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Reenvisioning velocity reversal

Reenvisioning velocity reversal as a diversity of hydraulic patch behaviors

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Abstract

Past research investigated the surpassing of mean velocity at riffle cross sections by that at pool cross sections for flows up to bankfull, termed “velocity reversals,” to understand one mechanism by which riffle-pool relief is maintained. This study reenvisioned the classic velocity reversal by documenting stage-dependent changes to the locations of peak velocity without cross sections. Instead, the dynamics of peak velocity patches were considered for flows spanning 0.2 to 22 times bankfull discharge through the use of a high-resolution DEM and two-dimensional hydrodynamic modeling. A remarkable diversity in peak velocity patch behavior was found across discharges, including gradual expansion and shifting as well as abrupt disappearance and emergence relative to the low-flow patch locations. These behaviors blended together to varying degrees to produce many reversals in peak velocity across morphological units, but it took substantially higher than bankfull discharge for peak velocities to move from riffles and chutes to fast glides and pools. The discharges at which reversals occurred among morphological units were significantly higher for the valley-confined reach than for the anastomosing reach.

Keywords

River hydraulics, velocity reversal, fluvial geomorphology, gravel-bed river, floods

I Introduction

A landform is an organized pattern to Earth's topography at any scale of interest that occurs commonly enough or is unusual enough to merit scientific scrutiny. Common landforms observed in gravel-bed rivers include riffles and pools, which are often organized as sequences (Milne, 1982). The cause of riffle and pool persistence is a long-standing subject in fluvial geomorphology (Gilbert, 1914). Diverse mechanisms have been investigated, and each has its own literature and merits. Examples include energy expenditure minimization and stream power distribution (Yang, 1971; Thompson, 2004; Parker et al., 2014), particle queuing and selective sediment sorting (Naden and Brayshaw, 1987; Almeida and Rodriguez, 2012; Bayat et al., 2014), turbulent velocity fluctuations (Clifford, 1993; Thompson, 2006; MacVicar and Roy, 2007), mean velocity reversal (Keller, 1971; Clifford and Richards, 1992; Caamaño et al., 2009), flow convergence routing (MacWilliams et al., 2006; Sawyer et al., 2010) and shear stress phase shifting (Wilkinson et al., 2004).

Among the mechanisms for riffle and pool persistence, velocity reversal has received the most attention, with both support and criticism (see supplemental introduction for a more in-depth review). As traditionally understood, the velocity reversal mechanism for the maintenance of riffle-pool relief involves a greater rate of increase in mean velocity at the pool cross section relative to the riffle cross section, such that mean pool velocity and sediment transport competence ultimately exceed that at the riffle at high flow (Keller, 1971). The role of the velocity reversal mechanism has been called into question due to the reported absence of reversals when assessed using cross section averaged velocity (Richards, 1978; Schmidt, 1990; Carling, 1991; Carling and Wood, 1994; Thompson et al., 1996); however,

evaluating the occurrence of velocity reversals is complicated by the use of cross section averages amidst lateral and longitudinal flow nonuniformity. Abrupt constrictions at the heads of pools produce flow separation that reduces the effective cross-sectional area of downstream flow through pools (Schmidt, 1990; Carling et al., 1994; Thompson et al., 1996; Thompson et al., 1999). Additionally, Clifford and Richards (1992) reported the presence or absence of a velocity reversal between riffle and pool depending upon the locations of the examined cross sections. These examples of nonuniform flow reveal the limitations of the traditional conceptualization of the reversal mechanism as one that involves mean velocity at riffle and pool cross sections.

The recognition of nonuniform flow and advances in computer modeling have spurred the use of multi-dimensional models for investigating the hydraulics in riffle-pool sequences. Two and three-dimensional model results have revealed multi-dimensional flow patterns, such as the routing of flow away from the deepest parts of pools (Booker et al., 2001; MacWilliams et al., 2006, Caamaño et al., 2012; Milan et al., 2013). However, cross section averages continue to be used to report the presence or absence of velocity reversals (Booker et al., 2001; MacWilliams et al., 2006; Sawyer et al., 2010), often to allow for a comparison with the results of prior studies.

In addition to observations of multi-dimensional flow patterns, other recent findings in river research have implications for the investigation of velocity reversal. White et al. (2010) reviewed aerial imagery spanning seven decades for the Timbuctoo Bend reach (TBR) of the lower Yuba River in Northern California, USA and reported both persistent and transient riffles, raising the question of whether velocity reversals occur at the reach scale amidst mixed riffle stability. The imagery

reviewed by White et al. (2010) spanned flow events up to 24 times bankfull discharge, and Sawyer et al. (2010) modeled a single flow event in the same reach that was 7.63 times bankfull discharge. Riffle-pool maintenance was documented as the relief between the two landforms increased as a result of the flood, and cross section averages were used to document velocity reversals in keeping with previous studies. While field measurements of velocity have typically been limited to discharges up to bankfull due to safety concerns, hydrodynamic modeling permits an investigation of velocity reversal beyond bankfull discharge. Lastly, a greater diversity of fluvial landforms beyond riffle and pool has been recognized through new geomorphic classifications (Wyrick and Pasternack, 2014; Wheaton et al., 2015). This poses the question as to whether velocity reversals operate outside of the conventional riffle-pool paradigm.

Investigation of spatially dynamic hydraulics among river landforms requires a modernization of analyses commensurate with that of the data and models of fluvial processes. In this study, theoretical developments were made and new methods were introduced to provide a spatially explicit conceptualization of river hydraulics. The changing shape, size and position of peak velocity patches with discharge suggest that the classic notion of a velocity reversal, involving peak velocities at riffle cross sections at low flows and pool cross sections at high flows, should be reenvisioned as a diversity of hydraulic patch behaviors. To investigate this concept, two-dimensional hydrodynamic modeling was used to obtain near-census hydraulics of the lower Yuba River (Abu-Aly et al., 2013) as opposed to spatially dense ADCP measurements that were not feasible given the desired spatial extent and broad discharge range, including dangerous floods. These model results were recently used to delineate sub-channel-width-scale fluvial landforms for the lower Yuba River

(Wyrick and Pasternack, 2014), including diverse morphological units (MUs) beyond the traditional riffle-pool classification. The specific objectives of this study were to (i) devise a strategy for spatially delineating peak velocities at each discharge; (ii) characterize how these regions of peak velocity behave in the river with increasing discharge; (iii) assess the occurrence of velocity reversals without the use of cross sections in the context of traditional riffle-pool couplets as well as all the units of each MU type; and (iv) compare the above for two reaches on the lower Yuba River, the wide, anastomosing Daguerre Point Dam reach (DPDR) and the valley-confined Timbuctoo Bend reach (TBR).

II Study Site

1 Lower Yuba River

The lower Yuba River flows east to west from the Sierra foothills downstream of Englebright Dam to its confluence with the Feather River (Figure 1). It is ~ 37.1 km long and drains 3480 km². Englebright Dam was constructed as a sediment barrier in 1941 to protect the lower Yuba River from further impact associated with the hundreds of millions of tons of sediment blasted off hillsides throughout the watershed during hydraulic gold mining (Gilbert, 1917). While the dam has resulted in downstream incision throughout the valley corridor of ~ 10 m over 65 years (Carley et al., 2012), the lower Yuba River remains a wandering gravel-bed river due to the immense transport and storage of sediment. The absence of large reservoirs on the Middle and South Yuba tributaries translates to a broad range of discharges for the lower Yuba River with flows overtopping Englebright Dam during large winter storms and spring snowmelt. Farther down the river, the Daguerre Point Dam is a

small diversion dam essentially full of sediment that marks the reach-scale transition from net incision upstream to net deposition downstream. The Daguerre Point Dam Reach and the Timbuctoo Bend Reach described below were chosen for this study as the strong contrast in reach properties relative to other reach pairs within the segment provided a broad range of hydraulic controls for which the resulting patterns of peak velocity could be documented.

