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Designing forward with an eye to the past: Morphogenesis of the lower Yuba River

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ABSTRACT

The early geomorphic evolution of the lower Yuba River (LYR), northern California, up to 1906 is reconstructed using cartographic, documentary, topographic, and stratigraphic evidence. The importance of early river mining is identified along with rates and patterns of floodplain aggradation and channel incision at the turn of the 20th century. The LYR is a classic example of anthropogeomorphic transformation of a river by episodic hydraulic mining sedimentation. This was followed by channelization, damming, dredging, and other engineering works to redirect, contain, and stabilize channels. These geomorphic changes and engineering controls continue to govern channel and floodplain form and process, control the trajectory of river responses, and constrain flood control, water quality, and aquatic ecosystem management options.

Returning a river system to a prior condition should not be the primary goal of river rehabilitation projects, especially if hydrologic inputs have substantially changed. Reconstructing former conditions may be impractical and unsustainable under modern circumstances. Instead, fluvial systems should be designed and managed for present inputs and processes while anticipating future conditions. Rapid changes in land use and climate that generate changes in runoff and sediment loadings are likely to generate morphological instability, and these changes should be considered in the design and management of fluvial systems. The past geomorphic evolution of fluvial systems should also be considered in design and management decisions to recognize trajectories and suppressed tendencies. Recognition of trends and system vulnerabilities may avoid potential blunders, such as removing critical stabilizing works. Complex causalities may be difficult to reconstruct from geomorphic form alone, however, due to process-form dynamics. Detailed research on the geomorphic and engineering history of a river is essential, therefore, if substantial changes and morphologic instabilities have occurred.

1. Introduction

River channel changes have been a central concern of geomorphologists for many generations (Gilbert, 1917; Leopold et al., 1967; Gregory, 2007). Fluvial systems are dynamic and the geomorphology of most alluvial rivers bears little resemblance to their past forms and processes. Historical channel-change data—as broadly construed by this study—include stratigraphic, pedogenic, sedimentologic, geochronologic, documentary, cartographic, and remote sensing information that may provide empirical evidence of changing channel and floodplain conditions through time. These changes are often accelerated and amplified if not directly caused by human activities. Geomorphologists have directed an increasing focus on fluvial changes caused by humans (Gilbert, 1917; Happ et al., 1940; Wolman, 1967; Knox, 1977; Wohl, 2001; Gregory, 2006; James and Marcus, 2006). Recognition that a river has gone through such transformations is essential to sound management.

The Yuba River is a classic example of anthropogenic fluvial change, which was made famous by a widely cited monograph by G.K. Gilbert (1917). Gilbert detailed a watershed-scale sediment budget that demonstrated the overwhelming effects of hydraulic mining sediment (HMS) in the basin and beyond to the Sacramento River and San Francisco Bay. The lower Yuba River (LYR) examined by this study is an alluvial fan emanating from the western margin of the Sierra Nevada that extends onto Sacramento Valley alluvium. The LYR was so completely overwhelmed with anthropogenic sediment that flooding and channel avulsions could only be controlled by massive engineering works that persist today. The LYR is not a typical river in this respect, but demonstrates the futility of efforts to restore some severely altered systems to pristine conditions, the importance of historical knowledge to recognizing the functionality of engineering works, and the danger of altering engineered systems without full understanding of the long-term system dynamics. The LYR has an iconic history of gold mining sediment and river engineering that has much to teach geomorphologists and river managers. Yet, little modern research has been done from an historical geomorphic perspective. Several river studies have documented recent geomorphic changes; some at finer resolutions such as pool-riffle sequences (White et al., 2010; Carley et al., 2012) or individual morphologic units (Wyrick and Pasternack, 2014a; Wyrick et al., 2014). A geomorphic change-detection based on surveys conducted in 1999, 2006, and 2008 indicates net annual erosion of 17,160 m^3 (22,450 yd^3) in the LYR after 1999, which was attributed to sediment trapping behind Englebright Reservoir (Wyrick and Pasternack, 2014b). Previous long-term historical studies of the LYR include a

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re-examination of the sediment wave concept (James, 2006), studies of channel and floodplain change between 1906 and 1999 based on DEM differencing (Ghoshal et al., 2010; James et al., 2012), a stratigraphic analysis of HMS (James et al., 2009), and a synthesis of historical fan evolution and mercury contamination (Singer et al., 2013). Preliminary analysis of historical data introduced by James et al. (2009) is greatly expanded upon by this paper.

As an example of the importance of geomorphic history, the early geomorphic history of the LYR is reconstructed here based on stratigraphy, historical documents, and maps. The analysis begins with a deeply buried Tertiary canyon, turns to channel conditions at the time of Anglo-American contact, impacts of in-channel river mining in the mid-1850s, and influx of mining sediment after 1857. A critical period followed through the early 20th century with river adjustments and engineering efforts to control flooding and sedimentation. The geomorphic history covered here extends to 1906, when Daguerre Point Dam was built on the LYR. Details of the geomorphic history from 1906 through 1999 remain to be documented.

In natural rivers, it is common to infer former processes from the present geomorphic form; e.g., deducing lateral planation processes for meandering channels. With extensive anthropogenic change such as engineering structures, however, interpreting evolutionary trajectories of geomorphic features is complicated by process-form dynamics that are described at the end of this paper. The multifarious nature of engineered rivers makes it difficult to infer process from geomorphic form alone and calls for analyses of independent historical and stratigraphic evidence to understand former conditions and processes.

2. Methods

The early historical analysis presented in this study is largely based on digitized cartographic evidence. Additional historic information is derived from contemporary photographs, surveys, and accounts recorded in local histories.

2.1. Cartometric data acquisition and processing

While quantitative measures of geomorphic change are commonly made from field measurements, aerial photographs, or modern remote sensing imagery, both qualitative and quantitative information about early post-European settlement geomorphic change can be derived from the study of maps. The qualitative use of early maps has several problems including errors of commission or omission, which may lead to false interpretations about the presence or absence of features at the time the map was made (James et al., 2012). These potential errors are compounded when early maps are used as base maps to generate later maps. Historic map interpreters must make judgments, therefore, about the accuracy of the cartography and the extent of field verification that was involved. Each map is an abstract spatial model of the contemporary system constructed for various purposes, and the precision and accuracy of the content varies spatially and thematically. In spite of limitations to historic cartographic data, the rich information content often justifies their use. For example, channel morphological changes, such as avulsions, lateral migration, abandonment of multithread channel branches, changes in sinuosity, and construction of engineering works, can often be identified and constrained in time.

Several historical maps and charts from 1856 to 1924 were scanned and georegistered to support the historical analyses. Most of the maps were scanned on a 28 × 43-cm (11 × 17-inch) flatbed scanner at point densities of 400 to 600 dpi. Some large-format maps were scanned in panels and reconstructed by digitally mosaicking the panels. Some early maps were yellowed and mottled and were converted to grayscale or filtered with Photoshop to improve legibility and clarity. In all cases, processing and editing avoided substantive alterations from the original maps. Maps were rectified using the georeferencing tool of ArcMap version 10.0 primarily with an affine (first order) transformation. The number of ground control points (GCPs) used ranged from five to 23 (Table 1), and one of two reference datasets was used for the transformations: (1) a 2009 USDA digital orthophotoquad with one-meter cell size when appropriate cultural features such as roads were present, or (2) section corners on a digital shape file of the Public Land Survey System (PLSS) for areas where few cultural features were identifiable. The use of PLSS section corners for georeferencing limits the accuracy for cartometric purposes, but provides a good approximate registration suitable for qualitative interpretations of early maps.

2.2. Historic maps used in the analysis

Most maps made prior to 1851 in this region are very small scale and provide insufficient detail and accuracy to be of use for geomorphic change detection (GCD). Fortunately, some mid- to late-nineteenth century maps of the LYR are relatively accurate and reveal important geomorphic information. The Wescoatt and Watson (1856) map of Marysville shows 3.5 km of the LYR at the Feather River confluence. Limited ground control was obtained around the perimeter of the map along the channels, so the low RMSE (2.94 m) underestimates the level of uncertainty associated with channel locations on this map. Nevertheless, this large-scale map of the Yuba–Feather River confluence shows channels in great detail that fall within the channel margins of later maps. The Wescoatt (1861) map is a large format wall map of Yuba County and maps in this report attributed to Wescoatt (1861) are excerpts from the larger map. The Pixley et al. (1865) map was scanned from a long scroll map along a railroad survey between the Bear and Yuba Rivers. Map registration was based on the public land survey (PLSS) digital map because cultural features, such as the roads are insufficiently accurate to be used for GCPs. Although planimetric accuracy of this map is limited for cartometric purposes, several important geomorphic features are qualitatively documented by this map.

Two similar topographic maps made under the direction of Mendell (1880; 1881) were published as Congressional documents. Both maps show the same multithread channels and few changes to channels and levees, but the earlier map includes a floodplain cross-section. The California Debris Commission (CDC, 1906) produced a set of four high-resolution (1:9600) topographic map sheets of the LYR with 0.6-m (2-ft) land and bathymetric contours based on detailed field instrumental surveys of the channels and floodplains. The large map sheets were scanned in nine panels at 400 dpi, edge-matched, and rectified. The set includes seven sheets of channel cross-sections and a longitudinal profile that were also scanned. Merging and registration were done using the PLSS because large areas of these maps lack suitable GCPs, especially in the east. The average RMSE for rectification of these sheets is 5.47 m, relatively high due to the need to merge panels for each sheet (Ghoshal et al., 2010).

2.3. Historic cross sections

Field surveys in 1906 produced numerous cross sections (CDC, 1906) that were analyzed to show floodplain morphogenesis from 1899 to 1905 or 1906. Contemporary measurements of net sedimentation were recorded at 40 cross sections on the original charts as areas of net cut or fill. Each change in net cross-section area between 1899 and 1905 or 1906 was multiplied by the distance to the next cross section immediately upstream to estimate volumetric changes in this period. For this study, changes in channel thalweg elevation were measured manually from the cross sections as the difference between the minimum channel elevation on each section between 1899 and 1905 or 1906. In some cases, thalweg elevation change represents cut or fill of a single channel. In other cases—because multithread channels and avulsions were common between surveys—the elevation change represents two different channels as the thalweg shifted channels. Changes in cross-section area, volumes, and thalweg and floodplain cross-section

Table 1
Sources and processing of historic map data.

Year	Surveyor/cartogr.	Publisher	Source	Scale	N GCPs	RMSE	Ref.
1856	Wescoatt & Watson	Britton & Rey	Yuba Co. Lib.	NA	8	2.94	2009 DOQ
1861	Wescoatt	DePue & Co.	UC Davis	c.1:63,360	6	28.39	PLSS
1865	Pixley et al.	Yuba RR	Calif. St. Arch.	1:12,000	11	37.38	PLSS
1880	Mendell	US Govt.	Congr Doc.	1:63,000	23	27.5	2009 DOQ
1906	CDC	US Govt.	UC Davis	1:9600	4 sheets	5.47 (avg)	PLSS

Abbreviations: N GCP = number of ground control points used; RMSE = root mean square error produced by registration; Ref. = reference dataset used in registration: DOQ = digital orthophotoquad with 1-m grid cells; PLSS = digital map of public land survey system (section and township corners).

changes were plotted by down-valley position to examine spatial relationships. Data generated from the CDC (1906) surveys are presented in the Supplement.

3. Pre-mining evolution of the lower Yuba River (LYR)

The Yuba River is one of the oldest master rivers in northern California. During the Cenozoic it headed in Nevada and flowed to the Sacramento Valley. It is the dominant tributary of the Feather River Basin, which flows into the Sacramento River above the city of Sacramento (Fig. 1). The LYR begins at Englebright Reservoir in crystalline rocks at the western Sierra Nevada margin. About 4 km below the dam it becomes an alluvial channel in a crystalline rock valley and about 20 km below the dam it emerges onto deep alluvium of the Sacramento Valley. (Additional mapping is provided on a Google Earth kmz file in the Supplement.)

