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Title:

Valley width variation influences riffle-pool location and persistence on a rapidly incising gravel-bed river

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Abstract

Decades of research have demonstrated that gravel-bed rivers exhibit multiple spatial scales of landform nonuniformity. Landform features such as valley-wall oscillations, alluvial fans, terraces, river meanders, point bars, boulder clusters, and logjams contribute to river corridor heterogeneity. Further, studies have shown that the locations of riffles and pools in gravel-bed rivers are closely associated with the spatial pattern of river-corridor morphological variability. These studies imply (but do not directly test) that persistence of riffles and pools through time is also conditioned by landform variability. Mechanistically, it may be hypothesized that overbank flows interact hydraulically with oscillating valley walls by way of a mechanism known as flow convergence routing. In such circumstances, can variation in valley width influence channel morphology, forcing riffle-pool location and persistence? To address this question, research was performed on a valley-confined, wandering, gravel-bed reach of the regulated lower Yuba River, California, USA that is incising from reduced sediment supply and flow regulation after a historic period of mining-related valley sedimentation. This study quantified stream planform change 1984-2006 and elevation change 1999-2006 using eight aerial photo sets and two digital elevation models, and it qualitatively assessed channel change in older aerial photos going back to 1937. Analysis revealed that the river has undergone rapid incision (0.11 m/year) and planform change in response to frequent floods, yet eight riffles persisted in the same locations, which coincided with the locally wide areas of the valley. Longitudinal profiles revealed that deep pools were associated with long valley constrictions. Geomorphic analysis and design needs to explicitly account for multiple scales of landform nonuniformity in order to rehabilitate natural fluvial processes.

Keywords: gravel-bed river; channel change; confined river; velocity reversal; flow-convergence routing; valley width; fluvial geomorphology

1. Introduction

The fluvial geomorphology of riffle-pool sequences on gravel-bed rivers has been heavily investigated for decades. Yet the scientific depth of knowledge of process-morphology mechanisms is not permeating through academic and practitioner communities, ultimately jeopardizing river management and ecological recovery. A key factor may be that the simplicity of traditional methods for performing hydrogeomorphic evaluation outweigh their now demonstrated invalidity. At the heart of the matter, lies the fundamental discovery that the fluvial geomorphology of riffle-pool sequences is inextricably tied to multiple spatial scales of landform nonuniformity.

1.1. The case against uniform flow

Consider the evidence. First, topographic constrictions and expansions (whether width-related and/or elevation-related) are ubiquitous in natural gravel-bed rivers; they control channel hydraulics, including locations of flow convergence (defined as the physical process of funneling flow from a larger to a smaller cross sectional area), divergence, and recirculating flow as well as locations of sediment deposition and bar instability (Richards, 1976; Keller and Melhorn, 1978; Jackson and Beschta, 1982; O’Conner et al., 1986; Keifer, 1985, 1989; Schmidt, 1990; Carling, 1991; Lisle and Hilton, 1992; Karasev, 1993; Bittner, 1994; Miller, 1994; McKenny, 1997; Jacobson and Gran, 1999; Booker et al., 2001; Repetto and Tubino, 2001; Repetto et al., 2002; Cao et al., 2003; Wu and Yeh, 2005; MacWilliams et al., 2006; Brown and Pasternack, 2007;

Harrison and Keller, 2007; Pasternack et al., 2008; Wilkinson et al., 2008; Sawyer et al., 2010). In this study, any deviation (positive or negative) in velocity from that associated with uniform conditions is termed “flow acceleration”; backwater conditions are one example.

Second, meander bends and channels adjacent to alternate bars experience vertically converging secondary transverse flow circulation cells, while diverging secondary transverse flow occurs between meander bends (or alternate bars) as secondary flow cells from upstream and downstream pools overlap (Leopold et al., 1964; Keller 1972; Deitrich et al., 1979; Thompson, 1986; Colombini et al., 1987; Wilkinson et al., 2008). Hence at the bed surface transverse flow is constantly toward the inside bend, helping to maintain sediment routing through the inside of the meander bend. At higher discharges secondary flow cells increased in length and overlap from increased secondary velocities and flow depth (Thompson, 1986).

Third, sediment often bypasses a pool’s deepest area, remaining on the inside of bends and depositing a lobate shoal longitudinally that forms point bars lateral to pools and riffles at meander inflection points (Keller, 1972; Thompson, 1986; Sear, 1996, Pyearce and Ashmore, 2005). The deposited point bars promote flow constriction and convergence at the head of pools, closing the loop on free-forming feedback. These sediment routing observations are consistent with hydraulic models of convective acceleration and secondary circulation in nonuniform flows that show peak near-bed shear stress (or depth-averaged shear stress) adjacent to width-constricting bars, not over the deepest part of a pool (Booker et al. 2001; MacWilliams et al., 2006).

Finally, pools have been observed to form in alluvial and semi-alluvial streams at “forcing” elements, such as alluvial fans, wood jams, boulder clusters, and bedrock outcrops (Keifer, 1985, 1989; Lisle, 1986; Miller, 1994; Montgomery et al., 1995; Thompson, 2001). The

94 abruptness of channel change at these forcing elements causes localized, high-frequency vortex
95 shedding around the constricting elements. In turn, that yields turbulent fluctuations in velocity,
96 lift, and drag that are all thought to be capable of scouring pools and routing sediment (Matthes,
97 1947; Lisle, 1986; Clifford, 1993a; Woodsmith and Hassan, 2005; MacVicar, 2006; MacVicar
98 and Roy, 2007; Thompson, 2006, 2007; Thompson and Wohl, 2009). These “forced” pools are
99 shortened and deepened by the re-circulating eddies, vortices, and boils caused by flow
100 separation at the non-streamlined forcing elements (Woodsmith and Hassan, 2005; Thompson,
101 2006).

102 Taken together, the literature cited above conclusively refutes the conjecture that uniform
103 flow is an appropriate assumption in analyzing physical mechanisms associated with the fluvial
104 geomorphology of riffle-pool sequences in gravel-bed rivers or in re-engineering gravel-bed
105 rivers. Knowing the single set of values defining bankfull dimensions has much less predictive
106 utility than presumed, because these values have not been tied to the key mechanisms associated
107 with channel nonuniformity. Metrics such as depth*slope or discharge*slope that are widely
108 used by practitioners to design ostensibly stable riffle-pool units are actually not capable of
109 characterizing or predicting the observed mechanisms responsible for riffle-pool formation or
110 maintenance in the majority of riffle-pool sequences in gravel-bed rivers. Yet practitioners will
111 not change their behavior until suitable replacement concepts and tools are available and
112 understandable to them.

