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Virtual manipulation of topography to test potential pool–riffle maintenance mechanisms

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ABSTRACT

In this study, numerical experimentation with two-dimensional hydraulic modeling of pool–riffle river topography drawing on the testbed data from the classic Keller (1971) study was used to investigate the effect of synthetically manipulating topography on the occurrence and magnitude of velocity and Shields stress reversals in a pool–riffle sequence. Reversals in velocity and shear stress have been used to explore mechanisms of pool–riffle maintenance, while Shields stress (a combined measure of transport capacity and substrate erodibility) is emerging in importance. The original site topography was modeled alongside six altered ones to evaluate the sensitivity of hydraulic reversals to subtle morphology — five incrementally wider pools and a filled pool. The Caamaño (2009) criterion, a simplified geometric threshold for predicting velocity reversals, was applied to each terrain to evaluate its utility. The original pool–riffle topography was just over the threshold for a velocity reversal and well over the threshold for a strong Shields stress reversal. Overall, pool widening caused a predominantly local response, with change to pool hydraulics and no change in section-averaged velocity in the riffle beyond the initial widening of 10%. Filling in the pool significantly increased the magnitude of reversals, whereas expanding it eliminated the occurrence of a reversal in mean velocity, though the Shields stress reversal persisted because of strong differentiation in bed material texture. Using Shields stress as a reversal parameter enabled the quantification of pool modification effects on pool–riffle resiliency. The Caamaño (2009) criterion accurately predicted reversal occurrence for the altered terrains with exaggerated effects, but failed to predict the weak reversal for the original topography. Two-dimensional modeling coupled with previously accepted hydrologic, geomorphic, and engineering analyses is vital in project design and evaluation prior to construction.

1. Introduction

Characterizing mechanistic linkages between fluvial form and process is the central aim of research in fluvial geomorphology, while sustainably instilling such linkages in engineering designs remains a grand challenge in river rehabilitation. New tools are emerging to address these topics using a near-census approach — comprehensive, spatially explicit observation of the landscape emphasizing the ~1-m scale as the basic building block for characterizing geomorphic processes and ecological functions. For example, 0.01- to 1.0-m resolution remote sensing imagery and topographic mapping data sets (Hilldale and Raff, 2008; Marcus and Fonstad, 2008), spatially explicit topographic change detection (Wheaton, 2008; Milan et al., 2011; Carley et al., 2012), and 1-m resolution two-dimensional (2D) hydrodynamic modeling (Pasternack et al., 2006; Abu-Aly et al., 2013) are driving more detailed and accurate assessments of existing theories as well as the next generation of new ones. In this study numerical experimentation of pool–riffle channel topography from the classic Keller (1971) study on velocity reversal was done using 2D hydrodynamic modeling to investigate the role of subtle landform changes on the occurrence and magnitude of velocity and Shields stress reversals, with implications for understanding process–form linkages and using them in river rehabilitation.

Pool–riffle sequences are fundamental morphological features in moderate-gradient alluvial channels (Richards, 1976). Pools are low points in the bed topography with relatively low water surface slopes and finer bed material. Riffles are high points in the topography with relatively steep water surface slopes and coarser bed material (Clifford and Richards, 1992). The role of pool–riffle relief in dictating the flow field is most significant under low flow conditions and becomes comparatively less pronounced as discharge rises (Cao et al., 2003; Brown and Pasternack, 2008). Meanwhile the understanding of pool–riffle dynamics has shifted over decades from a focus on relief (Keller, 1971) to relative wetted width between riffles and pools (MacWilliams et al., 2006; Sawyer et al., 2010). As an expression of interactive adjustments among hydraulics, bed scour, and sediment transport and deposition, pool–riffle sequences are responsible for generating a wide range of unique hydraulic patches that are critical in sustaining high-quality ecological niches necessary for diverse life history strategies by aquatic

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and riparian species (Woodsmith and Hassan, 2005; Moir and Pasternack, 2008; Pasternack and Senter, 2011). Enriching the understanding of pool–riffle hydrogeomorphic processes is therefore crucial to the advancement of river science as well as rehabilitation and management of alluvial rivers.

1.1. Velocity reversal concept

Explanations for the maintenance of pool–riffle sequences have been debated for decades. Many studies rely on the velocity reversal hypothesis by Keller (1971) that sought to explain the areal sorting of bed material. Based on observations from one small creek in the Central Valley of California, the hypothesis states that 'at low flow the bottom velocity is less in the pool than adjacent riffles' and that 'with increasing discharge the bottom velocity in pools increases faster than in riffles' (Keller, 1971). At low flows, fine sediment is winnowed from riffles and deposited in downstream pools. At or near bankfull stages, flow velocity in pools is said to exceed the velocity over riffles. The shift in location of peak velocity maintains topographic relief of pool–riffle couplets; high flows scour sediment previously deposited in the pool, flow diverges out of the pool leading to deposition of larger sediment at the downstream riffle. While Keller's data showed that pool velocity increased faster than riffle velocity as discharge increased within the channel, it did not actually reveal the existence of a reversal in Dry Creek as no measurements of bankfull and above-bankfull conditions were made.