3.1. Cenozoic evolution of the lower Yuba River

Sierra Nevada uplift and erosion and evolution of the ancestral Yuba channel system are key to the geologic evolution of the LYR. The steeply dipping ancestral Yuba channel and the extensive alluvial fan it constructed along the eastern margin of the Sacramento Valley indicate long-term geomorphic trends over geologic time. The ancestral Yuba channel system had formed by the Eocene Epoch with drainage divides well to the east of the present divide along the Sierra Nevada crest. At that time, the river flowed across an eastern plateau similar to the Altiplano of South America or the Tibetan Plateau in southern Asia (Wakabayashi, 2013). Sierra erosion and Sacramento Valley sedimentation rates were rapid during the Cretaceous, slow through the Eocene and Oligocene periods, and increased during the Plio-Pleistocene (Wakabayashi, 2013). Tilting caused by uplift to the east and subsidence to the west generated deep alluviation, channel avulsions, and fan extension in the Sacramento Valley to the west. Early Cenozoic strata along the eastern margin of the Sacramento Valley were severely deformed by westward tilting of the Sierra Nevada block in the Late Cenozoic. Two competing theories have been used to explain the timing of Sierra uplift. One theory is that the Sierra crest first rose and tilted in the Late Cenozoic (Lindgren, 1911; Unruh, 1991). An alternate theory is that late Mesozoic crustal thickening and batholith emplacement generated uplift much earlier, followed by late Miocene faulting on the east side of the Sierra coinciding with Basin and Range extension (Small and

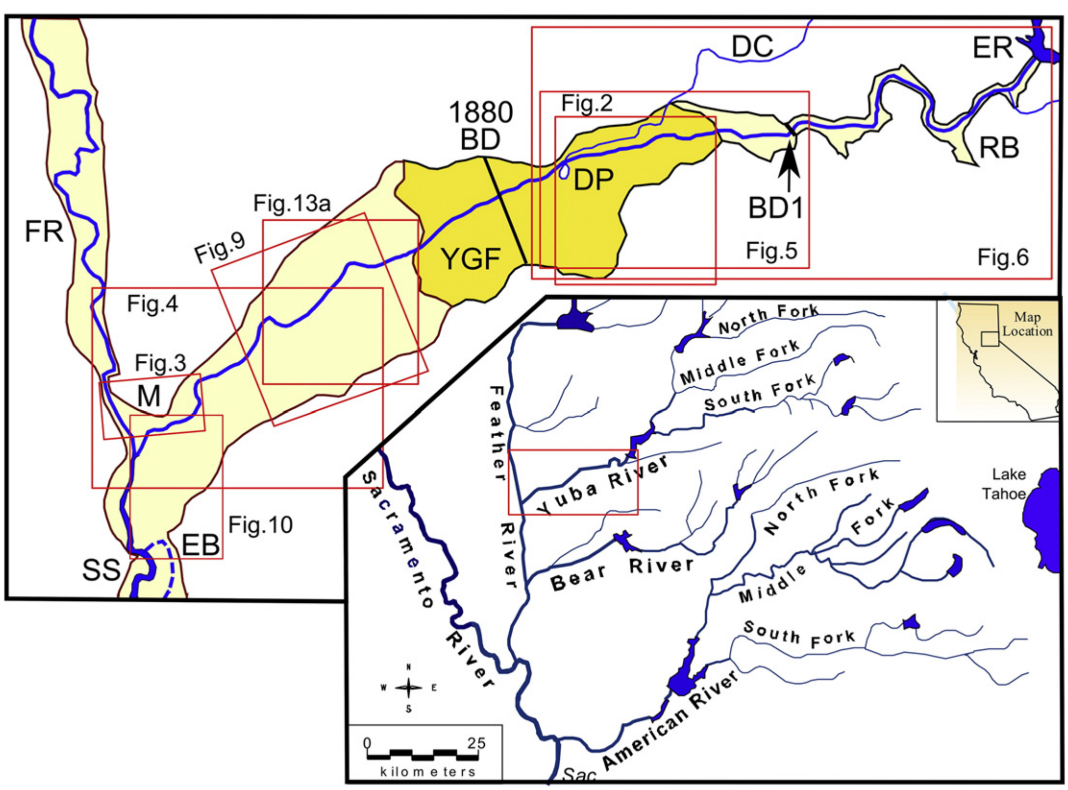

Fig. 1. Location of LYR and Yuba basin within the Sacramento Valley of northern California showing locations of figures. Abbreviations: 1880 BD = brush dam; BD1 = Barrier dam 1; DC = Dry Creek; DP = Daguerre Point; EB = Eliza Bend; ER = Englebright Reservoir; FR = Feather River; YGF = Yuba Gold Fields.

Anderson, 1995; Henry, 2009). Late Cenozoic uplift and steepening of channel gradients on the west flank of the Sierra can be explained by severe erosion and unloading (Stock et al., 2004; Henry, 2009).

Fluvial and deltaic sediments near the base of the ancestral Yuba paleovalley include Eocene auriferous sediments (Lindgren, 1911), which are unconformably overlain by thick fluvially reworked Oligocene through Pliocene volcaniclastics (Unruh, 1991). The lower reaches of the Eocene channel system were located near the modern LYR through the fan apex to Daguerre Point (Fig. 2). The Tertiary canyon system was relatively sinuous and crossed the modern LYR canyon at least twice below the present fan apex. Auriferous channel deposits in this area—exploited by hydraulic mines—dip steeply from about 100 m elevation to where they plunge below Quaternary alluvium east of Daguerre Point. Recent mapping of the paleo-valley system of the LYR (Hunerlach et al., 2004) reveals two parallel paleo-valleys joining east of Daguerre Point and turning abruptly to the south through a deep, narrow canyon (Fig. 2). Multiple Pleistocene glaciations caused the LYR channel system to oscillate between aggradation by glacial outwash and degradation by channel incision during interglacial periods. The paleo-canyon southeast of Daguerre Point was filled and abandoned by Quaternary channels that flowed west southwest at a higher level across the ridge adjacent to Daguerre Point. The Quaternary gravels to the west were not as rich in gold, which presumably explains why fewer mining camps were located below Daguerre Point in the 1850s.

3.2. Geomorphic conditions of the LYR at the time of European contact

Prior to the arrival of Europeans, indigenous Californians may have had substantial influences on ecological systems through changes in fire regimes, hunting pressures on herbivores, and distributing plants. The degree of ecological changes continues to be debated (Vale, 1998; 2002), but pre-European geomorphic impacts—in the form of altered rates of erosion and sedimentation—have not been demonstrated. Pre-Columbian anthropogeomorphic changes were likely subtle, given that the cultures were lithic and subsistence in nature (Doolittle, 2000; James, 2011). Little is known about the LYR channel system at the time of arrival of Europeans during the period of Mexican land grants and colonization in the early nineteenth century. Previous studies have described early conditions of the river prior to anthropic changes by Anglo American settlers in the 1840s (Gilbert, 1917; James et al., 2009). Historical accounts of river conditions prior to the arrival of Anglo Americans are limited and geomorphic change was exceptionally rapid following the arrival of Anglo Americans. Both the Bear Flag Revolt from Mexico in 1848 and the gold rush in 1849 occurred within the first decade of Anglo American settlement in California, and most witnesses were too preoccupied to document environmental conditions in detail. As the system was rapidly altered by sedimentation, agriculture, and engineering projects, much of the early geomorphic and stratigraphic evidence was obscured and must be determined through a veil of

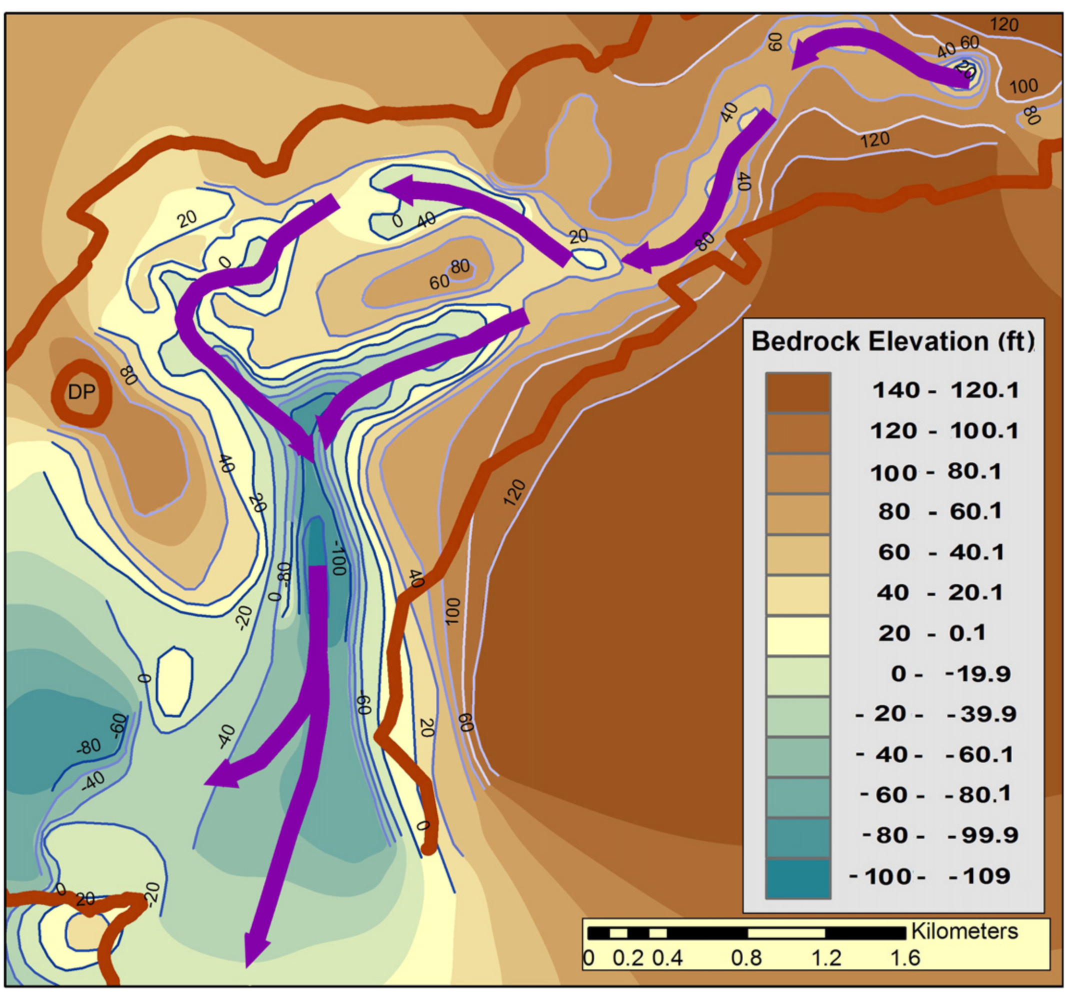

Fig. 2. Cenozoic LYR paleovalley cut into pre-Cenozoic metamorphic and crystalline rocks. Map begins in northeast near Longbar about 1 km above Dry Creek and 14 km below fan apex at Englebright Dam and extends west to Daguerre Point (DP). The paleovalley bifurcates above DP and flows south of the modern valley, which flows southeast. The bold brown line is the modern boundary between alluvium and colluvium or bedrock based on soil maps. Bedrock elevation and flow-lines adapted from Hunerlach et al. (2004).

anthropogenic change. Descriptions of the fluvial landscape may exist in the form of diaries, letters, and newspaper accounts, but a thorough documentation of pre-mining river conditions has yet to surface. Nevertheless, careful scrutiny of the available field, documentary, and cartographic evidence provides important information about pre-existing conditions of the LYR.

As has been described elsewhere in the Sacramento Valley, the pre-European Yuba channel near Marysville (located on Fig. 1) was characterized by a distinct riparian zone along stream banks. This zone was vegetated by tall trees, brush, and vines. On other rivers, this low floodplain has been described as the 'low bottoms' with a dark soil. Further from the channel above the floodplain, a terrace with fewer trees was capped by a reddish soil. These highly weathered soils with an iron-rich argillic B horizon remain exposed in the modern landscape. Ellis (1939) describes the low area across the LYR from Marysville as a forested wetland that extended to Eliza Bend on the Feather River with a topographic break to a terrace above:

> "In the early days, all the territory south of the present north channel of the Yuba River at the D Street Bridge was a vast wilderness of trees and underbrush, wild grape and blackberry vines, this dense forest extending down to Eliza Bend on the south and upstream on the Yuba River for many miles, covering in all, several thousand acres. The southerly boundary of this forest was the higher ridge of red dirt land… on the present Hammonton Road."
>
> [W.T. Ellis (1939, Ch. 38).]

Before the great floods of December, 1861 and January, 1862, channels below Daguerre Point remained largely free of HMS. Therefore, maps of the lower study area made before December, 1861 are presumed to be representative of channel positions prior to the devastating aggradation and avulsions that came later. Channels above Daguerre Point were substantially altered, however, by river mining and HMS during the 1850s. A few maps made prior to the water year 1862 floods are of sufficient detail and accuracy to provide cartographic information about channel conditions on the lowermost LYR prior to the massive influx of HMS. The Von Schmidt (1859) map of the lower Yuba and Feather Rivers shows pre-disturbance channel positions for the lower 10 km of the LYR (James et al., 2012, Fig. 3). At that time, the confluence with the Feather River was barbed. The LYR above Marysville was shown as a single-thread channel, although the Westcoatt (1861) map shows two anastomosed channels, indicating that this was an error of omission on the 1859 map.

An excerpt from a high-resolution map of Marysville reveals several details of the main Yuba channel within ~2.6 km of the confluence that are missing from other contemporary maps (Fig. 3). Of particular note is the sinuosity of the main channel and numerous sloughs on the north side of the floodplain; e.g., Simmerly Slough flowed through Marysville to the Yuba River. An excerpt of the Marysville area on a map of Yuba County (Fig. 4) shows that the barbed confluence with the Feather River had a chute that corresponds with the position of the modern LYR. The main channel to the east is in the same position as on the map of this area by Von Schmidt (1859), but a substantial southern anastomosed channel is shown a few km east of Marysville. The southern channel reappears on a later map (Mendell, 1881) as an abandoned channel. The abundance of sloughs and presence of the southern channel prior to substantial Anglo American channel changes indicate that the pre-settlement LYR near the Feather River was an anastomosing channel system. Anastomosed channels were initially attributed to rapid vertical accretion with banks stabilized by vegetation (Smith and Smith, 1980). Subsequently, additional environments have been identified where anastomosing channels occur, including rivers with cohesive banks and low stream powers (Rust, 1981; Rust and Nanson, 1986). Bank stratigraphy near Marysville reveals fine-grained cohesive sediment that dominated the pre-settlement banks and floodplain soils (James et al., 2009).

