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Arrested geomorphic trajectories and the long-term hidden potential for change

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ABSTRACT

Geomorphic systems often experience morphological changes that define a trajectory over decadal time periods. These trends can be halted by natural inhibitors such as vegetation, knickpoints, bed armor, or bank cohesion, or by anthropogenic inhibitors such as revetment, levees, or dams. Details about where and how channels and floodplains are stabilized are often poorly understood, which poses a risk that modern projects could unwittingly remove critical stabilizing elements (inhibitors) and unleash an episode of rapid change. The potential for destabilization is particularly keen for rivers that were severely altered by human activities but were stabilized by an inhibitor before readjustment was complete. This study uses aerial photographs to examine two cases of arrested geomorphic trajectories in the lower Yuba and Feather Rivers of northern California after 150 years of severe human disturbance. Channel adjustments were inhibited in distinctly different ways. First, channelization of the Feather River across a high-amplitude meander bend ~4 km below the Yuba-Feather River confluence resulted in a knickpoint at Shanghai Shoals that retreated upstream at an average rate of 3.67 m/yr from 1963 to 2013 with two episodes of rapid retreat. Shanghai Shoals was breached in 2013. Second, numerous wing dams on the Yuba River constructed in the early nineteenth century limit floodplain widening and prevent return to an anastomosing channel planform. Their stabilizing role is important to preventing mobilization of mining sediment with high concentrations of mercury. These rivers exemplify how arrested geomorphic trajectories may impact sustainable river management, and how recognition of fluvial evolution is essential to sustainable river management.

1. Introduction

1.1. Geomorphic trajectories

Conventional river management focuses on identifying and designing channels to equilibrium conditions, which are relatively stable. The long-prevailing concept of dynamic equilibrium envisions alluvial channel systems in which morphological changes are self-regulated and governed by negative feedbacks that dampen change (Gilbert, 1877; Hack, 1960; Lane, 1955; Mackin, 1948). This focus on stability underestimates the importance of change and the recognition that change and instability include a variety of potential theoretical outcomes (Brierley et al., 2008; Graf, 1979; Phillips, 1999). When anthropogenic alterations are considered, instability and transformation may be the rule, rather than the exception. Equilibrium is often disrupted by abrupt changes in tectonics, climate change, or human disturbance. Under these circumstances, adjustments may occur in channel size, shape, plan form, gradient, or boundary materials that are not easily accommodated by equilibrium or regime theory or the tools that they employ such as hydraulic geometry or other linear models. Modern river science and management seek to expand their conceptual and methodological basis from stable systems in equilibrium to dynamic systems prone to change. This can be seen in a growing emphasis on morphological change in classification systems (Downs, 1995) and river management (Brierley and Fryirs, 2015; Thorne, 1997). Concepts of change also call for the consideration of historical perspectives. For example, Macklin and Lewin (1997) stress the need for a greater understanding of river history at a variety of time scales. Alternative conceptualizations and methodologies have emerged, such as complex non-linear dynamics (Phillips, 2003, 1999) and evolutionary trajectories of channel systems (Brierley et al., 2008) that are more broadly applicable to river management. Although these approaches may be associated with greater

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uncertainties, they can be applied to a broad array of conditions changing over decades, including non-linear responses and anthropogenic activities for which governing conditions may change substantially (Brierley and Fryirs, 2015).

Research referring to trajectories has grown rapidly in recent years. Trajectories in geomorphic and ecological systems represent a tendency for systematic adjustments in rates, processes, or form over a period of time. Brierley and Fryirs (2005) note that knowledge of geomorphic trajectories is essential to predicting future change. Their River Styles Framework uses the trajectory of future river conditions to assess the potential for river recovery. Hughes et al. (2005) note that riparian restoration trajectories provide a more realistic assessment of variability and uncertainties in projecting habitats than assessments based on the use of reference conditions. The more specific concept of 'evolutionary trajectories' has been advanced in Australian and European river research that acknowledges complexities introduced by multivariate, nonlinear, or indeterminate evolutionary behavior that may govern fluvial change over decadal time scales (Brierley et al., 2008). Evolutionary trajectories recognize the importance of historical and anthropogenic changes, as well as process-based trajectories that can be used to assess the likelihood of future river behavior (Brierley and Fryirs, 2015). Surian et al. (2009) describe 'evolutionary trends' by studying changes in width and incision in five gravel-bed rivers in northeastern Italy, and relate these trends to human activities and river management issues such as bank protection maintenance. Ziliani and Surian (2012) describe three distinct multi-decadal 'evolutionary trajectories' in the morphological evolution of the Tagliamento River, Italy and attribute them primarily to reach-scale human activities. David et al. (2016) examine four time periods over 160 years in analyzing the evolutionary trajectory of the Garonne River, France. Lespez et al. (2015) use trajectory analysis with an historical and anthropogenic emphasis and contrast this approach with conventional principles based on preservation of natural geodynamic processes. They point out that restoration projects should not regard watershed controlling conditions as intransient, but should be developed from a regulated river perspective (Brierley and Fryirs, 2005; Downs and Gregory, 2004). Analysis of trajectories instills the recognition of complex non-linear dynamics and may reveal invalid assumptions that channels will necessarily recover to equilibrium conditions, (Piégay, 2016).

1.2. Arrested trajectories and boundary inhibitors

Alteration of a trajectory represents a non-linear response with respect to time. A shift in rates or directions of change may be caused by changes in thresholds, storage of mass or energy, feedbacks, and competitive relationships (such as channels in a braid bar vying for flow), which are all earmarks of non-linear dynamics (Phillips, 2003). Human manipulations of watersheds and river systems often change evolutionary trajectories and—especially where channel stabilization is engineered—may arrest trajectories. Arrested trajectories may represent the potential for substantial geomorphic change and tendencies for channel adjustments that could release large amounts of mass and energy if they are removed. This paper is concerned with changes in trajectories generated by resistant features that arrest or inhibit on-going processes at the boundary layer of fluvial systems. Inhibitors are essentially agents that impose a high threshold for change in boundary conditions. They are not uncommon, although they may be subtle or hidden and not recognized as such. Many anthropic structural changes to rivers, such as dams, levees, and bed or bank protection, represent arrested trajectories, but inhibitors may also be non-anthropogenic (Table 1). For example, the trajectory of an aggrading channel may be inhibited by a landslide or engineered dam that reduces sediment downstream. Similarly, a degradational trajectory may be inhibited by bed armor resulting from exposure of channel lag material or introduction of coarse cobbles.

The reaction to removal of inhibitors is often the same as the response to threshold exceedance, which has been extensively studied in geomorphology (Schumm, 1973, 1977; 1980). Threshold exceedance describes a process in which the application of forces results in little response until a critical resistance is exceeded, at which time a step-functional increase in response occurs. For example, in bedload transport, a *threshold of critical power* occurs when stream power exceeds resistive forces (Bull, 1979, 1980):

$$\text{Stream Power}/\text{critical power} > 1.0 \qquad (1)$$

Extrinsic threshold exceedance occurs when external forces have little response until they exceed the resisting forces. In contrast, *intrinsic threshold exceedance* may occur by internal, progressive weakening of the inhibiting factor (Schumm, 1973). In the case of arrested geomorphic trajectories, the emphasis is on recognizing factors that inhibit geomorphic response and can release potential energy if removed. Threshold exceedance is not necessary if the inhibitor is removed by human activities.

1.3. Anthropogenic disturbance as a common precursor or cause of arrested trajectories

Although local stabilizing features occur naturally, human disturbances and structures are commonly associated with inhibitors that arrest trajectories. Anthropogenic change may encourage arrested trajectories in two ways. First, channels may be stabilized directly by human structures, such as by bank or bed protection, dams, or levees. Second, human disturbance may generate a new geomorphic trajectory that is halted by natural or artificial means. Channel instability, erosion, sedimentation, and increased flood risks often result from disturbances and are locally engineered to halt the trajectory. Two case studies are presented here to provide diverse examples of arrested trajectories: a knickpoint that has protected a channel bed and wing dams that protect channel banks. Both impose inhibitors that govern channel and floodplain morphological evolution in systems in which recovery from a disturbed, aggraded condition has been temporarily arrested.

