1 Taking the river inside: fundamental advances from laboratory experiments in measuring and
2 understanding bedload transport processes

3 E.M. Yager^{a*}, M. Kenworthy^b, and A. Monsalve^a

4 ^aDepartment of Civil Engineering, Center for Ecohydraulics Research, University of Idaho, 322 E. Front St.
5 Suite 340, Boise, ID, 83702, USA

6 ^bDepartment of Water Resources, Center for Ecohydraulics Research, University of Idaho, 322 E. Front
7 St. Suite 340, Boise, ID, 83702, USA

8 * corresponding author. Telephone: +1-208-364-4935; e-mail: eyager@uidaho.edu.

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Abstract

Bedload transport in gravel-bed rivers impacts channel stability, the lifespan of hydraulic structures, physical components of aquatic habitat, and long-term channel evolution. Field measurements of bedload transport are notoriously difficult, which precludes understanding many of the processes and mechanics associated with grain motion. Such uncertainties are exacerbated when using bedload transport equations, most of which were derived using data from a single river or set of laboratory flume experiments. Recently, laboratory experiments have focused on better quantifying the processes that impact bedload fluxes, which can then be used to improve sediment transport predictions. We highlight recent advances in laboratory instrumentation that can be used in bedload transport studies. In particular, more accurate ways to measure bedload fluxes, near-bed turbulence, bed grain sizes, and topography hold great promise. Laboratory experiments have also fundamentally improved our understanding of the influence of sediment supply and armoring processes on bedload fluxes and channel conditions. The importance of flow hydrographs in controlling total bedload transport rates and bedload hysteresis has also been demonstrated using flume experiments. Finally, many details about the mechanics of grain motion including flow turbulence, bed arrangement, and particle transport statistics are only possible through laboratory investigations, and we feature key knowledge gaps that can be improved with further study.

Keywords: bedload transport; laboratory experiments; armor layers; hydrographs; sediment supply; turbulence

1. Introduction

Laboratory flumes have been used to better understand bedload transport in gravel-bed rivers for about 100 years (Shields , 1936) and have included a range of experiments from reach to grain scales. Such experiments are needed because of the following: (i) field measurements include many spatially and temporally variable parameters that influence bedload transport, whereas flume experiments allow for the isolation of the effects of each parameter; (ii) bedload transport in the field is notoriously difficult to quantify and has large uncertainties; (iii) changes in bed surfaces (e.g., grain sizes, elevation, roughness) during flow events are also difficult or impossible to measure; and (iv) grain scale mechanics of sediment motion and transport are much easier to quantify in a laboratory rather than field setting. Such motivations have spawned a growing percentage of published studies on bedload transport that include laboratory measurements. In addition, the range of investigated bedload processes has increased with better technology for measuring bedload fluxes, bed topography, flow turbulence, bed grain sizes, and the dynamics of individual grains.

Here, we have three primary objectives. First, we highlight recent advances in laboratory instrumentation that have significantly advanced the understanding of bedload transport in gravel-bed rivers. Second, we review how laboratory experiments have specifically highlighted the fundamental mechanics of bedload transport. In particular, we focus on four processes that are difficult to quantify or control for in the field: the importance of sediment supply, armor layer processes, flow hydrograph impacts, and grain scale mechanics. Each of these four topics is also a research area that has grown in recent years because of its importance in understanding and predicting bedload fluxes. Finally, we outline some key areas in which laboratory flume experiments are being focused, or could be focused in the future, to further fundamental research on bedload transport in gravel-bed rivers.

2. Advances in laboratory techniques

2.1. Bedload transport measurements

Measurements of bedload fluxes in laboratory flumes can include reach-averaged to highly local grain scale movements. Reach-averaged estimates are often accomplished through the use of a stationary basket, tipping basket, or bag attached to a load cell, which continuously measures the weight of the trapped sediment (e.g., Venditti et al., 2010a, b). Mini-Helley-Smith samplers or bedload traps (e.g., Nelson et al., 2010) can measure local bedload fluxes within a flume, but potential errors associated with these methods (Bunte et al., 2004) have prompted the use of new technologies. An increasingly popular technique is to record individual grain movements using high-speed (e.g., 250 Hz) high-resolution video cameras (Fig. 1A). Video recording of bedload transport has been employed by numerous studies in the past (Grass, 1970; Fernandez-Luque and Van Beek, 1976; Drake et al., 1988), but the onset of relatively cheap, high-speed, digital cameras have allowed for much more detailed and accurate analyses of bedload transport mechanics (e.g., Nelson et al., 1995; Lajeunesse et al., 2010; Roseberry et al., 2012; Yager and Schmeeckle, 2013).