The pre-mining condition of the middle reaches of the LYR near Daguerre Point can be inferred from the 1861 map of Yuba County, which indicates that major anthropic changes had already occurred prior to the water year 1862 floods (Fig. 5). Channel alterations are evidenced by 'canals' cutting off the major meander bends at Ousleys and Swiss Bars. Disregarding the canals, the channel had large islands described as 'bars' on the Westcoatt map, which indicate a wandering bed channel. Wandering bed channels are irregularly sinuous with stable, vegetated, anastomosing channels, and braid bars (Nanson and Croke, 1992). They have fewer channels or bars than braided rivers and a single dominant meandering channel that alternates with anastomosed reaches. Based on the cartographic evidence, the LYR fluvial facies changed from a wandering bed channel in the mid-fan area (Fig. 5) where sediment was coarser—presumably gravel-bedded—to an

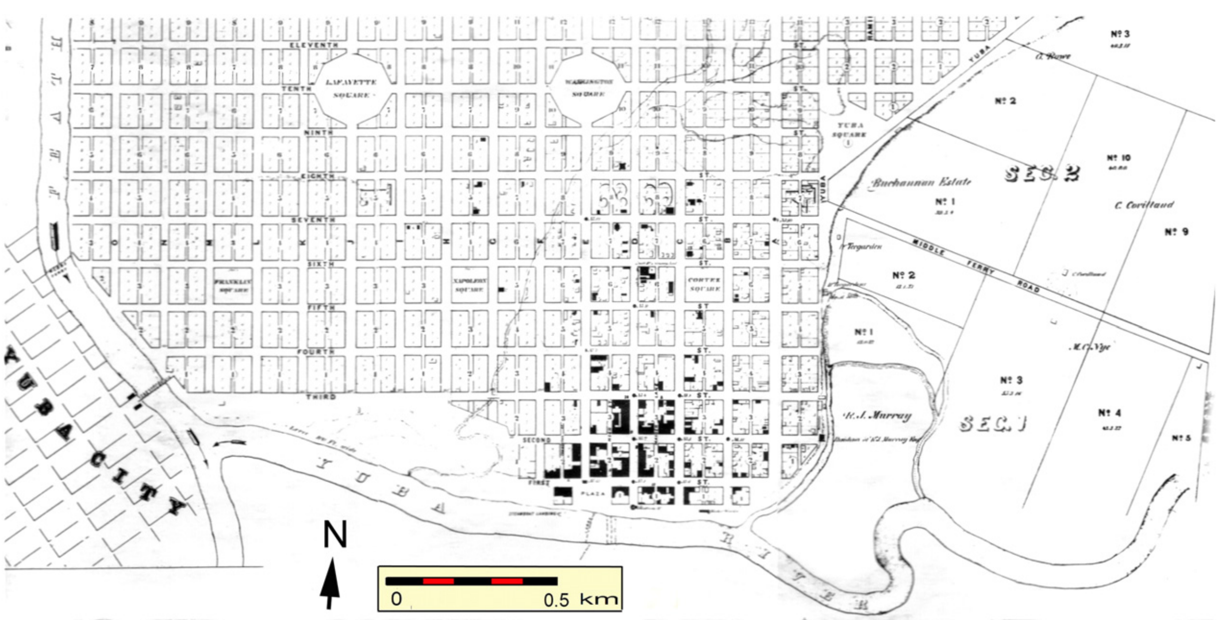

Fig. 3. Yuba River at Marysville with Simmerly Slough flowing through Marysville. Simmerly Slough entered the Yuba River above the 'B' in 'Yuba.' Excerpt from Wescoatt and Watson (1856).

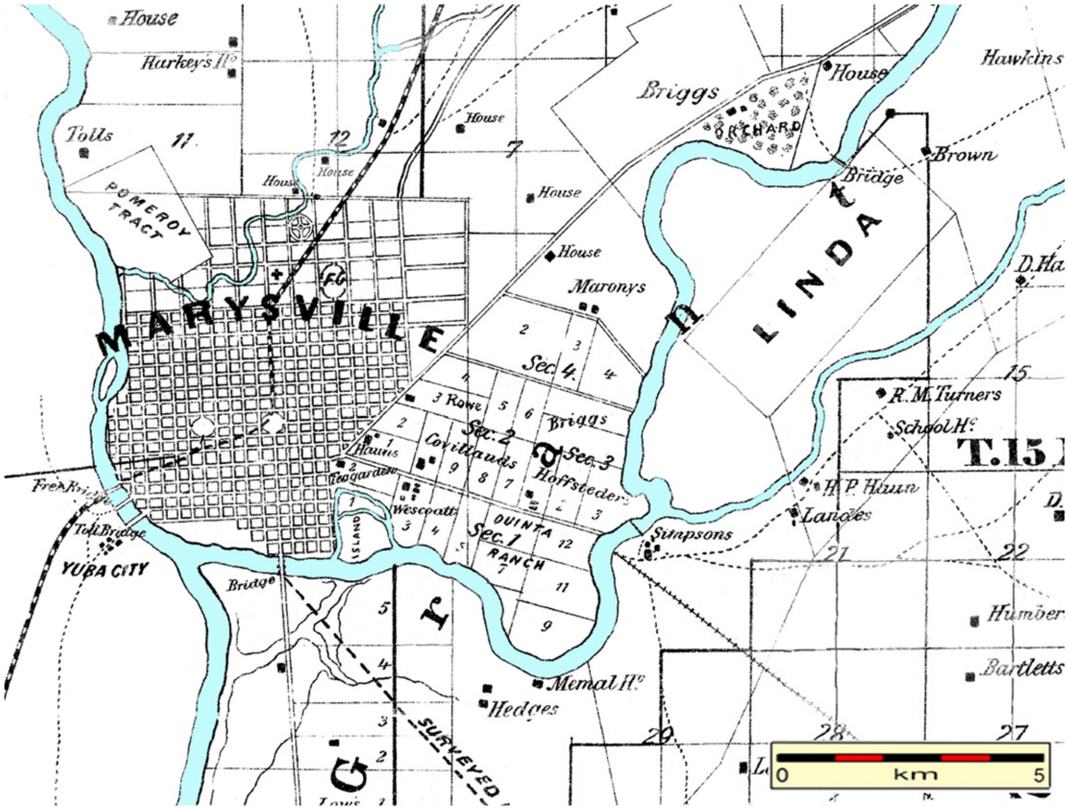

Fig. 4. The pre-disturbance LYR near Marysville. Channel color and scale bar added. Excerpt from Wescoatt (1861).

anastomosing system in the lower fan (Fig. 4) where banks were composed of cohesive silts. Bank stratigraphy in the mid-fan area below Daguerre Point often shows weakly cohesive sandy banks, e.g., at the U.S. Geological Survey stream gage (James et al., 2009; Fig. 10).

4. Initial impacts of mining in the LYR

The arrival of Anglo Americans in the LYR caused relatively abrupt changes. Mining impacts began with low-impact placer mining that

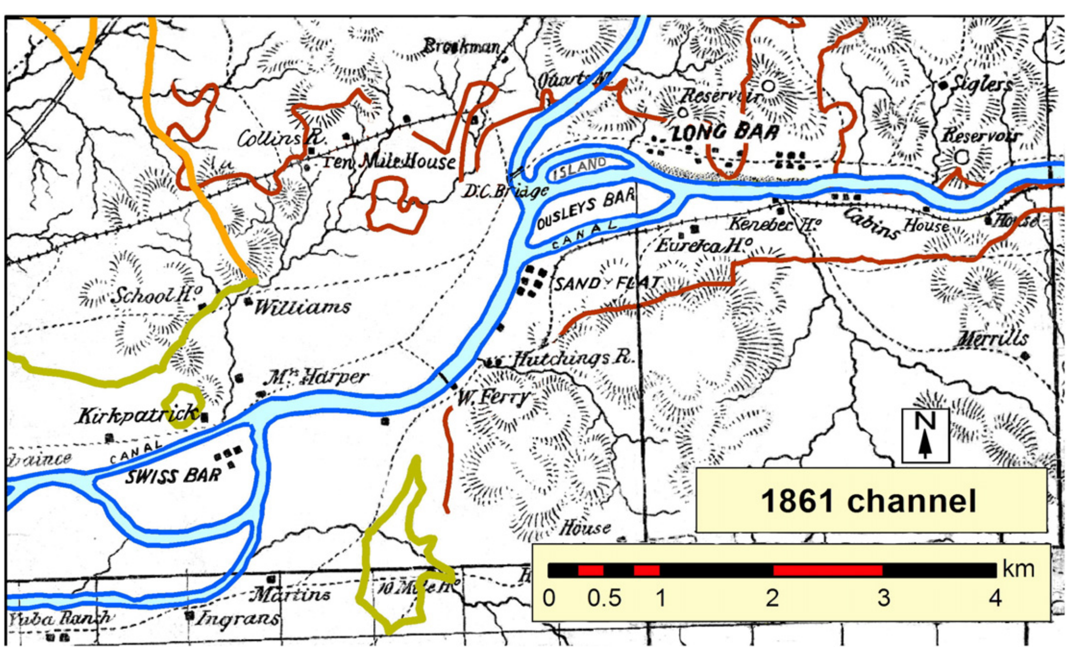

Fig. 5. Pre-mining LYR channel above Daguerre Point. Mine camps and settlements are shown by small solid squares. Broad colored lines are Quaternary terraces from GIS analysis of soil and geomorphology maps. Daguerre Point is closed circle north of Swiss Bar. Channel color and scale bar added. Excerpt from Wescoatt (1861).

rapidly evolved into highly mechanized and geomorphically disruptive river mining that altered and moved river beds. Mining impacts accelerated with burial of LYR valley bottoms by HMS. This history represents a revision of former interpretations. Gradual channel aggradation throughout the LYR beginning in 1850 was inferred by Gilbert (1917) from constant rates of HMS production, whereas a delayed and abrupt onset of sedimentation throughout the LYR with the 1862 floods was inferred by James (2006) based on general contemporary engineering reports. Neither of those conceptual models recognized the importance of river mining to early morphological change or spatially non-uniform patterns of local HMS aggradation beginning in the upper fan of the LYR above Daguerre Point.

4.1. River mining, 1849–1861

Early in the initial decade of gold mining, river mining—an intensive form of placer mining that shifted river courses in order to excavate channel gravels—greatly altered the LYR above Daguerre Point. The history of river mining in the LYR during the 1850s has not been well documented by historians and physical evidence of channel changes was subsequently buried by HMS and obscured by dredging and engineering works. Yet, historical evidence confirms that channels above Daguerre Point Dam were substantially altered by river mining prior to the onset of hydraulic mining sedimentation. The population of non-native Californians increased seven-fold from 13,000 in 1849 to 94,000 in 1850 (Thompson and West, 1879) and this growth was primarily in mining districts along rivers. Between 1848 and 1850 large encampments of miners were established at Landers, Rose, Bartons, Parks, Long, Kennebec, Ousley, and Swiss Bars (Fig. 6). By 1850, an estimated 2000 men occupied Rose Bar with tents, hotels, stores, and saloons (Thompson and West, 1879; Ch. 28; Hanson, 1924; Ch. 6).

Presumably, mining on the LYR was similar to other rivers in the region, except that the influx of HMS began earlier. Elsewhere, reworking of entire beds of rivers by river mining during the 1850s is well documented. Photographs and drawings from the Middle Fork American River illustrate the mechanical technologies employed and the extreme changes to river beds during this period (Fig. 7). Main channels were relocated with canals and flumes, groundwater tables were lowered with water-powered rag pumps, and channel-bed gravels were excavated down to bedrock. Contemporary accounts indicate considerable river-bed excavations along the LYR above Daguerre Point. For example, channel relocations are indicated by the ‘canals’ around Swiss and Ousley's Bars mapped in 1861 and the beginning of river mining at Rose Bar in 1849 is described prior to the onset of hydraulic mining:

Fig. 7. River mining on the middle Fork American River at Cromwell Bar. Photograph by Charles Weed (1858).

> “In September, 1849, a company of fifty men, among whom was William H. Parks, commenced to dam the river [at Rose Bar], so as to mine the bed. They completed the dam, and commenced work early in October. The rain set in on the eighth, and in two days the water overflowed the dam and washed it away… During the year the bar became very populous, and in 1850, there were two thousand men working here… The course of the river was turned [moved from its course] seven consecutive years, the last time in 1857. But little work was done here after that, and now the bar is covered by tailings from the [hydraulic] mines, many feet in depth.”
>
> [Thompson and West, 1879; Chapter 28.]