2 *Daguerre Point Dam Reach*

This reach begins at the Daguerre Point Dam and ends at a slope break with the downstream Hallwood Reach (Figure 2). Reach characteristics include a mean slope of 0.18%, a thalweg length of 5637 m, a mean bankfull width of 120 m, a floodway width of 313 m, an entrenchment ratio of 3.5 (*sensu* Rosgen, 1996) and a mean substrate size of 87 mm. According to the system of Rosgen (1996), its current condition may be classified as a C3 stream with slight entrenchment, moderate bed slope and cobble channel material (see Wyrick and Pasternack, 2012 for more metrics and classes). DPDR is the widest reach in the lower Yuba River. The channel is bounded by a training berm to the north and mining tailings on the southern side, and the parallel overflow channel north of the training berm, termed Daguerre Alley, conveys flow upon full inundation between 283.2 m³/s and 425 m³/s.

3 *Timbuctoo Bend Reach*

The Timbuctoo Bend reach begins at the onset of the alluvial valley downstream of the Narrows canyon and ends at the bedrock constriction where the Highway 20 bridge is located (Figure 2). This reach has a mean bed slope of 0.2%, a thalweg length of 6337 m, a mean bankfull width of 84.4 m, a floodway width of 134 m, an entrenchment ratio of 2.1, and a mean substrate size of 164 mm. According to

the system of Rosgen (1996), its current condition may be classified as a B3c stream, indicating moderate entrenchment and bed slope with cobble channel material. Several other reach classification metrics are reported in Wyrick and Pasternack (2012), while substrate details are provided in Jackson et al. (2013).

III Methods

This section briefly describes the spatially explicit model results used in the study, results processing to identify peak velocity patches and results analysis procedures for addressing the study objectives. Given that the purpose of this study was not to develop multi-dimensional models or prove their veracity but to extend their utility for analyses that improve scientific understanding, the full underpinnings of the 2D models are explained in the supplementary materials (section 3). This study built on a previously developed, meter-scale 2D hydrodynamic model that predicted depth-averaged velocities for ~ 35 river km for discharges ranging from 0.2–20 times bankfull (28.32–2840 m³/s) (Barker, 2011; Abu-Aly et al., 2013). This model has more than one million computational elements, with ~ 100 elements across the bankfull channel for the mean bankfull width. Given the floods modeled, it was necessary to use spatially distributed and stage-dependent vegetated boundary roughness (Katul et al., 2002; Casas et al., 2010). Despite the increasing use of 2D models in river science, there exist uncertainties, errors and limitations in this method (MacWilliams et al., 2006; Hunter et al., 2008; Legleiter et al., 2011; Jowett and Duncan, 2012) as is the case for empirical data (Brown and Pasternack, 2009), 1D hydrodynamic models (Horritt and Bates, 2002; Tayefi et al., 2007; Pasternack and Senter, 2011; Gibson, 2013), 3D hydrodynamic models (Tonina and Jorde, 2013) and multi-dimensional morphodynamic models (Camporeale et al., 2007; Chen et al., 2010; Feurich and Olsen, 2011). The choice of 2D hydrodynamic

modeling was sensible for this study as a way of capturing the effects of topographic steering and convective acceleration at the meter to decimeter scale over large study areas.

Although 2D simulations and hydraulic analyses were performed for 28 discharges, for the sake of brevity in reporting the findings, the metrics used in this study and described below were determined for the following discharges: 28.32 m³/s, 141.6 m³/s, 283.2 m³/s, 597.5 m³/s, 1195 m³/s, 2390 m³/s and 3126 m³/s. The flood recurrence intervals, in years, for the higher six discharges as computed for the Marysville gaging station (USGS #1141.61000) using HEC-SSP v. 2.0 are 1.2, 2.5, 4.7, 12.9 and 20.2, respectively. Baseflow for the lower Yuba River is 25 m³/s, and 141.6 m³/s is considered the bankfull discharge based on the evaluation and compilation of diverse geomorphic indicators (Wyrick and Pasternack, 2014). Thus, the range of analysis in this study was 0.2 to 22 times bankfull discharge—an extremely broad range compared to past field and modeling studies addressing this topic.

Peak velocity was targeted for analysis in keeping with previous studies that have investigated its relevance to sediment transport (e.g., MacWilliams et al., 2006; Caamaño et al., 2012). There remains strong interest to add to or replace velocity-based analysis with analysis of Shields stress for a more direct process-based evaluation of hydraulics (Pasternack, 2011; Jackson et al., 2015). Velocity remains important for assessing sediment transport capacity and potential channel change over Shields stress for as long as 1-10 m scale remote sensing of terrestrial and bathymetric bed material texture continues to be elusive, so we focused on velocity while also producing methods suitable for any hydraulic variable of interest as new data and model outputs emerge. Using the 2D hydrodynamic model, it was possible

to objectively report the locations of peak velocities at each discharge by delineating patches of raster cells interpolated from the model results that exceeded a threshold velocity value as explained in the following section. These patches were a basic unit of analysis in this study, and new metrics were designed to relate the spatial patterns of peak velocity across the ranges of discharges in the context of the velocity patches themselves as well as the underlying MUs. Ultimately, the changing locations of peak velocities were driven by the fluid mechanics programmed into any 2D hydrodynamic model, which enable multiple scales of topographic heterogeneity to drive multiple scales of hydraulic phenomena. Thus, the primary focus of this study was not the controls on peak velocity but instead the unknown behaviors of peak velocity patches in a complex landscape subjected to flows across two orders of magnitude.

1 Delineation of peak velocity regions

Investigations of velocity reversal have traditionally been concerned with changes to the locations of peak velocities from riffle to pool as documented with cross section averages across a range of discharges (Keller, 1971). To locate areas of peak velocity with spatial objectivity and avoid the uncertainties associated with the number (Gonzalez and Pasternack, 2015) and location (Clifford and Richards, 1992) of cross sections, a threshold velocity value was identified in this study above which only 5% of the wetted area exceeded this value for a given reach and discharge. These peak velocity patches were termed “Hi-5s” for shorthand, and it was decided that to investigate the potential for MU-scale channel change, patches of roughly similar size as the sub-channel-width-scale MUs were appropriate for this study. Too strict of a threshold yielded only very small peak velocity patches at a scale that might only be relevant to local turbulence processes and not bulk velocity

patterns across the MUs, while too liberal of a threshold yielded patches too large to resolve the differences in hydraulics and potential for change among the MUs. Five percent was selected using expert judgment after a sensitivity analysis was performed, i.e., testing Hi-0.1, Hi-1, Hi-10, etc. and comparing the resulting patches. For brevity, those preliminaries are not formally presented herein. While expert judgment was required for setting the peak velocity threshold, the Hi-5 approach avoided the subjectivity associated with determining the number and position of cross sections to use.

A similar application of a peak-velocity threshold was performed by Caamaño et al. (2012) to map a jet in a riffle-pool sequence that was defined as exceeding 90% of the maximum depth-averaged velocity within a reference pool cross section, but that article reported no sensitivity analysis and no objective basis for the use of 10%. Instead, it was stated that this value “best showed the spatial pattern and limits (i.e., edges) of the jet over the range of flows studied.” What the criteria were for judging “best” is unclear as well as what values were tested. Comparing to that study site, whose peak modeled velocity was ~2.6 m/s, the LYR reaches modeled herein had a peak velocity over 6 m/s, and thus it makes sense that this would require a more restrictive threshold to isolate peak regions, especially considering the high velocities needed to move ~ 100 mm diameter grains in LYR conditions. Most likely the choice of criterion will vary depending on the size and resolution of the hydrodynamic model as well as the river’s hydraulics. In future studies it could be beneficial to replace velocity with bed shear stress or Shields stress so that a more mechanistic threshold could be chosen on the basis of a sediment transport consideration, such as the threshold for bed material entrainment. For example, if a map of grain size distribution were available, then one could calculate peak Shields

stress and map patches using a process threshold value, such as 0.03, 0.045 or 0.06 (Pasternack, 2011), thereby reducing the subjectivity of the percentile threshold used herein for velocity.