114 *1.2 Building with channel nonuniformity*

115 One concept in line with the evidence that tentatively appears to translate well from
116 academic theory to stream restoration practice is the flow convergence routing mechanism for

riffle-pool maintenance that draws heavily from pre-existing literature, but is clearly articulated and analyzed by MacWilliams et al. (2006). Convergence of flow in this context is the funneling or focusing of flow. According to this concept, under low-flow conditions, vertical variations in topography along the length of a river control channel cross sectional area and hydraulics, driving vertical flow convergence and determining local sediment transport capacity. In this situation, pools have deep, slow, divergent flow and low transport capacity; riffles have shallow, fast, convergent flow and high transport capacity (Clifford and Richards, 1992; Brown and Pasternack, 2007). Transport rates for riffles are supply-limited in terms of mobile bed particle sizes. Under high-flow conditions, longitudinal variations in wetted width control channel cross sectional area and hydraulics, driving lateral flow divergence over wide riffles and convergence over narrow pools (Sawyer et al., 2010). Flow convergence over pools creates a zone of high velocity and shear stress at the pools (Carling, 1991; Booker et al., 2001; Cao et al., 2003, MacWilliams et al., 2006). These high velocity zones cause mobilized sediment to be routed through or around pools and deposited as riffles downstream where flow diverges and velocity, shear, and transport capacity reduces (Leopold et al., 1964; Keller, 1971; Lisle, 1979, Booker et al., 2001; Repetto et al., 2002; MacWilliams, 2006). As discharge increases, the effect of lateral flow convergence on velocity and shear stress increases (MacWilliams et al., 2006). At all discharges, flow divergence and deceleration is influenced by backwater conditions upstream of vertical and/or lateral constrictions (Clifford et al., 2005; Buffington et al., 2002; Pasternack et al., 2008). Notably, flow convergence routing does not include a mechanism related to fluctuation of turbulent intensities at forcing elements, so that has to be accounted for independently. It can account for the role of bed particle size differences in scour location and timing when sufficient data is available to be used in conjunction with a 2D or 3D numerical

model. As a result, it may be consistent with essential aspects of the particle queuing hypothesis (Naden and Brayshaw, 1987; Clifford, 1993a).

Evidence in support of the flow convergence routing concept is emerging from new research and re-interpretations of historical studies. Sawyer et al. (2010) directly observed riffle-pool maintenance at a site on the lower Yuba River during a flood discharge 7.6 times bankfull discharge and used a 2D hydrodynamic model to confirm that flow convergence routing occurred through the event. This direct observation and modeling study during a flow much higher than bankfull (not just approaching bankfull, as was common for many previous studies) is the strongest evidence to date. Previously, MacWilliams et al. (2006) used 2-D and 3-D models to confirm the presence of flow convergence routing at the classic Dry Creek study site upon which the velocity reversal was proposed by Keller (1971) and modeled in 1-D (Keller and Florsheim, 1993). In reviewing past literature, MacWilliams et al. (2006) found that most studies of velocity reversal (both for and against) provided results and discussion that indicated support for flow convergence routing (see Table 1 of MacWilliams et al., 2006).

Flow convergence routing has been used as a guiding hydrogeomorphic principal for riffle-pool sequence reconstruction on the regulated gravel-bed lower Mokelumne River in California since 2001. Elkins et al. (2007) demonstrated the immediate beneficial ecological response to this design approach. Wheaton et al. (2009) showed that after a sustained overbank flow release in the reach reconstructed with the flow convergence routing concept, riffle-pool relief was enhanced and high-quality fish spawning habitat on riffles increased.

1.3 Persistence of riffle-pool sequences

A remaining gap in understanding how multiple scales of channel nonuniformity influence maintenance of riffle-pool sequences relates to long-term, large-scale fluvial dynamics, recognizing a lack of decadal-scale studies of riffle-pool persistence in river valleys. An important concern is that many such rivers are now leveed and dammed, which has subjected them to systemic incision. Understanding the conditions necessary for persistence of riffle-pool sequences under the pressure of long-term incision is important for managing these rivers.

Floodplain and channel change in wandering gravel bed-rivers has been studied in Washington, Alaska, Canada, Scotland, England, France and China (Desloges and Church, 1987; Marston et al., 1995; Xu, 1996; Bryant and Gilvear, 1999; Passmore and Macklin, 2000; Winterbottom, 2000; Parsons and Gilvear, 2002; Burge, 2005; Burge and Lapointe, 2005; Froese et al., 2005; Beechie et al., 2006). However, the temporal role of valley-confining features (O’Conner et al, 1986; Grant and Swanson, 1995) such as hillslopes, canyon walls, abandoned terraces, or anthropogenic structures (e.g. mine tailings, levees, and roadways) is still unclear. A common observational approach for investigating their role has been to map riffle-pool attributes at a moment in time and then relate those to local valley width. For example, 56 out of 86 riffles mapped in 5.9 km of Boulder Creek, Utah were located at canyon expansions (O’Conner et al., 1986). Similarly, in certain reaches of the Current River, Missouri, higher gravel beds were associated with wider valleys (Jacobson and Gran, 1999). On the Cascapedia and Bonaventure Rivers (Quebec, Canada) Coulombe-Pontbriand and Lapointe (2004) found that valley width had an influence on riffle substrate size. McKenny (1997) reported a significant relation between riffle spacing and valley width on confined rivers. The above studies provide important evidence in support of the influence of valley-scale landform nonuniformity on riffle location, but lack information on the persistence of riffle-pool undulations through time.

The overall goal of this study was to test the role of valley width variations in influencing the persistence of riffle-pool relief in a rapidly incision river over decades through the use of aerial photo analysis. Because riffles and pools are two parts of a single landform (Bluck, 1971; Dietrich et al., 1987; Clifford, 1993a,b; Gregory et al., 1994; Thompson, 2001), analysis of the one that is more discernable in available data enables an understanding of the couplet. As described in section 3.4, that turned out to be riffles. Pool changes were also assessed using longitudinal profiles for two more recent dates spanning a seven-year period.

The hypothesis tested was that in a valley-confined, dynamic fluvial landscape, riffles (and their associated pools) persist in the same longitudinal positions from forcing imposed by valley width variation on hydraulics and sediment depositional patterns during large infrequent floods. In light of the literature, flow convergence routing was presumed to be the mechanism by which variations in valley width would influence flood hydraulics and in-bank channel change. Other mechanisms considered for each riffle that are also influenced by variation in valley width included meander dynamics, alternate bar dynamics, and turbulence-related local scour. To test the hypothesis, analyses were performed using a dataset from Timbuctoo Bend, a valley-confined wandering gravel-bed reach of the lower Yuba River in California, U.S.A. Key lines of evidence to test the hypothesis included (1) changes to wetted channel area relative to flood duration and peak magnitude, (2) riffle crest positions in historical aerial photos relative to undulations in valley width, and (3) longitudinal profiles from 1999 and 2006. The specific objectives of the study were to (a) assess whether the study reach is a dynamically changing landscape in response to floods at the inter-annual to decadal time-scale (and thus riffle-pool sequences are not relics of antecedent conditions), (b) determine the locations and persistence of riffles in Timbuctoo Bend, and (c) examine quantitative and qualitative relations between both

208 persistent and nonpersistent riffle locations and valley width. The hypothesis would be refuted if
209 riffles were found to persist in the narrowest valley cross sections or if their persistence was
210 related to channel meandering, alternate bar morphology, or bar instability.

212 2. Study Area

213 Timbuctoo Bend on the lower Yuba River, CA (basin area of $\sim 3480 \text{ km}^2$) from the
214 Narrows Pool ($39^\circ 13' 20'' \text{N.}$, $121^\circ 17' 40'' \text{W.}$) downstream to the Highway 20 bridge ($39^\circ 13' 13''$
215 N. , $121^\circ 20' 7'' \text{W.}$) is a wandering gravel-bed river with a thick mixed coarse sediment alluvial
216 fill, confining valley walls, significant variations in valley width, and dynamic flood regime with
217 frequent overbank floods (Fig. 1). Timbuctoo Bend has a frequently inundated floodplain,
218 partially vegetated islands, abandoned channel accretion, mixed coarse sediment, and an
219 irregular channel sinuosity of 1.1. Deer Creek, a regulated tributary with a basin area of ~ 220
220 km^2 , joins the Yuba River just upstream of the study reach. Inflow to the study reach is a
221 combination of the Yuba and Deer catchments. There are no hydrologically relevant tributary
222 inputs in Timbuctoo Bend itself. The physical setting of the river has been described previously
223 (James, 1991; Curtis et al., 2005; James, 2005; Pasternack, 2008; Sawyer et al., 2010).