When trajectories are arrested, the stabilizing element becomes a potential trigger and its removal may instigate a period of rapid change. Recognition of disturbed conditions, arrested trajectories,

Table 1
Examples of inhibitors that arrest fluvial trajectories.

A. Factors that alter water and sediment deliveries
1. Reduced loads: natural or engineered dams, detention and retention structures, terracing, land conservation, reforestation
2. Increased loads: dam breaching or removal, urbanization, abandonment of conservation measures, deforestation
B. Factors that protect against erosion or flooding
1. Bank protection: rip-rap, root wads, revetment, gabions, ramparts, wing dams, flood walls, vegetation, etc.
2. Bed armoring
3. Levees, floodwalls, or dykes that laterally constrain channels

and the stabilizing factors, therefore, is key to management that anticipates river responses. This is particularly important in disturbed rivers where arrested trajectories are common and extreme geomorphic responses may be pent up. Disturbance of river geomorphology has been one of the earliest and notable types of anthropogenic change to environmental systems. Logging, mining, grazing, and agricultural land use greatly increase water and sediment deliveries and channels adjust to these changes by aggradation, avulsions, lateral migration, and complete shifts of morphological type (e.g., from meandering to wandering or braided forms). In response to episodic disturbances, dams, levees, bank protection, and channelization employed to stabilize rivers and reduce erosion result in an arrested geomorphic trajectory. Detection of arrested geomorphic trajectories is important for river management because removal of stabilizing elements of the system could create an imbalance between applied hydraulic energy and the strength of channel boundary materials and unleash substantial geomorphic responses. Recognition of the hidden potential for geomorphic change through identification of arrested trajectories may be difficult when engineering was done long ago and poor records were kept. Identification usually requires river managers to comprehend extended periods of time and geographic extent based on geohistorical, geomorphic, and stratigraphic evidence.

2. An evolutionary perspective of the lower Yuba and Feather Rivers

Recognition of evolutionary trajectories is contingent upon knowledge of the geomorphic and institutional histories of systems. The two rivers in this study have a history of extreme physical change that resulted in their having played a pivotal role in the history of river management in the western USA.

2.1. Historical morphogenesis of the lower Yuba and Feather Rivers

European settlement in northern California after the gold rush in the mid-19th century rapidly introduced new technologies with few environmental constraints on their application. Intensive mechanized mining and deforestation in a land that had not previously been worked with metal tools resulted in rapid erosion and sediment production. Sediment produced by hydraulic gold mining caused deep floodplain aggradation along the eastern Sacramento Valley (Gilbert, 1917). Later, during the early twentieth century, gold dredging, channelization, sediment-detention structures, and dams drastically altered flood regimes and sediment budgets. Subsequent channel and floodplain changes during the late nineteenth and early twentieth centuries exemplify a complex of geomorphic trajectories that varied through time and space.

The Yuba and Feather Rivers flow out of the Sierra Nevada from the east and join in the Sacramento Valley of northern California (Fig. 1). The Yuba River drains 3484 km^2 at Marysville and is the largest tributary of the Feather River, which drains 10,301 km^2 above its confluence with the Yuba at Marysville. The Lower Yuba River (LYR) received the brunt of hydraulic mining sedimentation. Geomorphic evolution of the alluvial fan of the LYR during the California gold-mining era was an early subject of study and management due to extremely rapid aggradation and exacerbation of flooding in the Sacramento Valley. Gilbert (1917) raised global awareness of the Yuba River with his genius for quantifying large-scale complex phenomena to demonstrate fundamental physical relationships. He computed a watershed-scale sediment budget for the Sacramento Valley that demonstrated the over-whelming magnitude of hydraulic mining sediment (HMS) introduced to the major rivers flowing out of the northwestern Sierra Nevada into the Sacramento Valley. He showed that approximately 1.07×10^9 m^3 of HMS was produced from the 1850s to ca. 1907, that almost half (523×10^6 m^3) of it was produced in the Yuba basin, and that approximately half of that sediment (255×10^6 m^3) was stored along the LYR at that time. Gilbert provides an excellent snap-shot of broad-scale conditions of the LYR at the turn of the 20th century and the dynamics leading up to that point. Much subsequent work has been done at smaller spatial scales (Carley et al., 2012; Higson and Singer, 2015; Wyrick and Pasternack, 2014; Wyrick et al., 2014), but limited study has been devoted to broader geographic or historical time scales (James et al., 2009; James, 2015; Singer et al., 2013).

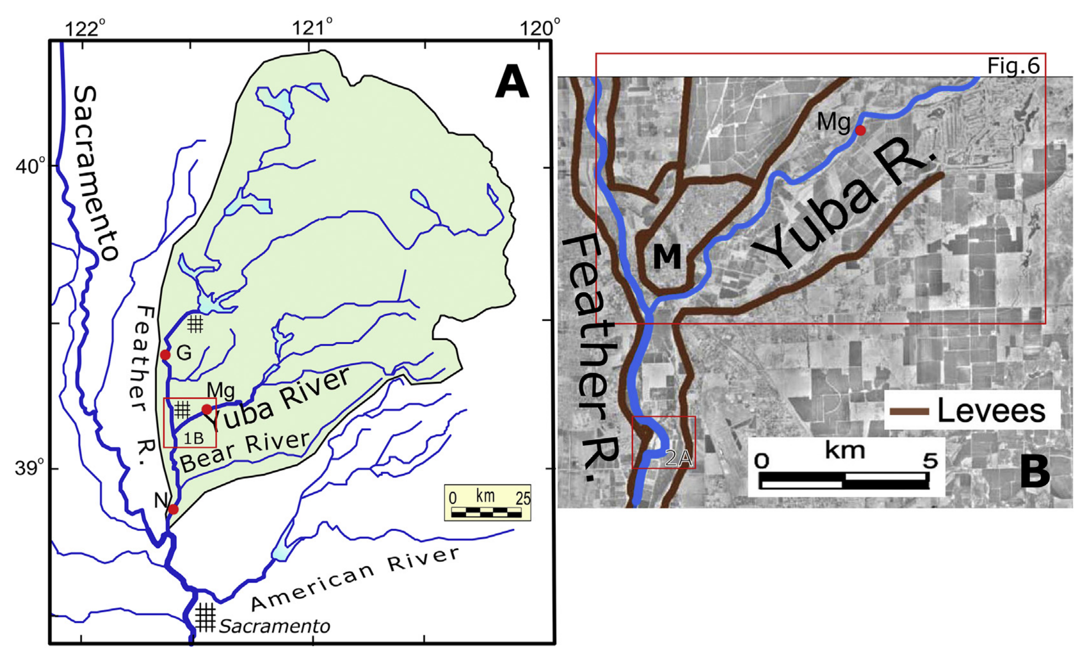

Fig. 1. The Feather River Basin. (A) Yuba and Feather Rivers join in the Sacramento Valley at Marysville (M). (B) The lower rivers flow through relatively flat agricultural lands of the Sacramento Valley controlled by extensive levees. G, Mg, and N represent U.S. Geological Survey streamflow gauges at Gridley, near Marysville, and Nicolaus, respectively.

2.2. Federal coordination of flood control

As channel sedimentation and flooding increased in the 1860s and 70s due to HMS, farmers began constructing a series of *ad hoc*, local levees that were not graded or coordinated. The resulting 'levee wars' led to a system of competing structures that forced flood waters from one area to another (Kelley, 1989). Modern river management policy in the Sacramento Valley can be traced to the 1893 Caminetti Act (*33 U.S.C.* Sec. 661 *et seq.*) (Hagwood, 1981; Kelley, 1989), which created the California Debris Commission (CDC) and charged it with improving and maintaining navigation. The act authorized the CDC, a federal agency, to engage in flood control, and ultimately raised the status of the CDC to the third river commission in the USA, after the Missouri and Mississippi River Commissions (Kelley, 1989). Up through the first decade of the 20th century, federal flood management policy was focused on containing the major rivers into single-channel systems through the use of levees as had been advised by the Humphreys Report for the lower Mississippi (Humphreys and Abbot, 1861). When the Jackson Report came out (CDC, 1911), however, river management policy for the Sacramento Valley shifted to an integration of flood control, navigation improvements, and sediment control in a system of bypass channels adjacent to the main channels of the Sacramento and Feather Rivers (James and Singer, 2008; Kelley, 1989).

