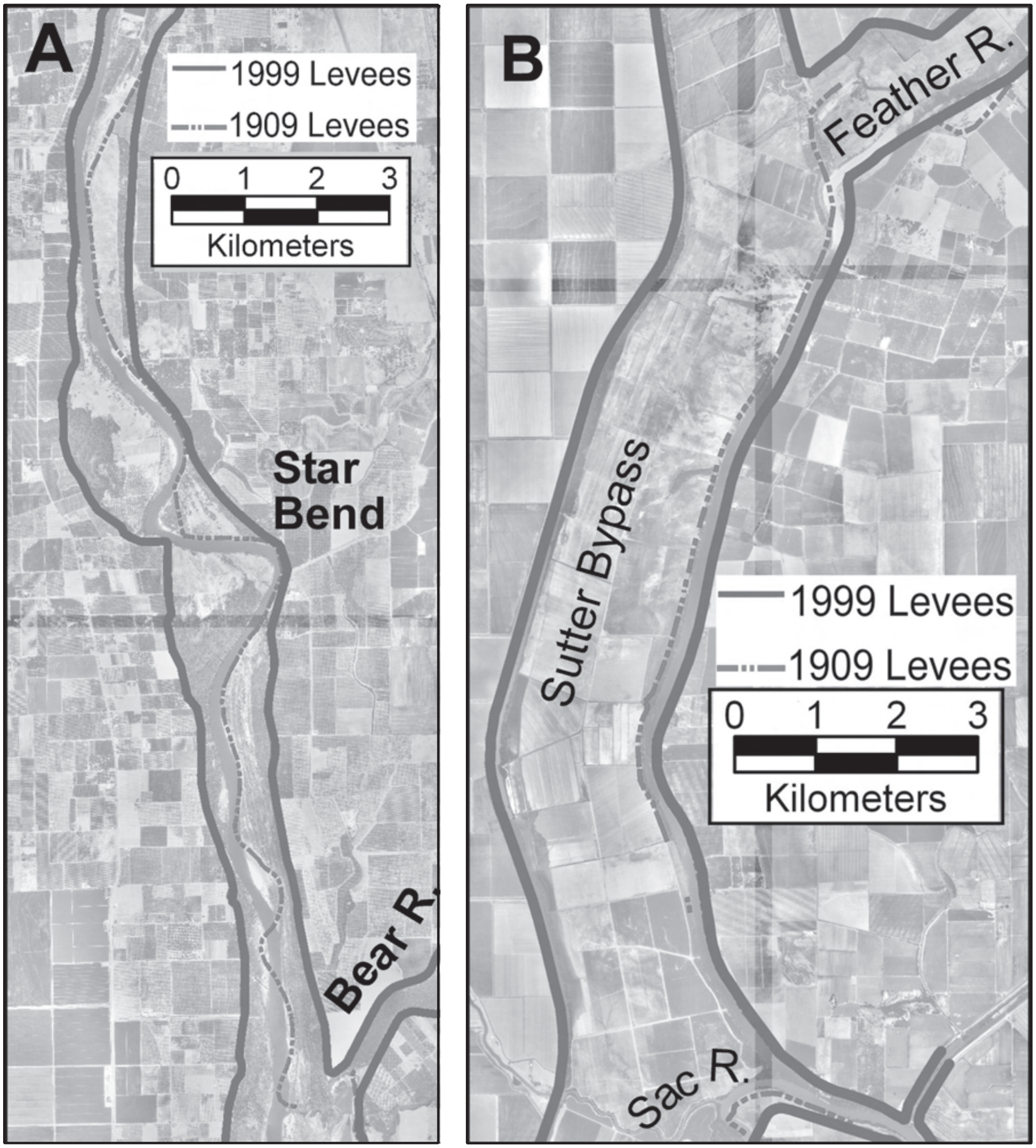

Figure 4. Widening of levee spacings from 1909 to 1999 on the lower Feather River. Levee spacings in 1909 were narrower as mapped from CDC (1912) maps. (A) On several reaches above Star Bend to Bear River, 1909 levees on the east bank constricted channels to little more than the width of the low-water channel. By 1999 these constrictions were gone. The 1909 west-bank levees were in essentially the same position as in 1999. (B) Below Bear River, levee positions on the east bank changed little from 1909 to 1999. A railroad embankment on the west bank constrained widths of moderate floods to <250 m. High floods flowed into Sutter Basin through crevasses. Sac—Sacramento River.

bend is shown prominently on other pre-mining maps (Gibbes, 1852; Wescoatt, 1861).

Mining Sediment and Channel Engineering

The rapid influx of hydraulic-mining sediment and human endeavors to control it caused extensive and prolonged channel changes to these Sacramento Valley rivers beginning in water year 1862. Owing to a lack of large floods in the late 1850s, little deposition of mining sediment in the Sacramento Valley had occurred previously:

> The history of the impairment of these rivers is a gradual one. 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, and particularly in the first five or six years succeeding the discovery of gold. In all these years there had been no great flood. The prolonged and excessively high water of 1862 brought down such masses of material that they could not escape observation. This flood was succeeded by others at intervals of six or seven years, and each of these had been observed to increase the evil. (Mendell, 1881, p. 6)

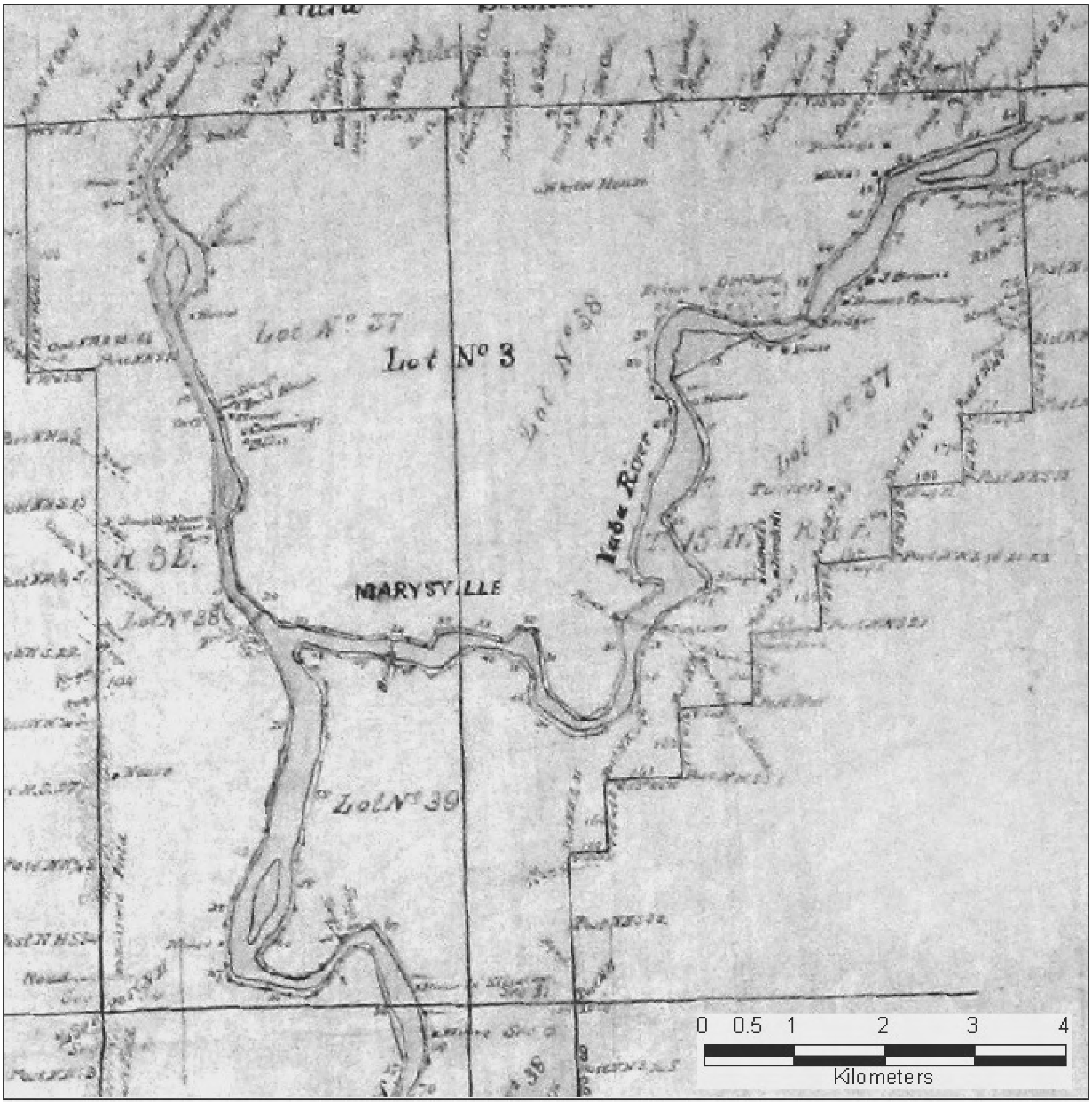

Figure 5. Excerpt of rectified north half of Von Schmidt (1859) map of lower Feather River (flowing north to south) and Yuba River (flowing from upper right). Scale added.

Some sedimentation may have occurred prior to 1862, although it is not well established:

> The effects of the mining debris first began to be seriously felt about 1860, and two years latter [*sic*] agriculture attained its maximum extent. The flood of 1862 left a sediment on Bear River about two feet thick, and created great alarm. (Chamberlain and Wells, 1879, Ch. 47)

Mining-sediment production rapidly decreased after an injunction on hydraulic mining in 1884. Channel aggradation and exacerbated flooding continued late into the nineteenth century, however, in spite of engineering works intended to control sedimentation and flooding (Hall, 1880; Mendell, 1881).

Channel avulsions on the lower Yuba River were rampant during the 1880s, but not on the lower Feather River. The early history of channel changes on the Feather has not been previously documented, but evidence presented in this paper indicates that nineteenth-century channel avulsions and lateral shifts were relatively minor there and increased in the early twentieth century after the main Yuba channel had begun to stabilize. Although the form and timing of change varied, the Yuba and Feather Rivers both changed substantially, as might be expected in fluvial systems so drastically altered. Levees, dikes, and other engineering works were constructed to stabilize the channel, and by the turn of the twentieth century, historical sediment deposits were largely bracketed by an extensive levee system (Figs. 2, 4). The following sections present a series of historical observations from maps and aerial photographs at selected river reaches progressing downstream from the Yuba to the Feather Rivers.

Yuba River above the Yuba Gold Fields

Bed aggradation in the lower Yuba River ranged from 23 m in narrow canyons near the fan apex to ~5 m near Marysville (Fig. 6). The 1906 longitudinal profile shows Yuba channel-bed elevations near peak aggradation. Sediment storage is conspicuous behind Barrier No. 1 Dam, which was destroyed by the 1907 flood (Gilbert, 1917). The ~10 m break in slope at Barrier No. 1 is due to scour downstream in addition to deposition upstream of the dam. Elevations of the pre-mining channel were approximated by the CDC (1906) on the basis of numerous channel borings and other available information. Few boreholes reached the pre-mining surface, but they provided many minimum depths of hydraulic-mining sediment in an area where the deposit widens considerably. Depths to bedrock were interpolated by the CDC (1906) from four known depths at two boreholes and two exposures in the dredge fields. The longitudinal profile in Figure 6 shows increases in bed elevations but not floodplain elevations.