224 Anthropogenic impacts have imposed opposite effects on the system. During 1853-1884,
225 many hillslopes in the Yuba catchment were hydraulically gold mined, causing hundreds of
226 millions of tons of coarse sediment to fill the river valley, snuffing out the existing pattern of
227 physical habitat (Gilbert, 1917; James, 2005). As a result, present-day valley width is defined as
228 the contact and slope break between the lightly vegetated, unconsolidated mining fill and the
229 soil-mantled, vegetated hillside. That means that variations in valley width have not been driven
230 by modern bank and valley-wall erosion processes, but are from ancient processes of valley

carving at the original historical time that the valley floor was at this same elevation. Subsequently, several dams (New Bullards Bar, Englebright, Spaulding, Jackson Meadows, Bowman, and Daguerre Point) were built in the Yuba catchment, blocking sediment transport and causing rapid incision (James, 2005).

Despite flow regulation, total storage is low on the Middle and South Yuba tributaries and winter floods cause significant geomorphic change to the lower Yuba River. Lower Yuba River flow is recorded at the U.S. Geological Survey (USGS) Smartville gage (#11418000) 0.5 km downstream of Englebright Dam. Since 1971 there have been over 100 uncontrolled flows overspilling Englebright Dam, and to overspill it the magnitude has to be close to the current bankfull discharge. Based on a thorough assessment of hydrologic records and geomorphic indicators, Pasternack (2008) concluded that the bankfull discharge since 1971 is $159.2 \text{ m}^3/\text{s}$ (Fig. 2). For the period 1942-1971 it was $\sim 328 \text{ m}^3/\text{s}$. Much of the floodplain is inundated at $\sim 540 \text{ m}^3/\text{s}$, but there are exposed gravel/cobble bars at flows of $736 \text{ m}^3/\text{s}$ (recurrence interval of 2.5 years using the 1971-2004 flow record). These may be evolving into terraces. Discharges associated with the 5-, 10-, and 50-year recurrence intervals for the 1971-2004 record are 1050, 1450, and $4025 \text{ m}^3/\text{s}$, respectively, providing sufficient peaks to regularly rework the valley fill of the study site (Pasternack, 2008). Fig. 3 illustrates significant one-year floodplain and channel change after a wet season with a peak discharge 19.4 times bankfull discharge.

3. Methods

The objectives of this study were accomplished through the use of aerial photo analysis and digital elevation model (DEM) analyses using ArcGIS 9 (ESRI, Redlands, CA). A number of studies have found GIS useful in analyzing river morphology and tracking planform change in

aerial photographs (Gurnell et al., 1994; Gurnell, 1997; Winterbottom and Gilvear, 1997; Winterbottom, 2000). Winterbottom and Gilvear (1997) showed that aerial photos can be used to accurately quantify channel bed elevation, and Winterbottom (2000) found GIS an effective and accurate tool in quantifying medium- and short-term channel changes on a wandering gravel-bed river from survey maps and aerial photos.

3.1 Aerial photos

Aerial photos were obtained (and where needed digitized) for 1937, 1947, 1952, 1958, 1984, 1986, 1991, 1996, 2002, 2004, 2005, and 2006. All images were co-registered through georectification in ArcGIS 9 using the 2002 digital orthophoto as the base image. Between twelve and fifteen ground control points located close to the channel were used to enable spline-transformation georeferencing (Hughes et al. 2006) for images from 1984, 1986, 1991, and 1996. Images from 1937, 1947, 1952, 1958 could only be rectified using 5-10 ground control points and a second order transformation, providing lower accuracy. As a result, these images were not used to precisely locate riffles and instead were only used to examine riffle persistence.

3.2 Digital elevation models

River corridor DEMs were built using the standard triangular irregular network (TIN) approach for 1999 and 2006 to enable channel-change investigation over the most recent seven years. The 1999 DEM was made by digitizing points from 0.6-m digital contours provided by the United States Army Corp of Engineers and using Corpscon 6.0 freeware to adjust elevations to the modern vertical datum (NAVD1988). The 2006 DEM was generated from scratch through terrestrial and boat-based surveying tied together with a common array of benchmarks

established with RTK GPS. Terrestrial and wadable bathymetric surveying were done by robotic total station, with the prism-pole operator walking an $\sim 3 \times 3 \text{ m}^2$ grid. A professional hydrography firm (Environmental Data Solutions, San Rafael, CA) was contracted to collect bathymetric points meeting the Class 1 standard ($\pm 0.15 \text{ m}$ vertical accuracy; USACE, 2002). TINs were converted to rasters when needed for computations. Further details on surveying and DEM methods are presented in White (2007), Pasternack (2008), and Sawyer et al., (2010).

3.3 Channel change quantification

Channel change was investigated to determine whether the reach is dynamic in response to modern floods or whether the locations of riffles and pools are simply relics of antecedent conditions. The massive infilling of mining sediment precludes relic morphologic units from pre-dating 1884, but this analysis helps characterize the scope of modern dynamism in the reach. A static channel was defined quantitatively as having $< 5\%$ of its planform wetted area change between two dates of available aerial imagery (after accounting for an area-uncertainty buffer described in the next paragraph).

Using the accurately co-registered imagery for 1984-2006, the wetted channel area was delineated in ArcGIS at 3-6 times zoom. The daily mean flow at the time of the photo was obtained from the Smartville gage to ensure flows at the time photos were taken were comparable and that measured channel change was not from merely a difference in stage. For consecutive photo sets, the surface area of channel fill and channel cut was determined. Channel fill was the area of previously wetted channel that was later dry surface; channel cut was the opposite. Areas of cut and fill were each measured and then summed in ArcGIS 9 to obtain the total area of planform channel change. These values are also reported as a percentage of total

area within the confining valley boundary for the scaling context. Following Hughes et al. (2006), a lateral buffer of 5 m was used to define a zone of no planform channel change that accounted for < 3% of the confined area. This buffer was checked to make sure it would account for stage differences for the dates of imagery (see section 4.1).

To gain insight into the driving process for channel change in the absence of detailed topographic data to drive numerical modeling, peak daily flows recorded at the Smartville gage and the duration of inundation of the majority of the floodplain (between the dates of two consecutive photo sets for both metrics) were determined and correlated against percent area of planform change. As mentioned in section 2 above, flood frequency analysis for this station and flood inundation analysis for the study reach were previously reported by Pasternack (2008) and Moir and Pasternack (2008). These studies were used to obtain recurrence intervals for individual large peaks between dates of photo sets and reference them to flood inundation conditions, providing insight into the area of channel change occurring for a given flow magnitude. 2D hydraulic models of peak floods in the reach by Pasternack (2008) and Sawyer et al. (2010) as well as DEM differencing analyses by Pasternack (2008) suggest that peak flow magnitude during a flood is more important than flow duration in causing channel change. A statistical test was used to see whether peak magnitude or duration of inundation of the majority of the floodplain had a stronger relation to amount of planform channel change.

Vertical channel change was assessed using longitudinal profiles extracted from the 1999 and 2006 DEMs. A static channel would be one whose mean longitudinal profile trend-line would not show a vertical change of more than 0.15 m over seven years (Sawyer et al., 2010) and whose pools and riffles would not change their relief. In ArcGIS 9, thalweg polylines were digitized manually and stationed at 3 m intervals. Station elevations were extracted from each

raster DEM and plotted versus distance upstream. The mean elevation change for the profile was calculated to determine if the reach was aggrading or incising overall. Slope-subtracted profiles that emphasize local riffle-pool relief were made for 1999 and 2006 (White, 2008). Most of this study focuses on the easily identifiable riffle locations, so the analysis of the longitudinal profiles provides insight into the coupling of riffle and pool response to regulated river dynamism.