Even as flood-management policy changed for the Sacramento Valley from single channels to a bypass strategy, two distinctly different flood-management policies were maintained for the Feather and Yuba Rivers. Given the massive HMS loadings in the LYR, federal efforts to integrate flood and sediment control resulted in a policy of levees and detention structures designed to retain sediment in the LYR and prevent delivery downstream. In contrast, given the historical navigability of the LFR between Sacramento and Marysville, sediment conveyance was encouraged through the LFR. Consequently, levee setbacks, channel dredging, sediment-detention dams, bank protection, training walls, and other engineering strategies differed between these two highly engineered rivers. For example, the policy resulted in levee setbacks >4000 m in the LYR that narrowed abruptly to 600 m at Marysville to encourage deposition, and levee setbacks averaging only ~1000 m on the much larger LFR (James et al., 2009).

The two case studies in this paper represent diverse examples of arrested trajectories in these rapidly changing channel systems. The Shanghai Shoals knickpoint on the LFR was a delayed response to dredging a canal across a large amplitude meander bend that eventually resulted in channel degradation being arrested. The shoals are now being breached, which is releasing this tendency. This paper reviews previous studies of the shoals, computes knickpoint recession rates, and tests a null hypothesis that headward migration of the knickpoint was episodic in response to large floods. The second case study examines wing dams that laterally confine channels in the LYR. Wing dams prevent channel widening in the LYR and channel avulsions that could return channels to their pre-settlement anastomosing form.

3. Methods and data used

The case studies are based primarily on analyses of aerial photographs. Mapping changes in Shanghai Shoals was performed using historical aerial photographs between the 1950s and present. Historical aerial imagery was derived from a variety of sources. Four images from 2003 to 2015 were downloaded from Google Earth Pro at maximum resolution (cell sizes: 0.18–0.33 m). In addition, two U.S. Dept. Agriculture (USDA) digital orthophotographs, 1988 and 2009, were used with a 1.0 m cell size, which is the marginal limit at which mapping at this scale can be done accurately. A high-resolution image was obtained from a 1999 study evaluating photogrammetry and LiDAR (Stonestreet and Lee, 2000), for which the date is inferred from a very similar, but poor-quality image from Google Earth that was acquired in 2000. Four panchromatic photographic prints flown prior to 1990 were obtained from archival sources and scanned at resolutions of 720 or 1200 dots per inch on an 11 × 17" flatbed scanner. A high-resolution (0.33 m) 2015 Google Earth image was georectified and the other images were registered to it. Positions of the shoals for each period were manually digitized from the imagery and distances were measured for each period along a digital line traced along the thalweg as the shoals migrated upstream through time.

In order to test a null hypothesis that headward migration of the knickpoint was primarily an episodic response to extreme floods, the annual maximum flood series was collected from the four nearest streamflow gauges: Feather River at Gridley (1964–1998), Feather River at Nicolaus (1955–1983), Feather River at Yuba City (1964–1975), and Yuba River near Marysville (1943–2014) (Fig. 1). Although the three Feather River gauges have incomplete records, histograms of the four available series show that all four gauges are strongly in phase with the annual maximum floods occurring within ±1 day each year. The Yuba River near Marysville annual maximum series—the most complete record—was plotted, therefore, to represent the timing of floods at Shanghai Shoals. To ensure against the possibility that the absence of shoaling on imagery from the 1950s was due to high water, mean daily flows at the near Marysville gauge that correspond with photograph flight times were tabulated (Table 2). Flows on the days of all three of the flights for images in the 1950s were moderately high (164, 104, and 190 m^3/s), but the shoals were very clearly demarcated on a much higher flow on December 30, 2005 (564 m^3/s).

Wing dams at two locations in the LYR were mapped using two sets of aerial photographs. A pair of 1947 panchromatic aerial photographs was georegistered and used in conjunction with a set of high resolution (0.15 × 0.15 m) 2008 orthophotographs of the LYR (CDWR, 2008). The 1947 imagery shows channel conditions at an early period prior to establishment of thick riparian vegetation but after most channel vertical incision was complete. The high-resolution orthophotographs show relatively recent, leaf-off conditions. Locations of wing dams were digitized from the rectified imagery as points on shape files and on a Google Earth Professional kmz file (Supplement). To show the contemporary geomorphic context of the wing dams, channel margins, sand bars, and historical terrace scarps were digitized as polylines from the 1947 imagery.

4. Breaching of Shanghai Shoals: releasing an arrested trajectory on the LFR

Regional-scale channel degradation of the LFR, representing a substantial geomorphic trajectory has been arrested locally for 50 years by a knickpoint at the Shanghai Shoals (also known as Shanghai Rapids) on the LFR below the Yuba River confluence. Shanghai Bend is a large meander bend in the lower Feather River (LFR) ~ 3 km below the Yuba River with a wavelength and amplitude of ~0.9 and 0.6 km, respectively (Fig. 2A). At the lower end of Shanghai Bend, a knickpoint ultimately formed where the flow came out of the meander loop and formed a sharp bend to the south (Fig. 2B). The shoals formed on a resistant clay of the Modesto Formation, over which the LFR had been diverted in the early 19th century by cutting off Eliza Bend, a pre-existing high-amplitude meander bend (James et al., 2009). A 1925 map of the flood-control structures shows that the LFR formed two channels at Eliza Bend (Fig. S1 in supplement). The old east channel around Eliza Bend was still open and perhaps dominant in 1925 and the dredged west

Table 2
Shoals retreat rates.

Start Period	Period (years)	Position (m)	Change (m)	Rate (m/yr)	Q (m^3/s)	
4/7/1956	0.00	NA	NA	NA	104	no shoals
6/17/1958	0.00	NA	NA	NA	190	no shoals
9/20/1963	0.00	0.00	0.00	0.00	5.95	shoals appear
5/28/1964	0.69	0.00	0.00	0.00	67.2	
~4/15/1979	14.9	15.5	15.5	1.04	NA	FERC; date approx.
10/15/1986	7.51	55.8	40.3	5.37	45.6	
~4/15/1988	1.50	106	49.8	33.2	NA	DOQ; date approx.
7/27/1999	11.3	106	0.00	0.00	3967	
7/14/2003	3.97	133	27.3	6.88	47.0	
12/30/2005	2.47	133	0.00	0.00	564	
5/24/2009	3.40	137	3.70	1.06	97.2	
5/2/2013	2.63	190	46.4	17.6	32.0	shoals breached
4/14/2015	1.95	190	0.00	0.00	14.6	

Total: 51.6 years Total Change: 190 m 3.67 = mean rate.