Degradation began high in the sediment fan of the Yuba River in the early twentieth century as documented by G.K. Gilbert. At Parks Bar, ~5 km downstream of the Narrows, where the Yuba River leaves the canyons at the east margin of the Sacramento Valley, Gilbert noted ongoing aggradation in 1905 and spreading of gravel onto the floodplain:

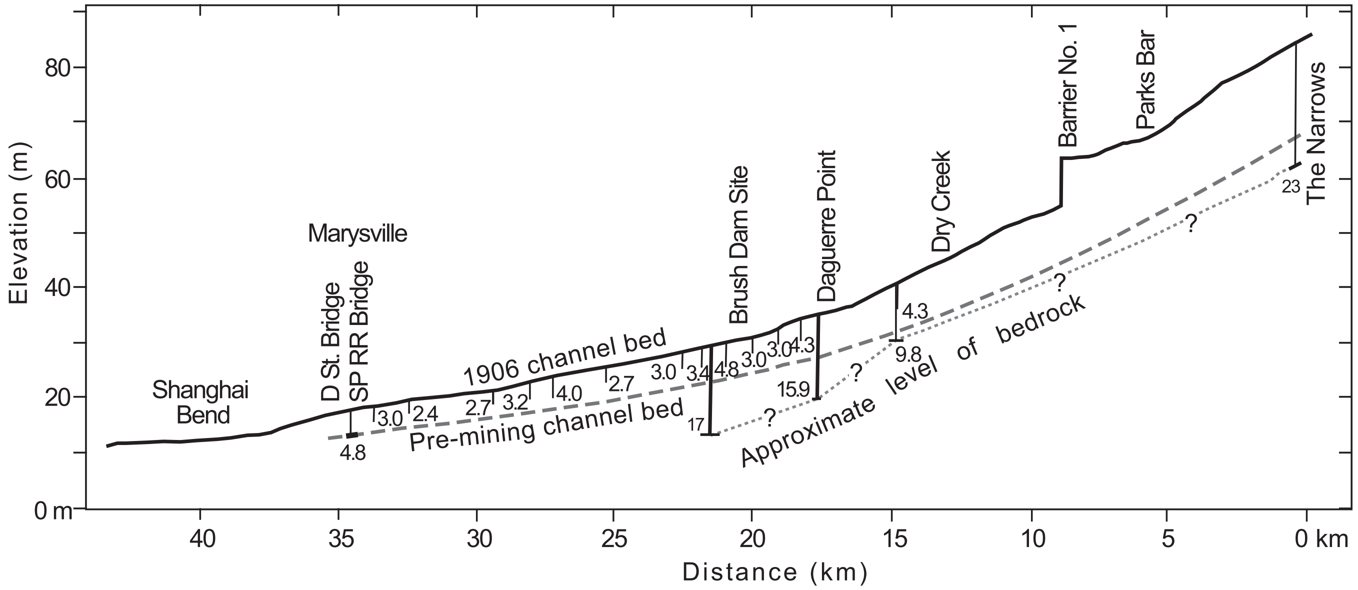

Figure 6. 1906 longitudinal profile of the lower Yuba River from The Narrows in the fan apex to Shanghai Bend below the Feather River confluence. Solid line is channel-bed elevation in 1906. Middle dashed and lower dotted lines are elevations of the pre-mining channel and bedrock, respectively. Numbers adjacent to thin vertical lines are depths of boreholes (meters) drilled in 1898–1899 that provide minimum depths of hydraulic-mining sediment. Two thick, vertical lines give depths to bedrock (17 and 15.9 m) on the basis of bedrock exposed by dredging. (Source: CDC, 1906.)

> … at the Smartsville bridge the river bed is a waste of white gravel. The condition of the bank along my road of approach indicates aggradation of the river bed by the last flood. Oaks are being buried by gravel. (Gilbert, June 1905; Book no. 3497, p. 36)

> At Parks Bar Bridge I found a bench or two. Found also the berm… This bar is only two feet [0.6 m] above a gravel bar… The filling of the channel here has made estuaries of side channels, and has caused spurs to be truncated… (Gilbert, 7 August 1905; Book no. 3499, p. 13)

In 1907, and again in 1913, Gilbert revisited Parks Bar and noted no further aggradation of the floodplain by large 1907 or 1909 floods, but floodplain degradation had not begun:

> At the Parks Bar Bridge I once photographed some small oaks half buried by gravel. Comparing the photos today I find practically no change. (Gilbert, 11 June 1907; Book no. 3504, p. 35)

> An old photo near Parks bar bridge shows trees partly [buried] by gravel. This gravel is a few inches lower now, but the main bar outside looks like the foto [*sic*], and I can not say that degradation has begun. It is partly certain however that aggradation is checked… (Gilbert, 4 August 1913; Book no. 3508, p. 29–30)

He recognized, however, that 3 m of channel degradation had occurred some time between 1905 and 1913:

> On Bakers contour, 1905, the highest and lowest contours of the cross section are 10′ [3 m] apart, and the difference between low water level and the high gravel bar above the bridge must have been as small as 10′, more probably 9′ [2.7 m]. In 1913, we find it 19′ [5.8 m]. This, taken in connection with the foto record—where the lowering close to the shore is a few inches—indicates that the summer channel has been deepened about 10′ [3 m]… (Gilbert, 6 August 1913; Book no. 3508, p. 34)

The pattern of channel incision often inferred from Gilbert's (1917) classic sediment-wave model differs from these observations. Channel incision did not progress from the Narrows downstream to Marysville between 1900 and 1905 but appears to have skipped over Parks Bar between 1900 and 1905. When incision began some time between 1905 and 1913 it was confined to the low-flow channel, leaving large amounts of floodplain gravels in storage. This topic will be revisited in the discussion of the Yuba-Feather confluence, where dredging suggests that channel degradation at Marysville may have resulted from local changes.

Approximately 5 km below Parks Bar, the Yuba River flows into a 12-km stretch dominated by extensive dredge spoils of the Yuba Gold Fields. The spoils are piled at the angle of repose in 7- to 20-m-high gravel ridges along both sides of the channel as measured on 0.5-m contour lines derived from 1999 LiDAR data (Stonestreet and Lee, 2000; Towill, Inc., 2006). Dredging exploited modern channel alluvium, hydraulic-mining sediment, and Quaternary alluvium, so the spoils are likely to be of mixed composition that vary in space (Hunerlach et al., 2004). A GIS comparison between 1999 and 2006 DOQQs indicates that a 250 m section of the south ridge along the channel margin was eroded laterally up to 12 m during that period. The ridge in this area is ~10 m high, so ~30,000 m^3 of dredge tailings may have been delivered directly to the channel from this short reach between 1999 and 2006.

Yuba River between the Yuba Gold Fields and Marysville

The floodplains above Marysville were the most extensively alluviated river reaches in the foothills or valley during the late nineteenth century. In the lower 12 km above the mouth of the Yuba River, gradients decrease, Holocene alluvium covers Quaternary outwash terraces, and floodplains widen. The 1859 map shows the pre-mining Yuba as a somewhat more sinuous, single-thread channel, although one large island is shown at the upper margin of the map (Fig. 5). A second master channel to the southeast was present in 1861 (Fig. 7), and probably earlier, even though it does not appear on the 1859 map.

Mining sediment ultimately spread out across the lower Yuba floodplain, causing multiple avulsions in the late nineteenth century. The first detailed survey of the Yuba floodplain was performed in 1879 by the Department of the State Engineer. The U.S. Army Corps of Engineers included this map in an annual report to Congress (Mendell, 1880). A revised version of the map, included in a later report to Congress (Mendell, 1882), shows undated paleochannels that match the 1859 channels (Von Schmidt, 1859) (Fig. 8). The 1859 channel passes under the south levee across from Marysville, which failed in 1997 and caused flooding in the

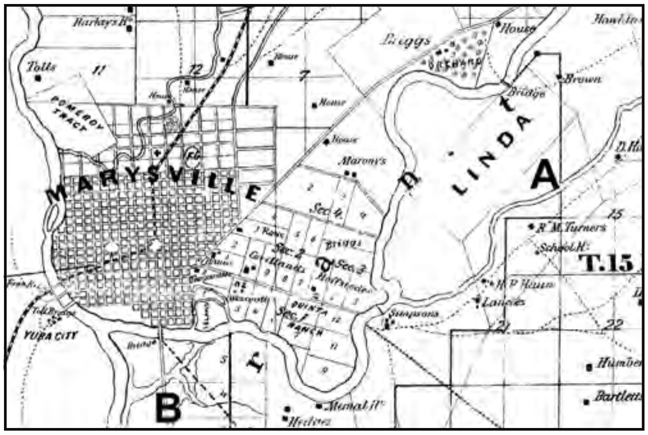

Figure 7. Excerpt from 1861 map of Yuba County, showing two features not shown on the 1859 map: (A) Channel southeast of the main channel around the area marked "Linda". (B) Western chute, cutting off confluence. These conditions should represent pre-mining channels. (Source: Wescoatt, 1861.)

town of Linda. Another channel scar, shown on the 1882 map almost 1 km north of the south levee, is labeled "pre-1876." This channel is interpreted as the same pre-mining channel shown on the Wescoatt (1861) map (Fig. 7) and indicates that the pre-mining Yuba River was a multithread channel system. The 1882 map also shows a channel system that hugs the south levee and is labeled "low-water channel in 1876." By the time of the 1879 Hall survey the low-water channel had apparently shifted 2 to 3 km to the northwest to its 1880 position. The 1880 report describes how the deposit at that time covered the lower banks:

> The cross-section on the Yuba map shows the elevation of this mass of detritus to be here above the general level of the country. This general level is the second bench of the bank, the first being covered. The original bed of the stream is said to have been 10 or 12 feet below the lower bench. (Mendell, 1880, p. 3)

Several reliable observations or maps were made of this area during the first decade of the twentieth century, when the Yuba River was an unstable system of shifting sand and gravel channels:

> For the lower 10 miles [16 km] of its course in the foothills the river is greatly clogged with debris from hydraulic-mining camps (estimated at many million cubic yards), and is between levees which have been raised from year to year to meet the overflow caused by the filling up of the area between them… The channels are irregular and change from winter to winter and sometimes during the summer… The changes in the bottom and in the position of the channel are so great that the gagings at the flood stages of the river would be unsatisfactory, and if undertaken from boats would be highly dangerous, if not impossible. (Manson, *in* Olmsted, 1901, p. 39–40)

Most of the main channel positions in Figure 8 are represented on a set of detailed topographic map sheets surveyed in 1906. They can also be seen on modern aerial photographs. This is particularly true of the 4-km-wide floodplain extending 5 km above the right-angle bend directly northeast of Marysville (Fig. 9). Shortly after Manson's description of the lower Yuba in 1901, channels evidently began to stabilize. The 2006 channel digitized from the low-water position on DOQQs (U.S. Department of Agriculture, 2006) corresponds closely in position with the 1906 low-water channel. The position of the upper 4 km of this reach corresponds with the approximate position of the

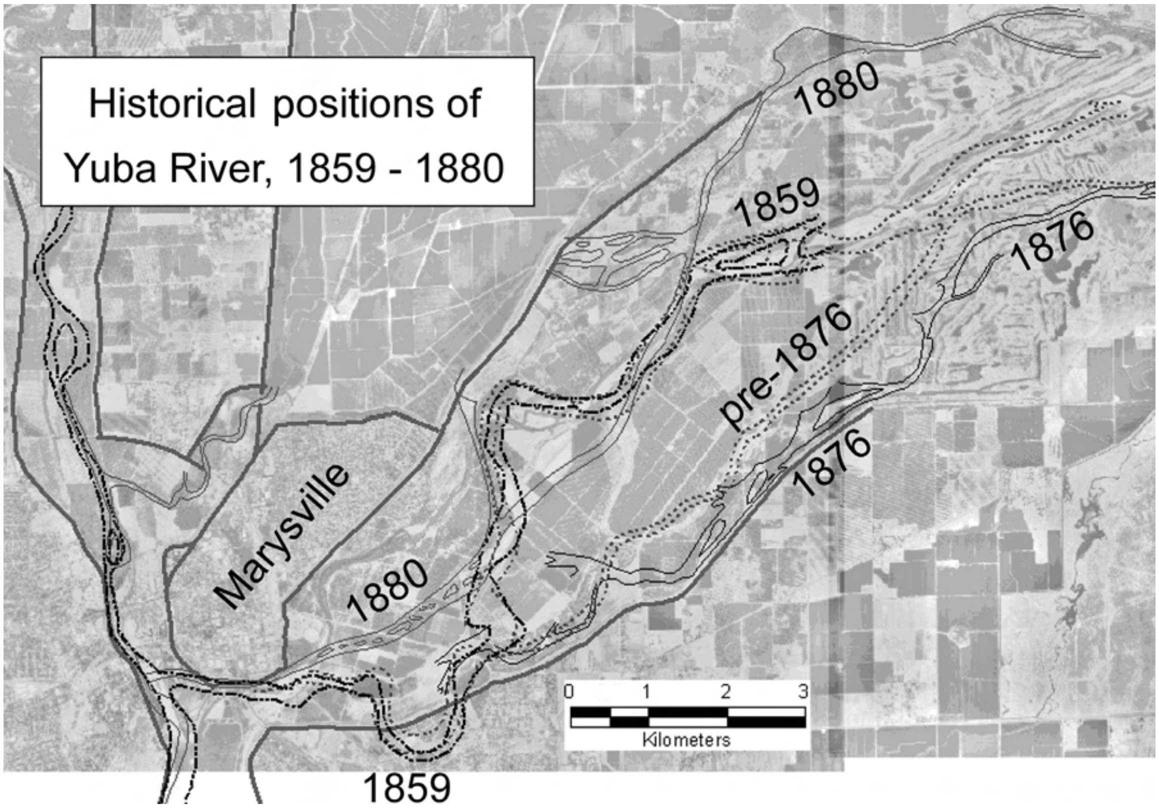

Figure 8. Early positions of lower Yuba River channels based on Mendell (1882) and Von Schmidt (1859) maps (cf. Fig. 5). North branch of pre-1876 paleochannels match 1859 channels. South branch of pre-1876 channel matches channel shown by Wescoatt (1861) and is interpreted as a branch of the 1859 channel. Channel along south levee was labeled "low-water channel in 1876" (Mendell, 1882). By 1880, much of the low-water Yuba channel had shifted 2 to 3 km northwest. (Source: Mendell, 1882, based on an 1879 survey by Hall, 1880.)

