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Formation and maintenance of a forced pool-riffle couplet following loading of large wood

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ABSTRACT

Pool-riffle maintenance has been documented in numerous studies, but it has been almost impossible to characterize detailed natural pool-riffle formation mechanisms because of the lack of baseline data prior to pool establishment. In 2013, a study was conducted on the Blackledge River in Connecticut to document the formation of a new pool-riffle couplet on a section of river that had previously been studied from 1999 to 2001. In 2001, the study reach contained a scour hole with a residual depth of 0.08 ± 0.09 m downstream of a 1930s paired deflector with no identifiable riffle immediately downstream. At this time, a large, severely undercut, hemlock tree was noted along the left bank. Sometime between fall 2001 and 2004, the tree fell perpendicular to flow across the channel and formed a large wood (LW) jam and new pool-riffle couplet several meters downstream of the old scour hole. Pool spacing along the reach decreased from 4.47 bankfull widths (BFW) in 1999 to 3.83 BFW after the new pool-riffle couplet formed. The new pool has a residual depth, the water depth of the streambed depression below the elevation of the immediate downstream hydraulic control, of 1.36 ± 0.075 to 1.59 ± 0.075 m, which resulted from a combination of 1.32 ± 0.09 m or less of incision below the old scour hole (95.6% or less of the depth increase) and up to 0.18 ± 0.09 m of downstream deposition and associated backwater formation (13.2% or less of the depth increase). To assess dynamic stability of the pool-riffle couplet over several flood cycles, surficial fine-sediment and organic material along the reach were quantified. The 23-m-long pool stores 25.7% of the surficial fine grained sediments and 15.4% of organic material along a 214-m-long reach that includes one additional artificially created pool. An adjacent 50-m-long secondary channel impacted by the LW jam stores 65.3% of the surficial fine-grained sediments and 54.8% of organic material along the full reach.

1. Introduction

Pool-riffle couplets are natural bedforms that produce variations in width and depth along channels and are critical for aquatic habitat (Heede and Rinne, 1990). Riffles provide spawning gravels and primary food-production areas for aquatic species, pools offer critical deep water during low-flow summer periods or when winter ice can cover much of the river surface, and together the features encourage hyporheic exchange (Gorman and Karr, 1978; Heede and Rinne, 1990; Ebersole et al., 2003; Hanrahan, 2007; Tonina and Buffington, 2007). Pool-riffle couplets occur in gravel-bedded, moderate-gradient channels, usually <0.02 gradient (Leopold et al., 1964; Montgomery and Buffington, 1997). Although numerous researchers have observed pool-riffle couplet maintenance processes of existing morphologies (Keller, 1971; Lisle, 1986; Clifford, 1993a; Thompson et al., 1999; Wilkinson et al., 2004; MacWilliams et al., 2006; Harrison and Keller, 2007; MacVicar and Roy, 2007a; Sawyer et al., 2010; Caamaño et al., 2010; Hodge et al., 2013; Milan, 2013b; Chapuis et al., 2015; Jackson et al., 2015), quantitative documentation of pool-riffle couplet formation has been an elusive goal. In particular, little data are available on the relative importance of pool scour versus riffle deposition in creating longitudinal undulations in elevation from an initial plane-bed condition. Similarly, it is not clear how pool-riffle couplet formation impacts channel-bed slope and sediment continuity along a reach. Once a pool forms, documenting the maintenance of the morphologic feature is equally important under dynamic sediment-transport conditions that include potential filling of the pool with fine sediments. A study of an LW jam on the Blackledge River in Connecticut provides quantitative data on natural pool-riffle couplet formation and subsequent maintenance of the bedform. We hypothesized that pool-riffle couplet formation is primarily a scour-dominated process that would have minimal impact on reach-length, channel-bed slope, and floodplain-inundation frequency. Field evidence suggests that an LW jam constricted channel flow and created the pool-riffle couplet through a combination of scour and fill. The pool-riffle couplet has maintained a large residual depth for at least 10 years and is a major storage site for organic matter and fine-grained sediments.