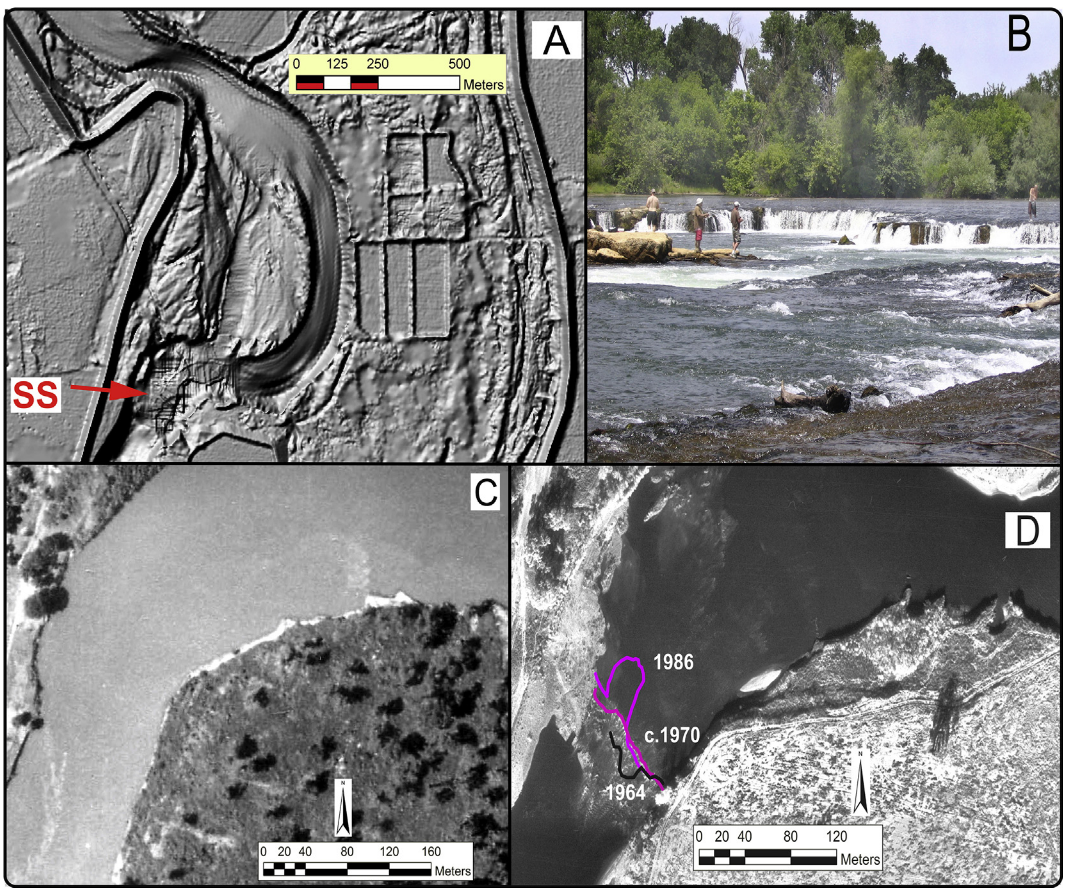

Fig. 2. Shanghai Bend and Shanghai Shoals on the lower Feather River (LFR). (A) Shaded composite from 1999 LiDAR and sonar imagery. The large amplitude bend developed after 1925 from a larger meander to the north and east. LiDAR and sonar data from U.S. Army Corps of Engineers (Stonestreet and Lee, 2000; Ayres, 2003).(B) Photograph of the shoals taken May 19, 2007 by author. (C) June 17, 1958 aerial image of shoals site before the shoals had formed (University of California Davis map library). (D) Positions of the Shoals in 1964, c.1970, and 1986 when the first horseshoe step appeared (photograph ca. 1970: California Dept. Water Resources).

channel had not yet become highly sinuous. This section reviews previous studies of the shoals and presents knickpoint retreat rates computed by this study.

4.1. Knowledge from previous studies

The hydraulics of Shanghai Shoals was studied by Pasternack et al. (2006) who described three active horseshoe steps with an abrupt western outer step and a dominant eastern inner 'slide' that had captured the majority of flow and migrated the furthest. They calculated a recession rate of ~5 m/yr for the main branch of the shoals at that time. The shoals have presumably been a broad-crested step throughout their evolution given the flat-topped shape of the clay layer on which it formed. Through much of their existence, the Shanghai Shoals formed one or more horseshoe steps; aka horseshoe falls, U-shaped steps, or duckbill weirs (Pasternack et al., 2006). The hydraulics involved in the erosion of steps in cohesive or rock materials have been studied as two- and three-dimensional flows. Studies in 2-D indicate that erosion is driven primarily by pressure fluctuations and the shear stress exerted by jets (Coleman et al., 2003). Horseshoe steps, however, are best analyzed as 3-D features due to complexities of convergent flows and varying step slopes and roughness elements. Convergent flows have higher velocities, shear stresses, and lift-force differentials between the center and edges that result in greater erosion and headward migration rates at the center (Pasternack et al., 2006). Flows passing over horseshoe steps experience substantial losses in potential energy, but not necessarily a loss in kinetic energy; i.e., the decrease in the water surface elevation below the step generally has a greater influence on flow energy than a decrease in velocity (Pasternack et al., 2006).

A previous study of aerial images of the shoals documented an average recession rate of 3.38 m/yr for the 35-year period between 1973 and 2008 (CBEC, 2011). The four aerial images available to that study (1973, 1987, 1999, and 2008) indicated relatively uniform recession rates for the three intervals ranging from 3.29 to 3.47 m/yr. They predicted that the eastern chute could reach the upstream end of the resistant clay unit within ten years. In fact, the shoals were breached in late January 2012 (CBEC, 2013) by extension of the eastern inner branch.

4.2. Headward retreat timing and rates determined by this study

As late as 1958, the shoals were not visible on aerial photographs (Fig. 2C). By 1963 the shoals had appeared and from 1963 to 1970 there was little change in its position. The initial shoals formed a single step or knickpoint that extended laterally across the channel in a relatively straight front (Fig. 2D). By 1986 the thalweg