4.2. Influx of hydraulic mining sediment (HMS), 1861–1884

The production and delivery of HMS in the Yuba Basin has been studied extensively (Gilbert, 1917). The LYR was a clear-water river in 1850, but by 1855 gravel deposits were playing out, mining camps were declining, and HMS was causing local channel aggradation. HMS arrived earlier on the LYR above Daguerre Point than in the comparable positions on the lower Feather, Bear, or American Rivers due to the close

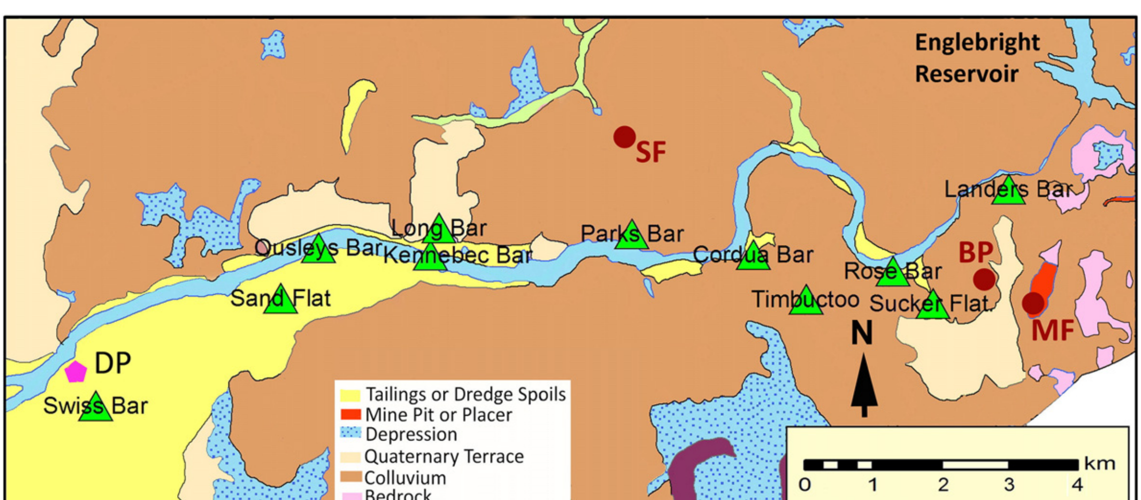

Fig. 6. Map of upper LYR with mining camps ca. 1855 (triangles). DP = Daguerre Point. Circles are hydraulic mine pits: SF = Sicard Flat, BP = Blue Point, MF = Mooney Flat. (Base map: SURGO soils.).
Data sources: Thompson and West (1879, Ch. 28), Hanson (1924), and Wescoatt (1861).

proximity of large hydraulic mines exploiting auriferous channel deposits associated with the ancestral Yuba River. Hydraulic mines, including Sicard Flat, Blue Point, and Mooney Flat (Fig. 6), were generating local tailings fans in the upper Yuba fan prior to the 1862 floods (Thompson and West, 1879; Chapter 28). Many of the mining camps, including Ousley's Bar, Parks Bar, Sand Flat, and Rose Bar, were abandoned by the late 1850s due to declining yields or burial by HMS. Channels at Rose Bar and Timbuctoo were completely buried by the 1870s:

> "Little [river] mining was done after that [1857], for the hydraulic operations nearby, too, wrought an unhappy change to Rose Bar. As the river rose sweeping its muddy water over the valley, the bar passed out of sight. In its stead was a long uneven bed of sand and cobble stones, interspersed with the cast off clothing of the miner or the detritus which he had caused. Over this bed ran numerous streams of muddy yellow water, while buried underneath no less than seventy feet was the once famous Rose Bar."
>
> [Hanson (1924; Ch. 11).]

The tailings fan at Rose Bar was produced by sediment from the Blue Point hydraulic mine. Stratigraphic evidence of historic fan genesis includes a milled plank protruding from the base of the thick alluvial sequence where the fan meets the Yuba River (Fig. 8). Drilling through the historical sediment near the turn of the 20th century found that HMS on the Yuba River long profile ranged from 26 to 30 m (85 to 98 ft) thick in the vicinity of the Rose Bar tailings fan (Gilbert, 1917; p. 47).

The amounts of HMS produced in the Yuba Basin and stored along the LYR were established by G.K. Gilbert's (1917) classic study, which detailed the processes of sedimentation along the Yuba and showed that almost half of the HMS produced in the northern mines was generated in the Yuba Basin, although its drainage area is less than a fifth of the total area of the basins draining the mines (Table 2). Typically, most sediment produced in a watershed remains close to the source, and sediment delivery ratios (SDR) normally decrease rapidly downstream to less than 10% of production in large basins (Roehl, 1962; Walling, 1983). Although substantial amounts of sediment remain stored on ridge tops near the hydraulic mines, an estimated 255 million m^3, almost half of the sediment produced in the basin, was quickly delivered and stored along the LYR (Gilbert, 1917). The SDR for the Yuba Basin was substantially greater than half of the HMS produced in the basin because additional sediment passed through to the Feather and Sacramento Rivers. The abnormally high SDR for such a large basin reflects the efficient delivery system between the mines and the Piedmont. The steep narrow canyons of the Yuba River in the Sierra Foothills provided little storage potential and conveyed an anomalously high proportion of the HMS downstream to the Sacramento Valley quickly and efficiently (James, 2006). Based on field surveys in 1878 and 1879, Manson (in Hall, 1880) estimated 17.2×10^6 m^3 of HMS, was stored in the mountain canyons above Deer Creek at the upper limit of LYR (Fig. 6). This was only 3.3% of the sediment produced in the basin. Turner's (1891) resurvey found only 4.7×10^6 m^3 (0.9% of total production) remained stored in the canyons. Even this small amount of HMS was largely gone by the time Gilbert visited the canyons in 1908. A substantial volume of HMS still remains in the mines and in low-gradient upland tributaries near the mountain mines, however, such as along Scotchman and Shady Creeks (James, 2005).

The spatial and temporal distribution of HMS deposition was non-uniform, but little quantitative data are available concerning the initial influx. Gilbert's (1917) analysis had few data for the onset of sedimentation prior to 1874, and assumed a gradual rise in channel-bed elevations between 1849 and 1874. However, most Sacramento Valley rivers did not begin to receive large quantities of HMS until the two floods of December, 1861 and January, 1862 (James et al., 2009). Prior to that time, HMS remained stored near the mines in the mountains.

Fig. 8. Tailings fan at Rose Bar composed of HMS. (top) View downstream towards left bank showing eroded fan face. (middle) View up into fan showing terrace scarp with milled plank near base of section. (bottom) Close up of plank protruding from HMS gravels.

> "Every few years the water rose quite high and covered the lowlands, but there were no disastrous floods until December, 1861. By the inundation caused by the incessant rains of that winter a great many frame buildings of the city [of Marysville] floated from their positions, while others undermined by the water fell crumbling to the ground. The people in the country had to leave everything and flee to higher ground for safety. This was the first appearance in any quantity of the disastrous debris from the hydraulic mines that brought ruin and devastation to much of Yuba Valley."
>
> [Hanson (1924; Ch. 11).]

Based on reports of the lack of regional sedimentation until water year 1862, James (2006) assumed that sedimentation along the LYR was limited until that time. Thus, the historical evidence presented

Table 2
19th century HMS production.
Source: Gilbert, (1917).

Basin	Drainage area (km^2)	Volume produced (m^3 10^6)	Vol. yr^{-1} 31 yrs (m^3 10^6 yr^{-1})	Mass produced[a] (t 10^6)	Specific production (t km^{-2} yr^{-1})	Total storage (m^3 10^6)	Storage/prod (~SDR[b]) (%)
Feather R. above Marysville	10,301	76	2.5	144	452	19	25.1%
Yuba River	3499	523	16.9	994	9161	255[c]	48.8%
Bear Basin	1143	271	8.7	515	14,532	116[d]	42.8%
American	5014	197	6.3	374	2408	46	9.7%
Totals	19,957	1068	34.4	2029	3280		

[a] Tonnes were computed from volumes using a bulk density of 1.9 t/m^3 based on coarse textures and compaction.
[b] Sediment delivery ratios are minimum values because additional sediment passed through to lower rivers.
[c] Storage in LYR from Deer Creek to Feather River estimated by Harts in 1906 (Gilbert, 1917).
[d] Storage in the lower Bear River was adjusted upwards from Gilbert's estimate based on floodplain coring (James, 1989).

here improves the resolution of the timing and spatial complexity of early anthropic sedimentation and channel change in the LYR. Evidence of substantial channel alternations by river mining was described in the previous section. In addition, local tailings fans below hydraulic mines near the edge of the Sacramento Valley caused substantial channel aggradation above Daguerre Point beginning in the late 1850s.

In response to the arrival of HMS, the LYR aggraded several meters and spread out across broad floodplains in a multithread channel system. A map by Wm. Ham Hall published in a report to Congress by Mendell (1880) shows three multithread channels above Marysville: a northern channel, a 'low water channel 1878,' and a 'low water channel 1879' (Fig. 9A). Some of these channels can be seen on the 1859 Von Schmidt map, suggesting that certain LYR main channel reaches were maintained through the aggradation period. The main channel was mapped in 1880 between two closely spaced levees, near the same position where it had been mapped in 1873 but with no levees shown on the map (Pennington, 1873). The main channel in 1880 was connected upstream by a series of braid bars through a gap in the levee. The Mendell map includes a valley cross section showing substantial channel aggradation (Fig. 9B). This section extends from a small tributary to the north—the lowest point of the section—across the main channel of the Yuba River. The bed elevations of all three LYR channels are > 3 m (10 feet) above the bed elevation of the tributary channel. The high bed elevations represent an unstable situation rife for a major channel avulsion without engineering intervention.

By the 1880s, HMS accumulating in the LYR was reaching the Feather River in increasing quantities, exacerbating flooding and impairing navigability between Sacramento and Marysville. Most of the floodplain lands above Marysville had been deeply aggraded and had lost their economic value, so a flood and sediment management strategy was devised to induce backwater and sedimentation in the LYR and to protect navigation downstream in the Feather River from HMS (Kelley, 1998; James et al., 2009). This plan included a combination of low barrier dams on the LYR, wide levee setbacks above Marysville to provide a sediment storage area, a levee constriction at Marysville to impede down-valley sediment transport, and levees with narrow setbacks on the Feather to encourage channel self-scouring. This strategy was apparently successful in retaining most of the sediment above Marysville.

In spite of catastrophic sedimentation of the LYR, some pre-mining channel and floodplain features persisted in the Marysville area at the turn of the twentieth century. For example, many of the old sloughs adjacent to the east levee of Marysville mapped in 1856 (Fig. 3) were still largely intact as sloughs, channel scars, or riparian wetlands in 1906. This may reflect success of engineering works in controlling channel migration around Marysville. Quite a different process was occurring about 1.5 km upstream from this site, where—if not for river engineering—the LYR would have cut off and joined the Feather River to the south at Eliza Bend. An 1865 map of the Yuba–Feather confluence area shows a set of small channels flowing from a large southern meander of the main channel towards the Feather River at Eliza Bend (Fig. 10A). These southern cutoff channels indicate that the main LYR channel was in the process of a major avulsion at the confluence during the late 1800s in response to the influx of HMS. This avulsion would have reduced the flow distance from the southern meander on the LYR to Eliza Bend from 9.3 km to 3.1 km, causing a threefold increase

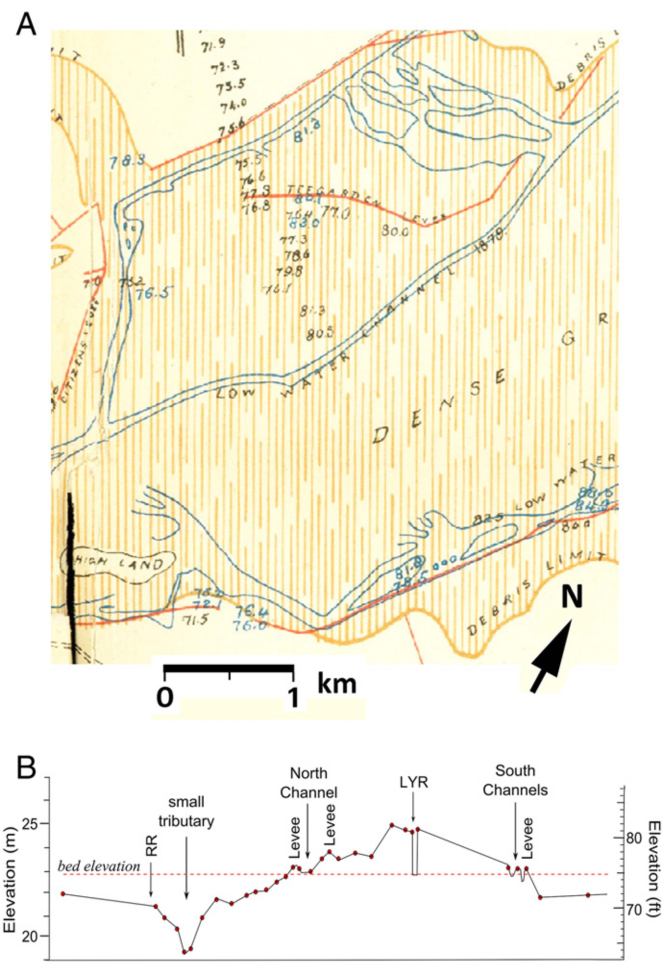

Fig. 9. LYR above Marysville in 1880. (A) Three channel systems were mapped between a series of levees. The central channel was the primary channel at the time of the 1879 survey. It shifted from the south channel after 1876. The northern channel was a high-water braided system. Dark brown lines are levees. (B) Cross section from top left third to bottom right third of map showing floodplain aggradation (view up valley, north to left). Bed of LYR main channel is almost as high as levees and >1 m higher than areas beyond levees. The lowest point on the section is a tributary beyond north levees adjacent to the Oroville Railroad. Excerpts of map with valley section from Mendell (1880); section redrafted.

