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Riffle-pool maintenance and flow convergence routing observed on a large gravel-bed river

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ABSTRACT

Geomorphologists have studied and debated over the processes responsible for natural riffle-pool maintenance for decades. Most studies have focused on small wadable rivers, but they lack much description of overbank flood conditions or a spatially explicit characterization of morphodynamics. In this study, 1-m horizontal resolution digital elevation models were collected from a riffle-pool-run sequence before and after an overbank flood with a 7.7-year recurrence interval on the relatively large gravel-bed lower Yuba River, California. Digital elevation model differencing was used to quantify the magnitude and pattern of flood-induced morphodynamic change. Cross section based analysis and two-dimensional hydrodynamic modeling of flows ranging from 0.147 to 7.63 times bankful discharge were completed to evaluate the hydraulic mechanisms responsible for the observed topographic changes. One key finding was that riffle-pool relief increased by 0.42 m, confirming the occurrence of natural hydrogeomorphic maintenance. Spatially complex patterns of scour and deposition exceeding 0.15 m at the scale of subwidth morphological units were reasonably predicted by the two-dimensional mechanistic model that accounts for convective acceleration. The one-dimensional cross section based method underperformed the two-dimensional model significantly. Consequently, multiple scales of channel non-uniformity and a dynamic flow regime caused the observed maintenance of the pool-riffle morphology through the mechanism of "flow convergence routing" proposed by MacWilliams et al. [MacWilliams, M.L., Wheaton, J.M., Pasternack, G.B., Kitanidis, P.K., Street, R.L., 2006. The flow convergence-routing hypothesis for riffle-pool maintenance in alluvial rivers. Water Resources Research 42, W10427, doi:10.1029/2005WR004391].

1. Introduction

Riffle-pool sequences are important morphological characteristics of low to moderate gradient gravel-bed streams. Local flow convergence and divergence in either freely formed (i.e., cross channel flow or sediment transport) or forced (i.e., channel bends, obstructions) channel patterns form such sequences (Lisle, 1986; Montgomery and Buffington, 1997). Pools are topographic depressions covered with finer sediment, while riffles are topographic highs covered with coarser bed material; these two features are defined relative to each other (O'Neill and Abrahams, 1984; Montgomery and Buffington, 1997). Under low-flow conditions, vertical variations in topography along the length of a river control hydraulics and sediment transport; pools having slow, divergent flow, low water-surface slope, and low transport competence; and riffles having faster, convergent flow, steep water-surface slope, and moderate transport competence (Clifford and Richards, 1992). Riffle-pool morphology creates physical heterogeneity, promoting habitat diversity for instream species (Gorman and Karr, 1978; Brown and Brown, 1984; Palmer et al., 1997; Giller and Malmqvist, 1998; Woodsmith and Hassan, 2005).

Explanations for riffle-pool sequence maintenance have been debated for decades. Geomorphologists historically observed a reversal in mean flow parameters (e.g., mean velocity, near-bed velocity, and bed shear stress) as a possible explanation for riffle-pool maintenance in gravel-bed rivers. The velocity reversal hypothesis states that "at low flow the bottom velocity is less in the pool than in the adjacent riffles" and that "with increasing discharge the bottom velocity in pools increases faster than in riffles" (Keller, 1971, p. 754). Gilbert (1914) first described a reversal in bottom velocity but was unable to quantify this observation. Lane and Borland (1954) later speculated that channel hydraulic conditions in riffle-pool sequences and channel geometry both affect scour and deposition patterns during high flow events. Actual velocity measurements were not taken to support these observations until Keller's (1969, 1971) studies on Dry Creek near Winters, California. Keller measured near-bed velocities at pool and riffle cross sections during several safely wadable discharges. He showed that velocities became similar as flow increased, but not that the near-bed velocity in the pool actually became higher than in the riffle. Thus, he coined the

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"hypothesis of velocity reversal" (Clifford and Richards, 1992; MacWilliams et al., 2006).

The velocity reversal hypothesis has been highly contentious in the scientific community. Uncertainty mainly arises from differing approaches to describing this phenomenon (Woodsmith and Hassan, 2005). Early studies, such as Teleki (1971) and Whittaker and Jaeggi (1982), refuted Keller's velocity reversal hypothesis because of inconsistency with hydraulic principles and insufficient description of water–sediment interface conditions. Other studies aimed to describe the velocity reversal hypothesis using alternative parameters, such as mean boundary shear stress (Lisle, 1979), section-averaged velocity (Clifford and Richards, 1992; Keller and Florsheim, 1993) and section-averaged shear velocity (Carling, 1991).