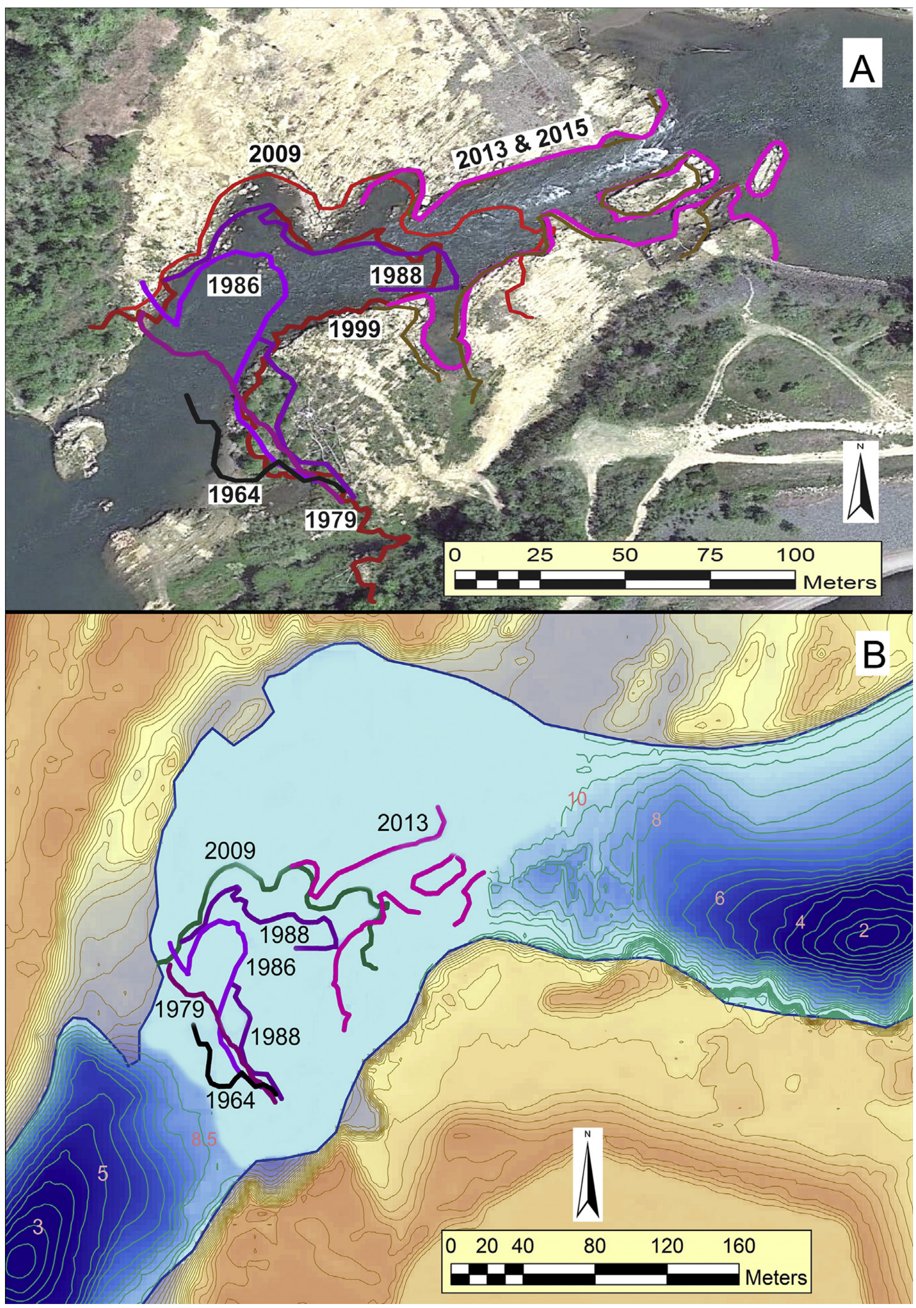

Fig. 3. Positions of the shoals for selected years. (A) Superimposed on 2015 aerial photograph from Google Earth. (B) Superimposed on shaded 2003 bathymetric map showing pools more than 8- and 5.5-m deep upstream and downstream, respectively. Contour interval is 0.5 m.

had begun to develop a horseshoe step on the west side of the channel. The step formed a longitudinal enclave about 40 m in length at the lower end of the shoals along the outside of the bend. As the channel deepened and narrowed, a clay bar began to emerge on the west bank, shifting the channel to the southeast. By 1988, two short horseshoe steps had formed upstream by a headward division of the original step (Fig. 3). The eastern step, which extended towards the inside of the bend, became the dominant zone of erosion as the flows coming out of the pool around the bend upstream were directed towards it. Between 1986 and 1999 that headcut widened and retreated upstream approximately 50 m. In 1999, a real-time kinematic channel bathymetric survey was conducted by boat with a fathometer and sonar transducer (Ayres, 2003). The shoals are not navigable, so bathymetry directly over the shoals was not mapped, but deep pools above and below the shoals reveal the structural control exerted by the shoals and 8 m of local thalweg relief (Fig. 3B). The shoals were breached in January 2012 and appear on the 2013 imagery as a shallow, narrow channel that had cut 46 m to the north end of the shoals. As incision progressed, the resistant bed material of the Modesto Fm. emerged exposing a clay bar across the channel that is ~190 m in the longitudinal direction. Little change was evident in the 2015 imagery.

Based on analyses of aerial photographs, the shoals retreated 190 m over 52 years at a long-term average rate of 3.67 m/yr (Table 2). While average rates are similar between the two recent studies, the higher temporal resolution of the new analysis presented here isolates two distinct episodes of rapid knickpoint migration that occurred around 1988 and 2013 separated by periods of relative stability (Fig. 4). Knickpoint retreat rates 1986–1988 and 2009–2013 were 33.2 and 17.6 m/yr, respectively. Comparisons with the flood series at the gauge on the LYR near Marysville shows that the two recession episodes were not directly correlated with large floods in a simple manner. A fairly large flood on Feb.19, 1986 preceded the 1988 erosion episode and may have been largely responsible for the 40 m of recession documented by aerial photographs between 1979 and November 1986. The most rapid rate of recession documented by the imagery was 50 m of headwater erosion in a brief period of two years after November 1986. The large 1986 flood may have destabilized the shoals causing much of the 90 m of recession between ca. 1979 and 1988. Unfortunately, the limited and irregular temporal resolution of the imagery prevents testing of this hypothesis. No large flows preceded the 2013 episode that breached the shoals, and large floods in water years 1965, 1997, and 2006 had little effect on recession rates.

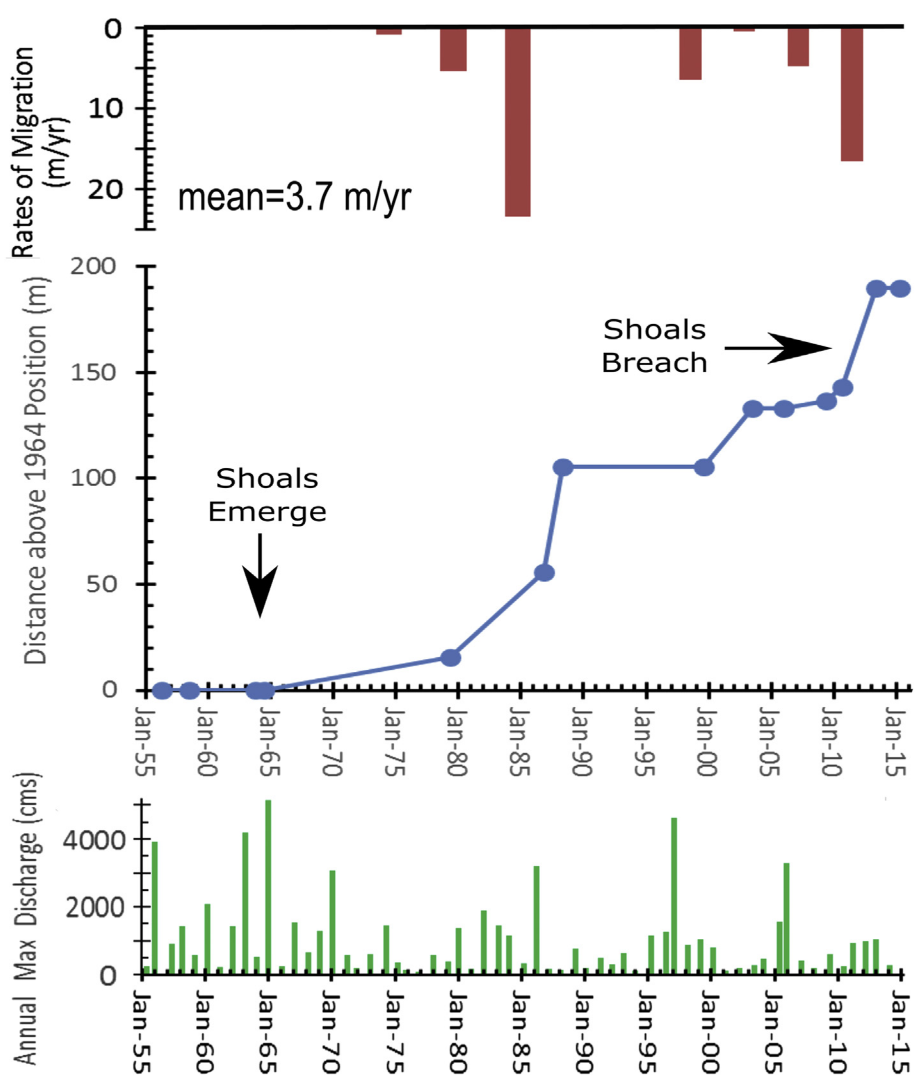

Fig. 4. Non-uniform rates of knickpoint retreat. Long periods of quiescence were separated by two rapid episodes around 1988 and 2013 when retreat was 50 and 46 m, respectively. The flood series from the gauge on the Yuba River near Marysville shows the 1986 flood coincided with the first period of recession, but other larger floods are not linked to retreat and the 2013 recession event was not related to large floods.

Presumably the second episode of rapid retreat resulted from progressive erosion that led to exceedance of an intrinsic threshold of stability. Several years of severe drought in northern California followed the breach.