Due to raster discretization, it may not be possible to select a threshold to exactly map 5.00% of the wetted area. Note that for a given discharge, the threshold velocity value used to isolate 5% of the wetted area with peak velocities equivalently delimited the upper 5% tail of the velocity distribution since the velocity values within the wetted area had associated raster cell areas. These peak velocity patches of diverse sizes and shapes were mapped in ArcGIS (ESRI, Redlands, CA) by reclassifying a velocity raster into Hi-5 and non Hi-5 regions. Raster Hi-5 patches were then converted into discrete polygons, and no filtering or processing of any kind was performed on the polygons.

2 *Changing velocities within Hi-5 zones and spatial persistence*

To conceptualize the discharge-dependent spatial patterns of peak velocity patches as represented by the Hi-5s, three zones were defined in relation to where Hi-5s were located at a lower discharge (Q_i) and adjacent higher discharge (Q_{i+1}). The zones were intended to express the spatial association of peak velocity patch locations between Q_i and Q_{i+1} . Figure 3 depicts these zones for a single patch at Q_i and Q_{i+1} for schematic purposes, but these zones were delineated across the entire set of Hi-5 patches in a reach for each pair of Q_i and Q_{i+1} within the discharge series. Figure 3(a) shows the location of the patch at Q_i where no overlap occurred with the patch at Q_{i+1} (zone one), the overlap region between the patch at Q_i and Q_{i+1} (zone two) and the location of the patch at Q_{i+1} where no overlap occurred with the patch at Q_i (zone three). The scenario in 3(a) represents a partial shift of the

patch between Q_i and Q_{i+1} given that the centroid of the patch has moved, but an overlap region is present (zone 2). Additionally, end members for the changes in Hi-5 spatial extent were identified with respect to these zones. Figure 3(b) shows a complete shift of the Hi-5 in which the patch centroid at Q_i is not coincident with itself at Q_{i+1} and no zone two exists. In Figure 3(c), an expansion occurs with no shifting since the patch centroid remains coincident and no zone one exists. Conversely, Figure 3(d) shows a contraction with no shifting. Not shown in Figure 3 are the emergence of a Hi-5 patch for which no patch was present at Q_i and the disappearance of a Hi-5 patch for which no patch was present at Q_{i+1} . These incremental changes to the Hi-5 patches are considered flow-dependent hydraulic behaviors in which a blend of the above end member behaviors may occur to yield a complex distribution of changing peak velocity locations. Past research has made many assumptions and conjectures about hydraulic patch behaviors that remain to be thoroughly tested (e.g., MacWilliams et al., 2006), and this new approach enables such testing.

As Hi-5s change location to some degree from one discharge to the next, the changes in velocity within the three zones were quantified to elucidate the reasons for this movement. For each pair of Q_i and Q_{i+1} in the discharge series, the actual change in velocity from u_i to u_{i+1} as well as the normalized change in velocity (dUn) were calculated for each raster cell within each zone.

$$dUn = \frac{u_{i+1} - u_i}{u_i} \div \frac{Q_{i+1} - Q_i}{Q_i} \quad (1)$$

Cells that were dry at Q_i but within a Hi-5 at Q_{i+1} were ignored in these calculations. The normalized values were computed to permit a fair comparison of how velocity incrementally changed across discharges within the three zones given that the

discharges investigated spanned wide increments. For each zone, the normalized values for all pairs of Q_i and Q_{i+1} were combined and plotted as histograms for comparison with the results of the other zones.

Additionally, a metric termed “spatial persistence” was introduced to quantify the extent to which the Hi-5s covered the same area, i.e., the presence of zone 2, as discharge rose beyond the lowest flow (Q_1). This metric was computed between Q_1 (28.32 m³/s) and each of the higher discharges Q_i .

$$\text{Spatial persistence} = \frac{\text{Zone two area between } Q_1 \text{ and } Q_i}{\text{Hi-5 area at } Q_1} \times 100\% \quad (2)$$

Spatial persistence is not merely statistical stationarity in the sense of a patch retaining the same size and shape even if it moves far away, as it also captures the degree to which a given patch changes location. Through a blending of the aforementioned patch behaviors, a patch can change its size, shape and position to move away from previously occupied terrain and lower the spatial persistence metric. Statistical stationarity of patches has value as an independent metric to consider, but because it neglects shifting it is inadequate to evaluate the mechanisms of channel change that involve changes to the locations of peak hydraulic variables.

As is evident in Equation 2, the growing area of the higher discharge patches outside the spatial extent of the 28.32 m³/s patches is not used to compute the metric, only whether the 28.32 m³/s patches become more or less overlain by these patches at the higher discharge; consequently, a decline in spatial persistence is not merely an artifact of increasing total Hi-5 area as discharge and wetted area rise. Whereas the changes in velocity within the three zones were calculated with

adjacent discharges to assess incremental patch dynamics, traditional literature evaluates velocity reversal in terms of a change to the location of peak velocities from their low-flow locations (typically over riffles and chutes), so spatial persistence was computed with the low discharge held constant at 28.32 m³/s to express the overall pattern of Hi-5 movement for the full discharge series. Another discharge may be used as the baseline for comparison in the future if a new purpose emerges instead of the standard low-flow baseline.

3 Hi-5 occupation and near-census peak velocity of landforms

Traditionally, river longitudinal profiles were only delineated into topographic highs (riffles) and lows (pools), and then velocity was plotted as a function of discharge for cross sections through both to see which was higher and at which discharges. For the sake of enabling comparison with past studies, a similar couplet analysis of riffle-pool velocity reversal was performed herein as the first step in evaluating the link between peak velocities and hydraulics, though cross sections were not used. Specifically, six riffle-pool pairs were identified in TBR and the 95th percentile velocities (U_{95}) were computed from the raster velocity values for each riffle and each pool polygon across the seven discharges. This was not done for DPDR due to the limited pool area in that reach. For each couplet, the plot of U_{95} versus Q was inspected to see if reversals in peak velocity were present or not, and if so, at what discharge. Granted, this analysis was not on a cross-sectional basis, but it honored the concept and intent of the traditional approach.

Recently, Wyrick et al. (2014) and Wyrick and Pasternack (2014) used near-census topographic maps and 2D models to show that gravel-cobble bed rivers are found to have many more landforms than just riffles and pools when

comprehensively analyzed instead of simply using a longitudinal thalweg elevation profile. Since then, Wheaton et al. (2015) used a different near-census DEM analysis approach with the same outcome that rivers exhibit a diversity of in-channel MUs, not just riffles and pools. As a consequence, the investigation of fluvial landforms and the processes responsible for their persistence and change needs to move beyond consideration of only the riffle-pool couplet. Although velocity reversals have traditionally been evaluated between riffles and pools, near-census data afford the opportunity to extend the assessment of peak velocity spatial patterns to all river landforms. Consistent with the flow convergence routing hypothesis, a velocity reversal may occur between any two landform types depending on their relative effective cross-sectional areas at two discharges, so there is incentive to broaden the scope of studies beyond riffles and pool. Thus, this study developed an approach and metrics for this purpose.

The landform delineation that Wyrick and Pasternack (2014) developed for MUs of the lower Yuba River at the sub-channel-width scale enabled a thorough morphological documentation of velocity reversal for the two study reaches herein. These landforms were delineated as geographically static features (between channel-changing floods) that exhibit certain combinations of depth and depth-averaged velocity at baseflow that are specific to each MU as determined by expert judgment. The eight MUs included riffle, pool, fast glide, slow glide, run, chute, slack water and riffle transition. Appendix A of that article includes the detailed map sheets showing the MUs for the lower Yuba River, including for TBR and DPDR.