3.4 Riffle persistence assessment

Aerial photo analysis is an expert-based, interpretive activity. Training in riffle identification was enabled by extensive field experience over a range of discharges and in performing the 2006 topographic survey of the study reach as well as by the availability of cross-comparable DEMs and aerial photos for 1999 and 2006. Riffle crests were identified for all photo sets in ArcGIS 9 by visual recognition of their shallow depth, high surface slope, high flow velocity, and (most importantly) for planview identification and disturbed surface (Keller, 1971; Emery et al., 2004). Picturing a pool-riffle sequence as an undulating surface, the riffle crest would be the relative peak in relief. In general, riffle crests were clearly identified in the aerial photos at the upstream edge of a disturbed water surface section. Further procedural details are available in White (2007).

Each riffle crest location was assigned a single point at the center position laterally on the riffle crest. Giving each riffle crest a discrete location allowed for ease of identification, statistical analysis, and comparison to valley width. For each identified riffle crest, the distance upstream from the Highway 20 bridge on the valley centerline was determined.

Riffle crests for the 1984-2006 images were separated into two categories: persistent and nonpersistent. Persistent riffle crests were defined as those that were present in all images 1984-

2006 and whose standard deviation in riffle position was $\leq 15\%$ of the distance between valley width constrictions (d_c). Causes of nonpersistent riffle formation were examined individually.

Basic statistical analyses were performed to determine the level of riffle crest persistence from 1984-2006. In Microsoft Excel 2003, mean, range and standard deviation of riffle crest position at each location was calculated. All values were later reported as a non-dimensional percentage of their respective distance between upstream and downstream constrictions (d_c), to place into context the distribution of riffle crests between constrictions. Additionally, upstream or downstream longitudinal riffle migration between one photo set to the next was determined.

Persistent riffles were also assessed at the smaller spatial scale of the geomorphic unit (10^0 - 10^1 channel widths) and compared with lateral channel migration patterns. Riffle locations identified in the earlier photo sets of 1937, 1947, 1952, and 1958 were compared with mean persistent riffles locations for 1984-2000.

3.6 Valley width influence

Valley width was quantified using ArcGIS 9 to allow comparison with riffle persistence. An analysis was made to determine if the high rate of incision into the valley fill composed of hydraulic mining sediment had significantly decreased valley width 1984-2006 (White, 2008). However, from the relatively steep slopes of valley walls and moderate width of the valley, changes in valley width from incision were negligible. Thus, the highest quality data available- the DEM and color digital aerial photo for 2006- were used to delineate valley width.

For this dataset, the boundary between the valley wall and alluvial sediment was delineated as the location where the steep, natural-sloping, soil-mantled, vegetated hills are met by the relatively flat, sparsely vegetated, coarse alluvial floodplain surface. This abrupt

transition was most accurately evident in the 2006 DEM visualized with 1.5-m contours. It was also highly visible on the 2006 aerial photo, since the exposed floodplain gravel/cobble fill appeared bright, while hillslopes were dark. First-hand knowledge from mapping the floodplain manually facilitated the delineation as well.

In addition to creating a valley boundary polygon, a valley centerline polyline was digitized by visually estimating the center between the valley boundaries on either side of the river down the length of the boundary polygon. The centerline was smoothed and stationed every 3 m, with cross sections perpendicular to the centerline at each station. For the set of 2000 cross sections, an attributes table was created with the following fields: distance upstream from the Highway 20 bridge, valley width moving upstream, and location of identified riffles.

The relation between persistent riffle crest locations for 1984-2006 images and the 2006 valley width was analyzed. Because valley width oscillated continuously with no abrupt thresholds, but differences in absolute amplitude, valley constrictions were defined as local minima in valley width. Widest points were defined as local maxima in valley width. These definitions are consistent with the hydraulic mechanism of flow acceleration in response to local changes in cross sectional area. Unfortunately, these valley conditions preclude meaningful, simple correlations between absolute valley width and metrics of riffle location.

For each persistent riffle crest, the valley constriction, the next upstream valley constriction, and the widest point between the two constrictions was located. All locations were reported as distances upstream of the Highway 20 bridge on the valley centerline. The distance from persistent riffle crests to their associated widest point, the distance from persistent riffle crest to their associated constriction, and distance between constrictions (d_c) were calculated and reported as a non-dimensional percentage of d_c . Using these data, a visual and process-based

inspection was made of valley width, persistent riffle locations, and slope-subtracted longitudinal profiles. The study hypothesis that riffle-pool location and persistence is linked with valley oscillations would be refuted if riffle crests were found to persist in the narrowest valley cross sections or if their persistence was related to channel meanders, alternate bar morphology, or bar instabilities. This was objectively testable without statistical analysis. With all data taken together, geomorphic evidence was compiled to gain insight into the mechanisms responsible for each persistent riffle's positioning.

4. Results

Over the 22 years studied, Timbuctoo Bend underwent significant planform change and rapid incision. When combined with Gilbert's (1917) mapping of channel positions, this study found that active lateral channel migration has continued for > 100 years. Seven of ten riffles persisted in the same location despite channel change. A relation was found between persistent riffle crest location and wide areas of the confining valley. Pools related to constrictions.

4.1 Planform channel change

Channel change is directly evident in the co-registered aerial photos and in the extracted wetted area polygons over four time intervals: 1984-1991, 1991-1996, 1996-2002, 2002-2006 (Figs. 4, 5). In Fig. 5a (1984-1991) the main channel shifted from one side of the valley to the other at three locations, and the channel bifurcated at the northern apex of the valley bend. Channel change for 1991-1996 showed main channel abandonment at the northern apex, shifting to a single main channel pushing against the southern valley wall (Fig. 5b). The single main channel at the northern apex moved to the center of the valley confinement 1996-2002, and

further upstream the channel shifted from the left center to the right on the outer bend (Fig. 5c). Channel bifurcation occurred just upstream from the Highway 20 bridge in Fig. 5d (2002-2006) and a side channel was cut through the floodplain at apex of Timbuctoo Bend in 2006, re-occupying the position of a side channel there in 1991 (Fig. 3c, 5a,d).

The area of channel change from period to period ranged from 12,758 m² (4% of the confined area) to 133,867 m² (34% of the confined area). The area of the wetted surface ranged from 389,466-467,397 m², on average 42% of the confined area (1,009,978 m²). Flows at the time the photos were taken ranged from 19-62 m³/s, while the peak flows between photos ranged from 203-3823 m³/s (Table 1). Based on the at-a-station width versus discharge relations for this reach from Sawyer et al. (2010), the typical change in width for this range of flows was ≤ 5 m, so the spatial buffer applied to the channel polygons covers the range of uncertainty associated with the range of flow and wetted width variation and excludes it from consideration.

Peak daily flows for each time interval, the recurrence interval of that peak daily flow, the ratio of peak flow to bankfull discharge, and the number of days that the majority of the floodplain was inundated in each time interval are presented in Table 1 along with the percent area of planform change. The peak flows for the seven time intervals ranged from 1.28-24 times bankfull discharge, which represents a wide range compared to past studies that often only evaluate near-bankfull conditions. Based on the flow estimate for inundating the majority of the floodplain (~ 540 m³/s), 123 days met this criterion over 22 years, with each interval having 0-26 days (Table 1). The coefficients of determination (R^2) for peak discharge versus change and duration versus change were 0.65 and 0.31, respectively. Given seven time intervals, the corresponding one-tailed p-values were 0.014 and 0.097, respectively. That means that there is >

98% statistical confidence of peak discharge influencing planform change and only a > 90% statistical confidence of duration of floodplain inundation influencing planform change.