1859 channel. The main Yuba channel evidently had returned to its approximate pre-mining position in the area of Figure 9 by 1906, where it has remained to the present. Between 1861 and 1906, however, during the period of rapid aggradation, the channel occupied several positions away from this location, as shown in Figure 8. The 1880 channel position corresponded with only 1 km of the present channel at this location. Channel scars on the 1906 map represent pre-1906 channel positions and high-water channels some of which remain active during large floods. The braiding index of high-water channels on the 1906 Yuba floodplain in this area was between 8 and 19 channels, the maximum value for the Yuba and Feather Rivers. Recently, and at a local scale, comparison of 1999 and 2006 DOQQs reveals substantial channel lateral migration with gravel-bar erosion and deposition within the confines of the main channel.

On the basis of fieldwork in the summer of 2007, a generalized stratigraphy of the Yuba River south bank exposed at the U.S. Geological Survey stream gauge near Marysville was created, using a total station to measure relative elevations (Fig. 10). The elevation of the south terrace is the same beyond and within a short 2-m-high levee, indicating that the levee was constructed after most terrace deposition had occurred. This terrace elevation extends south beyond the plot for ~2.5 km and is now covered by orchards. A matching terrace on the north side extends 1.5 km to the levee. The pre-mining soil is a reddish alluvial silt that supported trees that were buried by historical sediment.

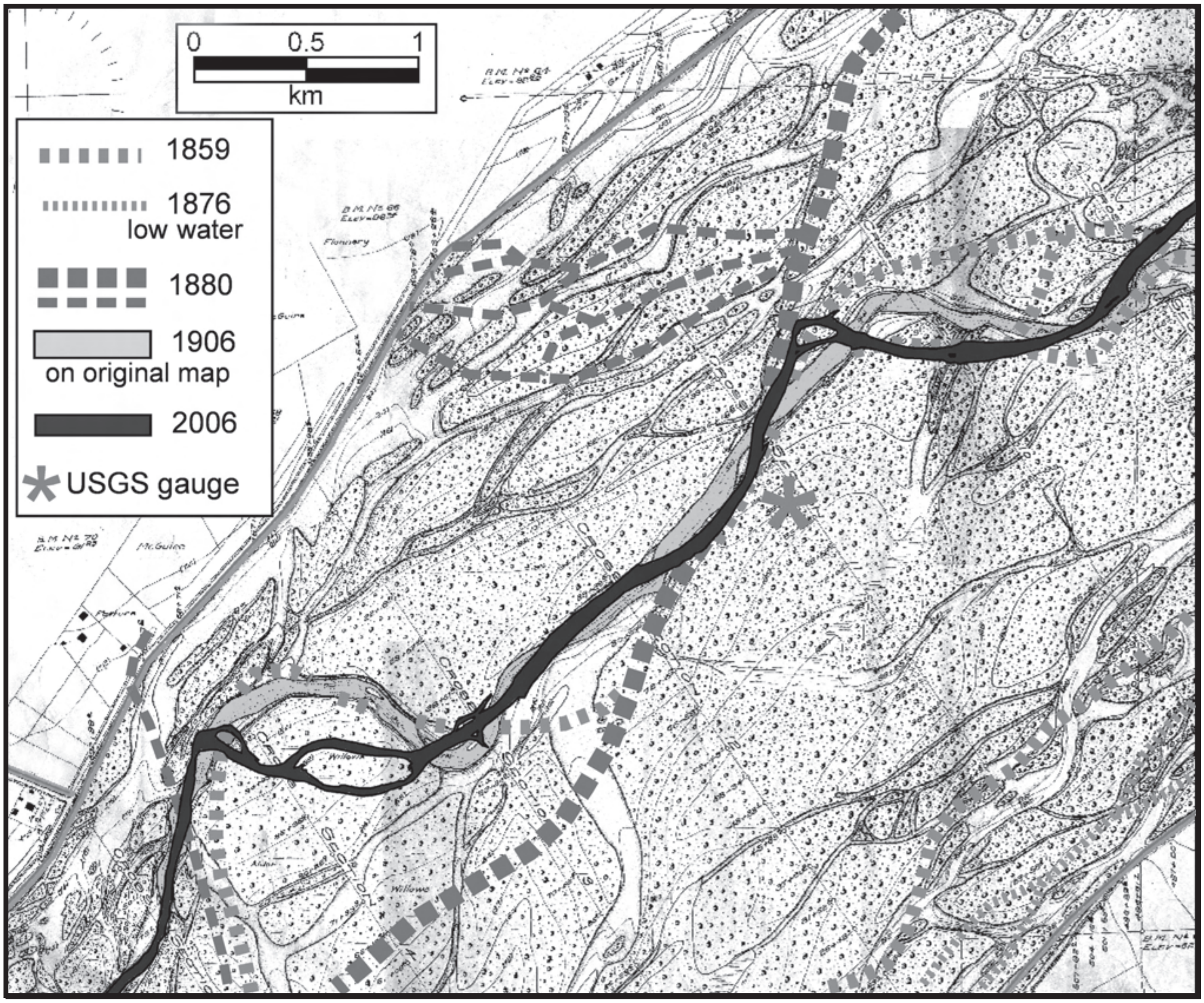

Figure 9. Low-water channel positions on Yuba River floodplain above Marysville. Floodplain base map and 1906 low-water channel are from CDC (1906, sheet 2). Northwest branch of 1859 channel is from Von Schmidt (1859). Southeast branch of 1859 channel, 1876 channel (in southeast corner), and 1880 channel are from Mendell (1882). Other channels on base map are 1906 high-water channels. Bordering lines along northwest and southeast floodplain margins are levees 4.1 km apart. U.S. Geological Survey stream gauge is site of stratigraphic section. Much of the modern channel has returned to its pre-mining (1859) position.

An abrupt wavy contact between the soil and the overlying historical alluvial sands and gravels suggests that scour occurred prior to deposition. The lowest unit of historical sediment is a well-sorted sand that appears to be associated with a scour hole around the roots of a stump (unit C). The overlying unit is a coarse, fining upward sequence that grades from gravel to fine sand with abundant white quartz pebbles (unit B). The upper bank is composed of quartzose sand with a distinctive white appearance and light-tan silts. A stump rooted in this exposure has two root crowns. The lower root crown corresponds with the level of the pre-mining soil, and the upper crown was rooted in unit B. These relationships indicate that the tree survived the initial first meter of sedimentation and was growing for some time on a layer of mining sediment.

The mineralogic composition of the historical sediment is consistent with the distinctive lithology of mining sediment found in tailings fans near the mines (James, 1991). The interpretation that the upper strata are composed of mining sediment is corroborated by total mercury concentrations of the fine fraction (<63 µm). Concentrations in units A, B, and C of 0.17, 0.42, and 0.61 ppm, respectively, are high in comparison with a concentration of only 0.05 ppm in underlying unit D, which is

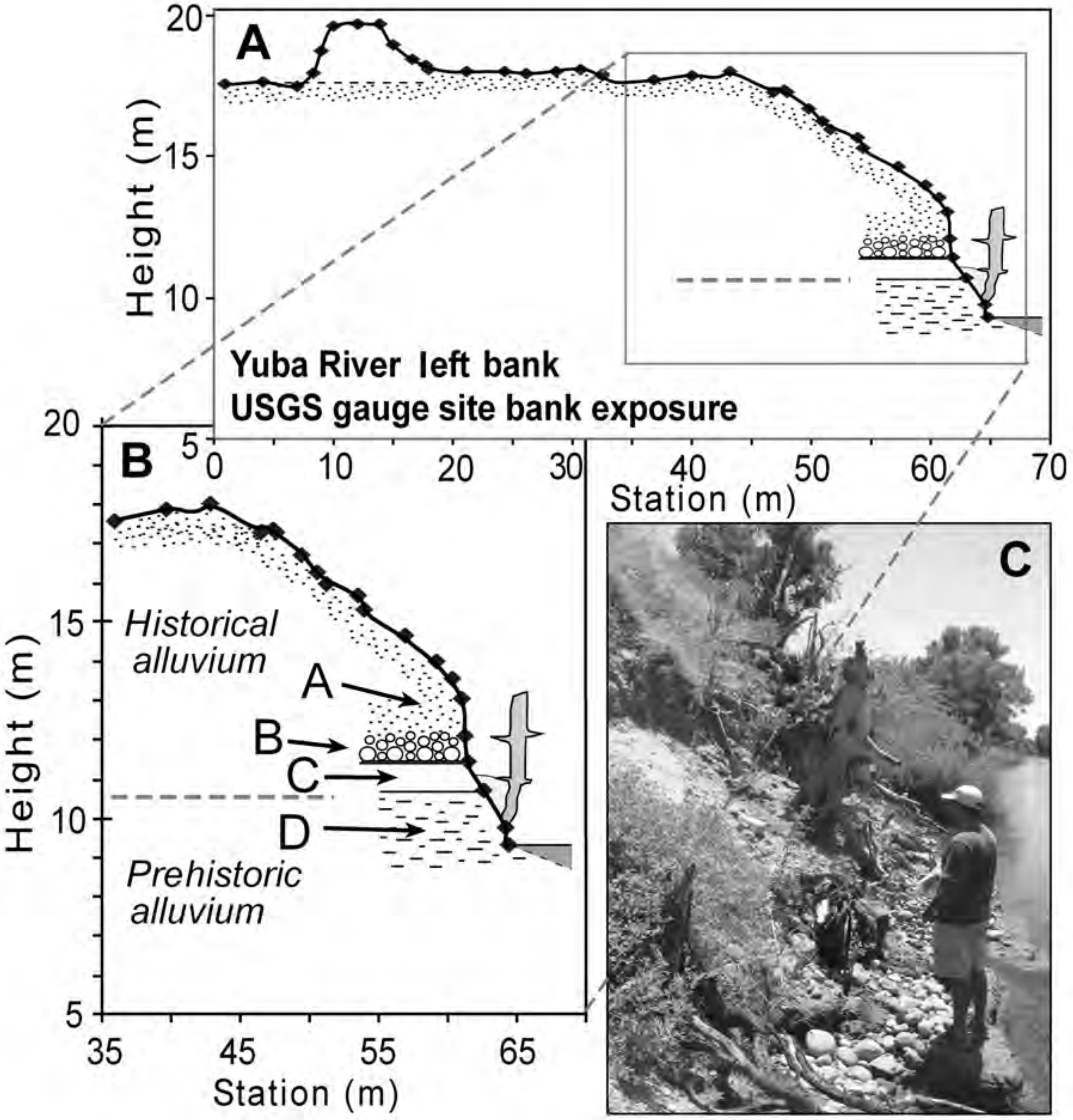

Figure 10. Historical alluvium at U.S. Geological Survey stream gauge on Yuba River near Marysville is >6 m deep. Stumps near base of section are rooted in prehistoric sediment. Center stump has two root crowns, indicating that tree survived initial burial.

typical of crustal abundance concentrations. Although dilution of mining sediment undoubtedly occurred as it was transported to the valley, these deposits are interpreted as dominantly mining sediment. Based on pebble lithologies, mining sediment dilution between the mountain mines and the Sacramento Valley in the Bear River was estimated at 22% (James, 1991).

The thickness of historical sediment from the lower contact to the high terrace surface ultimately reached ~7 m deep, but this may be close to the maximum thickness of mining sediment over the pre-mining floodplain level at this longitudinal position. The elevation of the pre-mining soil elsewhere on the pre-mining cross-valley profile is unknown. If the deposit thickness at this site was representative of the mean depth of mining sediment across the 4-km-wide Yuba floodplain, then the volume of the deposit in this vicinity would be ~28,000,000 m^3 per kilometer of valley length. At this depth a ~5-km-long reach of the Yuba floodplain in this vicinity would account for ~140 million m^3, or 55% of the 253 million m^3 of mining sediment estimated to have been stored in the lower Yuba (Gilbert, 1917). Realistically, the mean thickness of historical sediment at this position on the Yuba floodplain is likely to be <7 m.

Yuba and Feather Rivers near Marysville and Confluence

The pre-mining Yuba channel in the lower 8.9 km above Marysville was more sinuous (1.45) than the 2006 channel (1.22), owing to a broad meander bend southeast of Marysville (Figs. 5, 7, 8). Most of the 253 million m^3 of sedimentation in the Yuba River had occurred by the 1870s and was mapped in 1879 (Hall, 1880; Mendell, 1881, 1882). By 1865, distributary channels had formed, presumably in response to initial sedimentation, and as late as 1887 they carried floodwater and sediment from the south bend of the Yuba River to Elisa Bend on the Feather River near the present site of Shanghai Bend (Fig. 11). The broad Yuba meander was cut off at some time between 1861, when no cut-off channel is shown on historic maps, and 1880, when Mendell (1880) shows a new channel to the north. Mendell (1882) shows the southern channel as abandoned (Fig. 8). Although a map in 1873 (Hoffmann and Craven, 1873) shows no cutoff of the bend, a railroad survey map in 1865 (Fig. 11) shows both channels with an island between, suggesting that the cutoff had been initiated and was at least a high-water chute at that time. By 1880 the channel had avulsed to the northern cutoff near its present location along the north levee southeast of Marysville, and the southern meander bend was abandoned. Ultimately, a levee was built over the southern meander near where the levee failed in 1997 (Fig. 8).