To interpret the discharge-dependent trends of the Hi-5s in the context of the eight MUs, Hi-5 occupation of the MUs was introduced as a metric to quantify the

extent to which the Hi-5 patches in a reach occurred over a certain MU for each of the seven investigated discharges.

$$Hi-5\text{ occupation} = \frac{MU\text{ area overlain by Hi-5s}}{total\ MU\ area\ for\ reach} \quad (3)$$

Because MUs significantly differed in areal abundance within each reach, the Hi-5 occupation metric normalized the MU area occupied by the Hi-5 patches to the total MU area within a reach for a more fair comparison of this metric across MUs. For example, chutes often occur in very low abundance with little area, but have the highest velocity for in-channel flows and focus scour to cause knickpoint migration and riffle failure (Pasternack et al., 2008). A reversal in Hi-5 occupation was defined to occur when the percent of an MU occupied by the Hi-5s surpassed the percent occupied for a different MU. Velocity reversals were also documented through a more direct use of the near-census depth-averaged velocity results. For each of the seven discharges, U_{95} was computed within each MU for each reach to represent the peak velocities subjected to these in-channel landforms. Reversals in this metric were identified as the exceedance of a certain MU's peak velocity by that of another MU as discharge rose.

This approach presents a new development in the hydraulic analysis of river landforms in that it investigates the ensemble behavior of peak velocities across all polygons of each MU within a reach and compares them. The traditional couplet approach, in which one landform immediately follows the next down the river, is most appropriate given 1D model results or cross section averages of 2D model results. This is because, by definition, it couples the topographic change of the riffle and pool, since water and sediment can only be routed from one landform to the next for in-channel flows. The use of both spatially explicit model results and MU maps in the

present study meant that the hydraulics weren't exclusively linked between any given riffle and pool polygon. The reach scale was therefore considered appropriate for computing the above metrics as integrated quantities across all polygons of each MU.

IV Results

1 *Hi-5 extent across discharges*

With increasing discharge, Hi-5 patches in both reaches exhibited the behaviors of shift, expansion, contraction and emergence to varying degrees both longitudinally and laterally, yielding a variety of different patch shapes and sizes. Three supplemental figures have been included that show maps of absolute velocity for each reach and discharge for comparison with the Hi-5 behaviors. In DPDR, Hi-5s were mostly located at the inflections of meander bends at $28.32 \text{ m}^3/\text{s}$ where low topographic relief of the adjacent banks facilitated a rapid expansion in cross sectional area as discharge increased, leading to a downstream shift of Hi-5 patches into the next meander bends through $597.5 \text{ m}^3/\text{s}$ (Figure 4). Upon entering bends three and five, the Hi-5s experienced large lateral expansions within the bankfull channel through $597.5 \text{ m}^3/\text{s}$ as adjacent point bars maintained flow constrictions with higher topographic relief relative to the banks along the bend inflections. Just downstream of the dam, a Hi-5 experienced longitudinal and lateral growth as it expanded downstream and over the left bank. Once adequate depths were reached over the floodplain, water spilling out of the deep dam plunge pool rushed downstream at high velocity within this broad Hi-5. At bend one, a Hi-5 seemed to emerge at $141.6 \text{ m}^3/\text{s}$ just as the upstream and downstream Hi-5 patches contracted, and it spatially persisted across the entire discharge range with significant expansion

and a slight shift onto the downstream point bar. A high relief training berm consisting of hydraulic mining tailings bifurcated the flow through this reach beyond $283.2 \text{ m}^3/\text{s}$, which abruptly converged flow into bend one and sustained a Hi-5 here through the highest discharge. The Hi-5s at bends three and five contracted both laterally and longitudinally between $1195 \text{ m}^3/\text{s}$ and $3126 \text{ m}^3/\text{s}$, while the Hi-5 at bend four maintained a narrow ribbon at $2390 \text{ m}^3/\text{s}$ before disappearing at the highest discharge. The effective cross sectional area of flow at these bends ultimately expanded sufficiently with inundation of the adjacent point bars to dissipate the associated Hi-5s.

Diverse Hi-5 spatial patterns and discharge-varying behaviors were also observed in TBR where Hi-5 patches in site one mostly persisted with some shifting between $28.32 \text{ m}^3/\text{s}$ and $283.2 \text{ m}^3/\text{s}$ (Figure 5). The long, narrow Hi-5 patch in site two at $28.32 \text{ m}^3/\text{s}$ significantly shifted downstream in the channel through $3126 \text{ m}^3/\text{s}$, while its original position was occupied by another patch that shifted downstream and expanded laterally over the bankfull channel. At sites three and four, the Hi-5 patches shifted downstream of the inundating medial bars through $597.5 \text{ m}^3/\text{s}$ followed by nearly complete contraction of the site four patch by $1195 \text{ m}^3/\text{s}$ (Figure 6). While the medial bars bifurcated and constricted flow at low discharge, these features presented large effective cross sectional areas given sufficient inundation that dissipated the Hi-5s. The Hi-5 toward the upstream end of site four at $28.32 \text{ m}^3/\text{s}$ shifted moderately downstream and experienced expansion followed by some contraction across the full discharge range. The east valley wall pinched the flow in this region and helped maintain the Hi-5.

2 *Changing velocities within Hi-5 zones and spatial persistence*

Velocity thresholds for Hi-5 delineation were different for the two reaches given their geomorphic differences, but in both they displayed monotonic increases across discharges. The thresholds in DPDR were lower than those for TBR across all discharges (Table 1), which is consistent with the reach-scale greater width and lower slope that characterize DPDR relative to TBR. The monotonic increase in velocity thresholds implies that the full extent of zone three experienced an increase in velocity between any two discharges. For example, if a raster cell did not lie within a Hi-5 at $28.32 \text{ m}^3/\text{s}$ in DPDR, then its velocity fell below 1.2 m/s , so if it was in a Hi-5 at $141.6 \text{ m}^3/\text{s}$ then it must have increased to at least 1.7 m/s . This is confirmed by Figure 7 and Table 2, which show universal increases in velocity for zone three. In contrast, zone one for patches in both reaches exhibited more of a mix between positive and negative changes in velocity. These regions either experienced a decline or an insufficient rate of velocity increase across discharges to remain within a Hi-5. The very existence of decreases in velocity at peak velocity locations with rising discharge raises important questions about the validity and widespread use of river incision functions that neglect channel nonuniformity in landscape evolution models. Zone two represented an intermediate state between zones one and three in which velocity exhibited only a moderate change, mostly positive but sometimes negative, and still exceeded the Hi-5 velocity threshold for the higher discharge.

The Hi-5s in both reaches moved with respect to their locations at $28.32 \text{ m}^3/\text{s}$, but the rate at which this occurred differed by reach as captured by the spatial persistence metric. In DPDR, the spatial persistence of the Hi-5s declined in two stages beginning with a rapid decline between $28.32 \text{ m}^3/\text{s}$ and $283.2 \text{ m}^3/\text{s}$ that implies a stronger change to the location of the Hi-5s compared to those in TBR for

this discharge range (Figure 8). Daguerre Alley inundated between 283.2 m³/s and 597.5 m³/s, and spatial persistence in DPDR exhibited an abrupt slope break here with nearly identical values at these two discharges. This overflow channel provided a bypass for flow that slowed the increases in stage within the main channel. As a result, the secondary channel buffered against expansions in effective cross sectional area within the main channel meander bends where Hi-5s were present to halt the decline in spatial persistence. While TBR exhibited a smoother decline in spatial persistence, this reach stabilized at a lower value than for DPDR, indicating that the locations of flow convergence that coincided with Hi-5s shifted more significantly across the full discharge range in TBR than in DPDR.