When recorded from above a flume (planview), cross-correlation analysis of successive video frames (Fig. 1B) can quantify local bedload fluxes and the spatial variability in transport rates. This analysis requires calibration to visual counts of transported sediment in the videos (Yager and Schmeeckle, 2013) to yield total transport rates or the spatial distribution of bedload fluxes (Fig. 1C). With the development of more automated video analysis techniques, total sediment fluxes could potentially be quantified without any trap system at flume outlets (e.g., Zimmermann et al., 2008). Particle tracking programs or manual tracking of individual grains (Fig. 1D) can also be used to estimate particle velocities, wait times, and transport distances (e.g., Roseberry et al., 2012). Videos from the flume side (downstream transect) have been used to measure dune migration (Nelson et al., 2011) and particle saltation velocities, heights, and lengths (e.g., Lajeunesse et al., 2010; Chatanantavet et al.,

2013; see Bhattacharyya et al., 2013 for a review). Some potential limitations for video analysis of bedload transport include the following: (i) very high transport rates often cannot be measured because of problems identifying individual grains; (ii) planview videos only capture surface sediment transport; and (iii) sideview videos capture limited spatial variation in bedload transport.

2.2. Flow measurements coupled to bedload transport

Detailed measurements of flow velocities, pressures, and forces can elucidate the mechanics of sediment motion and have become more common in bedload transport research in the past 20 years. Acoustic doppler velocimeters (ADV) have been more commonly used in laboratory experiments but disturb the flow and can have difficulty obtaining measurements very close to the bed given the distance between the probe and the measurement volume (about 5-7 cm). Side-looking ADV configurations or acoustic doppler current profilers (ADCP) can provide flow measurements that are relatively close to the bed, although many ADCPs only operate with relatively large flow depths that can reduce their usefulness in laboratory flumes. Hot film probes have also been widely used to obtain near-bed one- or two-dimensional instantaneous velocities at one location, particularly in the fluid mechanics literature (e.g., Nakagawa and Nezu, 1977). These probes have the disadvantage of being relatively delicate and can be damaged from grain impacts, which can limit their use in bedload transport studies.

Recently, particle image velocimetry (PIV) and laser doppler velocimetry (LDV) have become the more widely used techniques to characterize turbulence. They measure one-, two-, or three-dimensional instantaneous velocities and do not disturb flow or bedload fluxes because they are minimally invasive. The technique of PIV can be particularly useful compared to ADV, ADCP, hot film, or LDV measurements if simultaneous quantification of many spatial locations is needed. Any of these instruments can quantify Reynolds stresses, turbulence intensities, and velocity profiles (e.g., Nezu and Rodi, 1986; Papanicolaou et al., 2001). Spectral and wavelet analyses of turbulence, quadrant analyses

to identify turbulence events such as bursts and sweeps, and visualization of coherent flow structures can also be performed with detailed turbulence measurements (e.g., Nelson et al., 1995; Nezu and Sanjou, 2008; Hardy et al., 2009; Valyrakis et al., 2011; Keylock et al., 2012). The techniques of PIV and LDV in particular can accurately measure near-bed shear stresses and flow velocities, which are important for predicting and understanding bedload transport.

In PIV, steady or pulsing laser sheet(s) illuminate the transport of neutrally buoyant particles (seeded or naturally occurring in the flow), which are recorded by high-speed video cameras. Auto- or cross-correlation analyses of particles between video frames provide instantaneous flow velocities, which are calculated in local areas (called interrogation regions) to capture the spatial variation in flow (Adrian, 2005). In two-dimensional PIV, spatial fields of instantaneous streamwise and vertical velocities are usually provided whereas three-dimensional PIV also measures the cross-stream velocity. The required camera speed and interrogation window size will depend on the experiment purpose (e.g., capturing instantaneous velocities at grain motion vs. measuring general turbulence statistics). Low turbidity and an optimal density of seeded particles are also required because too few particles or too many particles will not allow for accurate correlation analyses. A number of other conditions such as particle size, video camera angle, laser intensity, and laser reflection need to be properly considered; and a review on this technique and associated uncertainties is provided by Adrian and Westerweel (2011).