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1.1. Pool-riffle couplet delineation, formation, and maintenance

Although pools can be classified using various criteria (Leopold et al., 1964; Yang, 1971; Richards, 1976; O'Neill and Abrahams, 1984; Carling and Orr, 2000), in this study pools are classified as streambed depressions that occupy the main portion of the channel with a nearly horizontal water-surface slope at low flow. Therefore, pools can be objectively identified using the residual-depth criteria or control-point method, which assumes a depth and volume of impounded water by a downstream hydraulic control composed of sediment (Lisle and Hilton, 1992). Pools formed by obstructions to flow are called forced pools, and the remaining pools are termed free-formed pools (Montgomery et al., 1995). Riffles can be identified as areas with shallower depths, steeper water-surface slopes, and faster velocities at low flow. Because riffles can be viewed as the downstream expression of bars initiated by pool scour, researchers propose that pools and riffles should be treated as a single morphologic feature called the pool-riffle couplet or pool-riffle unit (Dietrich et al., 1979; Clifford, 1993b; Gregory et al., 1994; Thompson, 2001; Wilkinson et al., 2004).

Under the dynamic sediment-transport conditions that typify most alluvial channels, pool-riffle couplets must initially form under some flow condition and then be maintained during subsequent flow cycles if they are to persist as important morphologic features. Pioneering research on pools and riffle often attempted to provide reach-length scale explanations for why these features existed in rivers and did not always propose specific hydraulic mechanisms to explain the underlying scour and fill processes inherent in individual pool-riffle formation. For example, researchers have suggested that the somewhat regular spacing of pools and riffles may result from reach-scale, general morphologic tendencies that include development of quasi-equilibrium (Dolling, 1968), minimization of potential energy losses and power expenditures (Yang, 1971; Cherkauer, 1973), or development of oscillating turbulent-flow structures (Yalin, 1971; Richards, 1976). Other researchers suggest pool characteristics respond to flows leading to the minimization of stream power (O'Connor et al., 1986; Wohl et al., 1993; Thompson, 2002a) and pool-riffle bedform formation maximize resistance relative to flow energy (Wohl, 2007; Wohl and Merritt, 2008). Some early work attempted to draw links between meandering and pool-riffle formation (Leopold and Wolman, 1960; Tinkler, 1970; Yang, 1971). However, the processes of meandering, channel curvature, helical-flow development, and pool-riffle scour and fill are so clearly linked that a causal relationship is difficult to determine (Richards, 1976; Thompson, 1986). These various studies provide insight into why pool-riffle morphologies tend to form along alluvial channels, but these hypotheses generally lack mechanisms to explain how and why pool-riffle units form in specific locations.

Langbein and Leopold (1968) provided one of the earliest hydraulic mechanisms to explain pool-riffle formation. They explain the spacing of dunes, bars, and riffles as resulting from pulses of moving particles, called kinematic waves, with spacing governed by a balance of water velocity and wave amplitude effects (Langbein and Leopold, 1968). This hypothesis suggests that pool-riffle morphologies are primarily depositional in nature, without a specific mechanism for pool scour indicated. Yang (1971) suggested that dispersive forces at riffles could depress pools and raise riffles, but the mechanism already presupposes a nonuniform bed condition. For decades, researchers noted a concurrence of vortices and deeply scoured areas and postulated a causal relation between intense turbulence and pool scour (Matthes, 1947; Mlynarczyk and Rotnicki, 1989; Nelson et al., 1993; Roy et al., 1999; Thompson, 2007). Clifford (1993b) expanded on earlier work by Richards (1976) to suggest localized turbulent scour of a pool and downstream deposition of a riffle initiated by roller eddies upstream and downstream from an obstacle in the flow. According to this model, as erosion progresses the original obstacle is removed and the initial flow perturbation generates additional downstream pool-riffle units (Clifford, 1993b). Unfortunately, the study was not able to document the formation of a new pool-riffle unit, and the importance of vortex scour in pool formation has been demonstrated in flume experiments (Thompson, 2006) but not in rivers.