More mechanistic insight is evident from considering each time interval. The most significant change in wetted area, a 34% change, occurred between 1984 and 1986. In that interval a 23.8-year flood of 2832 m³/s (17.8 times bankfull discharge) occurred February 19, 1986. The largest flood, a 41.7-year event with a discharge of 3823 m³/s (24.0 times bankfull discharge) occurred 2 January 1997 and caused a change in wetted area of 29%. Another 24-year flood of 2815 m³/s occurring between 2005 and 2006 (31 December 2005) caused only a 14% change in wetted area, topped by a change in area of 17% occurring between 1991 and 1996 from 8-year event of 1228 m³/s, 1 May 1995 followed by a 9-year event of 1427 m³/s, 18 May 1996. An 8% change in wetted area was experienced for both a 4-year event between 1986 and 1991 and an 8-year event between 2004 and 2005. The least effective maximum event was the 203 m³/s flow, 27% above bankfull, during the photo period from 2002 to 2004, which only caused a 4% in area change. This was a very short time interval, and it was period of dry water years with the lowest peak discharge. Other one-year intervals showed more than double the change, because of a higher peak flow. Overall, the observed changes in wetted channel width for low-flow imagery (exceeding 5% area change) and the link between degree of change and magnitude of peak discharge confirm that the study reach has a dynamic planform morphology driven by floods.

4.2 Vertical channel change

Elevation change for the study reach was mostly incision, with 83% of the thalweg incised (Fig. 6). The reach-averaged incision was 0.78 m, a rate of 0.11 m/year. The incised-

area average incision was 1.11 m, a rate of 0.16 m/year. Areas of significant deposition occurred at ~ 1700 m, ~ 4300 m, and ~ 5500 m upstream from the Highway 20 bridge from downstream migration of riffle crests. Overall, the observed high rates of incision (much higher than 0.15 m over seven years) confirm that the study reach has a dynamic longitudinal profile.

4.3 Riffle persistence

Given that Timbuctoo Bend was found to be dynamic in response to modern floods, the next question was to determine whether individual riffle crests were persistent. Nonpersistent riffle crests appeared in particular locations for anywhere between one to six photo sets, with an average of three photo set appearances. The number of nonpersistent riffle crests for a given photo set ranged from one to four with an average of three. Nonpersistent riffle crests were all associated with localized channel nonuniformity (Fig. 7). Four locations occurred in association with transient emergent medial bars (Fig. 7a-d). Three locations were associated with bedrock protrusions into the bankfull channel (Fig. 7a,d,e). One location was also in a meander bend (Fig. 7d). Several locations were subjected to multiple localized geomorphic factors.

Eight riffle crests were determined to be persistent out of an average ten riffle crests per image. These eight riffle crests were numbered in sequence from downstream to upstream. They clustered in the same locations, within the established criteria of having a standard deviation of position $\leq 15\%$ of d_c , over the 6 km study reach for the entire 22 years (Fig. 8). Relative to valley and channel meanders, some persistent riffles occurred at the apex of bends, while others occurred in the cross-over straight sections. As a result, there is no systemic linkage between riffle persistence and meandering. Similarly, considering the bar-related concepts of riffle-pool occurrence in Wilkinson et al. (2008), there is no evidence of a link between alternate

bar morphology and riffle-pool location or persistence. There is a connection between bar instability and nonpersistent riffles.

The persistent riffle crest formed at the entrance to Timbuctoo Bend is located after the deep scour hole where a narrow bedrock canyon abruptly expands, bed slope drops, and the valley floor begins. This location is consistent with the mechanisms of flow convergent routing and turbulence-induced local scour at an abrupt expansion, and thus is not associated with undulating valley width. Because it represents the onset of sediment fill at the head of the valley and because its location at the head precludes some of the metrics used in the study, it was omitted from the quantitative analysis of variations in valley width within the valley itself. Nevertheless, its location and persistence is explainable and consist with the underlying hydrogeomorphic mechanisms associated with landform nonuniformity.

Statistical analysis of the remaining seven riffle locations in the valley itself shows that they did shift somewhat over time, but not far. The average standard deviation of the seven persistent riffle crests in the longitudinal location was within 9% of d_c (Table 2). The largest persistent riffle crest location standard deviation was 15% of d_c , with the tightest persistent riffle crest location standard deviation equal to 4% of d_c . The range of riffle locations varied wider from 8% of d_c to 45% of d_c with an average of 25% of d_c . Riffle migration between photo sets at the seven crests was almost equally matched between shifting downstream (53%) and upstream (45%), with 2% of intervals showing no migration.

Examining the persistent riffle locations for 1984-2006 at the finer resolution of the geomorphic unit (10^0 - 10^1 channel widths) showed that as the channel shifted laterally from one side of the confining valley to the next, riffle crests continued to persist in the same longitudinal position. At persistent riffle crest 1, the center of the channel migrated laterally ~ 150 m from

1984-1991, yet the persistent riffle crests remained in the same general longitudinal location (Fig. 9a). Similarly, at persistent riffle crest 2, the center of the channel migrated laterally ~ 100 m with no substantial change in location of the persistent riffle crest (Fig. 9a). For persistent riffle crest 3, two riffle crests, 1996 and 2005, were located at the same distance upstream despite their respective main channels being located on opposite sides of the valley confinement (Fig. 9b). For persistent riffle crest 4 (Fig. 9b), the riffle crests cluster tightly in the same general location for all 7 years depicted (standard deviation of 6.8% of d_c) even though the channel flows toward opposite valley walls for different years (1996 and 2005). Fig. 9c illustrates that for persistent riffle crest 5, the channel shifts from one valley wall to the other, but that the riffle crest stays a short distance upstream of a prominent valley constriction there. This crest is often associated with medial bar deposition forced by the constriction. The exact position of this riffle crest has the largest longitudinal spread in distribution for any persistent riffle crest (standard deviation of 15% of d_c), which relates to the transient shape of long medial bars there. Riffle crests for persistent riffle crest 6 (Fig. 9d) were centered between valley walls despite the channel shifting from the left center to the far right bank. Persistent riffle crest 6 also appears to have a tight distribution (standard deviation of 7.6% of d_c) and there was not much lateral channel migration. The existence of a meander bend exhibiting cutoff dynamics just downstream of riffle 6 likely influences its location and persistence, as discussed further in section 4.4. Finally, persistent riffle crest 7 occurred in a narrow section of the reach in the middle of a meander bend, but relative to the local valley-width oscillation, it was in the widest area of this section and was just upstream of the narrowest section. There is a large bedrock outcrop impinging on the channel at this narrowest constriction. Channel width at crest 7 has fluctuated over time- wide in 1952, narrow in 1984, wide since 1991- but channel position has

been stable (Figs. 4, 5, 10). This riffle is also just downstream of a terrace with cutbank scour at an old hydraulic-mining location called Rose Bar. The pools upstream and downstream of crest 7 incised 1999-2006, but the riffle crest remained at the same elevation. Rose Bar is not contributing sediment to fill in the pools, but it is possible that the bedrock constriction of the channel is helping the riffle to collect some sediment from cutbank scour during floods.