3 Hi-5 occupation of the MUs and peak MU velocity

The majority of the riffle-pool couplets in TBR showed at least one reversal in U_{95} (Figure 9), and those that did not show a U_{95} reversal did show a U_{95} convergence. Four of the six couplets showed a U_{95} reversal around 283.2 m³/s (Figure 9(b), (d), (e) and (f)), with the couplet in Figure 9(b) exhibiting another U_{95} reversal at a higher discharge. The couplets in Figure 9(a) and (c) showed a U_{95} convergence. All riffles showed declines in U_{95} at some point in the discharge series with abrupt drops at 283.2 m³/s for those in Figure 9(d), (e) and (f). As an indication of the potential for pool scour at the higher flows, it is important to note that the pool U_{95} exceeded 4 m/s in five of the six couplets with the highest pool U_{95} at 6.6 m/s in Figure 9(d). Finally, Jackson et al. (2013) reported that pools in the LYR have smaller diameter bed surface substrate than riffles (mean of 96 vs 118 mm, respectively), so even where there was only a U_{95} convergence, the implication of this size differential is that Shields stress would be substantially higher in pools than

in riffles at the highest flows modeled. Therefore, this variable would also exhibit a reversal.

The landform with the greatest Hi-5 occupation changed across discharges, and in both reaches most reversals occurred at flows many times higher than bankfull discharge. In both reaches, riffles and chutes experienced the greatest Hi-5 occupation at $28.32 \text{ m}^3/\text{s}$ compared to the other MUs (Figure 10). In DPDR, Hi-5 occupation of riffles remained mostly constant across all discharges, while chutes showed a large decline for flows above bankfull, leading to a series of reversals in this metric with MUs that were not overlain by Hi-5s below bankfull (Figure 10(a)). Hi-5 occupation of both riffles and chutes exhibited reversals with runs, fast glides, riffle transitions and slow glides from about $141.6 \text{ m}^3/\text{s}$ to $1195 \text{ m}^3/\text{s}$, which reflects the pattern in Hi-5 movement across MUs displayed in Figure 11(a). Because DPDR receives a large coarse sediment supply (Carley et al., 2012), in-channel landform relief is smaller than for upstream reaches like TBR that are systematically eroding. As a result, the shallow topographic troughs in most meander bends classify as fast glides instead of pools relative to river segment relief norms. Therefore, fast glides were the primary recipient of Hi-5 occupation at high discharges, but not until more than double bankfull discharge. While the pool in Figure 11(a) was overlain by a Hi-5 patch at intermediate discharges, the vast majority of pool area in DPDR was not exposed to Hi-5s across the full discharge range (Figure 10(a)). This result is due to the large buffering capacity of Daguerre Alley. Significant pool area occurs at the downstream end of Daguerre Alley just before it joins the main channel where velocities never reached high values across the investigated discharge range. While the Hi-5 occupation of pools remained close to 0% for all flows, the Hi-5 occupation of the other MUs converged to around 20% by $3126 \text{ m}^3/\text{s}$.

Riffles and chutes also showed the largest Hi-5 occupation at low flow in TBR, and reversals mainly occurred with runs, pools and fast glides from about 597.5 m³/s to 1195 m³/s. Despite being a confined valley, Hi-5 patches persisted over riffles and chutes for flows beyond four times bankfull discharge (Figure 10(b), Figure 11(b)). This is interpreted to be controlled by the topographic steering from topographically complex alluvial landforms within the valley, which retain control over hydraulics until the flow is valley wide. In contrast with DPDR, TBR exhibited large Hi-5 occupation of pools for flows of eight to twenty times bankfull discharge. At the highest discharge, Hi-5 occupation of pools, fast glides and runs remained elevated above that of the other MUs (Figure 10(b)). Overall, discharges dramatically higher than bankfull were required before pools and fast glides became dominated by Hi-5s in TBR and DPDR, respectively.

U_{95} for the MUs followed similar trends as Hi-5 occupation of the MUs, in which a higher U_{95} of an MU relative to the other MUs corresponded to a higher relative Hi-5 occupation (Figure 12). As with Hi-5 occupation of riffles and chutes, riffle and chute U_{95} exhibited reversals with the other MUs at lower discharges in DPDR than in TBR. Specifically, riffles and chutes had the highest U_{95} at 28.32 m³/s but were surpassed by runs, fast glides, riffle transitions and slow glides by 597.5 m³/s in DPDR (Figure 12(a)). Reversals in riffle and chute U_{95} within TBR occurred with runs, pools and fast glides by 1195 m³/s (Figure 12(b)). This was facilitated by the leveling off of U_{95} in chutes for a range of intermediate flood flows. These ensemble reversals are consistent with the occurrence of U_{95} reversals among the riffle-pool couplets. Pool U_{95} remained lower compared to that for the other MUs in DPDR at the highest discharges, mirroring the trend in Hi-5 occupation of pools. Pools in TBR had a low U_{95} at low discharge but the highest U_{95} at the two highest

modeled discharges. The other low-velocity MUs in TBR, slow glides and slack waters, had consistently low U_{95} across all discharges. Meanwhile, for DPDR, slow glides exhibited the strongest ensemble velocity reversal, while pools became relatively slower, and slack waters showed only a modest relative velocity increase compared to the other MUs.

V Discussion

1 *New spatial metrics for understanding hydraulic patch behaviors*

The metrics introduced in this study offered a spatially explicit foundation for investigating hydraulic behaviors that result from nonuniform flow mechanisms in rivers. The suite of delineated MUs (Wyrick and Pasternack, 2014) beyond riffle and pool permitted a more nuanced analysis of how landforms in the lower Yuba River interacted with flows across the wide range of simulated discharges. This delineation also allowed for near-census (meter-scale) predictions of velocity over the full spatial extent of individual MUs, thereby avoiding the selection of cross section locations that may confound the interpretation of velocity trends across discharges (Clifford and Richards, 1992). Finally, modeling discharges up to 22 times bankfull revealed previously unknown behaviors of peak velocity regions across river landforms, including the occurrence of velocity reversals as reenvisioned outside of the traditional cross section based framework.

2 *Inferring processes from hydraulics with new spatial metrics*

The delineation of the Hi-5s and computation of spatial persistence served to objectively identify and track peak velocity regions that can be used to more rigorously assess recent hypotheses for riffle-pool maintenance. The flow convergence routing mechanism described by MacWilliams et al. (2006) involves a

source of flow acceleration, such as a point bar at the head of a pool, that forms a jet and routes sediment around the deepest part of the pool. It was noted that the flow convergence appeared to be less confined to one side of the pool at the highest modeled flow, but no specific criterion was given to formally identify the location of the jet across discharges. The methods employed for the present study build upon the work of Caamaño et al. (2012) by not only defining the locations of peak velocity patches but also quantifying the changes to the spatial extents as discharge increased. This is important for objectively documenting reversals in peak velocity that occur locally in space such that only weak reversals in cross section averaged velocity occur (Jackson et al., 2015). Milan et al. (2013) proposed a hypothesis for riffle-pool maintenance that involves a zone of high sediment transport along the edge of a point bar adjacent to a pool at discharges just below bankfull which then shifts onto the point bar itself beyond bankfull discharge. Bend one in DPDR shows a Hi-5 that began to spill over the downstream point bar at high discharges and resembled this pattern (Figure 4), but future work could focus on hydraulic parameters that are more closely linked to sediment transport, such as Shields stress, to better evaluate this nonuniform flow mechanism.