At the turn of the twentieth century, floodplain sedimentation was continuing downstream in the lower Yuba near Marysville:

> The Yuba at Marysville has a broad channel with many sloughs and sand bars. The higher sands are grown with willows and cotton woods, and among these are fruit trees, illustrating the encroachment of the river sands. (G.K. Gilbert, June 1905; Book no. 3497, p. 38)

Bed degradation had begun at the Marysville D-Street gauge by 1905 (Gilbert, 1917), although overbank sedimentation probably continued after 1905.

Channels were dredged at several locations near the Feather-Yuba confluence as a means of flood control at the turn of the twentieth century. A cutoff of the lower Yuba River mouth was dredged by 1905, which diverted the confluence to the south. Gilbert described this cutoff as "new" in 1905 and reported that it had created a fan that dammed the Feather River:

> The Yuba has a new mouth, having been diverted by an artificial cutoff. At the mouth it is building a delta across the Feather, crowding the… channel close against the opposite bank. This has ponded the Feather above so that slack water extends for ½ mile. (Gilbert, 24 August 1905, Book no. 3499, p. 17)

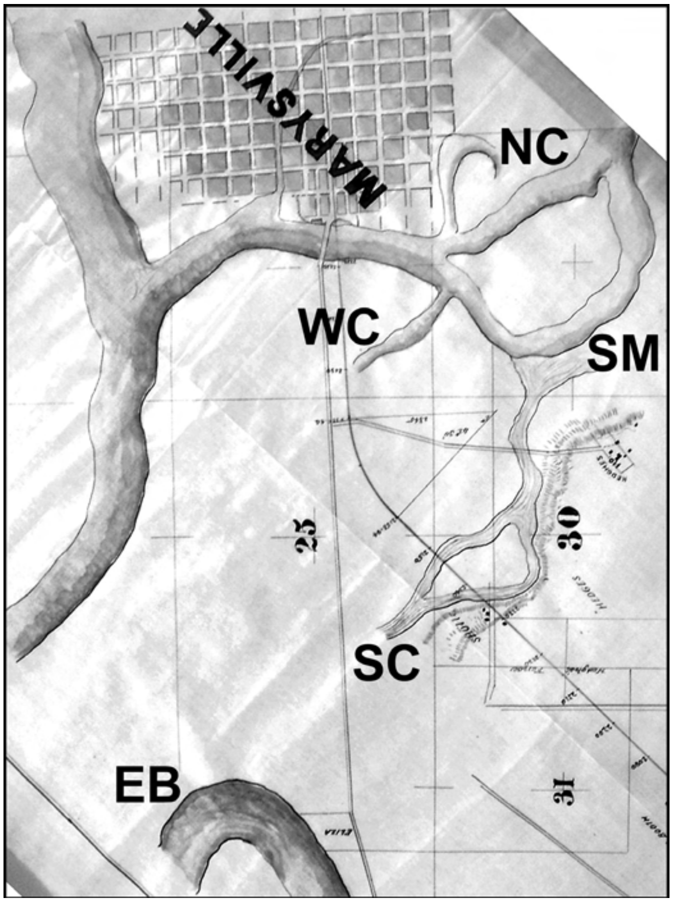

Figure 11. Excerpt from 1865 map of Yuba-Feather confluence, showing three cutoffs from the lower Yuba southern meander bend in early stages of channel aggradation. The *northern cutoff* (NC) became an avulsion, abandoning the *southern meander* (SM) over which the Linda levee was later built (Fig. 8). The *southern cutoff* (SC) apparently connected the Yuba River SM to the Feather River above *Elisa Bend* (EB), as shown on the Doyle (1887) map. The *western chute* (WC) may be the same high-water channel shown in 1861 (Fig. 7), which was later dredged. (Source: Pixley et al., 1865.)

The dam persisted and the impoundment behind it grew in length through at least 1913:

> The pool in Feather above Yuba is said to be 4–5 miles long. It has recently received a fine deposit—partly because of clearing of floodplain of brush. The Yuba channel now brings gravel to the mouth—so coarse as to include pebbles 1–2″ [2–5 cm] diameter. (Gilbert, 18 October 1913; Book no. 3508, p. 37)

The old confluence channel had become a high-water channel by 1909 (CDC, 1912), and by 1937 the abandoned channel scar was not easily distinguished on aerial photographs.

Two other substantial channel cutoffs were dredged near the Yuba confluence around the turn of the century and were mapped by the 1909 CDC survey. One ditch diverted flood flows from the Yuba River above the D Street Bridge opposite Marysville, ~3.5 km to the Feather River at Elisa Bend (CDC, 1912; Ellis, 1939). This cutoff began in a broad 160-m-wide high-water channel below the south end of the Southern Pacific Railroad bridge that passed under the D Street Bridge and fed into the Feather River (Fig. 12). The upper approach to the ditch apparently exploited the chute that existed between 1861 and 1865 (Figs. 7, 11). For 1909 a single ditch is shown connected to the high-water channel, beginning ~200 m below the D Street Bridge as a narrow, 30-m-wide channel, flowing southwest for 250 m and then directly south for 2.5 km to Elisa Bend. This ditch is not present on the CDC 1906 map. Ellis (1939) describes this ditch as a pair of parallel ditches that were dredged in two passes, one up toward Marysville, and a return trip to Elisa Bend. Vestiges of two ditches can be seen filled with sand ~1 km above Elisa Bend on aerial photographs (U.S. Department of Agriculture, 2006).

Another ditch was dredged from the mouth of the Yuba River 250 m above the Feather River confluence. This ditch was ~65 m wide with spoils on both banks. It flowed ~1.5 km to the southeast and joined the north-south ditch obliquely 1.3 km above Elisa Bend (CDC, 1912). None of this ditch remains, although the spoil piles can be seen in field patterns along the lower 800 m of its course. Both of the two ditches flowing into Elisa Bend are labeled “State Cutoff” on the 1909 map (CDC, 1912) and appear prominently on a later map (Crook, 1914). They are discussed further in the next section on Shanghai Bend.

A stratigraphic section was measured at a Yuba River north bank exposure near 2nd Avenue in Marysville (Fig. 13). The upper layers of sediment are interpreted as mining sediment as evidenced by stratification, coarse textures, quartz-rich mineralogies, and a relatively high total mercury concentration of 0.38 ppm in the fine fraction. The massive dark-brown silts at the base of the exposure are interpreted as pre-mining alluvium as supported by a total Hg concentration of 0.02 ppm. The contact between historical sediment and the underlying pre-mining surface is tentatively interpreted at an abrupt wavy contact nearly 6 m in depth. This represents almost 6 m of floodplain sedimentation in the lower Yuba near Marysville relative to previous estimates of 5 m of bed aggradation in this area (CDC, 1906).

Feather River Changes near Shanghai Bend

Elisa Bend, the precursor to Shanghai Bend, is shown on many early maps before and after the delivery of mining sediment began. The 1859 and 1861 maps show the original Elisa Bend, which is presumably a pre-mining feature of the river. On early maps (Von Schmidt, 1859; Wescoatt, 1861; Pennington, 1873; Hoffmann and Craven, 1873; Hall, ca. 1880a; Doyle, 1887) the upper approach to the bend was farther to the west. By 1895, however, the upper channel had been forced to the east by a new levee and flowed more directly south into the upper bend and then veered sharply eastward into Elisa Bend (Manson and Grunsky, 1895a). The eastward shift of the upper channel isolated an area of more than 3.5 km^2 of historical channel deposits from the Feather River to the west of the new levee. Along the modern west bank this surface is 3 m thick above the low-water line, and the bank is another 4 m above the thalweg, which is near the bank. A sample from a 1.2 m silt cap exposed in the bank had a total mercury concentration of 0.41 ppm, whereas the fine fraction isolated from the underlying sands had a concentration of 0.16 ppm Hg. Using 3 m as a minimum mean thickness of the deposit, the volume of mining sediment stored behind the levee in this reach is at least 10 million cubic meters.

After the turn of the twentieth century, channelization in the Shanghai Bend area was extensive. Surveys in 1906 and 1909 (CDC, 1906, 1912) show ditches above and below Elisa Bend, and later maps (Crook, 1914; Thomas, 1928) show two large ditches converging on Elisa Bend, as described earlier (Fig. 12). Another ditch was cut southward from above Elisa Bend and ran 4.8 km south along the west levee to where it rejoined the main channel. This straight channel was labeled “Dredged Canal” on the 1906 CDC map (Fig. 14A). By 1909, following major floods in 1907 and 1909, Elisa Bend had shifted southward and the upper entry to the ditch had been deflected eastward (Figs. 14A, 14B) and subsequently evolved into Shanghai Bend. Ultimately, the entire Feather River channel avulsed from Elisa Bend 1 km west into the ditch. The initial stages of the avulsion can be seen in 1909, although a secondary channel remained at Elisa Bend until at least 1999. By 1952, aerial photographs collected during low flows indicate that the eastern channel was heavily vegetated.

Topographic surfaces in 1999, derived from LiDAR bare-earth 3 m postings and bathymetric data from sonar (Stonestreet and Lee, 2000), reveal the modern configuration of Shanghai Bend (Fig. 14C). By 1999, Shanghai Bend had developed into a high-amplitude meander wave rotated 90° eastward from the orientation of Elisa Bend. Below Shanghai Bend, a shoal or knickpoint that drops 3 m and forms a barrier to river navigation developed across a cohesive soil unit. This break in the longitudinal profile may represent a headward limit to much of the vertical readjustment of the Feather River to pre-mining base levels. At present, the knickpoint is migrating upstream across

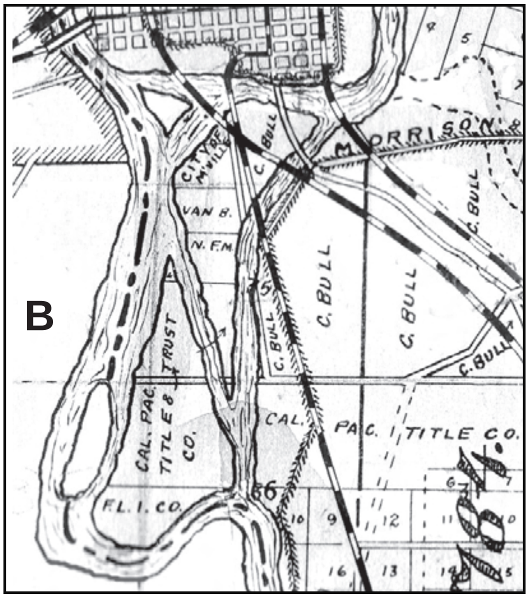

Figure 12. Channelization around Yuba-Feather confluence. Several ditches were dredged south of Marysville shortly before 1909. Two ditches connected with the Feather River at Elisa Bend, and another turned the confluence south. (A) Stratigraphic sections collected at XS are shown in Figures 13 and 15A. (Source: CDC, 1912.) (B) Ditches are prominent (cartographically exaggerated) on 1914 map. (Source: Crook, 1914.)

the high paleosol surface toward the old channel position to the east. When it reaches the deeper former channel position, bed incision may accelerate, allowing the lower base level to rapidly propagate upstream.

A stratigraphic section on the west bank of the Feather River above Shanghai Bend indicates ~5.5 m of historical sediment accumulation in this area (Fig. 15A). The historical contact here is interpreted as the abrupt contact and color break between units C and D, with several tree stumps rooted in the lower layer. Total mercury concentrations in sediment samples at this site support this interpretation. The low concentration (0.05 ppm) in unit D is consistent with background levels of mercury in the pre-mining surface, whereas higher concentrations of 0.18, 0.47, and 0.35 are typical of mining sediment that has undergone some mixing with surrounding sediments. One of several exhumed stumps rooted in the soil at the base of the section was ^{14}C dated at ~1885 (65 ± 35 yr BP), clearly indicating a historic age (National Science Foundation [NSF] Arizona accelerator mass spectrometry [AMS] facility). All vertical sections were measured during low water, so the pre-mining soil surface at this site is low relative to the present water line. This is consistent with an interpretation that the bed of the Feather River near the Yuba confluence has not yet returned to pre-mining levels and continues to degrade (U.S. Army Corps of Engineers [USACE] and State of California Reclamation Board, 1998; Eckbo, Dean and Williams, 2006, Ch. 5).

