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Magnetic tracing of fine-sediment over pool-riffle morphology

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ABSTRACT

Field studies documenting fine-sediment (<2 mm) transport in gravel-bed rivers are rare. For the first time in a fluvial environment, a technique that enhances the magnetic susceptibility of sand is used to trace its longitudinal dispersion and storage. This paper describes the methodology behind the artificial magnetic enhancement of iron-stained sand, and presents the results from sand tracing exercises conducted on two gravel-bed channels with pool-riffle morphology; one unregulated and sinuous in nature (site A), the other regulated and straight (site B), both situated on the River Rede Northumberland, UK. Two tonnes of magnetically enhanced tracer sand was introduced to site A and four tonnes to site B, to provide information on fine-sediment storage dynamics, interaction of fines with the stream bed, and rates of movement, expressed as virtual velocity (V_i). Sand transport pathways appeared to differ between the reaches; for site A, sand storage was found on bars and riffle margins with no storage or signs of transport through pools, and in contrast pool storage of tracer was a key feature shown at site B. Topographic forcing may cause differences in sediment sorting at site A; topographic highs tend to have low sand transport rates with sand grains becoming congested in these areas, whereas topographic lows show higher transport rates resulting in greater dispersion. Supply limitation of sand on the falling limb of the hydrograph may also become an issue in the topographic lows at this site. Hydrograph differences between the regulated and unregulated reaches could also play a role; however this could not be quantified in this study. There was no evidence of sand infiltration into the bed at site A; however marginal evidence for infiltration into the near-surface (0–15 cm) substrate voids was found at site B. The general lack of evidence for significant infiltration may reflect limited availability of void space in substrate framework gravels. Tracer sand was transported over the bed surface, with little vertical interaction with the substrate, despite periods of gravel mobilisation at site A. V_i over the study duration for site A was 2.28 m day^{-1}, and 0.28 m day^{-1} for site B. These values are greater than those calculated using existing predictive equations developed from gravel tracer data, possibly reflecting differences in the mode of transport between bedload and saltation load.

1. Introduction

Information regarding fine bedload (<2 mm) transport in rivers is limited (*e.g.*, Church et al., 1991), despite the significance of this grain-size class to the total sediment load, to instream biota such as salmonids, and macroinvertebrates (Jones et al., 2011; Kondolf et al., 2008; Milan et al., 2000), and its association with toxic heavy minerals in contaminated river systems (Petts et al., 1989). Sand is predominantly transported as the saltation component of the bedload (Garde and Ranga Rangu, 1977), and its transport is complex due to its interaction with bed morphology and the gravel component of the bed substrate.

1.1. Fine-sediments and pool-riffle morphology

In gravel-bed streams displaying pool-riffle morphology, its longitudinal dispersion has been linked with tractive force variability over the flow regime (de Almeida and Rodríguez, 2012; Jackson and Beschta, 1982; Lisle, 1979; MacVicar and Roy, 2011). At low flow, fines may be stored surficially in areas of low tractive force such as pool exit slopes, channel margins, and in the lee of coarse clasts (Carling and Reader, 1982; Lisle and Hilton, 1992, 1999). Fines may also be stored in void spaces between framework clasts in the sub-surface sediments beneath the armour (Carling and Reader, 1982; Milan et al., 2000). On the rising limb of a flood, tractive force increases over both riffles and pools, and may flush surficial deposits stored in pools (Lisle, 1979). At higher discharges approaching bankfull, the armour layer on the riffles is mobilised, releasing the substrate framework gravel and interstitial fines, increasing sediment-transport rates (Reid et al., 1985). The rate of tractive force increase with discharge has been reported as being greater for pools compared with riffles and can equal or exceed adjacent riffles (Keller, 1971; Milan et al., 2001), leading to pool scour and riffle aggradation (de Almeida and Rodríguez, 2012; Vetter, 2011). On the falling limb of a flood, gravels are deposited initially, and then fines may be selectively transported across the bed surface and deposited in areas of low tractive force (*e.g.* pool exit slopes) (Lisle and Hilton, 1992, 1999; Vetter, 2011).

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These sediment-transport processes are thought to be responsible for the observed sediment-sorting differences commonly observed between pools and riffles, with pools most commonly being reported as being finer (Milan, 2013a). de Almeida and Rodríguez (2012) further highlight that the falling limb of the hydrograph is particularly important in re-establishing grain-size differences between pools and riffles that are lost at high flow.

1.2. Gravel-bed structure

Gravel-bed rivers tend to show a vertical variation in sediment structure; often having a fines-free coarse surface layer of grains known as an 'armour', 'pavement', or 'censored layer', and a finer sub-surface mixture of framework gravels, the voids of which are filled to varying degrees by a matrix of fines (<2 mm). The terms 'armour' and 'pavement' have been used interchangeably by different workers, either to describe single-grained surface layers that experience regular disruption during floods, for example those under 'natural' hydrological and sediment supply regimes, or static surface layers found where the flow hydrograph and sediment regime have been altered, such as downstream of dams (Bray and Church, 1980; Parker et al., 1982; Sear, 1995). The terms 'mobile' armour and 'static' armour have also been used to describe these two situations, and are adopted in this paper (Sutherland, 1987; Powell, 1988). Censored layers present a third class of surface layer that are greater than one grain thick, comprise an open-work structure (Carling and Reader, 1982), and can be a feature of regulated gravel-beds below dams (Wyżga, 1993). Although there are some differing explanations for surface coarsening (Richards and Clifford, 1991), it is generally accepted that the bed surface becomes coarser after selective removal of fines, transported downstream across the bed surface into areas of lower tractive force, and infiltration into void spaces in the underlying framework gravels.