The velocity reversal hypothesis is controversial among the scientific community. Since its conception, many studies found velocity reversals in other river environments (Lisle, 1979; Jackson and Beschta, 1982), while others did not (Carling, 1991; Clifford and Richards, 1992). Uncertainty stems from the various parameters used to describe this phenomenon (Woodsmith and Hassan, 2005). Keller (1971) recorded near-bed velocities to support his hypothesis. Other field studies examined mean variables such as section-averaged velocity and shear stress (Clifford and Richards, 1992) or water surface gradient (Thompson et al., 1999). MacWilliams et al. (2006) organized past studies into a table and indicated whether they found a reversal or not. While past studies have included shear stress in their analyses, none have examined Shields stress as reversal parameter describing the maintenance of pool–riffle sequences.

Research continues to introduce alternative hypotheses for pool–riffle maintenance and to study more diverse settings. Building on the velocity reversal hypothesis and moving the focus to rivers whose alluvial landforms are highly forced by strong local outcrops, Thompson et al. (1999) proposed a model that incorporates flow-width constriction through a forced pool by recirculating eddies. Further field and laboratory studies examined interactions among discharge metrics, outcrop geometry, pool geometry, local hydraulics, and local morphodynamics in detail (Thompson and Hoffman, 2001; Thompson, 2002, 2006). The data collected by Woodsmith and Hassan (2005) did not indicate a reversal of mean velocity; to explain pool–riffle maintenance, these researchers suggested a conceptual model that combined mean bed shear stress and large-scale turbulent force. Similarly, MacVicar et al. (2010) examined forced pool–riffles and showed a reversal in near-bed velocity in the absence of a cross-sectional average reversal, pointing to localized turbulent forces. Notably, the ability of local turbulence to create near-bed hydraulic reversals in forced systems does not preclude the relevance of bulk hydraulic reversals. In forced settings, the onset of a bulk reversal could be a conservative estimate of when pool–riffle maintenance is beginning, and often river project designers seek high certainty of the presence of a key process.

MacWilliams et al. (2006) revisited Keller's field site, Dry Creek, and employed 2D and 3D numerical models to study the pool–riffle hydraulics. Both models predicted that a subtle velocity reversal took place on the pool–riffle sequence in Dry Creek, with the peak velocity occurring adjacent to the point bar and not over the deepest part of the pool by the outer cutbank. MacWilliams et al. (2006) indicated that the effects of lateral flow convergence resulting from a point-bar constriction and the routing of flow through the system were more significant in influencing pool–riffle morphology than the occurrence of a mean velocity reversal. Compatible ideas about the dominant role of width in pool–riffle maintenance (whether perceived in terms of channel, wetted, or 'effective' width) have grown in recent years (Repetto et al., 2002; Cao et al., 2003; Wu and Yeh, 2005; White et al., 2010).

In order to consolidate the findings of emerging research about the role of channel width on velocity reversals, Caamaño et al. (2009) proposed a highly simplified one-dimensional unifying criterion in which velocity reversal occurrence is a threshold function of the ratio of riffle to pool width, residual pool depth, and the depth of flow over a riffle. While much literature has focused on the existence of a single unifying hypothesis for the explanation of pool–riffle maintenance, the variability in support of these different hypotheses reflects the fact that different mechanisms may be at play in different circumstances, as evident in the citations earlier in this section. Indeed, the diversity in the literature now shows that no one mechanism governs all cases of pool and/or riffle maintenance, so studying each mechanism is important. This study provides new insights regarding hydraulic reversals, which are well established as one such maintenance mechanism and can be used by river practitioners in designing river rehabilitation projects (e.g., Wheaton et al., 2004, 2010; Brown et al., 2014).

1.2. Study objectives

In this study we experimented numerically with pool–riffle channel topography from the classic Keller (1971) study on velocity reversal using 2D hydraulic modeling to investigate the role of differences in width constrictions at the head of a pool on the occurrence and magnitude of velocity and Shields stress reversals, with implications for understanding process–form linkages and using them in river rehabilitation. The overall goal of this study was to refine the understanding of the role of width in pool–riffle maintenance by quantifying the flow-dependent sensitivity of reversals in velocity and Shields stress to systematic variations in wetted width at pools in gravel-bed channels with the aid of 2D hydrodynamic modeling. Considering only within bankfull flows, Cao et al. (2003) performed a numerical experimentation with a 2D hydrodynamic model. They showed that dramatic modifications to channel width could turn a bed shear stress reversal on or off. The question arises as to how sensitive the reversal mechanism is to incremental changes in channel geometry. By including overbank flows herein, a more comprehensive understanding of the system hydraulics was achieved.

We again returned to the pool–riffle couplet in Dry Creek near Winters, California that was mapped and monitored by Keller (1971), revisited by Keller and Florsheim (1993) in a 1D model study, and modeled in higher dimensions by MacWilliams et al. (2006). By using Keller's (1971) original Dry Creek study site as the starting topography for experimentation, it was possible to make new insights about the original hypothesis building on the reanalysis of MacWilliams et al. (2006). The use of Shields stress as a reversal parameter herein helped to describe the transport capacity specific to Dry Creek and yielded new discoveries about the transport regimes present that were previously missed for this case. In other settings, previous studies that included shear stress reversals did not relate the shear stress magnitude to substrate size. Contextualizing shear stress with river sediment size further strengthens the understanding of the process and thus the resiliency of the morphological units. In addition to testing for reversals, the Caamaño criterion was applied to each experimental topography during the analysis of 2D hydraulics to further evaluate the utility of that tool for use in pool–riffle evaluation and design. The results have significant implications for river science and management efforts because digital creation and testing of artificial fluvial terrain prior to