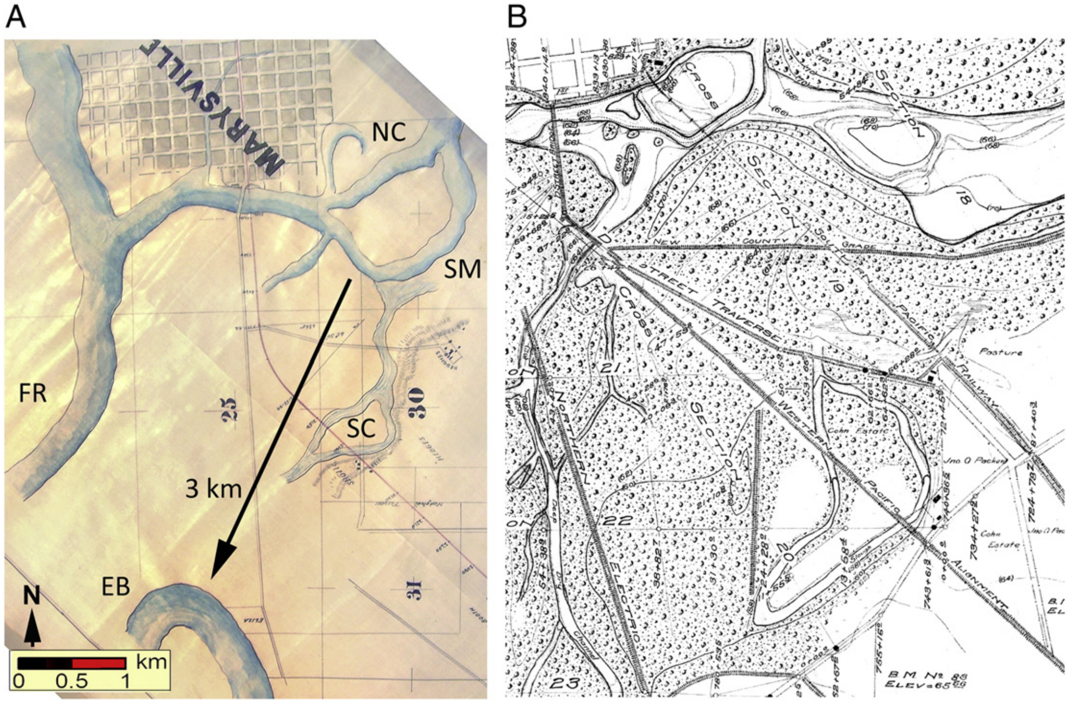

Fig. 10. Small channels between the south meander of the LYR and Eliza Bend on the Feather River formed in response to Yuba aggradation. (A) Railroad survey map (Pixley et al., 1865; James et al., 2009, Fig. 11) NC = Northern cutoff, SM = Southern meander, SC = Southern cutoff channels, FR = Feather River, EB = Eliza Bend. (B) Southern cutoff channels four decades later blocked by highway and railroad embankments. Excerpt from CDC, 1906.

in channel gradients that likely would have maintained a permanent avulsion of the confluence away from Marysville. Assuming no change in channel width, such an increase in slope would have tripled stream powers through the new confluence. Increased stream powers would have destabilized channels and increased sediment deliveries to the Feather River at Eliza Bend. The avulsion was apparently averted by levees and road and railroad embankments built along the south side of the channel and by dredging new channels further downstream on the Yuba to the Feather River (Fig. 10B). The fact that the LYR system did not permanently spill to lower outside surfaces in a major fan avulsion at Eliza Bend or northeast of Marysville attests to how effectively early levees and railroad embankments kept the river on the elevated fan.

5. Engineering controls 1880–1906

Early engineering works greatly influenced the initial geomorphic responses of the LYR floodplain to the arrival of HMS deliveries and aggradation of the system. They began during the early HMS period with ad hoc structures but increased in magnitude and number through the 1870s. Later structural flood- and sediment-control measures in the LYR are also critical to understanding changing river dynamics and to sustainable assessment and design of the system. The history of these engineering structures explains former channel locations and floodplain morphologies that can inform policy makers about design and evaluation of flood conveyance systems, modeling water and sediment transport, and anticipating channel morphological change. The LYR was initially responding to a complex suite of allogenic changes to physical inputs including increased sediment loads, trapping of sediment behind dams, and changes to flood magnitudes and frequencies due to reservoir operations. The river was not free to respond to these externally driven dynamics, however, due to historical and on-going engineering works such as levees, dams, wing dams, bank revetment, dredging, and channelization.

5.1. Ad hoc levees and government brush dams in the late 19th century

The nature of initial engineering changes to the LYR is difficult to reconstruct because limited records were kept, early structures were often abandoned, and the physical system was rapidly changing with episodic sedimentation and channel shifting. Numerous levees were constructed by local land owners to control river responses to rapid floodplain aggradation across heavily settled lowlands. These ad hoc channel manipulations were a logical extension of the alterations practiced earlier by river-mining communities during the 1850s. A precedent for aggressive river engineering had been well established and there were few limits or disincentives for river alterations based on concepts of preservation or property rights. Levee construction by independent local teams quickly evolved into a competition between landowners described as the 'levee wars' by which the least protected lands were most likely to be flooded with sediment-laden water (Kelley, 1998). This initially resulted in an uncoordinated system of ungraded levees of varying integrity. By the late 1870s, it was obvious that high sediment deliveries were going to continue for decades due to reworking of the massive deposits in storage and coordinated engineering was needed to control flooding, channel erosion, and sediment (Kelley, 1998).

An era of concerted engineering for the Sacramento Valley began in the 1870s when the federal government began to address navigation impairments in the lower Sacramento Valley that posed a clear threat to commerce. Constraining channel widths with brush wing dams to promote bed scouring was recommended by Mendell (1875). Knowledge of the massive volumes of HMS storage in the LYR was well established by 1880, so the LYR was designated as a sediment storage area, and the strategy turned to containing HMS within the LYR and preventing it from reaching the Feather River. Early federal intervention in the LYR began with construction of a brush dam in 1880 about two miles below Daguerre Point. The dam is shown on the Mendell (1881) map about 1 km too far downstream and is mapped more precisely by Doyle (1887). The dam abutted a colluvial slope to the north and extended 1.7 km to the levee on the south side of the river. It varied from one to 4.5 m in height and from 18 to 37 m in width at the foundation (Hall, 1881). The Yuba River brush dam failed during the first moderately high water in 1881 (Manson, 1882) with a series of breaks totaling 417 m in length or about 25% of the length of the dam. The area was subsequently dredged so there is little geomorphic evidence of the dam on the modern landscape. The CDC (1906) map (Sheet 3) shows a drainage channel passing through the former brush dam near the left abutment.

The brush dam failure in 1881 revealed the inadequacy of contemporary dam technology for controlling large mobile-bed alluvial rivers. Attention for the remainder of the 20th century shifted to the coordination of levees, bank stabilization, and channel works that would promote channel self-scouring and off-channel storage. The 1882 Rivers and Harbors Act ultimately sparked the initiation of dredging, snag removal, and construction of 'brush jetties' in the Sacramento Valley. Most of the HMS production in the upper Sierra foothills had been completed by 1884, but high sediment deliveries to the LYR continued in response to floods and failed engineering works. The River and Harbor Act of 1892 provided additional funds for dredging in the lower Yuba and Feather River, which ultimately included dredging a cut-off across the confluence with the Feather River.

By the turn of the 20th century, the LYR had a complex multi-thread morphology that varied in the downstream direction. Above Daguerre Point, the lateral extent of channels was constrained by Quaternary terraces, colluvium, or bedrock. Below Daguerre Point, the floodplain widened into shallow braid plains and anastomosing reaches that were manipulated by local flood managers to prevent channel erosion. Riparian vegetation had colonized the length of the LYR fan, decreasing flow velocities, and encouraging sediment deposition. Conditions of the channel ca. 1900 were described by W.T. Ellis based on repeated personal observations by boat:

> "…In those times, the entire Yuba River bottoms, from Marysville to the edge of the foothills, a length of about ten miles [16 km], with an average width of about two and a half miles [4 km], had a dense growth of trees, underbrush, wild grapevines, blackberry bushes, etc., except for the many channels themselves, and it was with very considerable difficulty that any roaming about an area of about 16,000 acres [6500 ha] was possible. Where a channel was observed and which showed that the river had an inclination to head towards our levee system, brush dams or brush mattresses would be constructed… such work was usually effective and it was a rare occasion that one ever washed away. While it was impossible to control the Yuba River, having a fall of about 9 feet to the mile [0.17%] and with a discharge of about 140,000 second feet [4000 m^3/s], we found by experience that in most cases we could guide and deflect the river to places where we wanted it to go."
>
> [Ellis (1939, p. 133).]

The barbed confluence of the LYR with the Feather River remained intact until November, 1893, when a cutoff was dredged through a low chute. When the upstream end of the cutoff was completed, the flow stage at the D Street gage dropped 43 cm (17 in.) the following day and the old channel rapidly filled with sediment. This cutoff reduced erosive shear against the far right bank of the Feather River where the old Yuba channel entered the Feather, but it did not reduce backwater up the LYR during floods (Ellis, 1939; p. 179).

5.2. Coordinated sediment detention, channelization, and dredging

A concerted effort to control the HMS was made in the first decade of the 20th century. The Caminetti Act, passed by the U.S. Congress in 1893, established the California Debris Commission (CDC) with the authority to devise methods for protecting navigation in the Sacramento River from HMS. After many years of study, the Yuba River was selected as the test basin in the Sacramento Valley for mitigation measures, because it had received much more sediment than any other basin. The initial strategy incorporated three key features (Ellery, 1908). First, four barrier dams were to be constructed across the LYR as sediment retention structures and raised in stages as they filled with sediment. Second, massive training walls combined with levees and dikes were to contain the main channel from 3 km above Daguerre Point to the Feather River confluence. Third, storage behind the dams was to be supplemented with storage in settlement basins adjacent to barriers No. 1 and No. 4.

In spite of the rapid demise of bush dams on the LYR and Bear River in 1880, another attempt was made in the first decade of the 20th century to detain HMS behind barrier dams across the LYR. Three barriers were ultimately built. The first two barriers were constructed of brush mattresses and rock-filled log cribs in 1903. Barrier No. 2 was completed to a low level across the river in the summer of 1903, but was destroyed by a flood that November and abandoned (Fig. 11). Barrier No. 1—built about 1.6 km downstream of Barrier No. 2—has a more complex construction and failure history (Ellery, 1908; Gilbert, 1917). The initial structure was partially completed before being destroyed by the November and subsequent 1903 floods. The design of Barrier No. 1 was changed to a rock-filled frame of piles and timber with a 0.5-m cap of concrete, ultimately planned to a height of 11 m. In the summer of 1904, it was built in two steps to a total height of 4.3 m. Storage filled with sediment that winter, so it was raised another 2.4 m in 1906 and a spillway was added. The additional storage capacity also filled quickly, and in 1907 the largest flood on record destroyed Barrier No. 1 completely. Ultimately, Barrier No. 1 trapped ~1.3×10^6 m^3 before it was washed out in 1907 (Gilbert, 1917). The Barrier Dam channel was mapped shortly before failure showing a 6-m (20-ft) drop in channel-bed elevations across the dam (Fig. 12).

After failure of Barrier No. 1, attention shifted to Barrier No. 4, now known as Daguerre Point Dam (DPD), 7 km downstream of the Barrier No. 1 site. Construction of DPD was initiated in 1904 as a cut across the neck of a low bedrock ridge that was lined with concrete for use as a spillway during high flows. The main channel of the river was diverted north across the neck of the ridge in 1906 by extensive levees, dikes, and training walls. Bedrock outcrops are rare in the LYR, so this strategy could not be used elsewhere. The DPD continues to control vertical adjustments on the LYR as shown by its influence on the long profile (Singer et al., 2013). To enhance the limited storage behind barrier dams, a series of structures was designed to divert high flows and sediment into nearby settling basins. As part of this design, parallel training walls separated by 610 m were anticipated to contain the main

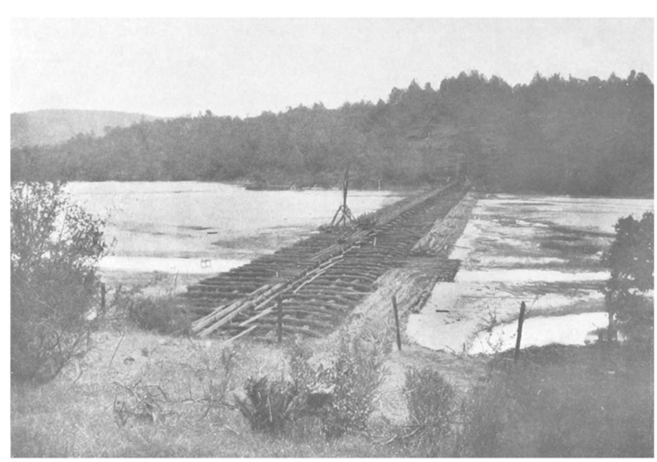

Fig. 11. Newly constructed Barrier No. 2 was destroyed by a flood a month after this photograph was taken. View south across Yuba River which is flowing left to right. Photographed Oct. 3, 1903.
CDC (1904).

