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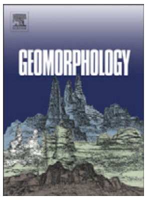

Sediment mobility in a forced riffle-pool

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ABSTRACT

Forced riffle-pools occur in gravel-bed rivers where a large nonalluvial element leads to local scour and deposition. To manage rivers where this type of morphology is found and to specify restoration measures that mimic this process, more field data on sediment mobility in forced riffle-pools is needed. The objectives of this study are to describe the spatial variability of sediment mobility and deposition in a developing forced riffle-pool and to use high-resolution flow velocity measurements to explain the observed dynamics. The field site is a forced riffle-pool in Moras Creek, a 6-m-wide gravel-bed stream with a 1.2% bed slope in Quebec, Canada. Topography and the movement of sediment particles equipped with Passive Integrated Transponder (PIT) tags are surveyed through a series of competent floods. Bed shear stress is estimated from near-bed measurements of time-averaged velocity and turbulent kinetic energy. The sediment transport regime of the creek is characterized by partial mobility, exponential distributions of path lengths, and a negative relation between particle size and path length. Full mobility occurs in the center of the pool and over the exit slope where flow is accelerated from the constriction of flow during two events above the bankfull discharge. Partial mobility occurs during the same events over the entrance slope to the pool. Lateral gradients of deposition and mobility suggest that the majority of sediment in motion is routed over the side bar at the entrance to the pool. High levels of turbulence intensity that occur as a result of flow deceleration may explain the removal of finer sediments from the head of the pool.

1. Introduction

Riffles and pools are commonly observed in gravel-bed rivers. Alluvial or “free” riffle-pool units are the characteristic bedform within gravel-bed rivers that have an overall slope of <1.5% (Grant et al., 1990; Montgomery and Buffington, 1997). The presence of nonalluvial elements such as boulders, bedrock outcrops, and large woody debris can create “forced” riffle-pools from a variety of plunging flow, backwater, and lateral scour effects in rivers that have a slope of up to 3% (Beschta and Platts, 1986; Bisson et al., 1987; Montgomery and Buffington, 1997). Forcing elements are frequently added to gravel-bed streams to encourage the formation of riffle-pools in an effort to capture their benefits for fish and invertebrate populations (Newbury and Gaboury, 1993; Rosgen, 2001). However, the effect of a forced riffle-pool on sediment mobility in a gravel-bed river is not well documented. Existing studies using Helley-Smith sampling (Hassan and Woodsmith, 2004) and painted tracers (Thompson and Wohl, 2009) have found a high degree of spatial variability in mobility and suggested that particles are mobilized more easily in the pool than in other areas of the channel because of local effects of turbulence. More research is needed to describe sediment mobility in a forced riffle-pool and to characterize the spatial distribution of shear stress.

Forced riffle-pools develop in channels transporting poorly sorted gravelly sediment. Early work in free riffle-pools suggested that phases of transport could be defined where fine material is transported over a static morphology in phase I, while bed armour is broken-up for transport in phase II (Jackson and Beschta, 1982), and these phases were used to explain cycles of scour and fill in riffles (Jackson and Beschta, 1982; Sidle, 1988). However, the flume experiments of Wilcock and McArdell (1993, 1997) demonstrated that sediment transport in gravel-bed rivers is more precisely described by partial mobility—i.e., the condition in which some sediment grains on the surface of the bed are transported while others remain immobile. Partial transport has been confirmed in gravel-bed rivers through typical ranges of flows (Ashworth and Ferguson, 1989; Lisle, 1995; Church and Hassan, 2002; Wilcock and DeTemple, 2005) and must be incorporated into a conceptual model of sediment transport and scour/fill in riffle-pools.

The presence of the pool and the forcing element causes hydrodynamic changes that may affect sediment mobility in these systems. In the deep center of a laterally-constricted pool, MacVicar and Roy (2007a,b) demonstrated that velocity and turbulence intensity profiles match what would be expected in flow undergoing convective acceleration (see for e.g., Yang and Chow, 2008). The highest downstream velocities occur near to the channel bed during

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acceleration and are likely to increase sediment mobility above what would be expected in an equivalent uniform flow. This process also occurs over the exit slope (or "tail") of the pool and provides a physical explanation for Keller's (1971) hypothesis of a near-bed velocity reversal to explain scour at high discharges in riffle-pools (MacVicar et al., 2010). In contrast, in the entrance slope (or 'head') of the pool upstream of the lateral constriction, flow deceleration occurs as the depth and cross-sectional area increase. Field results have shown that while mean velocities are relatively low near to the bed in this case, the flow is highly turbulent (MacVicar and Roy, 2007a,b), which again fits with expectations from experiments in nonuniform flows (Yang and Chow, 2008). High levels of turbulence can affect sediment transport from the short-term "impulse" of force transmitted by coherent turbulent events on sediment particles (Nelson et al., 1995; Sumer et al., 2003; Schmeeckle et al., 2007; Diplas et al., 2008). The effect that spatial variations in mean and turbulent flow properties may have on sediment mobility and the maintenance of forced riffle-pools is not well understood.