1.3. Infiltration mechanisms

Infiltration of fines into available interstitial voids can follow one of two styles; filling from the base upwards (Einstein, 1968), or bridging of near-surface voids between the framework gravels (Beschta and Jackson, 1979). The style of infiltration is dependent upon the size of the incoming fine-sediment and the size and shape of the receiving void spaces (Frostick et al., 1984). Scour and fill of the channel bed also influence the interstitial fine-sediment (matrix) component of the bed, through re-exposing infiltrated material or burying previously infiltrated fines (Lisle, 1989). The majority of studies that have monitored fine-sediment infiltration have been based in the laboratory and have used openwork gravels as the start point (*e.g.*, Beschta and Jackson, 1979; Carling, 1984; Einstein, 1968; Schälchli, 1995). Field studies have usually used traps to capture fines; *e.g.* empty solid walled traps (Church et al., 1991), or porous traps filled with openwork gravel (*e.g.*, Acornley and Sear, 1999; Sear, 1993). Few studies have investigated infiltration of fines into an undisturbed river bed.

1.4. Influence of flow regulation

In regulated rivers the flow hydrograph may be altered in a number of different ways depending upon the operation of the dam (Petts, 1984); however discharge magnitude and frequency are usually reduced (Williams and Wolman, 1984). Gravel supply is completely shut off, yet fine organic-rich sediments may be delivered to the channel downstream (Meade and Parker, 1985; Gilvear, 1988; Sear, 1995; Vericat and Batalla, 2005). Modified flow and sediment supply disrupt quasi-equilibrium within the channel, and the channel responds through altering its form and sedimentology (Brandt, 2000). The exact nature of channel response is dependent upon the nature of flow (*e.g.* hydrograph peak and shape) and sediment supply alteration, and generally decreases in magnitude with distance from the dam (Petts, 1979; Petts and Gurnell, 2005). Typically for the channel immediately downstream of the dam and upstream of the first major non-regulated tributary junction, reduced discharges are generally unable to mobilise the coarser gravels (Sear, 1995; Wyżga, 1993). However flows are usually capable of selective removal of the finer fractions, resulting in bed degradation, and surface coarsening (Fasnnacht et al., 2003; Galay, 1993; Sear, 1995). Occasionally, wash-out of interstitial fines occurs more deeply into the sub-surface resulting in an openwork or censored surface layer (Wyżga, 1993). However, sub-surface gravels have also been reported to experience enhanced siltation in some instances (*e.g.*, Petts, 1988; Sear, 1995). The pool-riffle bedform can also show a response to modified flow and sediment-transport regimes caused by flow regulation. In Sear's (1995) study on the river North Tyne, UK, riffles showed degradation and pools showed aggradation, in response to hydropower releases. de Almeida and Rodríguez (2012) further support Sear (1995), indicating that the reservoirs operating increased duration of low to medium discharges, with a reduction of peak flows, may cause significant degradation of pool-riffle morphology, and reduce sorting contrasts between pools and riffles.

1.5. Step-length data

A knowledge of transport distance (step-length) for different grain-size fractions is required in the calculation of sediment-transport rates, knowing the width and depth of the active layer (*e.g.*, Haschenburger and Church, 1998), and to improve understanding of sediment dispersion dynamics (Ferguson and Wathen, 2008; Haschenburger, 2011; Milan, 2013b). Despite its significant contribution to the total sediment load in gravel-bed rivers; sub-surface sediments in England typically contain between 15 and 48% <2 mm material (Milan et al., 2000), step-length data for the saltation load are not usually accounted for, despite known differences in size-based competence duration.

This paper aims to:

1) Explore spatial patterns of sand sorting over pool-riffle topography;
2) Examine sand infiltration into an undisturbed gravel-bed;
3) Contrast fine-sediment-transport and infiltration processes in an unregulated and a regulated channel; and
4) Provide step-length data for a series of flood events for the sand fraction.

2. Field location

The study focused on two 400 m reaches on the River Rede, Northumberland, UK, an upland gravel-bed stream (Fig. 1). The Rede has a Strahler order of four, and has its source area in the Cheviot Hills at 490 m above Ordnance datum (defined as mean sea level at Newlyn, Cornwall, UK). The study reaches were selected on the basis of one having a near-natural flow regime and a mobile armour (site A), and the other having a regulated-flow regime and static armour (site B). One of the reaches (site A) is sinuous (sinuosity = 1.7), and the other (site B) is straight (sinuosity = 1.1). Both sites had well-defined sequences of pools and riffles and were located 4.5 km and 7.5 km from the source of the river, having catchment areas of 18 km^2 and 41 km^2, respectively (Fig. 1A). Mean annual rainfall is 1026 mm, falling onto a catchment underlain by an impermeable geology of Carboniferous sandstones and shales, overlain by peat and till. Continuous stage was recorded at site A over the study duration, and converted to discharge using a rating relation (Fig. 2). Continuous stage was not available for site B, so discharge peaks for the flood events between survey dates were estimated using the Manning formulae, where hydraulic radius was calculated from trash-line observations surveyed relative to a fixed cross-section at the head of the reach. Site A (55° 19.942′ N, 2° 26.457′ W) is unregulated and experiences a flashy hydrological regime (with a bankfull discharge of 8.5 m^3 s^{-1}), whilst site B (55° 19.308′ N, 2° 23.573′ W) has been regulated since 1905 by the Catcleugh reservoir. Catcleugh