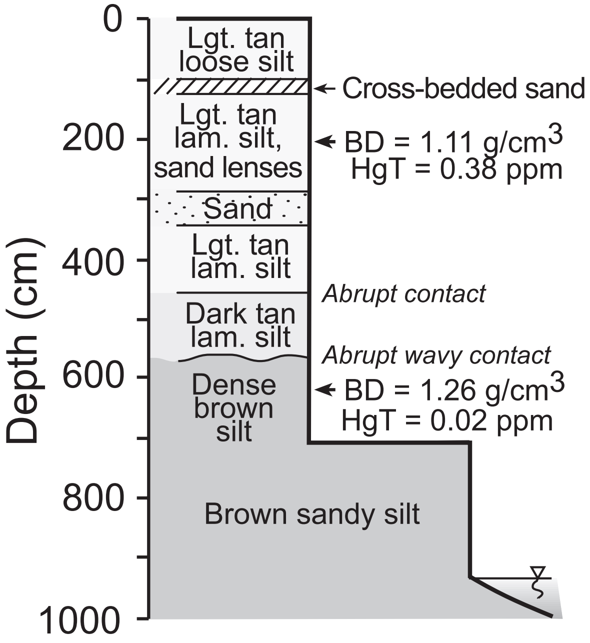

Figure 13. Stratigraphic section on north bank of lower Yuba River at Marysville. Dark, massive silts at base represent pre-mining alluvium. Historical sediment is highly stratified and at least 4.5 m thick and probably 5.8 m thick. BD—bulk density; T Hg—total elemental mercury concentration in sediment samples.

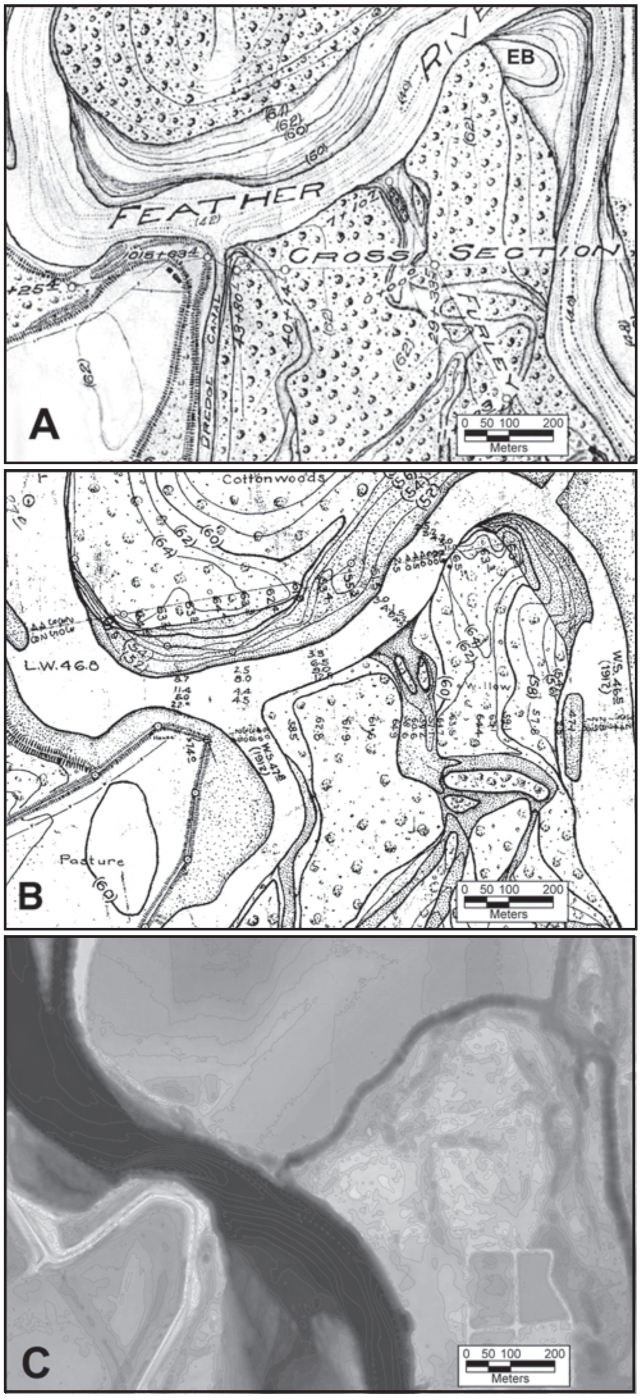

Figure 14. Feather River channel changes at Elisa and Shanghai Bends. (A) In 1906 the Feather River in this area was beginning to undergo changes in planform. Levees above the bend had shifted the channel eastward and altered the flow direction above the bend. The straight "Dredge Canal" to the south along the west levee initiated flows that bypassed Elisa Bend (EB) and ultimately resulted in an avulsion. (Source: CDC, 1912). (B) By 1909, much of the flow was passing south through the dredged channel, which had begun a meander to the east. Elisa Bend was shifting south in a lower-amplitude wave. (C) The 1999 topography of upper Shanghai Bend and the channel scar that was Elisa Bend. Derived from 1999 LiDAR and sonar data.

Low pre-mining surfaces and thick deposits of historical sediment extend along the right bank for a considerable distance above Shanghai Bend but not below the bend. Below the Shanghai Bend shoals a prominent soil can be seen on the west bank several meters above the low-water line. A stratigraphic section measured on the west bank below Shanghai Bend features a well-developed soil with a distinct A horizon and a reddish argillic B horizon (Fig. 15B). Total mercury concentrations corroborate the stratigraphic interpretations based on pedogenesis. Units A and B above the soil have relatively high total mercury concentrations of 0.10 and 0.14 ppm, respectively, whereas units C and D have low background levels of mercury of 0.04 ppm each. This soil is continuous for hundreds of meters at mid-bank where dead trees are rooted in the A horizon. The higher level of the pre-mining soil below the shoals is due to deeper incision below the shoals and to the westward shift of the channel into the dredged channel at a higher position in the pre-mining landscape. The pre-mining soil surface increases downstream in height above the low-water surface. By Boyd Pump House Boat Ramp, historical sediment is only ~1 m thick over a high pre-mining alluvial bank.

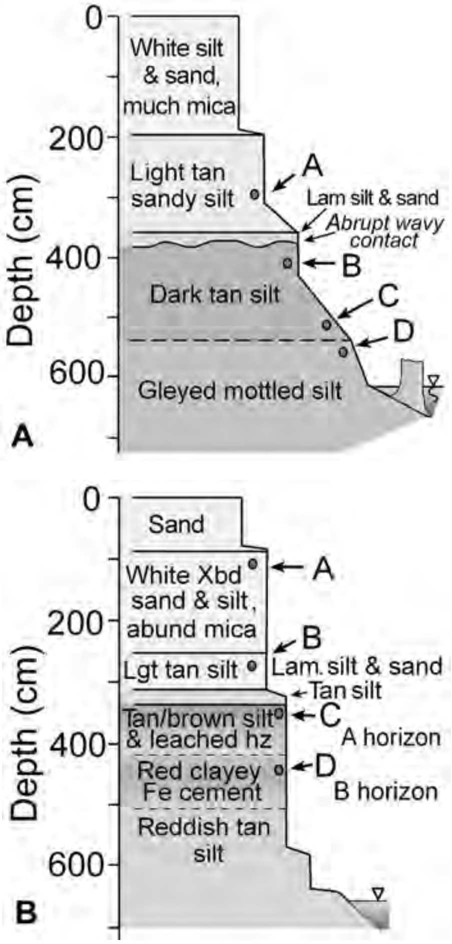

Figure 15. Stratigraphic sections of Feather River right-bank exposures. (A) Above Shanghai Bend, historical sediment is ~5.5 m thick. Total mercury concentrations in sediment samples A through D were 0.18, 0.47, 0.35, and 0.05 ppm, respectively. Stump rooted in unit D has a ^{14}C date of ~1885 (65 ± 35 yr BP). (B) Below Shanghai Bend a distinct soil marks a pre-mining surface ~3.3 m deep. Total mercury concentrations in units A and B were 0.10 and 0.14 ppm, respectively, signifying mining sediment, versus background values of 0.04 ppm in units C and D.

Feather River Changes near Star Bend

The earliest available historic maps indicate that Star Bend was largely stable throughout the period of mining and to the present. A large pre-mining island was mapped above Star Bend (Von Schmidt, 1859) that evolved into a broad meander bend through abandonment of the western channel. The west branch of the bifurcated channel was gone by 1909 (CDC, 1912). The east branch has not moved much and forms a large-amplitude meander above Star Bend that has remained horizontally stable (U.S. Department of Agriculture, 2006). The lower meander of Star Bend was largely stable from 1859 to the present, although the wavelength of the lower southern limb increased as the channel shifted ~500 m to the southeast by 1909 (CDC, 1912), leaving O'Connor Lake on the inside of the bend where the pre-mining channel had been.

Feather River Changes near Bear River Confluence

Large alternating point bars were present between Star Bend and the Bear River confluence in 1909 (CDC, 1912), in 1949 on an orthophotograph (U.S. Bureau of Reclamation [USBR], 1949), and on 6 May 1975 aerial photographs. The longitudinal bars were severely scoured by 3 November 1986 after a record flood, and the sinuosity of this reach has remained substantially less than it was in 1909. Farther downstream on the Feather River, two large islands were mapped in 1859, one above the present Bear River confluence, and another at the confluence. The upper island is shown on later maps (Doyle, 1887; Crook, 1914) but is shown on some maps as a large bar with a dominant eastern channel and a western channel remnant that is no longer connected on the upstream end (Hoffmann and Craven, 1873; Hall, ca. 1880a). The island is not shown on two 1895 maps (Manson and Grunsky, 1895a, 1895b), so its presence later (Crook, 1914) may be an artifact of cartographic replication of an older map, or it may indicate that the western channel was only a high-water channel. The lower island at the Bear River confluence persisted from 1859 through 1895 (Von Schmidt, 1859; Pennington, 1873; Hall, ca. 1880a; Doyle, 1887; Manson and Grunsky, 1895a, 1895b). By 1909 (CDC, 1912), however, this lower island had been converted to a point bar, with the eastern channel forming a high-amplitude meander bend, and the western channel reduced to a small lake (Rideout Lake) sealed off from the Feather River at the north and south ends. Both islands are missing on later aerial photographs (USBR, 1949; California Transportation Agency, 1952), and the sinuosity of this area of the Feather River is now greatly reduced (U.S. Department of Agriculture, 2006).

Sedimentation, channelization, and channel shifting were pervasive at the Feather-Bear confluence during the mining period. The Feather River channel was obscured in this area in the late 1870s (Hall, 1880). Berry, a local resident, described ditches and levees in the area that diverted flows and described widespread sedimentation and channel filling in the area coming from both the Bear and Feather Rivers:

> … the whole country outside of that levee is covered with deposit, and the channel filled in below; and what was formerly the mouth and lowland is all covered over, more or less… [with debris] from the Bear River and from the Feather [can't tell which]. Berry; testimony in 1876. (*Keyes v. Little York Gold Washing Co. et al.*, 1879)

The bed of the Feather River in this vicinity is now dominated by extensive sand sheets that are presumably dominated by reworked historical sediment (Fig. 16). During low water in June 2007, broad areas on the sand sheets were <12 cm deep.

Feather River Changes below Nicolaus

About 3 km downstream of the small town of Nicolaus, just before the Feather River enters Sutter Bypass, a large meander loop in the pre-mining channel had deflected flows to the north (Fig. 17). This bend, henceforth referred to as *Nelson Bend*, preceded the mining period and is shown on several early maps (Mileson and Adams, 1851; Von Schmidt, 1859; Pennington, 1873). The pre-mining Feather River was much more sinuous through this reach than at present. During the mining period, levees were constructed along the inside of the bend that forced flood flows through the circuitous meander (Pennington, 1873; Hall, ca. 1880a; Manson and Grunsky, 1895a). By 1909, the levee along the inner bend had been removed and a shallow "Overflow Channel" is mapped across the base of the bend (Fig. 17B). The bend is shown in the process of being cut off on a flood-control map (California Department of Public Works, 1925) where the bend is labeled "Nelson Bend" and the straight channel is labeled "Cutoff." It is not known if dredging was involved. By June 1952 the Feather River had completely shifted into the cutoff where it now flows, and Nelson Bend was largely filled with alluvium.

Channel aggradation by hydraulic mining sediment extended through the lower Feather River to the Sacramento River. By 1879 the bed of the Feather River near the Sacramento River confluence had risen between 0.9 and 1.2 m (3–4 ft) above its presettlement level (Hall, 1880). At this time, channel narrowing was noted in the Sacramento River between the mouth of the Feather River and the City of Sacramento, where channel deposits had been colonized by willows, and high pre-mining banks with riparian forest were set back from the contemporary channel margin (Mendell, 1882). Historic maps indicate that channel narrowing also occurred within the lower Feather River below Nelson Bend owing to development of alternating bars and a sinuous thalweg. Alternating longitudinal bars that cover approximately half a channel width were mapped by a topographic survey of the lower Sacramento River, which included the lower Feather River near the confluence (Hall, ca. 1880b). Alternating bars were also mapped in these reaches of the Feather River in 1909 (CDC, 1912) at a wavelength of ~12 low-flow channel widths. Alternating bars appear on a 1966 aerial photograph at a shorter wavelength of eight low-flow channel widths or four bankfull channel widths (Fig. 18). These post-mining bars indicate that channel narrowing was due to deposition of bed material in point bars. No bars are visible on aerial photographs flown 20 June 1958, 28 May 1964, 6 May 1975, and 10 November 1986 after a record flood, but they are present on 4 August 1966 aerial photographs (Fig. 18B). The disappearance and reappearance of bars indicate scouring and redeposition, and the transport of large volumes of sediment.