Because pools and riffles can persist for decades, some processes must operate to maintain these bedforms after they are formed. Pools generally scour at high flow, while riffles aggrade (Keller and Melhorn, 1978; Lisle, 1979; O'Connor et al., 1986). At lower flows, sand-sized particles move over a stable gravel-surface at riffles and settle on top of coarser sediments at the base of pools (Jansen and Brierley, 2004). As stage increases, bedload transport in pools exceeds rates in riffles (Jackson and Beschta, 1982), which uncovers coarse lag deposits at the bottom of many pools (Bowman, 1977; Milan et al., 2001). However, Chartrand et al. (2015) observed coupled and decoupled trends in sedimentation between pool-riffle pairs. In numerous settings, pools fill and volume is reduced in response to increased sediment supply and land use changes (Keller, 1978; Lisle, 1982; Lisle and Hilton, 1999; Wohl and Cenderelli, 2000; Goode and Wohl, 2007), which enhances sediment transport through the features (Jackson and Beschta, 1982; Lisle and Hilton, 1992; DeVries et al., 2001). The resulting flux of sediment creates unique pool depth relations for each discharge level (Lisle, 1982; Wilcock et al., 1996). Pool-exit slopes are also important for temporary sediment storage because they scour during peak flows and fill during falling stages (Lisle and Hilton, 1992; DeVries et al., 2001; Milan et al., 2002; Jansen and Brierley, 2004). In meandering systems, local bank erosion can also supply limited amount of sediment to pools (Milan, 2013a). Sedimentation focused in wake zones, and recirculating eddies are other important depositional areas in pools (Schmidt, 1990; Lisle and Hilton, 1992).

Despite general agreement on the timing of pool versus riffle scour and deposition, no single model for pool-riffle couplet maintenance has proven capable of explaining all situations, and different processes likely dominate in different pool-riffle couplets (Thompson, 2013). Local disruptions of sediment continuity produce variations in sediment supply relative to shear stress that create preferential zones of scour and deposition (Buffington et al., 2002; Wilkinson et al., 2004). For example, slower velocities in the backwater zone upstream of obstructions can limit entrainment and sediment supply to pools. Alternatively, sediment routing can occur, especially along meanders, where secondary currents preferentially route sediment over point bars and away from the pool center and exit-slope onto the downstream riffle with a resultant zone of scour in pools (Booker et al., 2001; MacWilliams et al., 2006; Thompson and Wohl, 2009; Milan, 2013a; Chapuis et al., 2015). Differences in surface grain-size distributions (Carling and Wood, 1994; Milan et al., 2001; de Almeida and Rodríguez, 2011; Jackson et al., 2015) and differences in bed sediment structures (including particle size, shape, protrusion, pivoting angle, and packing) lead to variations in entrainment rates in pools versus riffles that could be the primary process that maintain depth variations (Clifford, 1993a; Sear, 1996; Hodge et al., 2013). These processes potentially operate in either free-formed or forced pools. However, each of these processes is at least partially dependent on an existing pool-riffle topography or sorting pattern, and they fail to explain how a pool and riffle could be formed from an initially straight, plane-bed channel with homogeneous sediment characteristics.

According to the velocity-reversal hypothesis, bed velocities are higher over riffles at low flow but increase at a faster rate over pools as stage rises, leading to higher bed velocities and shear stresses in pools at high flow (Gilbert, 1914; Keller, 1971). Convergence of water-surface slopes, velocity, or shear stress have been documented in several studies (Yang, 1971; Robert, 1997; MacVicar and Roy, 2007a; Wohl, 2007; Rodríguez et al., 2013). Data from several field and model studies have demonstrated at least a weak water-surface slope, velocity, or shear-stress reversal between pools and riffles (Andrews, 1979; Lisle, 1979; Emmett et al., 1983; Keller and Florsheim, 1993; Carling and Wood, 1994; Sear, 1996; Thompson et al., 1999; Booker et al., 2001;