Visual inspection of older aerial photos showed several of the seven persistent riffles from 1984-2006 present in 1937, 1947, 1952, 1958 aerial photo sets, even though high-accuracy georectification could not be achieved for these older images. The 1937 aerial photo (21 October) set had a flow of $8.8 \text{ m}^3/\text{s}$ with turbid water, indicated by the high reflectance of the water surface. Heavy machinery was evident still mining the gravel fill adjacent to persistent riffle 7. Riffle crests in the same location as persistent riffle crests 5 and 6 were apparent in the presence of mid-channel bars. The 1947 photo set (22 February) had a flow of $42 \text{ m}^3/\text{s}$, also with turbid waters as well. It appeared that riffle crests were present in the same general location as persistent riffle crests 3, 4, and 6, and it was certain that a riffle crest was located in the same general location as riffle crest 5. The 1952 photo set (16 July) had a flow of $82 \text{ m}^3/\text{s}$, and followed spring runoff that exceeded bankfull for ~ 30 days over the months of May and June of that year. Riffle crests were present in the 1952 photo set in the same general location as all seven persistent riffle crests for 1984-2006 (Fig. 10). The 1958 photo set (31 August) had a flow of $20 \text{ m}^3/\text{s}$, and had riffle crests present in the same general locations as persistent riffle crests 2, 5, 6, and 7. Riffle crests were present for all photo sets at persistent riffle crests 5 and 6 locations.

4.4 Valley width relations

Valley width over the entire 6-km segment ranged from 102-314 m with a mean of 164 m (Fig 11a). For the seven persistent riffle crests in the valley, their respective mean constriction width was 143 m, and the mean widest point was 209 m. The mean d_c was 425 m, ranging from 320-515 m.

No persistent riffles were located at local valley width constrictions (Table 2). Persistent riffle crests 1-5 (Fig. 11a, horizontal bars) were always located in the wide part of the oscillating valley width (Fig. 11a, vertical arrows). The amplitude of valley width oscillation was large for crests 1-4 and small for crests 5 and 7, but that value showed no special influence on riffle location or persistence. Amplitude may influence medial bar dynamics and the size and length of side channels, as the largest amplitude oscillations all had large depositional bars with intermittently flowing side channels. Riffle crest 7 was associated with a very small undulation in valley width, but the pools on either side of it were particularly deep and occurring in the locally narrowest valley cross sections (Fig. 11b,c). Considering all riffle crests except crest 6, the average longitudinal distance from riffle crest to widest valley point was 10% of d_c . The distances between the mean persistent riffle crest and the downstream and upstream constrictions for all seven riffle crests were 52% and 48% of d_c , respectively.

Riffle crest 6 was statistically differentiated from the other riffle crests. This crest is just upstream of a tight meander bend whose apex occurs at a wide location in the valley. As a result, most of the valley width is filled with a large point bar composed of mining sediment. On several occasions, the channel in the bend migrated or cutoff between images (Figs. 5, 9d), showing how tight the bend is even though the valley meander itself is not unusually tight there. Meander dynamics caused frequent channel change and preclude riffle crest 6 from being located

in the widest valley location. This forced it to be located further upstream, though not in the narrowest location.

One large valley width oscillation in the middle of the reach downstream of persistent riffle crest 5 had no persistent riffle crest there (Fig. 11a, X marker). This oscillation has the widest length down the valley of any oscillation other than the one at the valley head. Sometimes this area has a very large medial bar with side channels, and nonpersistent riffle crests occur at those times (Fig. 7c). Other times one of the side channels incises deep enough to dry out the side channel and eliminate the associated riffle crest. Since 1991, the channel on the north side of the valley has been abandoned. Both longitudinal profiles show a deeply incised straight channel there since at least 1999 (Fig. 6, 11b,c). The former medial bar is becoming a high terrace above the floodplain, as evidenced by its exposure in a recent large flood (Fig. 3b, upper right of photo). The depth of incision makes avulsion to the north less likely now, and the growing terrace may be functioning as its own channel-floodplain constrictor, precluding riffle re-formation. The dynamics at this site strongly support the notion that large width oscillations influence medial bar formation. However, the unusual length of the wide area is enabling incision to create new constricting landforms within it rather than a massive single riffle crest.

The longitudinal profiles enable consideration of both riffle and pool locations in 1999 and 2006. Comparing valley width (Fig 11a) to slope-subtracted bed elevations for 1999 and 2006 (Fig. 11b,c), riffle crests 1-5 and 7 visually line up with locally wide valley areas. The absolute amplitude for crest 7 is admittedly low, but the local hydraulic constriction is easily recognizable in Fig. 9d. Meanwhile, pools coincided with constrictions. The locally deepest pool was located 3,830 m upstream of the Highway 20 bridge. It was located in the longest narrow section of the reach (Fig. 11b). The next two deepest pools, located between riffles 6-7

and 7-8, were in the second longest narrow section of the reach. The deep pool downstream of crest 1 was in the narrowest cross section in the whole reach. Considering riffles and pools together as a seamless continuum of channel form, the undulation of bed elevation is in phase with the oscillation of valley width, even though neither one is a simple sinusoidal function.

5. Discussion

The results of this study show that Timbuctoo Bend is dynamic from large peak floods, its riffle locations are in phase with valley width undulations, and riffle crests persist over decades. The geomorphic observations are consistent with flow convergence routing associated with multiple scales of landform nonuniformity. Deviations in the overall process-form relation were observed at individual sites and were explainable by specific types of channel nonuniformity, including an abrupt canyon expansion, an abrupt channel meander, bedrock outcrops into the bankfull channel, and medial bar dynamism. No reference to alternate bars, meanders, bar instability, bed material differentiation, or particle queuing was necessary to explain reach-scale riffle persistence (Wilkinson et al., 2008; Clifford, 1993a). The only way to describe and comprehend the fluvial geomorphology of the reach is to frequently refer to aspects of the multiple scales of landform nonuniformity, especially valley width oscillations.

5.1 Analysis of Timbuctoo Bend's riffles

The valley-confined, wandering gravel-bed reach of the lower Yuba River from the Narrows Pools to the Highway 20 bridge is unquestionably a dynamic fluvial landscape. Planform channel change ranged from 4% to as much as 34% of the confined area per interval between aerial images over the 22-years. Intervals have gotten shorter as imagery is repeated

more frequently since 2000, but based on the established criterion of 5%, planform channel change occurred over all time intervals, except the driest one that was also a 2-year interval. Peak daily discharge during each time interval statistically outperformed duration of floodplain inundation in explaining the magnitude of channel change. Additionally, the majority of the reach has been incising at a remarkable rate of 0.16 m/year. With frequent floodplain inundation as well as planform and vertical change occurring over every time interval, it is clear that riffles and pools did not persist from a lack of geomorphic dynamism.

Nonpersistent riffles were vulnerable to large floods. A number of nonpersistent riffle crests formed when large mid-channel gravel bars were deposited (Fig. 7). However, these large mid-channel gravel bars proved unstable and were frequently destroyed and re-formed. A nonpersistent riffle crest that did persist for three of the seven time intervals from a sudden bend in the valley (Fig. 9d) was removed by a 41.7-year event of 3823 m³/s. A nonpersistent riffle crest that persisted due a local bedrock outcrop (Fig. 7e) for 5 of the 7 time intervals was removed by a 7.7-year event of 1218 m³/s in 2005.