4.3. *Discussion of previous hydrodynamic models of flow and erosion at the shoals*

An early 1-D simulation of changes in channel hydraulics that would be caused by a discharge of 283 m^3/s (10,000 cfs) following removal of the shoals indicated that flow velocities immediately upstream of the shoals would increase 40 cm/s (CBEC., 2011; Mussetter Engineering, 1999). According to that simulation, increases in velocity in the LFR upstream at Marysville would only be 3.0 cm/s due to complexities of flow interactions with the Yuba confluence. More recently, a 2-D hydrodynamic and sediment-transport model (MIKE21C) was used to simulate changes in flood hydraulics and geomorphology on the LFR after partial breaching of the shoals in January 2012 (CBEC, 2013; CDWR, 2014). To anticipate hydraulic effects on water surface profiles (WSP) and geomorphic change above and below the breach, three conditions were modeled: (1) pre-breach, (2) incipient-breach dimensions in 2012 based on bathymetric surveys and aerial photographs, and (3) a projected enlarged breach (Fig. 5). The cross-section shows the dimensions of the pre-breach channel and the initial post-breach channel in 2012. The initial deepening of the channel was approximately 2 m. For a maximum simulation, a channel cross section through the shoals was used that was about 5.5 m lower than pre-breaching and 76 m wide at the bottom based largely on extension of the large eastern chute (CDWR, 2014). Complete removal of the shoals was not modeled. The simulated geomorphic changes are based on results from a single flood hydrograph less than one month in duration. A 3-km longitudinal profile through Shanghai Shoals and Shanghai Bend shows the high variability of the LFR channel-bed topography (Fig. 5).

The MIKE21C model simulations of decreases in WSP at the shoals between pre-breach and 2012 conditions were 1.46, 0.43, 0.09, and 0.0 m for the floodplain activation flood (FAF), 2-, 10-, and 100-years flows, respectively (CBEC, 2013). (The FAF is a representative flow of at least 7 days duration that has a ~1.1-year recurrence interval.) In agreement with the Mussetter Engineering (1999) study, CBEC model results indicate that lowering of WSPs through the shoals will be substantial during frequent small floods but negligible for larger events. Model runs also simulated how WSPs would be lowered in response to future enlargement of the 2012 post-breach conditions to a projected breach (Fig. 5). The results indicate that, broadly through the LFR, lowering of the 2-, 10-, and 100-year water-surface profiles will be subtle with breach enlargement; on average 0.033, 0.091, and 0.091 m, respectively. Much of the lowering of water surface profiles below the shoals can be attributed to a major levee setback and decreased floodplain roughness downstream along the LFR. More locally at the shoals, the maximum decrease in WSP from present to projected enlarged shoals conditions was 0.18, 0.06, 0.0, and 0.0 m for the FAF, 2-, 10-, and 100-year flows, respectively.

Geomorphically, the Mike21C model simulations of LFR channel-bed elevation changes under various flow and shoal geometry conditions reveal a longitudinal pattern of alternating aggradation and degradation with relatively short wavelengths and amplitudes at smaller flows. For the two-year flow, minor erosion and deposition occur above and below the shoals (CBEC, 2013; Fig. S2 in supplement). Comparisons of the projected enlarged breach with the 2012 and pre-breach shoals configuration suggest that the enlarged breach will make more difference in bed erosion

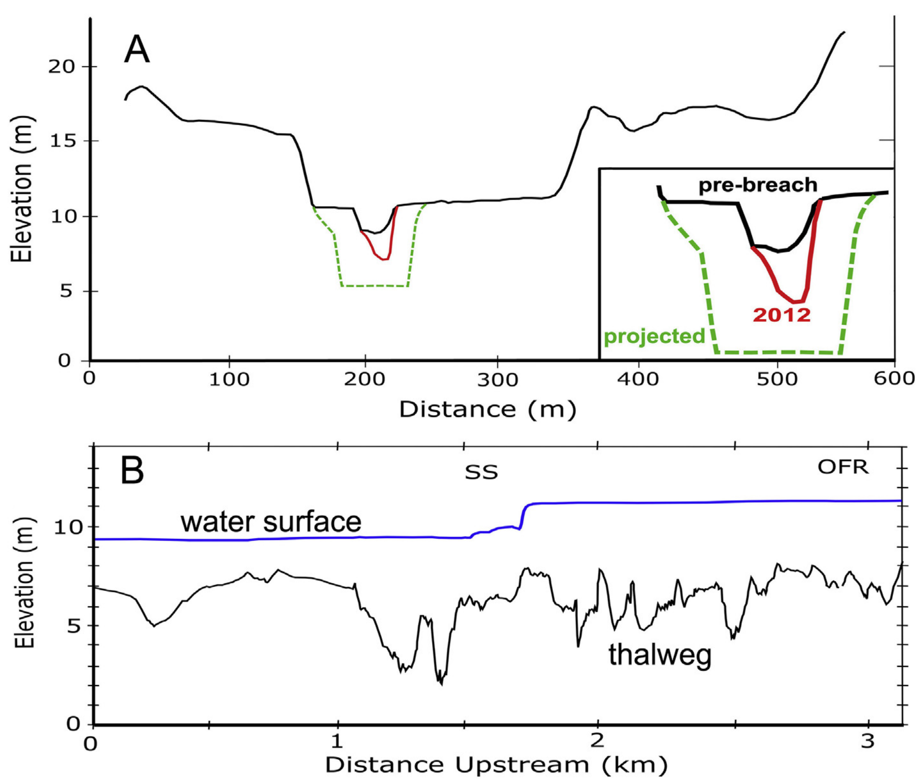

Fig. 5. Geomorphic profiles. (A) The cross section shows the 2012 breach through Shanghai Shoals and the 'projected' maximum aperture (dashed) modeled by the CBEC (2013) study. View downstream. (B) A 2012 low-flow water surface and longitudinal profile through Shanghai Shoals (SS) up to the confluence with the Old Feather River (OFR) above Eliza Bend. Both profiles adapted from CBEC (2013); cf. CDWR (2014); used with permission.

and sedimentation during two-year events than in 10- and 100-year events. The two-year simulation suggests that the projected enlarged breach will generate increased bed degradation of 0.61 m within the first km above the shoals that diminished to 'small perturbations' upstream in Marysville (CBEC, 2013).

4.4. Implications of the breach at Shanghai Shoals

During the nineteenth century hydraulic mining era, geomorphic trajectories in the LFR were governed by strongly positive sediment budgets (inflows >> outflows) leading to sediment storage. Subsequently, bank protection and damming upstream resulted in decreased deliveries of HMS and negative budgets (outflows > inflows). Normally, such a deficit in sediment deliveries would result in a modern trajectory of channel degradation. Although the dominant base-level control on the LFR is at Fremont Weir, 39 km downstream of the shoals and below the confluence of the Feather River with the Sacramento River, Shanghai Shoals exerts local base-level and structural controls on meander sinuosity above the knickpoint. Removal of the shoals will release the hidden potential for bed lowering and allow resumption of a trajectory of net erosion above the shoals, where the channel bed is composed primarily of non-cohesive alluvium dominated by sand and fine gravel (CBEC, 2013; Table 4).

The confluence area of the LFR and LYR stores a substantial amount of hydraulic mining sediment (HMS). During the 19th century hydraulic mining era, much HMS was deposited near the confluence of the LYR and LFR. Field observations made by G.K. Gilbert between 1905 and 1913 (U.S. Library of Congress) describe backwater up the LFR above the Yuba confluence. Gilbert's notes indicate that the extent of the backwater up the Feather grew from 0.8 to 3 km from 1905 to 1913 and was associated with sedimentation (James et al., 2009). In the LYR at Marysville, where levee constriction and dredging in 1905 encouraged bed scour (James et al., 2009), channel-bed elevations largely returned to pre-mining levels by the 1960s (Graves and Eliab, 1977). Below the LYR/LFR confluence, however, the channel bed has not returned to pre-mining levels. Tree stumps rooted below the low-water line indicate that the bed had been at least 2 m below the 2007 low-water level. Wood from one inundated stump on the right bank, ~2 km below the confluence and 2 km above Shanghai Bend, was dated by ^{14}C to the late nineteenth century (1885 $\pm$ 35) indicating that the banks had been lower prior to the arrival of HMS (James et al., 2009). The elevated modern channel represents a large amount of sediment storage that may be attributable to high base levels maintained by the shoals.