The current study took place at the same field site used by MacVicar and Roy (2007a,b) to describe the hydraulic variability in a forced riffle-pool. The study began when a large piece of wood debris in a creek was moved during a flood and continued over the subsequent 18 months as a series of flood events created a forced riffle-pool in a new location. Coarse sediments were tagged with Passive Integrated Transponders (PIT tags) (Lamarre et al., 2005), which provided a new level of detail in the description of sediment mobility and deposition in a forced riffle-pool. The objectives of the current study are to describe the spatial and stage-dependant dynamics in sediment mobility and deposition in a forced riffle-pool and use the near-bed hydraulics to explain the observed sedimentary dynamics.

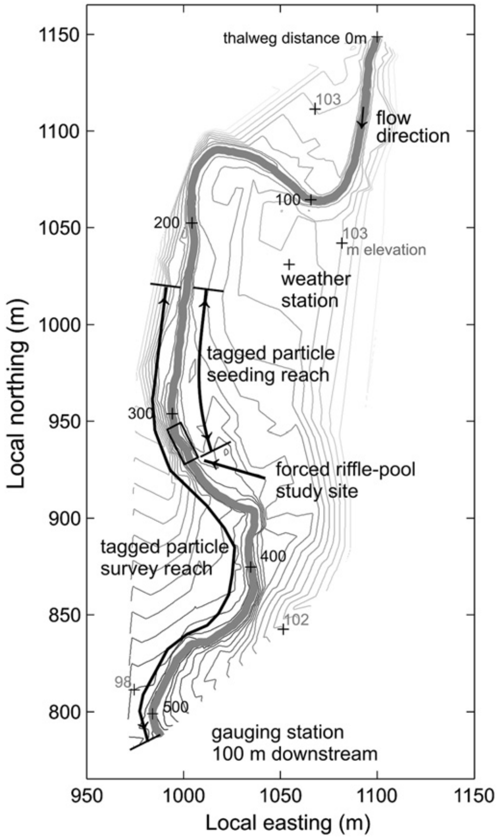

Fig. 1. Site map.

2. Methodology

2.1. Field site and climatic conditions during study period

Moras Creek is a sinuous creek located in eastern Quebec, Canada (Fig. 1). The average bankfull width (B) is 6 m, the bankfull depth in the riffle (Z_B) is 0.7 m, the average bed slope (S) is 1.2%, and the bankfull discharge (Q_B) is 4.9 m^3/s. A survey of the creek over a streamwise distance of 500 m identified seven pools that spanned the width of the channel. Five of those pools, including the four deepest (residual depth >0.5 m), were associated with forcing mechanisms such as boulders, impingement on the valley wall, or wood debris. Representative particle sizes (random walk Wolman pebble count, $n=800$) are $D_{16}=18$ mm, $D_{50}=60$ mm, and $D_{84}=190$ mm. Heterogeneous glacial till contributes a wide range of particle sizes to the stream and the largest measured particle was 900 mm in diameter. The study site is a riffle-pool located at the downstream end of a relatively long straight reach that is characterized by a plane-bed with occasional steps. The riffle-pool is forced by a fallen tree and has a residual depth of 0.8 m (Fig. 2). Sediment is coarser in the riffles and finer in the pools and generally matches the two-dimensional sedimentological model of Sear (1996). Lateral bars were present both upstream and downstream of the tree and were composed of intermediate–sized particles.

The site was monitored from May 2003 until November 2004. A pressure transducer was installed to record the water level at 10-min intervals from early spring to the fall (100 m downstream of monitoring reach Fig. 1). Stream gauge data from the neighbouring Bulstrode River (station number 030106 in the Centre d'expertise hydrique du Québec database) was used to determine flooding dates during the late fall and winter. Because of the large difference in drainage area (Moras Creek, ~14 km^2; Bulstrode River, ~340 km^2), flood event dates and stage were confirmed wherever possible in Moras Creek by measuring the height of high water marks such as floated material and ice formation in branches above the bankfull level. Nine events occurred that were equal to or exceeded the bankfull depth during the study period, with the three largest events on 21 July 2003, 15 April 2004, and 31 July 2004 (Table 1). Precipitation data from a rain gauge at the site were compared with 42 years of records from a meteorological station in Sherbrooke (80 km to the south) to estimate the return period of these events. The rain gauge at the site recorded 11 days with more than 25 mm of rainfall from October 2003 to November 2004, which is approximately double the yearly average at Sherbrooke and confirms that a number of low frequency events occurred within the study period. The largest daily rainfall of 69.6 mm on 31 July 2004 has only been exceeded twice at the Sherbrooke station, which indicates that this event was approximately a 15-year storm.

2.2. Measurement of erosion/deposition and sediment movement

Stream bed topography within the studied riffle-pool was surveyed between floods to estimate local scour and fill. A Trimble 5600 total station with a vertical precision of ±2 mm was used to obtain surveys with spatial densities of 1.7 to 7.9 pts/m^2 (Table 1). While the strategy was to survey after all flood events that were significant for sediment transport, preferably at the same time as the mapping of the locations of tagged particles, this was not always possible because of equipment failures and the high frequency of competent floods. Erosion and deposition were estimated from the difference between successive topographic surveys to quantify changes in bed height.

Passive Integrated Transponder (PIT) tags were used to track sediment movements as described in Lamarre et al. (2005). These tags offer a number of advantages over other tracing techniques, the most important of which are their high recovery rates (>85%) in narrow