Over the 22 years spanned by the study, eight riffles clustered in the same locations. For the seven that occurred in the oscillating valley walls, there was a tight distribution of position relative to the distance between downstream and upstream constrictions (the average standard deviation being 9% of d_c). These riffle locations were not random, nor did they show a tendency to migrate upstream or downstream; they were persistent and explainable by hydrogeomorphic process. Many of the same riffle crests that persisted over the study period were also evident in the 1937, 1947, 1952 (Fig. 10), and 1958 photo sets, extending their persistence over many decades. Although the channel migrated laterally from one side of the valley to the other,

intensive incision cut down through deep valley fill, islands formed and vanished, and side channels were cut and filled, these seven riffles clustered in the same location.

The fact that riffles persisted for decades in the same locations despite remarkable change, including construction of large reservoirs, indicates some stabilizing mechanism. The study revealed a close relationship of persistent riffle crest location to the widest point of the confining valley as well as a match between valley constrictions and occurrence of deep pools. The average distance of riffle crests to the widest point was 16% of d_c , in contrast to the average distances to downstream and upstream constrictions of 52% and 48% of d_c respectively. The only outlier was persistent riffle crest 6, which is explainable by the evidence of meander cutoffs just downstream where the wide valley coincides with a sharp bend (Fig 9d). No other location showed a link between riffle location/persistence and meander position.

The strongest evidence of the relationship between riffle locations/persistence and valley width is provided by the 1999 and 2006 slope-subtracted bed elevation plots (Fig. 11b,c). The vertical undulation of the bed was in phase with the lateral oscillation of valley walls, though neither was a simple sinusoid. Past mechanistic studies that experimented with oscillating valley walls resulted in similar undulating bedform depositional patterns in phase with the oscillations, with relative highs lined up with the widest portion of the channel and the relative lows lined up in the narrowest portion of the channel (Repetto et al. 2002; Wu and Yeh, 2005). Mechanistically that is driven by flow convergence routing. However, in those studies, walls were vertical, not sloped.

There are important differences between hydrogeomorphic processes in a narrow canyon versus a wall-confined valley floor. In both systems, wetted width and the positioning of flow convergence routing varies as a function of stage (i.e. the shape of the at-a-station width relation,

as summarized for confined rivers by Wyrick and Pasternack (2008)). In a wall-confined valley with a wandering gravel-bed river, stage-dependent flow convergence routing is largely triggered by the transition of width from the low-flow channel up to the valley width. It is the slope of the wetted width versus discharge relation over that stage range (at-a-station) that matters. For a narrow canyon whose semi-alluvial floor is inundated at a stage lower than or at bankfull, the governing width metric would relate to the change in width up the canyon walls. In Timbuctoo Bend, the role of absolute valley width would only come into play at a stage above which valley walls are hydraulically influencing flow for the majority of the reach. Given the high mean width of the valley, it would take an enormous increase in discharge at flood stage to change the absolute value of width enough to influence the positioning of flow convergence routing. In contrast, the factor of 2-3 longitudinal differences in valley width influence flow convergence routing as soon as valley walls are hydraulically relevant ($> 540 \text{ m}^3/\text{s}$), and they remain an impact at all higher stages. Thus, the at-a-station slope of the valley walls themselves has little influence relative to the downstream undulations in valley width.

5.2 Multiple scales of landform nonuniformity

Timbuctoo Bend on the lower Yuba River exhibits flow-accelerating features at all spatial scales. Pebble clusters and boulders roughen the bed. Boulder clusters, wood accumulations, and man-made structures protrude into the bankfull channel. Rock outcrops, meander bends, point bars, medial bars, riffle crests, and pool troughs vary bankfull channel dimensions. Alluvial terraces, valley wall undulations, valley meanders, and patches of vegetation vary river corridor dimensions. These are all common features to natural (and many regulated) gravel-bed rivers that have been widely reported in the literature, as presented in

section 1.1. Academic research has characterized this morphological phenomenon very well and this study adds to that further by linking riffle-pool persistence to valley wall undulations.

Varying the rate of change in wetted channel and/or valley width as a function of stage, the driver of flow convergence routing, has been shown in other studies to influence sediment depositional patterns. In numerical models and flume experiments, a sediment depositional pattern was observed in which relative highs lined up with the widest portion of the channel and the relative lows lined up in the narrowest portion of the channel, resulting in channel width oscillations in phase with bed undulations (Repetto et al. 2002; Wu and Yeh, 2005). Also, bar instability associated with valley-width oscillations exhibits feedbacks with channel hydraulics (Wilkinson et al., 2008). In a full-scale, stream-manipulation experiment, Wheaton et al. (2009) showed that controlled variations in channel width did promote riffle-pool maintenance in a narrow channel.

5.3 Implications for river hydraulics

The problem in gravel-bed river research and practice today lies in the application of over-simplified hydraulic and sediment-transport prediction tools. Sawyer et al. (2010) illustrated for the pool-riffle-run sequence at the apex of Timbuctoo Bend that there is no flow rate (in the range of 0.15-7.64 times bankfull discharge) for which flow is approximately uniform. They demonstrate that cross section hydraulic analyzers perform poorly, because they neglect flow acceleration. Brown and Pasternack (2009) investigated a simpler straight channel in a different gravel-bed river and still found that cross section based hydraulic analyzers performed poorly at estimating velocity, bed shear stress, and fish habitat conditions.

Contrary to conventional thinking, there is no evidence of the existence of a shift in flow from nonuniform to approximately uniform at some extremely high flow for valley-confined gravel-bed rivers. Pasternack (2008) examined flows for the same site as Sawyer et al. (2010) up to 19.4 times bankfull discharge and saw no evidence of flow uniformity for that wider range. The evidence demonstrates that at ever higher discharges, flows just shift their primary hydraulic constraint from bed to valley wall conditions. Oscillations in valley width as well as multiple scales of valley-wall roughness cause hydraulic variability that yields relatively high transport capacity and pool scour at valley constrictions. Riffles located in the widest parts of the valley would either incise at a slower rate than pools for large floods or actually receive sediment deposits eroded off the pools, such as on the rising or falling limb of a flood. This results in channel bedform morphology being in phase with valley width oscillations (Fig. 11).

These findings call into question the use of hydraulic and sediment-transport prediction tools that assume uniform flow for gravel-bed rivers over the full range of discharge possible. The computational error is not just a slight shift in numbers, but actually a change in the whole interpretation of process. Whereas uniform flow results in velocity, shear stress, and channel incision estimates always increasing with discharge, nonuniform conditions can reverse the direction of change and yield lower values of those important variables at higher discharges (Sawyer et al., 2010). Any sediment transport relation ostensibly for a gravel bed river with riffles and pools that yields continuously increasing sediment load as a function of increasing discharge is suspect. Developing sediment transport relations that account for landform nonuniformity is no easy task, but it is necessary now. This has wide implications in geomorphology, ranging from landscape evolution modeling to river rehabilitation practice.

5.4 Implications for geomorphologic practice

Understanding width-variation controls on forming and maintaining key riverine features, such as riffles and pools, may assist in managing the long-term evolution of morphological diversity and the associated distribution of aquatic and riparian habitats. A widely used approach for designing stream channels simply scales design channel dimensions to grow uniformly as a function of increasing bankfull discharge and does not account for downstream oscillation in channel and valley width. Sometimes after bankfull dimensions are specified by a geomorphologist, engineers or construction crews end up constructing width variation for other reasons or by accident. For example, on the Robinson Reach of the Merced River in the Central Valley of California, engineers actually designed the river to be ~ 30% narrower in riffles than intervening pools to speed up water to achieve velocities preferred by spawning salmonids. That resulted in quick riffle scour and pool infill- a costly waste of money invested in cleaning and placing rounded river gravel/cobble on inherently unstable riffles. On the Bear Creek tributary of the Fall River in northeastern California, bankfull dimensions were specified by a geomorphologist, but the use of an excavator to dig out pools in a “C” channel riffle-pool sequence from a position on the bank perpendicular to flow resulted in pools having vertical walls and being significantly wider than riffles at all in-bank stages. Subsequently, placed gravels for instream habitat scoured out of riffles and settled into the over-widened pools. Sawyer et al. (2009) report on the importance of construction methods for gravel-bed river rehabilitation. These specific examples illustrate the need for better incorporation of the mechanisms associated with multiple scales of landform nonuniformity in geomorphic practice.