Carley et al. (2012) reported that pools in TBR did scour between 1999 and 2006. If the scour was caused by sustained high mean sediment transport capacity through pools per the mechanism of flow convergence routing, then the depth-averaged peak hydraulic behaviors revealed in this study demonstrate that pool scour was limited to the highest observed flows during that seven year period, which included a peak of 22 times bankfull discharge. However, there is also the possibility that pool scour was driven by turbulent intensity fluctuations associated with a dissipative jet through a uniformly large pool over a much lower range of flows

(Thompson, 2006; MacVicar and Roy, 2007). This study cannot confirm one mechanism or the other in a pool as the 2D model lacks the fluid mechanics of turbulent fluctuations and Carley et al. (2012) only reported the net change in seven years. However, Sawyer et al. (2010) presented the year-over-year DEM difference in one pool-riffle-run sequence in TBR for a flood of 7.63 times bankfull discharge, in which the highest velocity during the flood peak was over the mainstem pool but was not over a deep forced pool against a large bedrock protrusion on river right. The mainstem pool with the highest mean velocity exhibited widespread scour, but scour depth was limited to ~0-1.2 m. In contrast, forced pool scour with lower mean velocity was 0-2.6 m. Therefore, there is strong evidence from TBR that both mean hydraulics and turbulent fluctuations in hydraulics contribute to channel change as independent mechanisms with different intensities and areas as a function of topographic heterogeneity and discharge. Conceptually, the scour of new primary and secondary channels by the process of avulsion, as evidenced in TBR, is also clearly driven by the mean velocity of a burst of water across the floodplain as it makes a new path and not by turbulent fluctuations, so it is unlikely that all scour processes can be explained by turbulence processes alone. There is a place for both, and peak velocity patch analysis can help evaluate the causes of channel change.

3 *How peak velocity patches change location*

As envisioned in Figure 3(b) to (d), several general behaviors were observed for the changing spatial extent of peak velocity regions including shifting, expansion, contraction, emergence and disappearance (not shown) that occurred at different rates in the longitudinal and lateral directions. The velocity changes within Hi-5 zone three (Figure 7(c) and (f)) indicate that the emergence or expansion of Hi-5 area as

discharge rose was not merely a result of increasing wetted area, but a more rapid velocity increase here relative to zone one where Hi-5 contraction or disappearance occurred. The extent to which velocities changed within the Hi-5 zones between two discharges was reasoned to be in part a function of the discharge step, so the normalized change in velocity was calculated in an attempt to account for this and meaningfully compare the velocity changes for all discharge pairs across the three zones. However, different degrees of velocity change were not determined exclusively by the discharge step as the role of stage-dependent topographic features was also apparent. For example, the low relief of the banks along meander inflections in DPDR allowed rapid expansions in effective cross sectional area here with only a slight increase in discharge above the low flow such that the Hi-5s shifted significantly away from these regions of velocity decline or slow increase (Figure 4). In contrast, the higher relief of the medial bars in TBR preserved flow convergence in the adjacent channel threads through higher discharges such that velocity increased sufficiently here to prevent rapid Hi-5 shifting (Figure 6).

Overall, peak velocity patches moved across landforms at a greater rate in DPDR than in TBR as indicated by the discharges at which reversals in Hi-5 occupation of MUs and peak MU velocity occurred (Figures 10, 12). The more entrenched TBR required a larger increase in discharge for effective cross sectional areas and peak velocities to reverse between riffle and other landforms. The eventual stabilization of Hi-5 spatial persistence at the highest discharges in both reaches indicates that regions of flow acceleration were relatively static through the reaches once flows expanded laterally beyond the floodplain and were constrained by the valley walls. A historical photographic analysis of riffle persistence such as that conducted by White et al. (2010) for TBR has not been done for DPDR, but it

would help clarify whether the extent of peak velocity movement across discharges has consequences for the number of persistent and transitory riffles present in each reach. Reach-scale analysis of nonuniform hydraulics across riffles can also be used to evaluate the reverse domino mechanism described by Pasternack et al. (2008), in which the scouring of a riffle crest reduces the backwater conditions subjected to the next upstream riffle, thereby enabling scour of its crest during high flows and sequentially propagating the scour to additional upstream riffles in a reach. Spatially persistent regions of peak velocity or another hydraulic parameter over riffles could indicate the susceptibility of the riffle network to failure.

4 Scaling up from sites to reaches

Whereas many past studies only evaluated riffle and pool landforms for a single pairing, this study made use of a segment-scale classification of MUs, which recognized that shallow, wide troughs (herein “fast glides”), deep troughs (“pools”), and narrow troughs (“chutes”) are not the same landform and might be influenced by different processes. The greater pool area in TBR reflects the presence of more pronounced bed undulations forced by bedrock and boulder valley constrictions in this reach. DPDR is not confined by valley walls and has little bedrock exposure, so there are few abrupt channel obstructions and constrictions. At low discharge in TBR, this created a strong depth contrast between shallow riffles and extensive deep pools. Conversely, a weaker depth contrast was present at low flow in DPDR between shallow riffles and extensive but only moderately deep fast glides. Considering the flow convergence routing mechanism as well as the Caamaño criterion for velocity reversal, it is possible to interpret that reversals in Hi-5 occupation and peak velocity within TBR overall required a larger increase in

discharge before the effective cross sectional area at riffles expanded sufficiently over the adjacent floodplain to surpass that of the deep pools.

At the riffle-pool couplet scale, the peak velocity patterns within TBR are consistent with the reach-scale results. Four of the couplets showed reversals just above bankfull discharge, and two only showed a convergence by the higher flows, yielding an ensemble reversal between riffles and pools in TBR at an intermediate discharge. The riffles in Figure 9(d), (e) and (f) experienced large width expansions as flow moved out of the bankfull channel that resulted in not only a reversal with the corresponding pools but also a decline in the peak riffle velocities. The double reversal that occurred for the couplet in Figure 9(b) is indicative of the multiple scales of landform nonuniformity that characterize TBR (White et al., 2010), in which strong variations in flow width at different stages within the valley corridor produce dynamic peak velocity patterns across discharges. Given the comparison of the couplet peak velocity patterns with the ensemble behaviors of the peak velocities, the processes previously conceived of as occurring at individual MUs can be scaled up to an entire reach and can yield interpretable results consistent with the flow convergence routing mechanism and the dominance of topographic steering on landform persistence and change.

VI Conclusion

Advances in topographic mapping and hydrodynamic modeling must be matched by advances in analyses of results. This study employed a more spatially representative approach to identify peak velocity regions and document how these move across discharges in a large gravel-bed river. While the use of depth-averaged velocity neglected the 3D aspect to the occurrence of peak velocities, two-

dimensional modeling was considered to be an appropriate compromise for analyzing hydraulics at the one-meter scale across tens of river kilometers (i.e., millions of computational elements already without multiple vertical layers). By simulating discharges spanning near baseflow to large flood flows, diverse hydraulic behaviors such as peak velocity patch shifting, expansion, contraction, emergence and disappearance were found to result from different topographic features activated by different flows. Transparently defined thresholds for peak velocity mapping allowed for more objective observations of the changing spatial extents of these regions. Peak velocity patches shifted to areas where entirely positive changes in velocity occurred between discharges, while the patches disappeared from areas that exhibited small velocity increases or declines. Two reaches within the lower Yuba River both displayed multiple peak velocity reversals among morphological units at discharges above bankfull due to significant spatial differentiation of the peak velocity patches. The lower discharges for which peak velocity reversals occurred within the Daguerre Point Dam Reach were attributed to lower entrenchment and less pronounced bed undulations in this reach relative to the Timbuctoo Bend Reach that permitted more rapid reversals in effective cross sectional area. The diverse, discharge-dependent peak velocity patch behaviors suggest that a fair evaluation of the occurrence of velocity reversals in complex fluvial settings like the lower Yuba River necessitates new techniques for analyzing and interpreting multi-dimensional model results. Moreover, assessing the presence or absence of hydraulic mechanisms associated with the changes to the locations of peak hydraulic parameters should involve a more multi-dimensional strategy such as that presented in this study to more robustly discern the implications for geomorphic change.

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Table 1. Velocity thresholds for Hi-5 delineation in DPDR and TBR across the seven discharges investigated.

	Threshold velocity (m/s) for discharge (m ³ /s)						
Reach	8.32	41.6	83.2	97.5	1195	2390	3126
DPDR	.2	.7	.1	.3	2.6	2.9	3.1
TBR	.6	.6	.1	.6	3.9	4.5	4.8

Table 2. Average change in velocity in the three Hi-5 zones between adjacent discharges in DPDR and TBR.