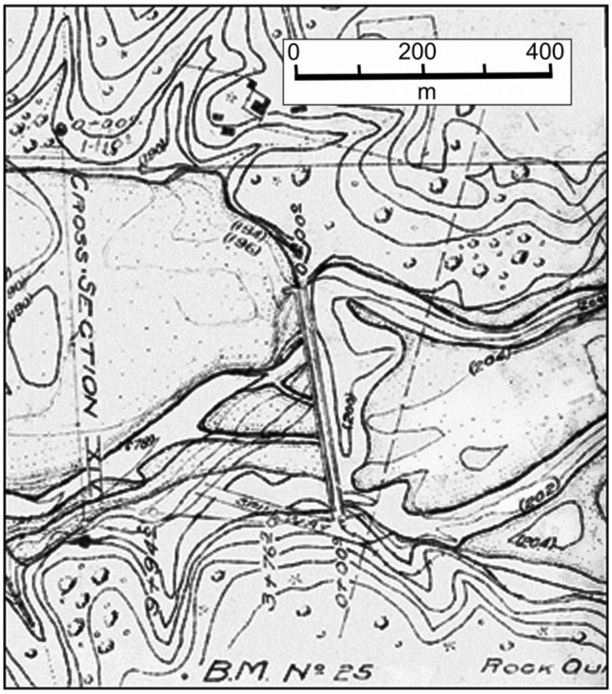

Fig. 12. Barrier No. 1 dam site with a large repository of HMS detained behind the dam as demonstrated by the 6-m (20-ft) drop in the channel below the reservoir. This sediment was released the following year when the 1907 flood breached the dam. Excerpt from CDC (1906) map with 0.6 m (2-ft) contour interval (1:9600).

channel for the length of the LYR from 3 km above Daguerre Point to the Feather River confluence. Construction of the training walls was initiated when the CDC authorized gold-dredge companies to mine river gravels under the condition that they pile their tailings according to the training wall specifications, i.e., 6 to 10 m high piles of large cobbles on a base ~10-m wide. By 1910, training walls were completed along a length of 4.0 km on the north side of the river and 3.2 km on the south side (Ellery, 1911). Later, the tailings walls were extended a few km above and below DPD, but they were never extended downstream to the Feather River. The training walls remain today and contribute coarse material to the main channel that armors the bed for a considerable distance downstream.

An important development that enabled construction of the training walls and facilitated channelization projects was the introduction of dredges and their evolution into extremely large bucket-ladder dredges. In 1903, W. P. Hammon introduced two bucket-ladder dredges to the LYR and began a mining operation, which acquired additional dredges from 1906 to 1968. Extensive dredging in this region ultimately led to a large area of channel diversions and dredge spoils known as the Yuba Gold Fields (YGF). Over the years 21 dredges operated in the YGF (Clark, 1970) and large-scale gold dredging exploited HMS, Quaternary, and Tertiary alluvium to substantial depths. The dredges were occasionally employed in river engineering operations such as channelization projects near the Feather River confluence. In at least one case ca. 1905, the LYR channel was dredged from below the Feather River confluence to the YGF and back (Ellis, 1939). By the 1930s, dredging had largely transformed the YGF.

6. Floodplain Morphogenesis, 1899 to 1906

Episodic floodplain aggradation is often followed by a period of channel vertical incision as sediment loads decline. This in turn, is typically followed by a period of channel widening and creation of a new floodplain at a lower level (Simon and Hupp, 1986). The history of these channel morphological changes in the LYR is not well documented, but inferences can be made from maps and cross sections based on contemporary topographic surveys. This evidence indicates that substantial channel incision that was to follow had not yet occurred in the first decade of the 20th century except in the upper fan.

Based on the 1906 map (CDC, 1906) and forms present at the time of maximum aggradation, floodplain morphology in the mid-fan area varied from anastomosed main channels to braid bars (Fig. 13A). The braid index in this area varied from 12 to 20 and the areas between channels were covered with willows (*Salix* spp.), alders (*Alnus*), cottonwoods (*Populus*), brush of various compositions, and sand. Many of the CDC valley cross sections show multiple surveys from 1899 to 1905 or 1906 (Fig. 13B). The section shown in the figure experienced a net fill of 129 m^2 across a 4207 m (2.6 mi.) floodplain width, or a mean deposition of 3.1 cm from 1899 to 1906 (0.44 cm/yr). From this section up to the next section upstream approximately 100,400 m^3 were deposited during the seven-year period. Deposition rates in the LYR at the turn of the 20th century averaged 2.87 cm over the period or 0.43 cm/yr. These rates were much slower than during the 1860s' and 70s' hydraulic mining period but indicate an on-going process of net storage.

Thalweg depths and floodplain cross-section changes were plotted against down-valley position to reveal spatial patterns of net erosion and deposition towards the end of the aggradation period. The pattern reveals a distinct imprint of both fan evolutionary processes and engineering structures (Fig. 14A). As was documented by Gilbert (1917), incision of the fan apex near the Narrows (0–6 km distance on the plot) is well-expressed by losses in both sediment cross-section areas and thalweg elevations. A few km downstream below Parks Bar, however, construction of Barrier No. 1 induced floodplain and channel-bed aggradation upstream and degradation downstream. Throughout the upper fan (above Barrier No. 1), changes in channel-bed and floodplain elevations were strongly in phase during this period. Further downstream, thalweg elevation changes were modest, varying largely between no change and 1 m of incision, with the exception of 1 or 2 m of scour below Barrier No. 1 and Daguerre Point, respectively. The mean cross-section area and thalweg elevation change below Barrier No. 1 were 58 m^2 of fill and 0.48 m of incision, respectively, indicating that channel degradation concurrent with floodplain aggradation dominated the LYR below Parks Bar during this period. Thalweg incision was in an incipient stage of development, while overbank sedimentation continued to build up the floodplain surface except below Daguerre Point. These observations coincide with closure of Daguerre Point Dam and construction of training walls and dykes that protected the local floodplain from floods and sedimentation. Channel degradation was modest compared to what was to follow after 1906. Ultimately, the floodplain was converted to a terrace and larger channels became a series of high-water ephemeral channels that remain active during increasingly infrequent floods (James et al., 2009).

The total net change in channel and floodplain sediment volume for the LYR during this short period was 1.8×10^6 m^3, which is a small fraction (0.71%) of the total HMS volume stored in the LYR. This net deposition follows a tremendous decline in the down-valley delivery of HMS since hydraulic mining was enjoined in 1884. The spatial pattern of sediment deposition during this period reflects several factors (Fig. 14B). Incision in the upper fan apex was associated with efficient transport of in-channel sediment and net erosion. Maximum erosion volumes occurred below Daguerre Point due to training walls that protected floodplains from overbank sedimentation and encouraged channel incision. Net deposition was dominant above Daguerre Point and Barrier No. 1 dams, where channel filling and overbank sedimentation were substantial.

Floodplain widths, which varied from less than 200 m in the fanhead to 4000 m in the mid-fan area, and back down to 600 m at the levee constriction at Marysville, were not strongly related to erosion or depositional volumes. Most of the storage at the turn of the century occurred near Marysville, where floodplain widths decrease. Factors that likely governed this pattern of erosion and deposition include decreased flow velocities above the constriction, backwater from Feather River

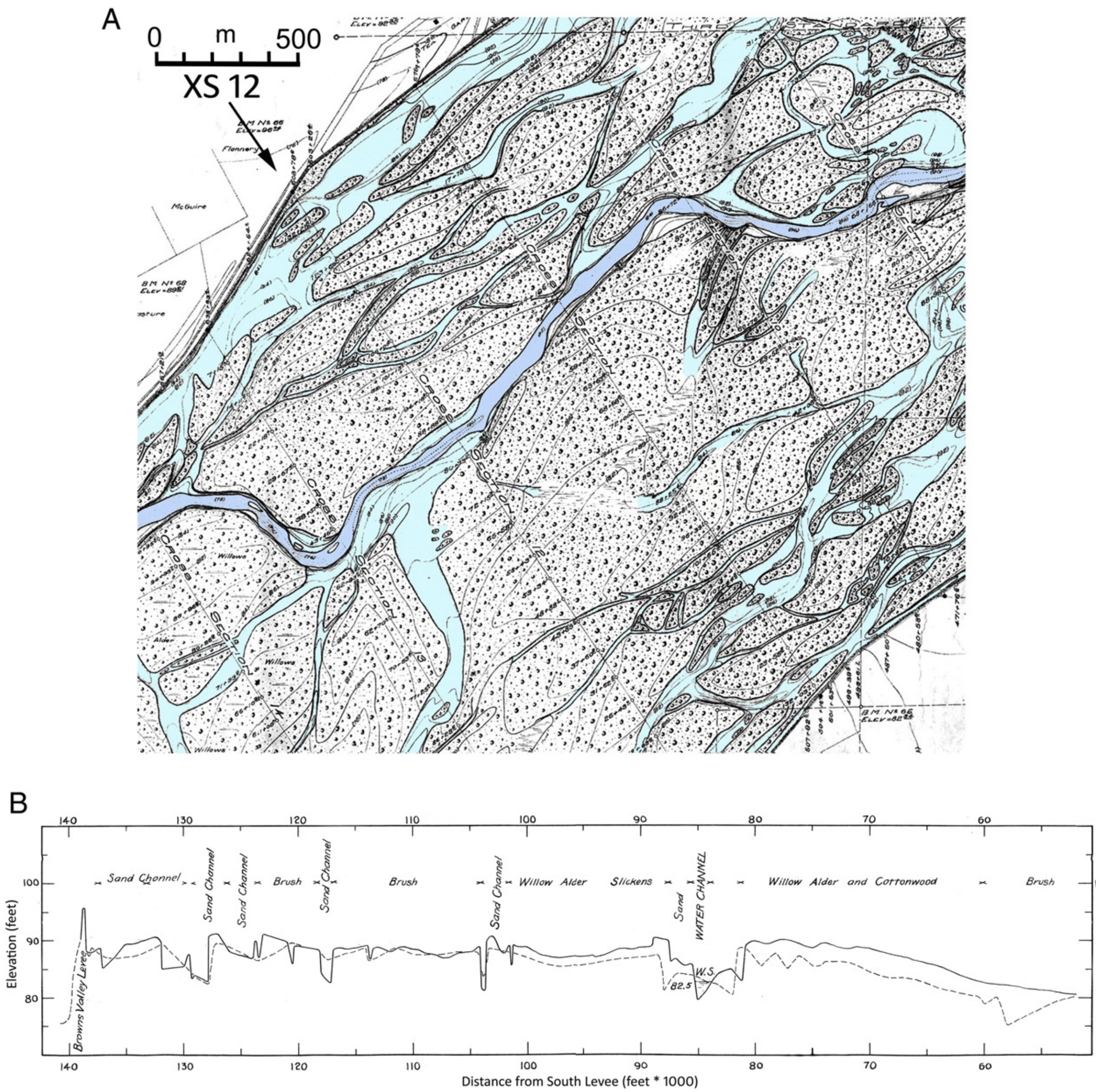

Fig. 13. Aggraded LYR with braided and anastomosed channels. (A) Excerpt from CDC (1906) map (sheet 2, 1:9600, 0.6 m contours). Arrow shows position of cross section 12. (B) North portion of cross-section #12 across floodplain showing 1899 surface (dashed) and 1906 surface (view upstream with north to left). Comparison of maximum floodplain elevations (90 ft = 27.4 m) with maximum elevations in 1880 (Fig. 9) shows deposition of at least 2.4 m and much infilling of low floodplain areas from 1880 to 1906. Cross sections identify types of vegetation and sandy areas present in 1906. (South end of the original section is not shown.) Channel color and scale bar added.

floods, recruitment and redistribution of sediment from below Daguerre Point, armoring of the bed by coarse sediment from training walls below Daguerre Point channel dredging, and greater transport capacity of fine-grained sediment. This pattern demonstrates a downstream shift of the LYR HMS deposits during this period.

Subsequent to the period covered by this paper, a period ensued that was characterized by continued incision in the upper fan, intense gold dredging, channelization, and channel regulation in the mid fan, and channel stabilization by wing dams and revetment and incision in the lower fan. Details of that geomorphic history remain to be written, but they are important to the management of the LYR because they will shed light on important patterns and trends. For example, channel stability in the lower fan belies a latent tendency for channel widening that was arrested in many places by hard engineering. Remobilization of HMS along the LYR could release a vast repository of HMS, which is highly problematic due to mercury toxicity of the HMS (Hunerlach et al., 2004; James et al., 2009; Singer et al., 2013).