Increasingly, field-validated hydrodynamic models are being used to describe and evaluate hydraulic and geomorphic phenomena (Keller and Florsheim, 1993; MacWilliams et al., 2006; Pasternack et al., 2008). Complete morphodynamic models that simulate mass and momentum conservation of water and sediment in dynamic gravel-bed rivers would be ideal, but they have not been widely used and validated yet. Simplified morphodynamic models that ignore momentum conservation violate observed interdependencies between depth and velocity as a function of stage in rivers and are not accurate enough for the questions under investigation. Conversely, significant limitations have been reported when only semi-analytical equations or one-dimensional (1D) hydraulic models are used to evaluate gravel-bed river dynamics, because these tools do not incorporate necessary hydrodynamic mechanisms (MacWilliams et al., 2006; Brown and Pasternack, 2009). It has been posited that two-dimensional (2D) and three-dimensional (3D) models yield a compromise at this time between the two unsatisfactory endmembers in that they enable spatially detailed characterization of velocity and bed shear stress at high flows under which field measurements are impractical. In one such study, MacWilliams et al. (2006) were able to determine that the velocity reversal hypothesis was not adequate to describe processes responsible for riffle-pool maintenance on Dry Creek in a reexamination of Keller's original study using 2D and 3D models. Instead of rejecting Keller's (1969, 1971) ideas, they proposed the concept of flow convergence routing as a "new working hypothesis" to describe these processes. It states that flow converges in riffles at low flows, causing armoring, gradual incision, and diminishing relief; but that during high magnitude, infrequent floods, flow converges in pools, causing rapid scour that enhances relief. MacWilliams et al. (2006) also reviewed all studies of velocity reversal (incorporating a range of flow parameters) and stated that these should be viewed as a "suite of multiple working hypotheses for explaining riffle-pool morphology" based on different maintenance mechanisms present in varying channel conditions. In this study, the flow convergence-routing hypothesis is further explored in conjunction with the velocity reversal hypothesis to qualify riffle-pool maintenance mechanisms in a large, dynamic gravel-bed river system.

A key gap in the existing knowledge of riffle-pool maintenance is the lack of studies in larger gravel-bed rivers, defined as those with a non-dimensional base-flow width to median bed material size ratio $>10^3$ and a width too large to be spanned by the length of a fallen riparian tree. Most previous studies sought to observe pool and riffle hydraulics over a wide range of flows. This necessitates safe and practical wading conditions or a narrow channel that can be spanned by a simple bridge for measuring hydraulic variables during floods (e.g., Keller, 1969, 1971; Richards, 1976a,b; Clifford and Richards, 1992), and therefore previous efforts have focused on relatively small streams. In small streams, wood, boulders, and bedrock outcrops often create channel constrictions and significantly alter channel hydraulics (Thompson et al., 1998, 1999). In such circumstances, pool geometry is controlled by constrictions where flow and sediment convergence encourages scour and pool maintenance, while exit slopes control deposition at the pool tail (Thompson et al., 1998). However, such localized features impact on large gravel-bed rivers is unknown.

The overall goal of this study was to address this critical research gap by investigating the mechanisms of natural riffle-pool maintenance on a large river meeting the above criteria. Two key elements enabled the characterization of riffle-pool response on a large river to an infrequent flood: (i) a uniquely managed river basin (as described in Section 2) in a Mediterranean climate in a water year with two long periods of low flow punctuated by a single high magnitude, short duration flood that enabled detailed pre- and post-flood channel characterization and (ii) a pairing of field observation and high-resolution 2D hydrodynamic modeling that simulated the effect of vertical and lateral channel non-uniformity on bed scour during the peak of the flood. 2D models have limitations as set forth below, but they can be used to explore hydrodynamic mechanisms beyond what is possible from empirical equations or simpler 1D models.

The specific objectives of this study were to (i) measure channel change at an ecologically important riffle-pool unit on a large dynamic river before and after an overbank flood and determine if relief was maintained; (ii) quantify riffle-pool reversals in point-scale depth-averaged velocity and bed shear stress as well as section-averages of those variables; (iii) compare the abilities of one-dimensional cross section based hydraulic geometry analyses and 2D hydrodynamic modeling to predict channel conditions such as width, depth, velocity, and discharge-slope relations—these are two different analysis tools used by different groups of practitioners, so it was helpful to use both to see what they reveal and then intercompare their findings; (iv) relate the observed pattern of scour and deposition caused by the flood to non-dimensional shear stress predictions provided by a 2D hydrodynamic model and (v) reassess whether the flow convergence-routing hypothesis was suitable to describe processes responsible for riffle-pool morphology maintenance for a large river. By combining observational field data, cross section analyses, and mechanistic modeling, obtaining a new and unique perspective on riffle-pool maintenance for large rivers was possible. Although this study does not end discussion about natural riffle-pool maintenance, it supported evidence of flow convergence routing and geomorphic significance in a large gravel-bed river for the first time.

2. Study area

The Yuba River basin (California) flows SW on the western slope of the Sierra Nevada in northern California and drains a 3490-km^2 watershed in Sierra, Placer, Yuba and Nevada counties (Fig. 1). The North, Middle, and South Forks of the Yuba River converge in a canyon above Englebright Dam; and then Deer Creek, a sizable regulated tributary draining ~220 km^2, joins the Yuba ~1.9 km downstream in the canyon.

During the California Gold Rush (mid to late 1800s) gold-bearing tertiary sediments were hydraulically mined after in-channel deposits were exhausted. As a result of hydraulic mining, mercury-laden hydraulic mine tailings from tributaries substantially increased the sediment supply to the Yuba River. Before hydraulic mining, hillslope erosion naturally dominated sediment production (James, 2005). According to Gilbert (1917), unlicensed hydraulic mining supplied ~522 million m^3 of sediment to the Yuba River until the Sawyer Decision of 1884 ended such large-scale operations (Curtis et al., 2005).

Englebright Dam (storage capacity of 82.6 million m^3) was built in 1941 as a debris barrier on the main stem Lower Yuba River (LYR). In 1971, New Bullards Bar Reservoir (storage capacity of 1.19 billion m^3) was completed at a site ~28 km upstream from Englebright on the North Fork Yuba River. Given that the Middle and South Forks do not have large reservoirs, large winter rainstorms and spring snowmelt commonly produce uncontrolled floods that overtop Englebright. Historically, large natural interannual variations in discharge occurred (Fig. 2), with rapid flow fluctuations in November through March from direct storm runoff, a sustained snowmelt flow from April