The modest channel-bed degradation indicated by model simulations represents short-term changes based on limited breach geometries. Over decadal time scales, however, the cumulative effects of multiple floods over a range of magnitudes will progressively lower the bed below and further upstream than what was simulated. Repeated moderate-magnitude floods will be competent to entrain unconsolidated bed material and lower the bed. In addition, incision below the base of the argillic (clay-rich) B horizon of the Merced Fm. allows undercutting of the resistant surface layer that will result in bank failures, lateral erosion, and breach enlargement. Eventually, the breach aperture will erode beyond the projected dimensions simulated and erosion will propagate upstream (CDWR, 2014; James et al., 2009).

The LFR channel from the Yuba confluence to the shoals is likely to be lowered in the near geomorphic future. No known bedrock exposures, dense paleosols, or coarse channel-lag deposits occur in the alluvial bed of the LFR between Shanghai Bend and the Yuba confluence, so headwater retreat of a soft-sediment knickpoint is likely to follow breaching of the shoals. Migration of the knickpoint up the LFR could be followed by complex response propagating up tributaries (Schumm, 1973, 1977) and elevated sediment deliveries to the LFR (CBEC, 2011; James et al., 2009). It is not clear if or to what extent lowering of the base level on the LFR will propagate up the LYR beyond Marysville. Bed scour has already lowered the channel through the Marysville reach essentially to pre-mining elevations (Graves and Eliab, 1977). Additional hydrodynamic simulations should be conducted over extended periods with repetitive floods recording cumulative geomorphic changes to test the potential migration of incision up the LFR and up through the constricted reach of the LYR at Marysville to the vast repositories of sediment upstream.

The shoals represent an arrested geomorphic trajectory that was breached by exceedance of an intrinsic threshold. The stabilizing element that prevented response was progressively weakened until relatively moderate-magnitude flows became capable of breaching it. In this case, the internal weakening of the threshold was caused by progressive headward retreat of the knickpoint. Ultimately, scour and undermining will remove the resistant clay layer and allow moderate-magnitude flows to regrade alluvium through the reach and excavate unconsolidated sediment stored upstream. To some extent, this may be similar to the breaching of a resistant clay-rich conglomerate in the bed of the lower Bear River in the 1950s, which allowed resumption of channel incision for thirty years (James, 1991). This change in trajectory points out the limitations of river management that does not consider the potential for major changes in the system indicated by geohistorical information.

5. Wing dams to contain flows and erosion on the LYR

5.1. Mapping and describing wing dams

Geomorphic features in the LYR and LFR are relatively young and display relatively little pedogenesis, so they can be easily mapped using soil maps. In particular, surfaces covered with HMS lack a B horizon, which corresponds with the Entisol soil order in the U.S. Dept. of Agriculture (USDA) soil taxonomy. This allows HMS to be mapped using SURGO data (Fig. 6), a digital soils database produced by the U.S. Department of Agriculture. Features such as the secondary channels were distinguished by grouping 'Riverwash,' Xeropsamments, and Xerofluvents as three classes of recent alluvium related to floodplains, high-water channels, and historical terraces, consisting primarily of HMS. All soils that have a moderate degree of pedogenesis, such as Alfisols and Mollisols were mapped as surfaces not covered by HMS (Table S1 in supplement), although those surfaces may have received thin deposits of HMS. This map shows that most surfaces between the levees in the LYR and LFR are covered with a substantial thickness of HMS or dredge spoils. It also shows a high-water channel system adjacent to the modern LYR that is covered with sand and gravel. High-water channels were active at various times from 1859 to ca. the 1930s, but now only flow during extreme floods. The map belies a history of aggradation by HMS that covered valley bottoms with sediment, followed by channel incision that left historical terraces.

Several channel evolutionary models hold that vertical incision of alluvial channels is normally followed by a period of widening and floodplain creation at a lower level (Piégay, 2016; Schumm et al., 1987; Simon and Castro, 2003; Simon and Hupp, 1992). This is the trajectory that would normally be expected for the LYR. Channel widening, with the associated bank failure and flooding, however, is associated with substantial economic and safety issues, so engineering structures are often used to arrest widening with bank protection or flow diversions. In the LYR below the Yuba Gold Fields (YGF)—a terrain dominated by dredge spoils—channels incised but bank hardening by revetment and wing dams built in

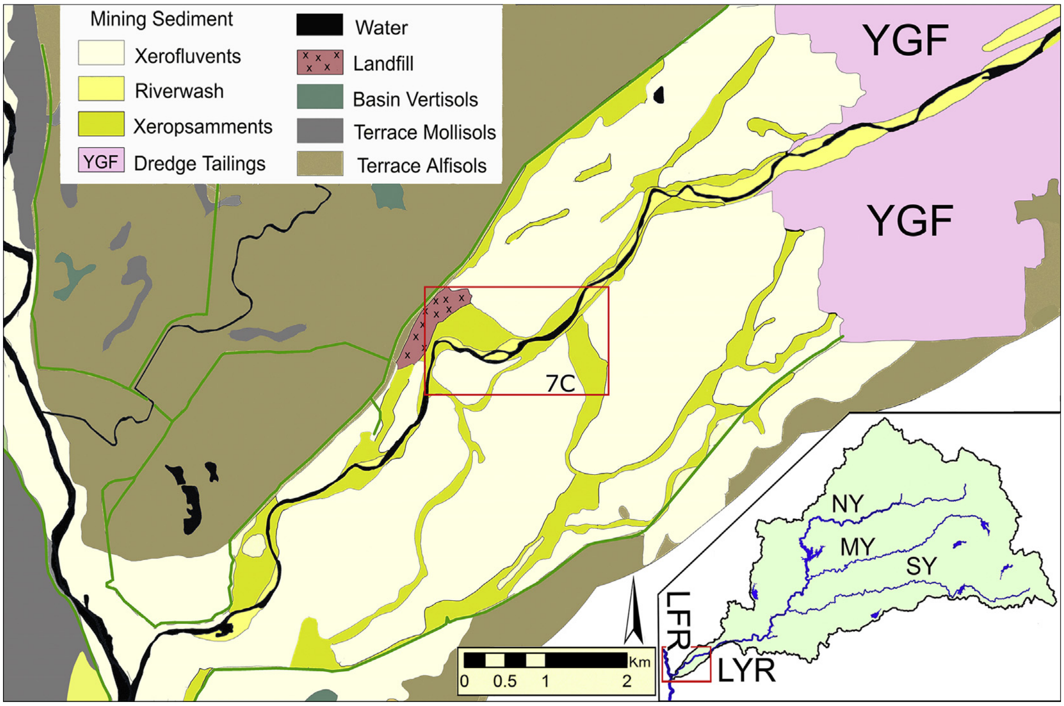

Fig. 6. Soils of the LYR were mapped from SURGO digital soils data classified to emphasize Entisols; that is, soils with relatively little pedogenesis. These surfaces are covered by HMS or dredge spoils. Vertisols, Mollisols, and Alfisols (dark shades) are well-developed soils that lack thick layers of HMS. The Yuba Gold Fields (YGF) are dominated by dredge tailings.

the early twentieth century prevent the incised main channel from widening. Wing dams may be important to maintaining lateral channel stability, but they prevent the meander belt from enlarging, so flood conveyance, sediment-storage capacity, and areas of riparian habitat are limited.

Numerous wing dams were constructed on the LYR below the YGF. Those remaining are typically 5–25 m long and composed of angular mafic boulders (Fig. 7A & B). Fifty four wing dams were located in a 7-km reach below the YGF using a 2008 orthophoto (kmz in supplement). An additional 12 wing dams appear on a 1947 aerial photograph (Fig. 7E), but the sites are now obscured by vegetation. The wing dams appear on 1947 images and presumably pre-date the U.S. Geological Survey streamflow gaging station near Marysville, which began collecting data in 1943 at the site of a prominent wing dam (Fig. 7B). Since they are positioned deep within the main channels, they indicate the degree to which channels had incised by the 1940s. Digital mapping of the wing dams indicates that they are located along the main-channel margin to prevent bank erosion and widening. In one case, they were clearly designed to divert flow away from a high-water channel that had been active during the period of channel aggradation (Fig. 7C, D & E). It is possible that the evolutionary trajectory of the post-mining channel system in this area would have reverted back to the anastomosing system that it had prior to the arrival of European settlers (James, 2015). If so, the wing dams and other bank armoring arrested this trajectory. In any case, they represent inhibitors that prevent formation of a multithread channel, limit floodplain formation and meander belt widening, and encourage the single-channel morphology that is prevalent.