7. Designing for the future, recognizing past trends and processes

Conventional restoration projects are often aimed at past morphologies that may no longer be stable under existing hydrogeomorphic conditions. Instead, design, rehabilitation, and management should be aimed at present and anticipated conditions, but without losing the dynamic long-term view of historical geomorphology. Although this study does not include important changes to the system after 1906, the conceptual basis of the evolutionary approach allows identification of trajectories (Brierley et al., 2008) and complex process-form dynamics.

7.1. Restoring to a by-gone past

Conventional definitions of river restoration have been based, at least in part, on returning channels and ecosystems to some form of pre-disturbance conditions (NRC, 1992; Brierley and Fryirs, 2005; Bennett et al., 2011). For example, river restoration is commonly linked

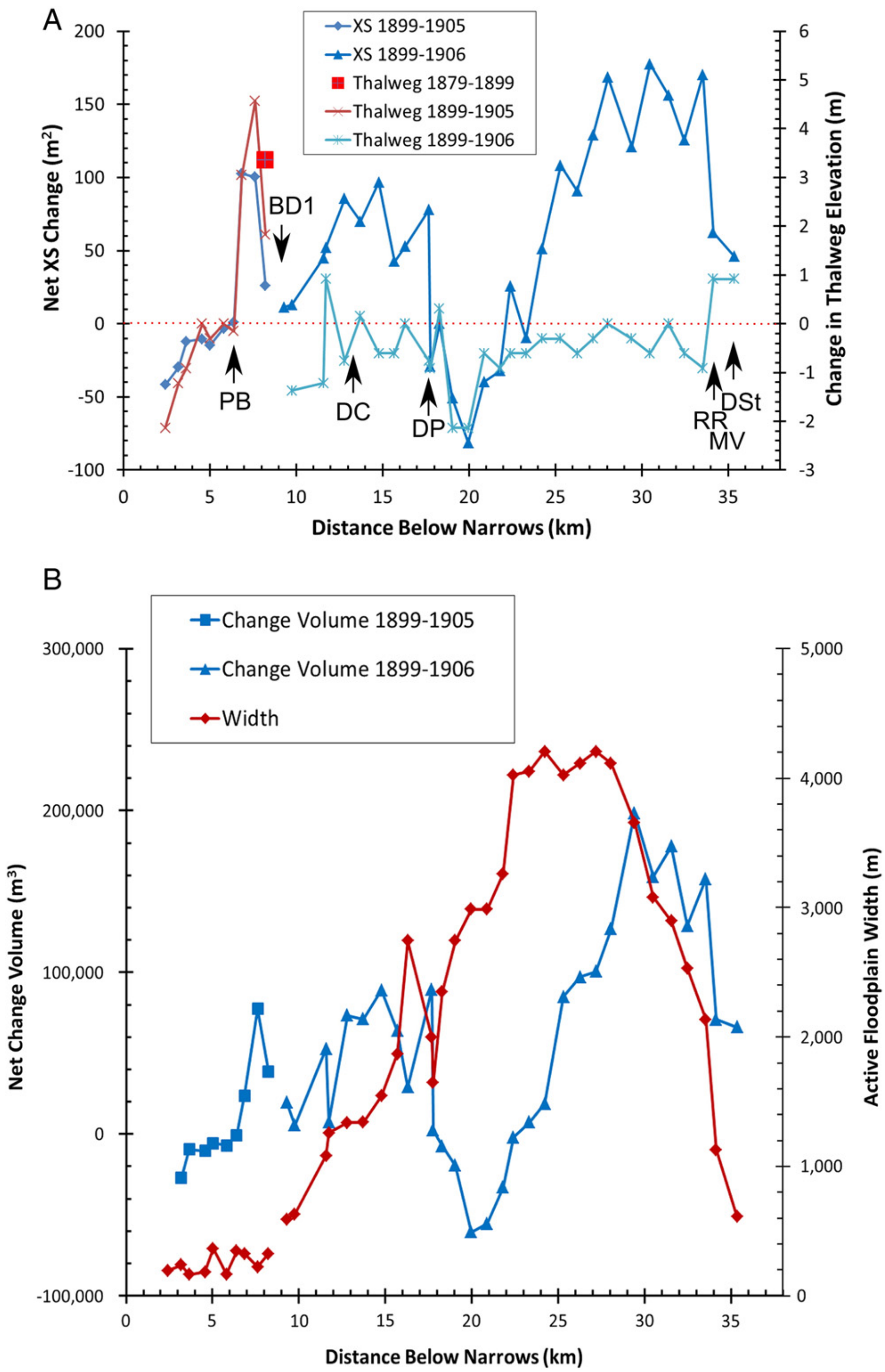

Fig. 14. Channel morphological and sediment changes from 1899 to 1905 or 1906. (A) Net floodplain sediment cross-section area and channel thalweg elevation changes. PB = Parks Bar, BD1 = Barrier No. 1, DC = Dry Creek, DP = Daguerre Point, RR = Railroad, DSt = D Street, MV = Marysville. Thalweg incision was minor (<1 m) except in the fan apex above PB and below BD1 and DP. Substantial floodplain sedimentation above BD1, DP, and MV. (B) Net change in volumes and active floodplain widths.
Data from CDC (1906).

to the use of local reference channels that represent pre-disturbance conditions. Restoring to a pre-disturbance condition is a form of conservationism that may appeal intuitively to environmental scientists and managers but has come under close scrutiny recently for many reasons. First, pristine fluvial reference reaches are difficult to define or locate in nature, which raises questions about 'what is a natural stream' and whether or not they exist (Graf, 1996; Wohl, 2001; Nilsson et al., 2005; Wohl and Merritts, 2007; Montgomery, 2008). Second, designing new fluvial systems to past conditions has serious limitations even where appropriate reference channels can be located. Hydrologic and geomorphic regimes often have been greatly altered, so re-establishing the past river morphology will not necessarily result in stability under the new conditions (Rhoads et al., 1999; Dufour and Piégay, 2009). For example, flood and sediment magnitudes in urban areas often are greatly amplified (Schueler and Holland, 1994; Walsh et al., 2005; Chin, 2006). Channels returned to pre-disturbance dimensions and geometries are not stable if water and sediment loadings are not also mitigated, which is a difficult, watershed-scale challenge. Third, realistic river rehabilitation goals must be economically and environmentally feasible (Brierley and Fryirs, 2005). For example, removal of legacy sediment from a deeply aggraded former floodplain to restore lateral connectivity may not be practical if it requires deforestation of large areas of environmentally valuable lands and creates a problem with sediment disposal. Restoration of buried riparian wetlands beneath the extensive LYR historical terrace system, which is laden with elemental mercury, would only be practical in limited areas. Fourth, one of the key goals of restoring or rehabilitating streams is to restore more diverse and robust ecosystems and regain ecological services. Yet, in many cases the flora and fauna present under predisturbance conditions may be extirpated or extinct, and difficult to restore.

7.2. Design for the future

Ideally, the goals of river rehabilitation projects should be to design for the present and the future based on an appreciation for the past. The outcome should be a set of desirable and sustainable conditions that manifest past conditions but can be attained by practical means. A dynamic balance should be sought between hydrologic inputs over a range of flows and channel and floodplain geomorphologies that produce optimal hydraulic, ecologic, and water-quality conditions. Channel morphologic designs should optimize future conditions in order to achieve a balance between form and process (Dufour and Piégay, 2009; Brierley and Fryirs, 2009; Rinaldi et al., 2012). System design should employ sustainable biological and geomorphic principles as well as environmental esthetics and diversity. In some cases this may be achieved by restoring various aspects of the past environment, but *a priori* assumptions should be critically evaluated. Anticipating the future is always an uncertain enterprise but general tendencies may be projected for a specified time frame with accurate knowledge of historical trajectories, potential thresholds, and inherited geomorphic instabilities. Land-use changes can be incorporated into rainfall–runoff and erosion models to compute water and sediment loads. If intensified agricultural land use and urban land use are expected, models may indicate increases in loadings rather than a return towards pristine conditions. Conversely, if vegetative recovery is expected through agricultural land abandonment or urban land management, reduced loadings may be anticipated. Geomorphic responses to climate change are more difficult to project at the regional scale. As likely future effects of climate change become better understood, however, these projections should also be incorporated in models to anticipate changes in watershed runoff and sediment loads for forward-looking river management plans.

7.3. Looking back: importance of geomorphic history to river management

A serious danger in moving away from restoration to previous conditions could be further neglect of historical research on rivers. This danger is particularly keen given the difficulties in defining natural river conditions and separating anthropogenic changes from those caused by climate change, tectonics, or other factors. Consequently, some restoration scientists may be inclined to reduce or omit efforts to study past conditions. Although the past may not be the best target for river rehabilitation, the history of geomorphic change remains critical to understanding the dynamics of fluvial systems (Brierley et al., 2008). Many aspects of historical geomorphic studies—such as concepts of change over time, recognition of evolutionary trajectories, and landscape memory—can inform wise planning and management of rivers. Unfortunately, historical knowledge and analysis is often discounted by river scientists and engineers who tend to disregard non-technical perspectives as non-essential information (Rhoads et al., 1999). Place-based knowledge, such as geomorphic evolutionary history, is often dismissed as idiographic, anecdotal, qualitative, subjective, or lacking in theoretical or scientific rigor. Nomothetic generalizations that allow the application of universal laws of science and mechanics are a primary approach in river science to the geomorphic design employed by river rehabilitation projects. Yet, the idiosyncratic nature of fluvial systems with complex geomorphic and engineering histories may result in unique situations that cannot be properly treated without the application of specific place-based knowledge (Brierley et al., 2013). Probabilities of outcomes can be identified based on reductionist principles, but these generalizations should not be applied deterministically to specific cases without careful scrutiny (Phillips, 2001). Combinations of unanticipated processes may result in improbable outcomes—the so-called 'perfect storm'—making prediction from deterministic laws difficult (Phillips, 2007), particularly if those laws are applied from a generalized perspective that all watersheds are the same. Nor should a channel morphological classification system be substituted for broader management or restoration goals. Thus, it is essential to consider each geomorphic system unique and to make an effort to know the histories and spatial patterns of processes in order to recognize idiosyncratic tendencies. The general geomorphic form of a reach—whether it is anastomosed, high or low sinuosity meandering, or wandering—and the degree of hard engineering to be applied should be determined based on forward-looking anticipation of general conditions. Open-channel hydraulics, hydraulic geometry laws of drainage composition, and other analytical relationships should be applied at a later stage after knowledge of the river system long-term dynamics has been established. In short, a balanced approach to river science calls for both a nomothetic and idiographic understanding; i.e., generalized principles drawn from scientific methods applied within a place-specific context for which the complex spatial and historical relationships are known. These principles are in accordance with recommendations that river restoration efforts should focus on river processes but should recognize the complexities and uncertainties inherent to those processes (Wohl et al., 2005).

An important benefit of past knowledge is recognition of the trajectories and rates of geomorphic change that may indicate on-going processes or tendencies. River management requires not only the specification of processes, but also of the longitudinal and historical trajectories of processes that lead to the conditions at each site (Brierley and Fryirs, 2005). For example, recognition that trends are away from or back towards previous conditions is essential. Moreover, past channel positions and morphologies may document rates of progressive changes such as lateral migration or periodicities of episodic changes such as avulsions. This knowledge of channel processes and rates of morphological change can guide design or evaluation of flood conveyance systems, sediment transport, and the potential for destabilization of sedimentary units. Historical evidence also leads to recognition of fluvial features, such as paleochannels, sediment characteristics, soils, topography, and vegetation. Paleochannels may underlie levees and pose a threat of failure by piping or erosion. Sediment repositories may be instable or toxic and could pose an environmental or public-safety hazard.