Considering the number of confined systems from various engineered channel controls and natural topographic controls, the implications of this study may be particularly useful in

rehabilitation of constricted reaches. For example, if the goal of river management were to improve gravel-bar sustainability in leveed rivers, it may be useful to vary the width between the levees. Also, understanding width controls on sediment deposition and scour would aid in determining where gravel injected below dams may deposit and form riffles or merely settle into the bottom of old gravel mining pits. As demonstrated by Brown and Pasternack (2009) and Wheaton et al (2009), when constructing riffles below dams, it is helpful to use flow convergence routing to assess the sustainability of design elements. Other processes associated with multiple scales of channel nonuniformity, including meander dynamics and turbulence-induced local scour, need to be incorporated into design aids too.

6. Conclusion

This study showed that the lower Yuba River from the Narrows Pool to the Highway 20 bridge is a dynamic fluvial landscape whose channel morphology is influenced by peak flood magnitude and undulating valley walls. Even though the river is incising rapidly from mining sedimentation followed by flow regulation, riffles persist in the same locations longitudinally from the stabilizing role of oscillating valley width. The mechanism behind this appears to be flow convergence routing, which causes sediment to deposit in the widest portion of the confining valley from reduced flow velocities, shear and bedload transport capacity during floods. This study provides further evidence that the phenomenon of multiple scales of landform nonuniformity is the hallmark of gravel-bed rivers with sequences of riffles and pools. Bankfull channel dimensions and sediment transport relations predicated on the assumption of uniform flow have little value in predicting landform nonuniformity, and thus cannot explain or predict the relevant physical processes.

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Table 1

Attributes of individual photo sets and those for the period between photo sets

Water year	1984	1986	1991	1996	2002	2004	2005	2006
Date of photo (m/d/y)	4/24/84	10/6/86	7/2/91	7/16/96	9/30/02	4/1/04	9/23/05	9/28/06
Mean daily flow at time of photo (m ³ /s)	42	35	37	58	19	62	23	21
Date of peak daily flow between two photo sets	n/a	2/19/86	3/25/89	5/18/96	1/2/97	5/8/03	5/20/05	12/31/05
Peak daily flow (m ³ /s) between two photo sets	n/a	2832	742	1427	3823	203	1218	3089
Recurrence interval of peak daily flow (years)	n/a	23.8	4.1	9.1	41.7	1.6	7.7	24.0
Ratio of peak daily flow to bankful discharge	n/a	17.8	4.66	8.96	24	1.28	7.64	19.4
Number of days of floodplain inundation**	n/a	21	4	43	25	0	4	26
Area of planform change* (%)	n/a	34%	8%	17%	29%	4%	8%	14%

*Area of Planform Change = $\{[(\text{Area of Cut}) + (\text{Area of Fill})] / (\text{Total Area Within Valley Boundary})\} \times 100\%$.

**Threshold for inundating the majority of the floodplain was 540 m³/s (Pasternack, 2008).

Table 2
Characteristics of persistent riffles and their relation to valley width variations

Riffle crest ID	1	2	3	4	5	6	7	Mean
Mean riffle crest location distance upstream (m)	652	962	1407	1775	3197	4577	4971	
Associated widest point distance upstream (m)	616	975	1436	1756	3164	4340	4913	
Associated downstream constriction distance upstream (m)	329	844	1195	1628	3036	4231	4694	
Associated upstream constriction distance upstream (m)	844	1195	1628	2039	3356	4694	5179	
Distance between constrictions distance upstream (d_c) (m)	515	351	433	411	320	463	485	425
Range in riffle crest position (% of d_c)	12%	30%	30%	21%	45%	26%	22%	26%
Standard deviation in riffle position (% of d_c)	4.1%	10%	12%	6.8%	15%	7.6%	7.4%	9.1%
Distance from mean riffle crest to downstream constriction (% of d_c)	63%	34%	49%	36%	50%	75%	57%	52%
Distance from mean riffle crest to widest point in the valley (% of d_c)	7.3%	7.7%	11%	6.5%	13%	51%	12%	16%
Distance from mean riffle crest to upstream constriction (% of d_c)	37%	66%	51%	64%	50%	25%	43%	48%

Fig. Captions

Fig. 1. Timbuctoo Bend on the lower Yuba River, CA from the Narrows Pool downstream to the Highway 20 bridge. Inset maps show location within the Yuba River catchment and in California, U.S.A.

Fig. 2. View looking downstream of a near-bankfull flow of $142 \text{ m}^3/\text{s}$ at the pool-riffle-run sequence at the apex of Timbuctoo Bend. Bankfull indicators include onset of inundation of the island and willows growing at the bank's slope break.

Fig. 3. View looking downstream of the apex of Timbuctoo Bend a) before, b) during, and c) after a recent 24-year flood. The sequence shows willows removed, side channel formation, and extensive erosion of the mid-channel bar.

Fig. 4. Georectified photos for a) 1984, b) 1991, c) 1996, and the orthophoto for d) 2002.

Fig. 5. Wetted channel change over four time intervals: a) 1984 to 1991, b) 1991 to 1996, c) 1996 to 2002, and d) 2002 to 2006.

Fig. 6. Longitudinal profiles for 1999 and 2006 showing significant net incision, but also maintenance of riffle-pool relief. Numbers are the identifiers for each persistent riffle crest

Fig. 7. Nonpersistent riffle crests occurring in association with localized channel nonuniformity, such as transient medial bars and bedrock outcrops.

Fig. 8. 2006 aerial photo of the study reach with the confining valley border delineated and locations of persistent riffle crests 1984-2006 identified as secchi disks. Each disk represents the location of a crest in a single year's imagery.

Fig. 9. A close up of persistent riffle crests a) 1 and 2, b) 3 and 4, c) 5, and d) 6 and 7. Even as dynamics such as channel migration and mid-channel bar removal or formation, the riffle crests remained clustered in the same general locations.

1018 Fig. 10. 1952 riffle crest locations (black triangles) are located in close proximity to the mean
1019 riffle crest locations 1984-2006 (secchi disks).

1020 Fig. 11. Illustration of the connection between a) valley width and slope-subtracted longitudinal
1021 profiles for b) 1999 and c) 2006. Horizontal bars show the positional area of each persistent
1022 riffle location, vertical arrows show points of greatest valley width for each oscillatory cycle,
1023 open circle is location of persistent crest 8 at the head of the valley, X denotes a large
1024 oscillation with no persistent riffle crest, and numbers are the identifiers for each persistent
1025 riffle crest.

1026

a) 1984

b) 1991

c) 1996

d) 2002

a)

b)

c)

d)

c)

d)

b)

a)

e)

- Persistent Riffle
- ▭ Valley Confinement

Figure 9. A close up of persistent riffle crests a) 1 and 2, b) 3 and 4, c) 5, and d) 6 and 7.

The illustrations show the channel the channel migrates, mid-channel bars are removed and formed yet the riffle crests have remained clustered in the same general location.

a)

b)

c)

d)