Below the zone of alternating bars, several crevasses were shown in the west bank railroad embankment in 1909 (Fig. 19). Crevasse splays of hydraulic mining sediment are likely to have been deposited through these crevasses during the late nineteenth century. Most of this railroad embankment had been removed by the time the Sutter Bypass was completed, although some rock and boulders remain. Levee spacings are now ~2 km wide in the lower Feather River along Sutter Bypass (Fig. 3).

Figure 16. Sand sheets in bed of Feather River below the Feather-Bear confluence are composed largely of legacy sediment from the hydraulic-mining era. October 1998. (Source of photo: California Department of Water Resources.)

DISCUSSION AND CONCLUSIONS

This paper uses historical and stratigraphic data to constrain the timing and location of major channel changes. Modern geospatial processing methods can be applied to historical maps and have ushered in a new era of historical cartometrics. Yet, simple examination of unrectified historical maps may provide crucial information about the dynamics of river-channel change over historical time periods. Historical analyses illustrate a variety of past and ongoing channel morphological changes that are relevant to management of these rivers. Channels in the Yuba and Feather Rivers appear to have been more similar in character in the premining period than after sedimentation commenced. Both channels were somewhat sinuous with occasional large, stable islands. The timing and style of channel changes in response to hydraulic

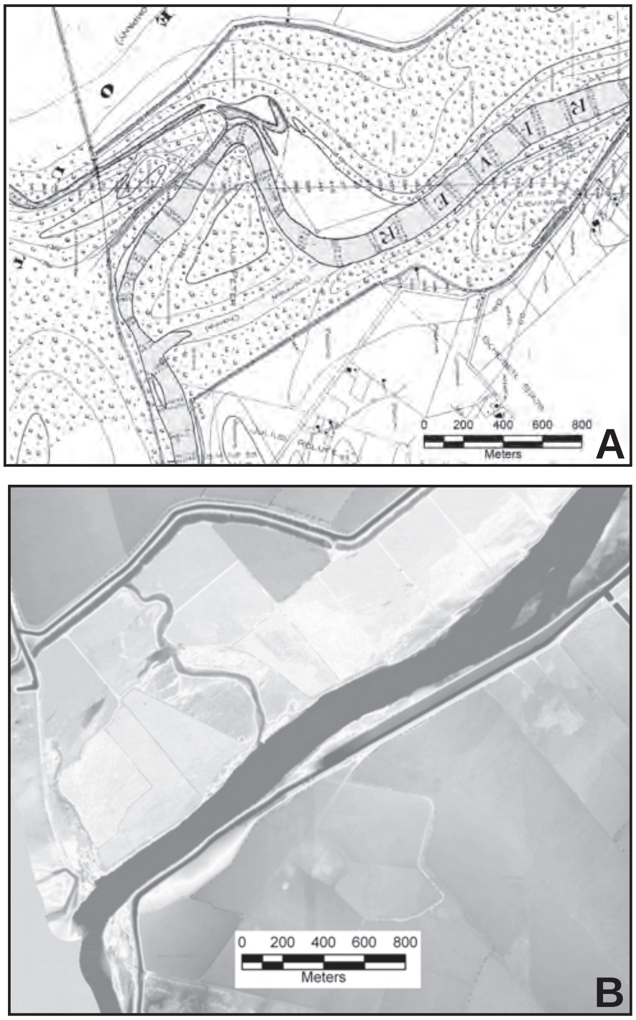

Figure 17. Lower Feather River at Sutter Bypass confluence. (A) 1909 CDC map: incipient cutoff of Nelson Bend. (B) Shaded-relief map with oxbow lake largely filled in 1999. Derived from LiDAR, a digital elevation model (DEM), and sonar channel bathymetry (Stonestreet and Lee, 2000; Towill, Inc., 2006).

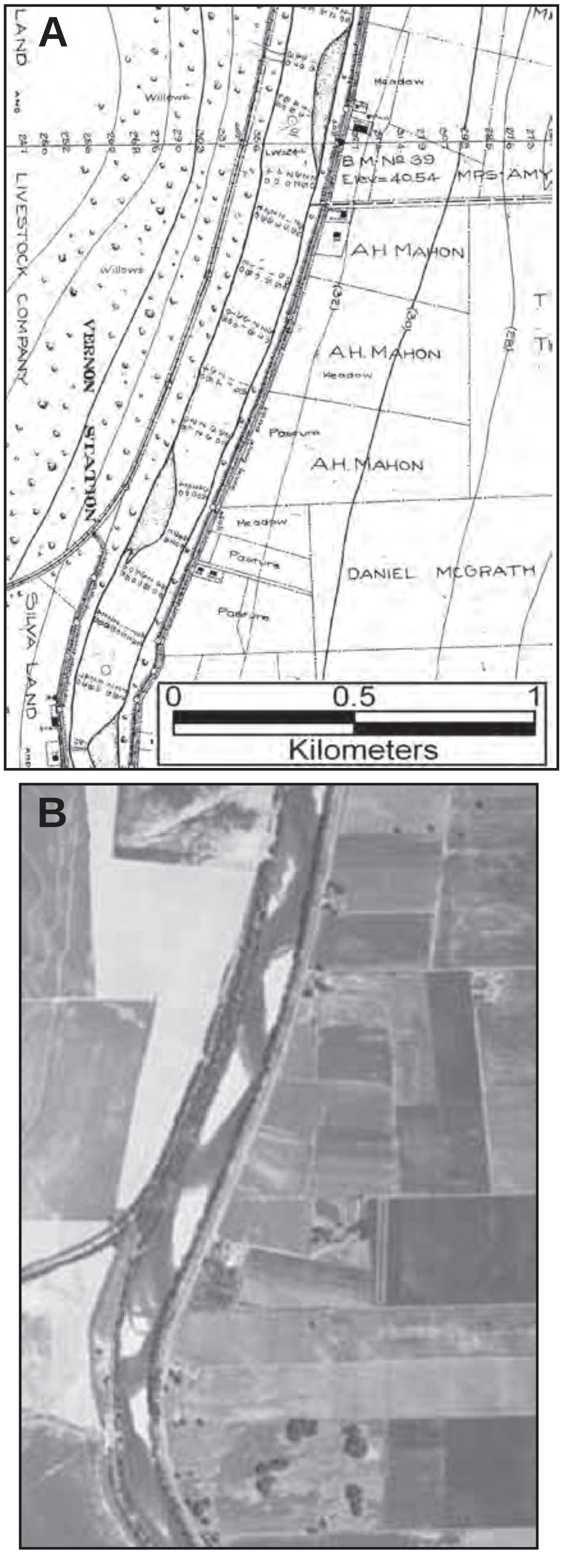

Figure 18. Alternating longitudinal bars on lower Feather River from the beginning of Sutter Bypass to the Sacramento confluence. (A) Long-wavelength bars on 1909 map (CDC, 1912). (B) Short-wavelength bars on 4 August 1966; aerial photograph (Earth Resources Observation System [EROS], 1966).

mining differed greatly between the two rivers. The Yuba River underwent major morphologic changes early in the mining period, including deep and broad channel and floodplain deposition that resulted in cutoffs of meander bends, channel avulsions, and development of distributary channels. Signs of morphologic change in the Yuba River had begun to appear by the mid-1860s and were in advanced stages by the time of topographic surveys in 1879 (Hall, 1880; Mendell, 1880, 1882). Channels continued to change through the turn of the twentieth century, when the Yuba floodplain was shown on large-scale (1:9,600) maps supporting a broad multithread high-water channel system. After 1906, channel changes on the Yuba River appear to have decreased in magnitude. Substantial amounts of local erosion and sedimentation can be documented by planimetric analysis of channel changes in recent years—e.g., lateral channel migration in the Yuba Gold Fields between 1999 and 2006—but large-scale channel avulsions were less common in the twentieth century, presumably owing to hardening of the flood-conveyance system with wing dams and riprap.

Morphologic changes in the Feather River were associated more with a single large channel shifting or avulsing, which occurred later than in the Yuba River. Some of the changes can be attributed to large-scale channelization and levee projects. Several large, pre-mining meander bends and islands on the Feather River persisted until the twentieth century. For example, Elisa Bend and Nelson Bend remained through 1909 (CDC, 1912), and Star Bend has remained largely unchanged to the present. In addition, large islands above Elisa and Star Bends persisted with minor changes until 1909. By 1909, however, the Feather River began showing signs of major morphologic change. Two large islands near the Bear River confluence were gone by 1909, probably because of hydraulic-mining sediment delivered by Bear River. Channel dredging is clearly associated with at least one of the changes—the westward avulsion of Elisa Bend and possibly the Nelson Bend cutoff. The Feather River continues to flow in most of the lower 4.8-km-long dredged channel below Shanghai Bend. The relatively cohesive older alluvium of this artificial channel helps to stabilize the channel and inhibits lateral migration. Abandonment of channels around islands may reflect increased sediment loads that encouraged construction of natural levees and longitudinal bars. This interepretation is supported by maps that show the upstream ends of channels being sealed before the downstream ends. Morphologic changes in the Feather River continued after the turn of the twentieth century. Comparison of detailed topographic maps surveyed in 1906 and 1909 at Shanghai Bend and the Feather-Yuba confluence reveal extensive changes caused by the 1907 flood (CDC, 1906, 1912).

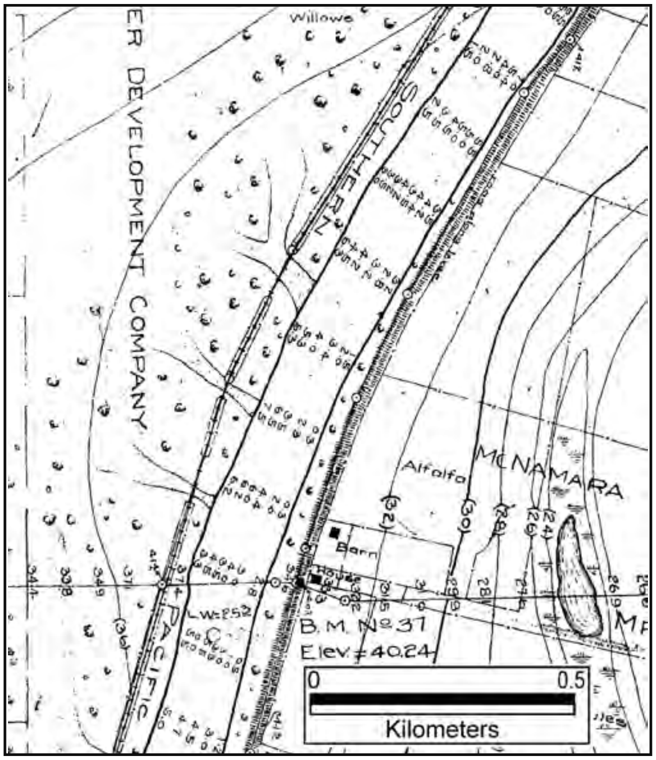

Figure 19. Crevasses through Southern Pacific Railroad embankment delivered water and sediment from lower Feather River to Sutter Basin. (Source: CDC, 1912.)

A schematic diagram summarizing contrasts between the lower 10 km of the Yuba River and the lower Feather River below the Yuba confluence during three time periods is shown in Figure 20. In the late nineteenth century (ca. 1880; T1 in Fig. 20) the lower Yuba River was undergoing deep aggradation and channel instability. In the upper fan area above Parks Bar the channel had aggraded by ~18 m, and this thickness decreased downstream to 5 or 6 m near Marysville. Deposits increased in lateral extent downstream, reaching widths up to 4 km. Attempts to dam or constrict the channel with levees failed, so a system of widely spaced levees evolved that encouraged sediment deposition and channel shifting across a wide floodway. Multiple high-water channels, frequent avulsions, and local braiding characterized the lower Yuba River during this period. Changes to the lower Feather River in the late nineteenth century were quite different. Sediment deliveries were less and finer grained, overbank sedimentation was less extensive, stream powers were larger, and channels maintained lateral positions. Nevertheless, bed aggradation was severe near the Yuba and Bear River confluences. Low-flow channel-bed elevations rose throughout the lower Feather River below the Yuba confluence to the Sacramento River. Between the mouth of the Feather River and the City of Sacramento, the bed of the Sacramento River had risen ~1.5 m (5 ft) and narrowed (Mendell, 1882).