7.4. Identifying process over geomorphic time

Geomorphic evolutionary history—based on stratigraphic and documentary evidence—can empirically test theories of fluvial development over centennial to millennial time scales. These are time scales over which field, instrumental, remote sensing data normally do not extend, so reconstructions rely upon alternative forms of evidence. Yet, these time scales are essential to understanding the context of global environmental change and river design stability. Fluvial processes and forms at a given time and place are contingent on previous conditions. This conditioning may be spatial or temporal, i.e., hydrogeomorphic and hydraulic changes that occurred upstream, laterally, vertically, or earlier in time may precondition responses at the site. Thus, the system may be responding to a memory of events passed through time

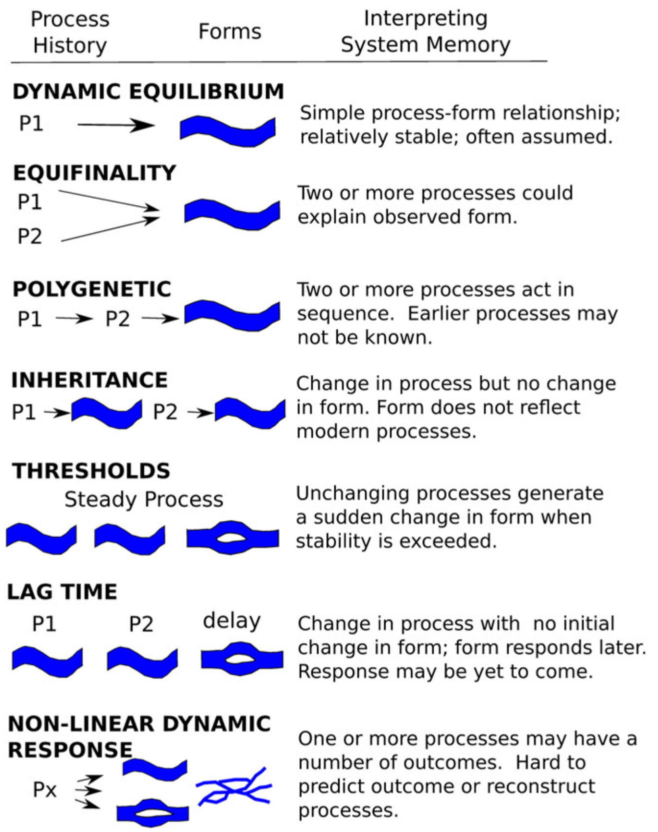

Fig. 15. Process-form dynamics that introduce potential complexities in the temporal evolution of landforms. Geomorphic systems retain a memory of past processes, but interpreting process history from form is non-trivial.

or space. This explains why a dynamic understanding of processes is critical to river management. Increasingly river science is adopting a view that rivers and river processes are prone to substantial changes through time (Brierley and Fryirs, 2005). Consequently river form may reflect a complex of past process regimes and inherent instabilities may exist. This is particularly true in anthropogeomorphically altered systems.

Several geomorphic principles of process-form dynamics illustrate the danger of assuming a simple process regime dominated by dynamic equilibrium over extended time periods. Where dynamic equilibrium dominates, the system can be assumed to be governed by negative feedbacks that will tend to stabilize channel morphology over time, but equilibrium should not be assumed without knowledge of the system. The present morphology may not represent a long-term balance between current processes and form. Complexities may be introduced by linkages between process and form caused by equifinality, polygeneticism, or inheritance, or they may arise from the timing of changes due to threshold response, lag times, or non-linear dynamics (Fig. 15). With equifinality the same form may result from one of a set of possible processes and false assumptions of causality lead to errors in interpretation. Polygenetic landforms result from multiple processes that generated the form, which may have different histories and durations. Inherited forms are a result of former processes no longer operating. It may be difficult to know which processes were responsible for the form observed in any of these cases. Similarly, the timing of changes may complicate interpretations of process from fluvial form. Channels may respond only after a flood exceeds thresholds of stability imposed by armoring, vegetation, or engineering works. Channels that appear to be stable may become instable once they are perturbed. Similarly, lag times may occur when response to a process change is delayed. Both thresholds and lag times result in morphological responses that are out-of-phase with process changes, which can generate hysteresis, obscure governing processes, and result in transient forms. Complex non-linear dynamics (NLD) include a broad class of processes for which there may not be a direct correspondence between environmental controls and system response, or potential responses may be in any direction (Phillips, 2003). Although this complicates interpretations of form, understanding the possibility of NLD enables the formulation of testable hypotheses and may avoid errors based on simplistic notions of causality. These concepts are difficult to incorporate in generalized concepts of river systems without knowledge of the geomorphic history of the specific system. Given these and other complexities, geomorphologists have learned to respect the difficulties of using form to infer processes over decadal or centennial time without an understanding of river history. As humbling as it may be to be confronted by such large uncertainties, recognition of process-form dynamics is a key component to sustainable river management.

When human disturbances are great process-form complexities often increase due to changes in hydroclimatology, sediment production and delivery rates, and various engineering works. A unique anthropogenic trajectory may result from processes such as polygenetic causality, inheritance, and high thresholds of stability that may be cumulative through time. The anthropogenic trajectories in the LYR vary spatially and should be recognized individually for different parts of the system. For example, the training walls above and below Daguerre Point Dam established a unique trajectory by preventing lateral channel migration and connectivity while providing a persistent source of coarse bed material downstream. The walls are part of a polygenetic sequence preceded by channel relocations during river mining, aggradation by HMS, gold dredging, and dam construction. Coarse material derived from the training walls creates an armored channel bed downstream, which imposes a threshold of stability that is not exceeded by small flows. Similarly, terrace-scarp revetment and wing dams below the Yuba Gold Fields result in inherited fluvial forms that are distinct from the channel widening that would occur without protection. Another example of a major anthropogenic trajectory is the levee constriction near Marysville that decreases longitudinal connectivity with the Feather River and encourages local fine-grained sedimentation during floods.

8. Lower Yuba River management

Various strategies could be adopted for managing the LYR fluvial system, ranging from passive restoration (do nothing) to active strategies that may retain, remove, or add stabilizing engineering structures and manipulate the geomorphology. These strategies should be based on an understanding of how the system evolved over time.

8.1. Present management strategies

Restoration of rivers in California is often constrained by water shortages due to over allocations of available resources that threaten to deplete flows during dry periods. Restoration in rivers that flow into the Sacramento Valley is also constrained by the need for levees to protect against flooding that would otherwise extend broadly (Kelley, 1998). Both water resources policy and levee infrastructure in the LYR have received substantial attention in the last decade. The LYR Accord was adopted to resolve instream flow issues concerning fisheries and water supplies in an effort to coordinate hydropower, irrigation, flood control, recreation and fishery benefits for the Yuba River Development Project (SWRI, 2007). The Accord includes three fundamental agreements: for fisheries, conjunctive use, and water purchases. It established a LYR River Management Team (RMT) to conduct applied and theoretical research. In addition, the Three Rivers Levee Improvement Authority (TRLIA), established in May 2004 to oversee levee improvements in south Yuba County, is working to provide 200-year flood protection along the Yuba, Feather, and Bear Rivers. Construction of slurry walls in the south levee connecting the LYR to the Feather River has been completed and four alternatives for a new levee in the south side of the Yuba Gold Fields are being studied to handle the 200-year flood event.

River restoration planning in the LYR has largely focused on within-channel habitat. Several studies and projects to protect and encourage anadromous fish have been conducted by the U.S. Fish and Game Department, Anadromous Fish Restoration Program (AFRP), including projects for barriers and screens in and around Daguerre Point Dam (DPD) and water temperature studies. The National Marine Fisheries Service (NMFS) has called for the U.S. Army Corps of Engineers to design and implement actions to improve fish passage at DPD and to provide fish passage at Englebright Dam for the first time since 1941. Alternatives for fish passages through Englebright and New Bullards Bar are under consideration. Collection and transfer methods are being considered including fish lifts and floating surface collectors. Alternatively, the crest of Englebright Dam could be lowered 24 m (80 ft) by notching the dam and constructing a fish ladder to climb 56 m (185 ft). At the large watershed scale, the South Yuba Citizens League is raising awareness, conducting river clean-ups, and coordinating restoration efforts. These projects are encouraging for sustainable water supplies and the future ecological integration of the LYR with the upper basin. Many questions remain unanswered, however, concerning restoration and management of the geomorphic system.

8.2. Applying historical findings to potential restoration strategies for the LYR

Restoration of LYR floodplains to pre-mining conditions is severely constrained by several factors including changes in water and sediment regimes, deep floodplain aggradation by toxic Hg-rich alluvium, floodplain morphogenesis, and hard engineering of the channel. Floodplain morphogenesis resulted in entirely different channel and floodplain geomorphic forms than pre-disturbance conditions, and these changes occurred in complex spatial and temporal patterns. In general, early river mining was followed by deep burial of the pre-mining floodplain and channel avulsions. This was followed by channel engineering and dredging. Most of the dominant resulting landforms are polygenetic, but the extent and sequence of anthropogenic processes differ. Restoration potential is constrained by these conditions that vary downstream and define multiple suites of trajectories of channel-change tendencies with cumulative effects. At the upper limit of the LYR study area, immediately below Englebright Dam, channels have incised to bedrock, little sediment is available for recruitment, and management has focused on reintroduction of fine gravel (Pasternack et al., 2010). Downstream below the tailings fan at Rose Bar, channels are graded but are not in equilibrium as they continue to incise into historical HMS gravels (White et al., 2010). Further downstream in the Yuba Gold Fields, high dredge-spoil ridges and immense training walls limit channel lateral connectivity and Daguerre Point Dam has fixed the base level. The ridges and walls produce coarse material during floods that armor channel beds and impose thresholds for channel incision.

Below the Yuba Gold Fields, channels incised into a broad historical braid-plain that was left as a terrace several meters above the relatively narrow modern floodplain. The natural trajectory for incised channels to widen their floodplains by lateral migration has been arrested by extensive bank protection including wing dams and revetment. Normally, a key goal of river restoration would be to improve lateral connectivity of floodplains and promote restoration of riparian wetlands (Sparks, 1995). Wetlands expand aquatic and riparian habitats, improve water quality by sequestering suspended sediment and nutrients, and reduce flood peaks downstream by storing flood waters. Restoration of wetlands along the LYR would be particularly beneficial to migratory birds on the Pacific Flyway. The historical evidence for anastomosing and wandering channels on broad floodplains documented by this paper indicates that pre-mining channels were well-connected to extensive areas of lowland habitat and wetlands. Due to narrow floodplains and high terraces, laterally reconnecting channels in this area to their former floodplains cannot be accomplished by simply increasing discharges. One strategy to widen floodplains could be to promote lateral channel migration by reducing protection of terrace scarps. At present, however, this strategy should be discouraged until the potential mercury toxicity of the stored sediment is better understood (Singer et al., 2013). Moreover, the history of floodplain evolution in the LYR suggests that removal of stabilization structures to promote lateral migration could result in rapid geomorphic responses such as channel avulsions that would be difficult to control.

9. Conclusion

The LYR is an extreme example of a river that experienced anthropogeomorphic change since the mid-19th century, a transformation chronicled by an astute classical geomorphic treatise (Gilbert, 1917). As an acute case of anthropic fluvial change, the LYR illustrates the futility of seeking to restore systems to pre-disturbance conditions. A nexus of past mining activities, engineering structures, and river management policies generated an idiosyncratic set of conditions that—on the broad scale—cannot be properly treated by standard methods based on natural river processes. Mining and river channel management from 1850 to 1906 created a unique, highly engineered channel system. Almost half of the 1.1 billion m^3 of HMS produced in the northern Sierra Nevada was produced in the Yuba Basin and almost half of that sediment was deposited along the LYR by the turn of the twentieth century. In response to this episodic aggradation, extreme engineering measures were taken to stabilize and control the river, including levees, dams, and bank protection. The devastation of this sedimentation has long been known, but other historical changes to the channels and floodplains, such as river mining, erosion protection, dredging, channelization, leveeing, and other engineering works have received little attention from geomorphologists. Managing the LYR in its altered state requires an understanding of how it evolved to that geomorphic condition.

Returning rivers to a previous identifiable condition should not be the primary goal of river design and management, especially if water and sediment regimes have changed. A river rehabilitation project designed to return a system to previous conditions is not inherently bad, if watershed conditions are similar to what they were in the past. The methodology may fail, however, if hydrogeomorphic inputs have changed substantially in response to land-use and land-cover alterations. In the case of the LYR, water and sediment inputs have been drastically changed, and early channel and floodplain morphologies would not likely be in equilibrium with current water and sediment loads. Furthermore, removal of channel bank protection could destabilize large repositories of toxic sediment.

River design should be based on realistic projections of water and sediment loads, balanced with concerns for water quality and habitat diversity. Projections should include present and future conditions embracing concepts of global environmental change and climate change as guiding principles for long-term sustainable planning. Robust systems should be designed that can withstand changes in climate, hydrology, sediment loads, and biota. Outcomes should balance natural and social needs and be achievable by practical measures. Historical research is needed to recognize when, where, and how fluvial systems have been disrupted by anthropic changes. In such cases, simplistic interpretations of long-term system behavior should not be made, such as assumptions of stability governed by dynamic equilibrium and other stabilizing negative feedback mechanisms.

Geomorphic history is essential to river management, but the benefits of evolutionary knowledge are often overlooked or discounted. Much of what is known about anthropogeomorphic fluvial change has been derived from historical evidence. Geomorphic history indicates that change is common to river systems and that episodic change is particularly common in humanized landscapes. Wise river management policies call for recognition of the geomorphic processes that have been operating on a system through knowledge of the geomorphic and engineering history and an understanding of why engineering structures were initiated. These processes represent a highly idiosyncratic system memory that is essential to understanding the dynamic nature of fluvial systems.

> "'…once upon a time, an old lady had decided to read Webster's unabridged dictionary all through, from beginning to end and when she had completed her task, she was asked if it had been interesting; she replied, that it had been exceedingly interesting to her, the only trouble was, that the subject changed quite often.' So, I said, the same thing applies to the Yuba River, the channels and their conditions 'change quite often' and only constant observations,… permits of necessary knowledge to have definite information as to that river's eccentricities and changes and which is impossible by casual observations in a few years…"
> [Ellis (1939; pp. 138-139) recounting his testimony in federal court.]

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.geomorph.2015.07.009 These data include the Google map of the most important areas described in this article.

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