		Average velocity change (m/s) for discharge pair (m ³ /s)					
Reach	Zone	28.32/141.6	141.6/283.2	283.2/597.5	597.5/1195	1195/2390	2390/3126
DPDR	1	0.099	0.108	0.014	0.079	0.115	0.018
TBR		0.359	-0.267	-0.146	-0.386	0.076	0.096
DPDR	2	0.499	0.310	0.343	0.328	0.398	0.271
TBR		1.081	0.532	0.489	0.366	0.704	0.266
DPDR	3	0.939	0.566	0.521	0.473	0.786	0.369
TBR		1.696	1.072	1.168	0.950	1.344	0.588

Figure 1. Map of the lower Yuba River in its local and regional contexts.

Figure 2. Maps of the two study reaches, Daguerre Point Dam Reach (DPDR) on top and Timbuctoo Bend Reach (TBR) on bottom, and their location along the lower Yuba River in the inset map.

Figure 3. Hi-5 patch at a lower discharge (dark gray circle) and higher discharge (light gray circle) with zones one (lower discharge peak velocities only), two (overlap between peak velocities at the two discharges) and three (higher discharge peak velocities only) (a), Hi-5 shift (b), Hi-5 expansion (c) and Hi-5 contraction (d).

Figure 4. Maps of the Hi-5 delineation in DPDR for which the velocity color ramp was scaled to each of the seven discharges investigated with bankfull discharge at 141.6 m³/s. Numbers 1-5 in the bottom panel denote the meander bend locations.

Figure 5. Maps of the Hi-5 delineation in sites one and two in TBR for which the velocity color ramp was scaled to each of the seven discharges investigated.

Figure 6. Maps of the Hi-5 delineation in sites three and four in TBR for which the velocity color ramp was scaled to each of the seven discharges investigated.

Figure 7. Histograms for the normalized changes in velocity for the three Hi-5s zones aggregated across all discharge pairs within DPDR in (a) to (c) and TBR in (d) to (f).

Figure 8. Plot of the spatial persistence of the 28.32 m³/s Hi-5s across the seven discharges investigated.

Figure 9. Plots of the 95th percentile peak velocity for the riffle and pool within each of the six couplets across the seven discharges investigated.

Figure 10. Plots of Hi-5 occupation of the MUs in DPDR (a) and TBR (b) across the seven discharges investigated.

Figure 11. Maps of the MUUs for sites in DPDR (a) and TBR (b) with Hi-5 extents across selected discharges and inset maps showing the site locations within the reaches.

Figure 12. Plots of the 95th percentile peak velocity for each of the eight MUs in DPDR (a) and TBR (b) across the seven discharges investigated.

Supplemental materials

1 Introduction Supplements

None.

2 Study Site Supplements

None.

3 Methods Supplements

3.1 *Physical data information*

Field data collection efforts were explicitly intended to characterize geomorphic, hydrologic and hydraulic attributes of the LYR at roughly meter-scale resolution in support of a near-census approach to river assessment, including 2D hydrodynamic modeling. The types of data collected included topography and bathymetry (Pasternack, 2009; White et al., 2010; Carley et al., 2012) as well as hydraulic data: water surface elevation, depth, velocity magnitude and velocity direction (Barker, 2011; Pasternack et al., 2014). Details about spatial coverage, resolution and accuracy for the digital elevation model (DEM) used in this study are provided below.

Topographic data came from airborne LiDAR scanning (excluding Timbuctoo Bend) at flows ~ 10–16% of bankfull discharge plus thorough in-water mapping using total stations and RTK GPSs as well as boat-based bathymetry mapping with a single-beam echosounder coupled to an RTK GPS and professional hydrographic software. Basic information describing topographic and bathymetric field data in the Yuba River downstream of Englebright Dam are reported in the box below. A supplemental site

23 map figure has been provided to indicate the location of the other reaches in the Yuba
 24 River.

25

Attribute	Description
Aerial extent	Entire river, except the Narrows Reach
Years of data collection	Englebright Dam Reach (EDR) was mapped in 2005 and 2007 and Timbuctoo Bend Reach (TBR) was mapped in June–December 2006. From highway 20 down, most bathymetry was mapped in late August to early September 2008, with some high-flow data collection in March and May 2009 as well as small additional near-bank and near-DPD gaps mapped in November 2009. Ground-based topographic surveys were done in November 2008 and November 2009. Lidar of the terrestrial river corridor was flown on September 21, 2008.
Bathymetric Resolution	<p>EDR: Within the 24.92 m³/s inundation area, points were collected along longitudinal lines, cross-sections and on ~1.5x1.5 m grids, yielding an average grid point spacing of one point every 1.4 m. (54.3 pts/100 m²).</p> <p>TBR: Within the 24.92 m³/s inundation area, points were collected along longitudinal lines, cross-sections and on ~3x3 m grids, yielding an average grid point spacing of one point every 1.9 m. (28 pts/100 m²).</p> <p>All else: Within the 24.92 m³/s inundation area, points were collected along longitudinal lines, some cross-sections and some localized grids. The average grid point spacing is one point every 1.3 m. (59.8 pts/100 m²).</p>
Topographic Resolution	<p>EDR: Outside the 24.92 m³/s inundation area, points were collected with a combination of grid-based ground-based reflectorless laser scanning of canyon walls and total station surveys of accessible ground, yielding an average grid point spacing of one point every 1.8 m. (31.3 pts/100 m²).</p> <p>TBR: Outside the 24.92 m³/s inundation area, points were collected on a grid, yielding an average grid point spacing of one point every 3 m. (11.4 pts/100 m²).</p> <p>All else: Outside the 24.92 m³/s inundation area, points were mostly collected with lidar, yielding an average grid point spacing of one point every 0.43 m. (554 pts/100 m²).</p>
Bathymetric Accuracy	<p>EDR: comparison of overlapping echosounder and total station survey points yielded observed differences of 0.061-0.091 m.</p> <p>TBR: comparison of overlapping echosounder and total station survey</p>

	<p>points yielded observed differences of 0.061-0.091 m.</p> <p>All else: comparison of overlapping echosounder and total station survey points at one site yielded observed differences of 50% within 0.15 m, 75% within 0.18 m and 94% within 0.3 m. Comparison of boat-based water edge shots versus RTK GPS surveyed water's edge shots yielded observed differences of 75% within 0.03 m, 91% within 0.061 m and 99% within 0.15 m.</p>
Topographic Accuracy	<p>EDR: regular total station control point checks yielded accuracies of 0.0091-0.018 m.</p> <p>TBR: regular total station control point checks yielded accuracies of 0.0091-0.018 m.</p> <p>All else: compared against 8,769 ground-based RTK GPS observations of elevation along flat surfaces, 54% of LIDAR points were within 0.03 m, 86% were within 0.061 m and virtually all of the data were within 0.15 m. Regular total station control point checks yielded accuracies of 0.0091-0.018 m. RTK GPS observations had vertical precisions of 0.018 m. Comparison of lidar water edge points versus the same for RTK GPS yielded observed differences of 30% within 0.03 m, 57% within 0.061 m and 92% within 0.15 m.</p>

26

27 3.2 2D hydrodynamic modeling details

28 The surface-water modeling system (SMS; Aquaveo, LLC, Provo, UT) user
29 interface and sedimentation and river hydraulics—two-dimensional algorithm (Lai,
30 2008) were used to produce these 2D hydrodynamic models of the LYR with
31 internodal mesh spacing of 0.91–1.5 m according to the procedures of Pasternack
32 (2011). SRH-2D is a 2D finite-volume model that solves the Saint Venant equations
33 for depth and velocity at each computational node and supports a hybrid structured-
34 unstructured mesh that can use quadrilateral and triangular elements of any size, thus
35 allowing for mesh detail comparable to finite-element models. A notable aspect of the
36 modeling was the use of spatially distributed and stage-dependent vegetated
37 boundary roughness (Katul et al., 2002; Casas et al., 2010). Model simulations were
38 comprehensively validated for flows ranging over an order of magnitude of discharge