By the turn of the twentieth century (T2 in Fig. 20), the tendency for channel-bed aggradation in the Yuba had shifted to lower reaches. Channel beds in the upper reaches above Parks Bar had begun to incise, abandoning floodplains as terraces that continued to receive overbank deposits. Channel beds near Marysville incised in response to extensive channel dredging and establishment of narrow levees near the Feather River confluence. By 1906 a long reach of the main lower Yuba channel, 5–10 km above Marysville, had returned to its pre-mining position. Multiple high-water channels remained active in the Yuba River, but main channel incision and enlargement lowered the frequency of flows in these channels. Hardening of the main Yuba channel, including revetment and wing dams, stabilized the banks, narrowed moderate-magnitude flows, and encouraged incision. Levee spacings remained wide, however, so large flows spread out and overbank deposition continued during large floods, such as in 1907 and 1909. In contrast, the lower Feather River during the period 1900–1910 began to undergo lateral channel changes. Some of this activity was caused by dredging and by levees in addition to responses to mining sediment. For example, the channel avulsion from Elisa Bend to Shanghai Bend was encouraged by levee encroachment upstream that shifted the attack angle into the bend and a dredged channel that cut off flows above Elisa Bend. During this period, narrow levee cross-channel spacings along the lower Feather River severely constricted flood flows, reduced bed aggradation, and limited lateral channel adjustments. Some early mid-channel islands, which had been stable through the mining period, were converted to meander bends by sedimentation of one of the channels.

During the second half of the twentieth century, main channel erosion continued in the lower 10 km of the Yuba River, but lateral changes were relatively minor. Bank stabilization continued to limit the ability of the main channel to erode laterally while wide floodways continued to spread overflows across broad areas, reducing shear stresses that could have otherwise generated new channels or enlarged high-water channels. Stream regulation upstream also reduced sediment deliveries and magnitudes of peak flows. Several small high-water channels were abandoned—many leveled by agricultural activities—but a few remained active as flood bypass channels. In the Feather River,

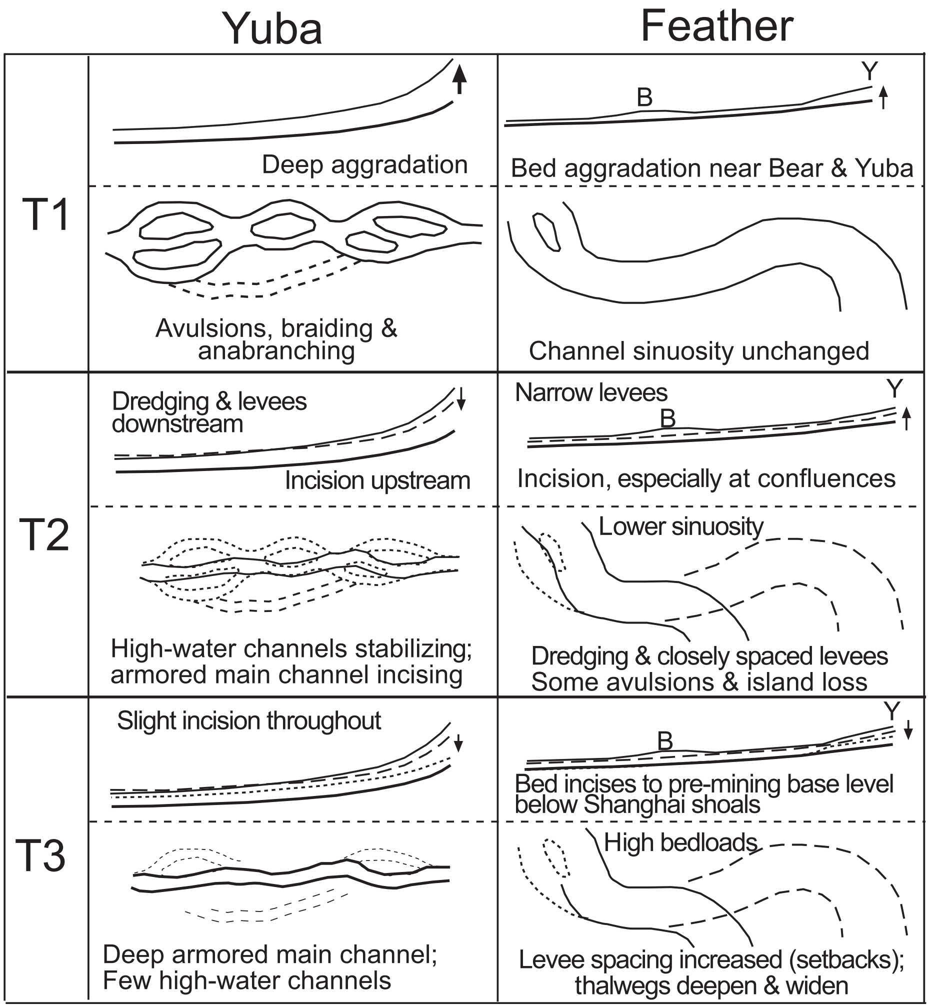

Figure 20. Schematic representation summarizing Yuba and Feather River morphologic changes for three periods (simplified and not to scale). Yuba River long profiles for each period extend from below bedrock canyon (below Narrows) to Marysville. Feather River profiles are from Yuba confluence to mouth at Sacramento. Map views are at a larger, reach scale. T1—1880; T2—1900–1910; T3—1950–1999.

levee setbacks before 1950 reduced flow depths and increased conveyance. Levee spacings remained small relative to the smaller Yuba River, however, and this continued to encourage bed scour, although large amounts of bed material remain as vestiges of the mining era. Lateral migration can be seen in many channel reaches on modern aerial photographs, but the rates are less than those earlier in the twentieth century (T2 in Fig. 20), when lateral channel changes were substantial.

The strong differences in channel morphological change between the Yuba and Feather Rivers were due in part to contrasting styles of river management. In essence, an experiment in river engineering was initiated in the late nineteenth century, and the results reveal a lesson in how large rivers respond to such management in the long term. Explanations for slower, more subtle changes on the Feather than on the Yuba River include less mining sediment, finer sediment, later arrival, and the differences in large-scale river engineering efforts. The contrasting styles of river management between the lower Yuba and Feather Rivers amplified other differences between the two systems and are manifested in modern fluvial forms. An emphasis on navigation resulted in narrowly spaced levees on the Feather River, which constrained deposition and the ability of the river to change in planform. Levee cross-channel spacings appear to have been successful at promoting bed scour, although large sand sheets in the modern bed indicate that this is an ongoing process. Less extensive twentieth century changes to the Yuba River planform probably reflect structural bank-protection measures and may not have applied in areas such as the Yuba Gold Fields or upstream where these measures are lacking.

The geomorphic importance of legacy hydraulic-gold-mining sediments in the Yuba and Feather Rivers needs to be carefully considered by river managers in the region. For many years a conceptual model of regional sediment transport prevailed that led to an oversimplified view of the mining sediment either passing through piedmont rivers or being permanently stored there. Flaws with this viewpoint arise when sediment budgets are considered over longer time scales, when historical data are consulted at higher spatial and temporal resolutions, or when the importance of sediment remobilization is considered from the viewpoint of flood or toxic hazards.

Some theoretical lessons can be learned from the behavior of these rivers. Detailed historical information indicates that channel-bed incision on the Yuba River did not progressively translate downstream from the Narrows to Marysville as sediment-wave theory predicts. Based on an analysis of low-flow stage elevations at the two sites, Gilbert (1917, p. 30; cf. Gilbert's Fig. 4) concluded that peak elevations of aggraded channels passed through the Narrows upstream of Smartsville ~1900 and passed Marysville by 1905. By this model, little time separated the initiation of bed degradation in the upper debris fan from the fan toe at Marysville. Gilbert's field notes, however, show that the spatial and temporal patterns of degradation above Marysville were more complex and slower, and that channel degradation did not simply progress downstream from the Narrows to Marysville. Degradation that began at the Marysville gauge in 1905 apparently preceded degradation upstream at Parks Bar, ~20 km above Marysville and 5 km below the Narrows. In fact, early channel incision at the Marysville D Street gauge may have been a response to two human alterations of the channel in that area. The channel had been constricted by levees spaced only 640 m apart at the gauge location, and dredging of a new confluence directly below the gauge took place shortly before 1905.

Field and historical evidence indicate that mine tailings have persisted in many locations along the Yuba and Feather River floodplains, and in most cases these deposits are not protected from erosion by levees or dams. Most of the storage is in high terraces that formed during the period of maximum aggradation, but much sediment is stored within the channels. The thickness of historical sediment in terraces varies in the longitudinal and lateral dimensions. On the Yuba River, historical sediment depths thin downstream from the fan apex to Marysville. Three recent topographic surveys measured the thickness of historical sediment in a sequence progressing downstream. The sections record a minimum thickness of 10.5 m above the low-water surface exposed in a historic terrace at Forbes Ranch ~6 km below the Narrows, a deposit 7 m thick in a south-bank exposure ~8 km above Marysville, and a 5.8-m-thick deposit in the north bank at Marysville.

On the Feather River, historical sediment in stream-bank exposures ranges from 1 to 5 m thick, depending on proximity to the Yuba and Bear River confluences and the history of lateral channel displacement. Thicknesses decrease abruptly below Shanghai Bend because an avulsion shifted the channel away from the deepest historical deposits. Knowledge of former channel positions is crucial to locating deep repositories of historical sediment. Approximately 10 million cubic meters of historical sediment is stored behind the west levee above Shanghai Bend, largely under a residential development. Total mercury concentrations (0.41 ppm) in a silt cap exposed in the bank along this deposit indicate toxicity and suggest that more testing is needed on the west side of the levee. Such storage that is isolated by levees and urbanized is not representative of most Yuba and Feather River deposits. Soil maps indicate that most of the historical sediment storage in these rivers is between the main levees, although many of the Yuba River floodplain deposits are stabilized by wing dams and riprap on channel banks. Large amounts of bed material are present along or within the main channels, including dredge spoils and gravel bars in the Yuba River and sand bars and sand sheets in the lower Feather River. Floodplain overbank deposition and abandoned channel filling are ongoing during floods except where lands are protected by levees or other structures (Eckbo, Dean and Williams, 2006; section 5.2, p. 7).

A recent study of the lower Feather River was conducted as part of an environmental impact assessment for a levee setback project (Eckbo, Dean and Williams, 2006; section 5.3, p. 27). The study conducted HEC-6 numerical sediment transport analyses for large floods and concluded that most channel degradation on the Feather River had been completed by the mid-1960s, that further degradation was unlikely within "an engineering time frame (50 years)," that channel base levels are controlled by sedimentation from the Yuba and Bear Rivers, and the channel is stable at these time scales. It concluded that the channels will remain relatively stable as long as hydraulic-mining debris stored in these channels continues to supply sediment. Ultimately ("hundreds to thousands of years in the future"), however, as sediment supplies decrease, the rivers will likely cut down to pre-mining elevations and begin migrating laterally. From an engineering perspective of evaluating channel hydraulic conditions, this interpretation may be largely correct with one important exception. The headward migration of the shoals below Shanghai Bend could lower base levels 3 m and initiate a major geomorphic response upstream. Comparison of 1999 sonar bathymetry with the DOQQs (U.S. Department of Agriculture, 2006) indicates that the shoals propagated 150 m upstream over that period. The 1999 bathymetry shows that <160 m separates the 2006 position of the shoals from a deep pool in the main channel upstream. Once the resistant bench is breached, an episode of channel incision generated by a 3-m base-level lowering could propagate up to the extensive historical deposits in the Yuba Gold Fields at DaGuerre Point Dam. The implications of this scenario are so far-reaching that a detailed hydraulic analysis should be conducted to test likely river responses to breaching of the shoals.

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REFERENCES CITED

Bernhardt, E.S., Palmer, M.A., Allan, J.D., Alexander, G., Barnas, K., Brooks, S., Carr, J., Clayton, S., Dahm, C., Follstad-Shah, J., Galat, D., Gloss, S., Goodwin, P., Hart, D., Hassett, B., Jenkinson, R., Katz, S., Kondolf, G.M., Lake, P.S., Lave, R., Meyer, J.L., O'Donnell, T.K., Pagano, L., Powell, B., and Sudduth, E., 2005, Synthesizing U.S. river restoration efforts: Science, v. 308, p. 636–637, doi: 10.1126/science.1109769.

California Debris Commission (CDC), 1906, Map of the Yuba River, California from the Narrows to its mouth in the Feather River. Made under direction of Major Wm. W. Harts, U.S. Army Corps of Engineers, by G.G. McDaniel, Jr., August to Nov., 1906: scale 1:9,600.

California Debris Commission (CDC), 1912, Map of Feather River, California from Oroville to Southerly Limit of Gold Dredging Grounds. Surveyed under direction of Capt. Thos. H. Jackson, U.S. Army Corps of Engineers by Owen G. Stanley, Sept. to Oct., 1909: scale 1:9,600, 18 sheets.

California Department of Public Works (CDPW), 1925, Revised Sacramento Flood Control Project: Maps and Charts, sheet 1 of 7.

California Transportation Agency (CalTrans), 1952, Aerial photographs flown June 22, 1952. AAZ-1K-182-184: California State Archives, Box 9 of 9.

Chamberlain, W.H., and Wells, H.L., 1879, History of Yuba County, California: A Memorial and Biographical History of Northern California: Oakland, California, Thompson & West, 150 p.

Crook, L.B., 1914. Official map of Yuba County, California/Compiled from official records and surveys: San Francisco, Bashford Smith, University of California, Berkeley, Earth Science Library, scale 1:63,360, 1 sheet.