5.2. *Implications of wing dams in the context of flood- and sediment-control policy*

Early federal flood-control policy was aimed at sequestering sediment in the LYR by the use of large levee setbacks and sediment-detention dams (James and Singer, 2008; Kelley, 1989). Wing dams may appear to have been a departure from this policy, but they came later after the main channel had incised. They represent a shift from the strategy of encouraging storage of suspended and bed sediment to one encouraging channel-margin storage of bed material and bank protection to prevent remobilization of stored sediment. After the failure of multiple barrier dams up through 1907, confidence in the use of dams as sediment detention structures was shaken and an increasing emphasis was placed on training walls (James, 2015). The construction of large training walls within the YGF established a precedent for channel lateral-confinement strategies in the LYR that was condoned by the federal government. Later, the main channel below the YGF incised, the former floodplain emerged as a terrace with decreasing flood frequencies, and agriculture became established on it. Wing dams induced main channel scour and protected landowners on the terraces from flooding and bank erosion.

Recent realization of the abundance of mercury in HMS constrains management possibilities for the LYR. Management strategies in similar situations—where channels have incised into relatively narrow floodplains bounded by high terrace scarps—normally encourage floodplain widening to accommodate floodwater, provide sediment storage space, and establish ecological habitat. Removal of bank-stabilization structures to encourage channel self-widening is precluded in the LYR, however, by elemental mercury concentrations of HMS stored in the terraces and high-water channels that are commonly on the order of 400 ppb (James et al., 2009; Singer et al., 2013). Approximately a quarter billion cubic meters of HMS were stored in the LYR (Gilbert, 1917), so complete removal is not practical. Thus, removal of bank stabilizing elements could initiate a long-term widening trajectory and mobilize Hg-laden sediment. River management of the LYR must consider strategies to stabilize the HMS rather than allowing channel widening or lateral migration to remobilize the mercury and deliver it downstream to vulnerable wetlands (James, 2015).

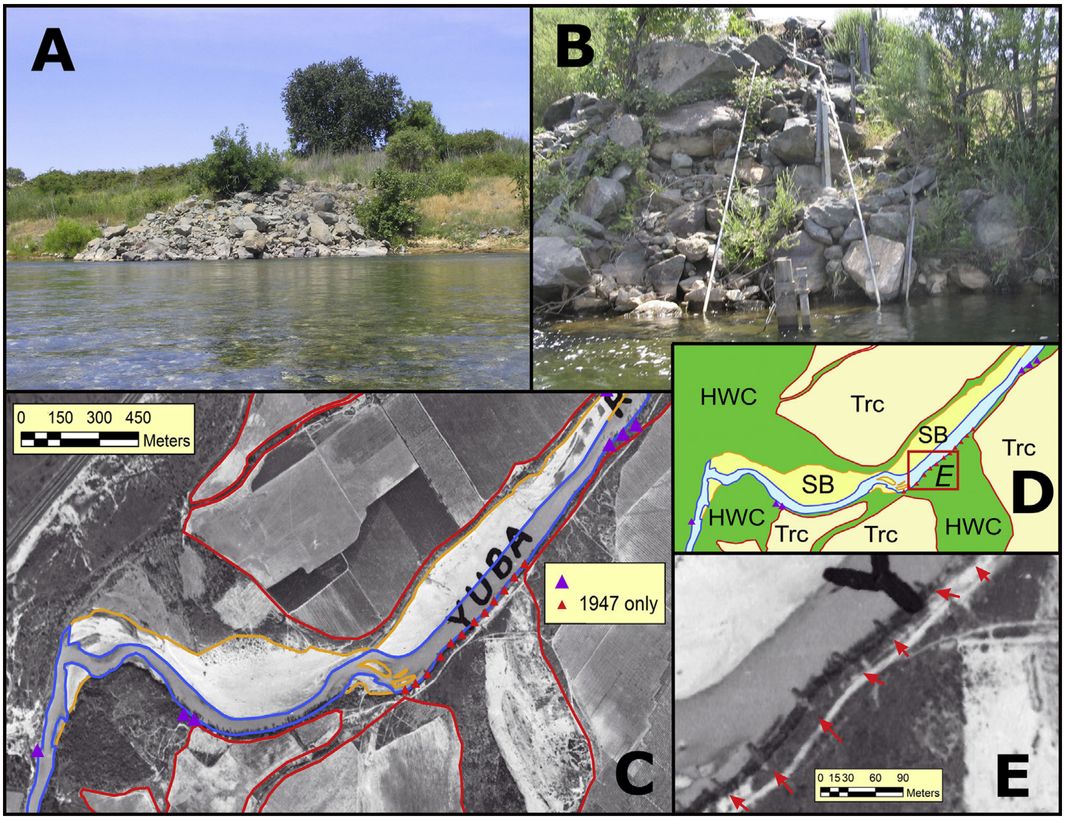

Fig. 7. Wing dams on the LYR. (A) A wing dam protruding from the right bank. (B) On the left bank at the U.S. Geological Survey streamflow gauging station near Marysville. (C) 12 wing dams in 1947 on the left bank (below "YUBA") prevent flows from eroding into or reoccupying a former channel. Relatively narrow modern channel flows from upper right to lower left. (D) Index map of geomorphic surfaces. HWC = high-water channels and floodways; SB = sand bars; Trc = historical terrace. (E) Blowup of 1947 aerial photograph showing several wing dams at high-water channel inlet.

6. Conclusion

Environmental trajectories are common and many river scientists recommend that their consideration should be an integral component of river management. In many cases, trajectories have been arrested by natural or human inhibitors. This study documents the potential magnitude and dynamic geomorphic context of change if inhibitors are removed and how those inhibitors can be hidden. Two examples of arrested trajectories are presented. At Shanghai Shoals in the LFR, exceedance of an intrinsic threshold by knickpoint retreat is releasing an arrested geomorphic trajectory. Breaching of the shoals will likely elevate sediment loads for decades, following the trajectory that has been common in the LFR and LYR; i.e., channel-bed degradation that regrades the channel and has the potential to remove large quantities of sediment. Headward retreat of the shoals and the process of breaching took 50 years and was predictable, although episodic and associated with large uncertainties about timing and magnitudes. On the LYR, wing dams constructed to prevent bank erosion have arrested lateral channel migration, channel widening, and potential return of channels to anastomosing planforms. Entrenchment of the LYR channel has constrained habitat viability due to poor lateral connectivity, limitations to the hyperheic zone, and sediment dynamics. In this case, meander belt widening, which could improve riparian and aquatic habitats, is arrested by wing dams and other bank protection but the option to remove them is limited by mercury stored in high terraces. If bank protection is compromised, however, a predictable new trajectory of channel widening can be anticipated. Spatial and temporal details may be obscured by uncertainties, but the need to deal with mercury laden sediment should be anticipated as an ultimate geomorphic response.

Evolutionary trajectories are diverse potential paths of change that should be contemplated by careful geohistorical and geomorphic research. Wise river management policies call for a clear recognition of changes to systems and an understanding of what inhibits trajectories. The geomorphic evolution of rivers can be complex but knowledge of this complexity is important to management of rivers with substantial amounts of change. Identifying past conditions promotes recognition of the nature and location of geomorphic forms, soil and sediment, habitat potential, toxic materials, archaeological sites, and other important features. Evolutionary perspectives also reveal past and present trajectories that are essential, especially where they have been arrested by stabilizing works that could otherwise be seen as non-essential candidates for removal. Arrested trajectories that could be released should be identified and considered in river management in conjunction with knowledge of the evolutionary path unique to the geomorphology of that river.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2017.02.011.

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