39 (0.1 to 1.0 times bankfull) using three approaches: (i) traditional cross-sectional
 40 validation methods, (ii) comparison of LiDAR-derived water surface returns against
 41 modeled water surface elevations and (iii) Lagrangian particle tracking with RTK GPS
 42 to assess the velocity vectors. Model set-up and performance details are reported in
 43 the box below:

44

Attribute	Description
Model domains	For the whole river, there were 5 modeling reaches to make the computational process more efficient. They are given the abbreviations, EDR, TBR, HR, DGR and FR below. For maps and details about them, see (Pasternack et al., 2014)
Computational Mesh Resolution	<p>EDR: 0.91 m internodal spacing for all Q</p> <p>TBR: For $Q < 141.6 \text{ m}^3/\text{s}$, 0.91 internodal spacing. As flow goes overbank, cell size increases to 1.8 m. For flows $> 597.5 \text{ m}^3/\text{s}$, different mesh has 3 m internodal spacing.</p> <p>HR: For flows $0-36.81 \text{ m}^3/\text{s}$, 0.91 m internodal spacing. For flows $36.81-212.4 \text{ m}^3/\text{s}$, 1.5 m internodal spacing. For flows $> 283.2 \text{ m}^3/\text{s}$, 3 m internodal spacing.</p> <p>DGR: For flows $0-36.81 \text{ m}^3/\text{s}$, 1.5 m internodal spacing. For flows $36.81-212.4 \text{ m}^3/\text{s}$, 1.5 m internodal spacing. For flows $> 283.2 \text{ m}^3/\text{s}$, 3 m internodal spacing.</p> <p>FR: For flows $0-36.81 \text{ m}^3/\text{s}$, 1.5 m internodal spacing. For flows $36.81-212.4 \text{ m}^3/\text{s}$, 1.5 m internodal spacing. For flows $> 283.2 \text{ m}^3/\text{s}$, 3 m internodal spacing.</p>
Discharge Range of Model	EDR was 19.82 to $3126 \text{ m}^3/\text{s}$; all else was 8.495 to $3126 \text{ m}^3/\text{s}$.
Downstream WSE data/model source	<p>EDR: Some WSE observations combined with slope-based translation of the Smartville gage WSE data to the end of the reach.</p> <p>TBR: Direct observation of WSE at a limited number of flows $< \sim 339.8 \text{ m}^3/\text{s}$. For higher flows the</p>

	<p>downstream WSE was taken as the upstream WSE from the HR model at that flow.</p> <p>HR: Continuous direct observation of WSE at flows $< \sim 623.0 \text{ m}^3/\text{s}$. For higher flows the downstream WSE was taken as the upstream WSE from the HR model at that flow.</p> <p>DGR: Reach ends exactly at Marysville gaging station, so the WSE data is of the highest quality and abundance. Continuous WSE data for all flows $\sim 14.16 - 3126 \text{ m}^3/\text{s}$.</p> <p>FR: Continuous direct observation of WSE at flows $< \sim 623.0 \text{ m}^3/\text{s}$. For higher flows the downstream WSE was set to yield an upstream WSE equal to that at the Marysville gage.</p>
River roughness specification	<p>Because the scientific literature reports no consistent variation of Manning's n as a function of stage-dependent relative roughness or the whole wetted area of a river (i.e., roughness/depth), a constant value was used for all unvegetated sediment as follows: 0.032 for EDR (a deeper bedrock canyon), 0.03 for TBR (based on preliminary testing in 2008-2009) and 0.04 for the rest of the LYR (based on validation testing of 0.03, 0.035, 0.04, 0.045 and 0.05 as possible options). For vegetated terrain, the Casas et al. (2010) algorithm was used to obtain a spatially distributed, flow-dependent surface roughness for each model cell on the basis of the ratio of local canopy height to flow depth.</p>
Eddy viscosity specification	<p>Parabolic turbulence closure with an eddy velocity that scales with depth, shear velocity and a coefficient (e_0) that can be selected between ~ 0.05 to 0.8 based on expert knowledge and local data indicators.</p> <p>$Q < 283.2 \text{ m}^3/\text{s}$: $e_0 = 0.6$</p> <p>$Q \geq 283.2 \text{ m}^3/\text{s}$: $e_0 = 0.1$</p>
Hydraulic Validation Range	<p>Point observations of WSE were primarily collected at $24.92 \text{ m}^3/\text{s}$, with some observations during higher flows, but not systematically analyzed. Velocity observations were collected for flows ranging from $15.01 - 141.9 \text{ m}^3/\text{s}$. Cross-sectional validation data collected at $22.65 \text{ m}^3/\text{s}$ above DPD and $15.29 \text{ m}^3/\text{s}$ below DPD.</p>
Model mass conservation (Calculated vs Given Q)	<p>0.001 to 1.98 %</p>
WSE prediction accuracy	<p>At $24.92 \text{ m}^3/\text{s}$ there are 197 observations. Mean raw deviation is -0.0018 m. 27% of deviations within 0.03 m,</p>

	49% of deviations within 0.076 m, 70% within 1.5 m, 94% within 0.3 m. These results are better than the inherent uncertainty in LiDAR obtained topographic and water surface elevations.
Depth prediction accuracy	From cross-sectional surveys, predicted vs observed depths yielded a correlation (r) of 0.81.
Velocity magnitude prediction accuracy	5780 observations yielding a scatter plot correlation (r) of 0.887. Median error of 16%. Percent error metrics include all velocities (including $V < 0.3$ m/s, which tends to have high error percentages) yielding a rigorous standard of reporting.
Velocity direction prediction accuracy	5780 observations yielding a scatter plot correlation (r) of 0.892. Median error of 4%. Mean error of 6%. 61% of deviations within 5 degrees and 86% of deviations within 10 degrees.

45

46 Using the workflow of Pasternack (2011), SRH-2D model outputs were
47 processed to produce rasters of depth and velocity within the wetted area for each
48 discharge. The first task involved creating the wetted area polygon for each discharge.
49 To do this, point files of depth results were first converted to triangular irregular
50 networks (TIN) and then to a series of 0.9144-m hydraulic raster files. Depth cells
51 greater than zero were used to create a wetted area boundary applied to all
52 subsequent hydraulic rasters. Next, the SRH-2D hydraulic outputs for depth and
53 depth-averaged velocity were converted from point to TIN to raster files within ArcGIS
54 10.1 staying within the wetted area for each discharge. The complete dataset was a
55 series of 0.9144-m resolution hydraulics rasters derived from SRH-2D hydrodynamic
56 flow simulations at the following discharges: 8.5, 9.9, 11.3, 12.7, 15.0, 17.0, 17.6,
57 19.8, 22.7, 24.9, 26.3, 28.3, 36.8, 42.5, 48.1, 56.6, 70.8, 85.0, 113.3, 141.6, 212.4,
58 283.2, 424.8, 597.5, 849.5, 1195.0, 2389.9 and 3126.2 m³/s.

Despite best efforts with modern technology and scientific methods, the 2D models used in this study have uncertainties and errors. Previously it has been reported that 2D models tend to underrepresent the range of hydraulic heterogeneity that likely exists due to insufficient topographic detail and overly efficient lateral transfer of momentum (Pasternack et al., 2004; MacWilliams et al., 2006). For this study those deficiencies result in a conservative outcome, such that there could be more fine details to the sizes and shapes of peak velocity patches than what is revealed herein. Overall, this study involves model-based scientific exploration with every effort made to match reality at near-census resolution over tens of kilometers of river length using current technology, but recognizing that current models do have uncertainties.

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