Doyle, J.M., 1887, Yuba County, State of California: University of California, Davis, Map Library, scale 1:125,000, 1 sheet.

Earth Resources Observation System (EROS), 1966, U.S. Geological Survey Historic Aerial Photograph Catalog System: http://edc.usgs.gov/products/aerial.html (July 2007).

Eckbo, Dean and Williams (EDAW), 2006, Final environmental impact report for the Feather River levee repair project: An element of the Yuba-Feather supplemental flood control project. Vol. I: Ch. 5. Report for Three Rivers Levee Improvement Authority: http://www.trlia.org (July 2007).

Ellis, W.T., 1939, Memories; My Seventy-Two Years in the Romantic County of Yuba, California; Introduction by Richard Belcher: Eugene, University of Oregon, 308 p.

Gibbes, C.D., 1852, A new map of California by Charles Dayton Gibbes from his own and other recent surveys and explorations: New York, Sherman & Smith, Sacramento, California State University, scale 1:1,330,560, 1 sheet.

Gilbert, G.K., 1905, 1907, 1913, Excerpts from unpublished field notes: Transcribed by L.A. James at National Archives, Washington, D.C.

Gilbert, G.K., 1917, Hydraulic-Mining Debris in the Sierra Nevada: U.S. Geological Survey Professional Paper 105, 154 p.

Gilvear, D.J., and Harrison, D.J., 1991, Channel change and the significance of floodplain stratigraphy: 1990 flood event, Lower River Tay, Scotland: Earth Surface Processes and Landforms, v. 16, p. 753–761, doi: 10.1002/esp.3290160809.

Gilvear, D.J., and Bryant, R., 2003, Analysis of aerial photography and other remotely sensed data, *in* Kondolf, G.M., and Piégay, H., eds., Tools in Fluvial Geomorphology: Hoboken, New Jersey, Wiley & Sons, p. 135–170.

Graf, W.L., 1996, Geomorphology and policy for restoration of impounded American rivers: What is "natural"? *in* Rhoads, B.L., and Thorn, C.E., eds., The Scientific Nature of Geomorphology, Proceedings of Binghamton Symposium, 27th, 27–29 September 1996: New York, Wiley & Sons, p. 443–473.

Greenland, P., 2001, Hydraulic Mining in California: A Tarnished Legacy: Spokane, Washington, Arthur H. Clarke, 320 p.

Gregory, K.J., 2006, The human role in changing river channels: Geomorphology, v. 79, p. 172–191, doi: 10.1016/j.geomorph.2006.06.018.

Gurnell, A.M., Peiry, J.L., and Petts, G.E., 2003, Using historical data in fluvial geomorphology, *in* Kondolf, G.M., and Piégay, H., eds., Tools in Fluvial Geomorphology: Hoboken, New Jersey, Wiley & Sons, p. 77–101.

Hall, W.H., 1880, Report of the State Engineer to the Legislature of California, Session of 1880: Sacramento, California Printing Office.

Hall, W.H., ca. 1880a, Part of Sutter County along Feather River showing property ownership. Hand-inked map on parchment with survey notes: Sacramento, California State Archives, item 5290-33.

Hall, W.H., ca. 1880b, Sacramento River from American River to Knights Landing. Survey line of river. Hand-inked map on parchment with survey notes: Sacramento, California State Archives, item 5290-52.

Hoffmann, C.F., and Craven, A., 1873, Map of the Tertiary auriferous gravel deposits lying between the middle fork of the American and the middle Yuba Rivers, *in* Memoirs of the Museum of Comparative Zoology, V. VI, Part I. J.D. Whitney: University of California, Davis, Map Library, scale 1:63,360, 1 sheet.

Hooke, J.M., and Kain, J.P., 1982, Historical Changes in the Physical Environment: A Guide to Sources and Techniques: London, Butterworth, 236 p.

Hughes, M.L., McDowell, P.F., and Marcus, W.A., 2006, Accuracy assessment of georectified aerial photos: Implications for measuring lateral channel movement in a GIS: Geomorphology, v. 74, p. 1–16, doi: 10.1016/j.geomorph.2005.07.001.

Hunerlach, M.P., Alpers, C.N., Marvin-DiPasquale, M., Taylor, H.E., and De Wild, J.F., 2004, Geochemistry of Mercury and Other Trace Elements in

Fluvial Tailings Upstream of Daguerre Point Dam, Yuba River, California, August 2001: U.S. Geological Survey Scientific Investigations Report 2004-5165, 66 p.

James, L.A., 1989, Sustained storage and transport of hydraulic mining sediment in the Bear River, California: Annals of the Association of American Geographers, v. 79, p. 570–592, doi: 10.1111/j.1467-8306.1989.tb00277.x.

James, L.A., 1991, Quartz concentration as an index of alluvial mixing of hydraulic mine tailings with other sediment in the Bear River, California: Geomorphology, v. 4, p. 125–144, doi: 10.1016/0169-555X(91)90024-5.

James, L.A., 1994, Channel changes wrought by gold mining: Northern Sierra Nevada, California, *in* Marston, R., and Hasfurther, V., eds., Effects of Human-Induced Changes on Hydrologic Systems: American Water Resources Association, p. 629–638.

James, L.A., and Singer, M.B., 2008, Development of the lower Sacramento Valley flood-control system: An historical perspective: Natural Hazards Review (in press).

Kelley, R., 1954, Forgotten giant: The hydraulic gold mining industry in California: Pacific Historical Review, v. 23, p. 343–356.

Kelley, R., 1959, Gold vs. Grain: The Hydraulic Mining Controversy in California's Sacramento Valley: Glendale, California, Arthur H. Clarke, 327 p.

Kelley, R., 1989, Battling the Inland Sea: American Political Culture, Public Policy, and the Sacramento Valley, 1850–1986: Berkeley, University of California Press, 395 p.

Keyes v. Little York Gold Washing Co. et al., 1879, *53 Cal. 724, California Supreme Court*.

Kondolf, G.M., and Larson, M., 1995, Historical channel analysis and its application to riparian and aquatic habitat restoration: Aquatic Conservation, v. 5, p. 109–126, doi: 10.1002/aqc.3270050204.

Kondolf, G.M., and Micheli, E.R., 1995, Evaluating stream restoration projects: Environmental Management, v. 19, p. 1–15, doi: 10.1007/BF02471999.

Manson, M., and Grunsky, C.E., 1895a, Sutter Basin. Compiled from surveys made and data collected by the late State Engineer Dept. Commissioner of Public Works, Calif.: University of California, Davis, Map Library, 1 sheet.

Manson, M., and Grunsky, C.E., 1895b, Sacramento Valley from Iron Canon to Suisun Bay. From surveys made by the late State Engineer Dept. Commissioner of Public Works: University of California, Davis, Map Library, scale 1:126,720, 1 sheet.

May, J.T., Hothem, R.L., Alpers, C.N., and Law, M.A., 2000, Mercury Bioaccumulation in Fish in a Region Affected by Historic Gold Mining: The South Yuba River, Deer Creek, and Bear River Watersheds, California, 1999: U.S. Geological Survey Open-File Report 00-367, 30 p.

May, P., 1970, Origins of Hydraulic Mining in California: Holmes Book Co., 88 p.

Mendell, Col. G.H., 1880, Mining debris in Sacramento River: *House Document 69, 46th Congress, 2nd Session:* 11.

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.*

Mendell, Col. G.H., 1882, Report upon a project to protect the navigable waters of California from the effects of hydraulic mining: *House Document 98, 47th Congress, 1st Session:* 110.

Mileson, M., and Adams, R., 1851, A complete map of the Feather & Yuba Rivers with towns, ranches, diggings, roads, distances: Marysville, California, R.A. Eddy, scale 1:475,200, 1 sheet. Original at Berkeley is a negative.

Montgomery, D.R., 2008, Dreams of natural streams: Science, v. 319, p. 291–292, doi: 10.1126/science.1153480.

Mount, J., and Twiss, R., 2005, Subsidence, sea level rise, and seismicity in the Sacramento–San Joaquin Delta: San Francisco Estuary and Watershed Science, v. 3, no. 1:http://repositories.cdlib.org/jmie/sfews/vol3/iss1/art5/ (December 2008).

National Research Council (NRC), 1992, Restoration of Aquatic Ecosystems. Committee on Restoration of Aquatic Ecosystems: Washington, D.C., National Academy Press, 552 p.

Novotny, V., and Chesters, G., 1989, Delivery of sediment and pollutants from nonpoint sources: A water quality perspective: Journal of Soil and Water Conservation, v. 44, no. 6, p. 568–576.

Olmsted, F.H., 1901, Physical characteristics of Kern River, California, by F.H. Olmsted, and Reconnaissance of Yuba River, California, by Marsden Manson: U.S. Geological Survey Water-Supply and Irrigation Paper 46, Washington Printing Office, 57 p.

Patrick, D.M., Smith, L.M., and Whitten, C.B., 1982, Methods for studying accelerated fluvial change, *in* Hey, R.D., Bathurst, J.C., and Thorne, C.E., eds., Gravel-Bed Rivers: Chichester, UK, Wiley & Sons, p. 783–815.

Pennington, J.T., 1873, Official map of Sutter County, California. Compiled and drawn from official surveys: Yuba County, California, Library scale 1:63,360.

Petts, G.E., 1989, Historical change in large European alluvial rivers, *in* Petts, G.E., and Muller, H., eds., Historical Change in Large European Alluvial Rivers: Chichester, UK, Wiley & Sons, p. 1–11.

Pixley, F.M., Smith, J.F., and Watson, N., 1865, Map of the location of the Yuba Railroad from Lincoln to Marysville: Sacramento, California State Archives scale 1:12,000. Excerpt from Long scroll map (>8 ft long by ~14 in. tall).

Public Land Survey System (PLSS), 2001, Downloaded from California Environmental Resources Evaluation System (CERES): http://www.ceres.ca.gov/ (December 2008).

Roehl, J.E., 1962, Sediment source areas, and delivery ratios influencing morphological factors: International Association of Hydrological Sciences, v. 59, p. 202–213.

Singer, M.B., 2007, The influence of major dams on hydrology through the drainage network of the Sacramento Valley, California: River Research and Applications, v. 23, p. 55–72, doi: 10.1002/rra.968.

Singer, M.B., Aalto, R., and James, L.A., 2008, Status of the lower Sacramento Valley flood-control system within the context of its natural geomorphic setting: Natural Hazards Review, v. 9, no. 3, p. 114–115.

Stonestreet, S.E., and Lee, A.S., 2000, Use of LIDAR mapping for floodplain studies, *in* Hotchkiss, R.H., and Glade, M., eds., Proceedings, Building Partnerships—2000 Joint Conference on Water Resource Engineering, Planning, and Management: Minneapolis, Minnesota, American Society of Civil Engineers, doi: 10.1061/40517(2000)58.

Thomas, G.C., 1928, Thomas Brothers map of Marysville and Yuba City: Sacramento, California State Archives.

Towill, Inc., 2006, Project Report for Topographic Surveys of the Lower Feather and Bear Rivers for the Sacramento and San Joaquin River Basins Comprehensive Study, California: Contract no. DACW05-99-D-0005 for U.S. Army Corps of Engineers, Sacramento District.

Trimble, S.W., and Cooke, R.U., 1991, Historical sources for geomorphological research in the United States: Professional Geographer, v. 43, p. 212–228, doi: 10.1111/j.0033-0124.1991.00212.x.

U.S. Army Corps of Engineers (USACE) and State of California Reclamation Board, 1998, Yuba River Basin Investigation, California: Draft Feasibility Report, Appendixes and Environmental Impact Statement/Environmental Impact Report: USACE Sacramento District.

U.S. Bureau of Reclamation (USBR), 1949, Controlled mosaic compiled at 1:19,200 by Fairchild Aerial Surveys from 1:20,000 photography dated March, April, and May, 1949: Sacramento Archives.

U.S. Department of Agriculture (USDA), 2006, Digital Orthophoto Quarter Quad Mosaic. National Agriculture Imagery Program (NAIP), Aerial Photography Field Office: Salt Lake City, USDA FSAS APFO, acquired 8 September 2006.

Von Schmidt, A.M., 1859, Plat of the New Helvetia Rancho finally confirmed to John A. Sutter. Surveyed under instructions from the U.S. Surveryor General by A.M. Von Schmidt, Deputy Surveyor, September–October 1859: Sacramento Archives, scale 80 chains to an inch (1:63,360), 1 sheet.

Walling, D.E., 1983, The sediment delivery problem: Journal of Hydrology, v. 65, p. 209–237, doi: 10.1016/0022-1694(83)90217-2.

Walter, R.C., and Merritts, D.J., 2008, Natural streams and the legacy of water-powered mills: Science, v. 319, p. 299–304, doi: 10.1126/science.1151716.

Wescoatt, N., 1861, Official map of Yuba County, California: San Francisco, Lith. Britton & Co., University of California, Davis Map Library, scale ca. 1:63,360, 1 sheet.

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