Similarly, LDV uses laser beams to measure one-, two-, or three-dimensional instantaneous velocities at one location in the flow column. One-dimensional LDV operates by intersecting two laser beams (usually split from one beam) in the flow, where they interfere and through which neutrally buoyant particles can reflect light. The fluctuations in light intensity reflected by the particles are used to calculate the flow velocity. To measure more than one component of velocity, three different types of lasers with different wavelengths are combined. Potential problems are similar to PIV, such as a need

for low turbidity and proper laser alignment and calibration. Like ADV measurements, LDV cannot simultaneously measure flow velocities at more than one location and therefore cannot be used to obtain instantaneous velocity profiles or spatial distributions of near-bed turbulence. Reviews on this technique are provided by Boutier (2012) and Durst et al. (1981).

In addition to flow velocities, detailed pressure and force measurements have been used to better quantify the role of turbulence in grain motion. Force sensors (measuring at 40-500 Hz) placed either within or attached to grains measure lift and/or drag to determine the correlation of these forces with grain motion, flow velocities, and particle arrangement (e.g., protrusion above the surrounding bed surface) (e.g., Schmeeckle et al., 2007). Most of these force measurements occur on fixed (rather than mobile) grains and therefore cannot determine the exact forces during particle motion. In contrast, three-dimensional accelerometers (measuring at ~500 Hz) implanted in mobile grains (Johnson, 2011; Underwood, 2012) can measure the exact times (and possibly forces) of entrainment and disentrainment (Fig. 2A) and when coupled with 3-axial gyroscopes can provide the particle orientation (Valyrakis and Pavlovskis, 2014). Micropressure sensors (measuring at ~1000 Hz) installed in stationary (e.g., Hofland et al., 2005; Dwivedi et al., 2010; Celik et al., 2014) and mobile (Schott and Yager, 2012) grains (Fig. 2B) can be used to determine turbulence-induced changes in pressure gradients (Fig. 2C) on particles. In particular, the difference between pressure sensors at the upstream and downstream ends of grain, or the grain top and bottom, has been used to approximate drag and lift forces, respectively. These velocity, force, and pressure measurements can be combined or used in isolation to better quantify the role of turbulence in the onset of grain motion (see section 3.4).

2.3. Bed topography and grain size distributions

Measurements of bed topography are needed in bedload transport experiments to quantify bed slope, channel roughness, bedform characteristics, and/or scour and deposition. In addition to bed topography, accurate descriptions of bed grain size distributions are needed because grain size partially

controls the following: (i) flow properties such as velocity fields, turbulence, and water depth; (ii) energy losses caused by particle and form roughness; (iii) habitat for fish and invertebrates; and (iv) bedload transport rates and mobile grain sizes. For example, reach-averaged flow properties (e.g., velocity, flow depth) are often calculated as functions of grain roughness (Rickenmann, 1994; Comiti et al., 2007; Ferguson, 2007; Zimmermann, 2010; Rickenmann and Recking, 2011), which is typically parameterized using a characteristic bed grain size (e.g., D_{84} , the grain size for which 84% of the sediment is finer). Bedload transport equations also require a representative bed grain size (Shields, 1936; Meyer-Peter and Müller, 1948) or a complete surface grain size distribution to predict fluxes (Parker, 1990; Wilcock and Crowe, 2003). With the onset of high resolution photographs and detailed measurements of bed topography in laboratory flumes, estimates of bed grain sizes and elevations are becoming intricately linked. Specifically, detailed elevation maps can be used to infer grain size distributions, whereas photographs can be analyzed to determine grain sizes and bed elevations.

The most commonly used method to measure bed elevations are bed scans using laser profilers, which are often attached to an instrument cart that moves parallel to the bed above the flume surface. Laser scans have very high accuracy (± 0.1 - 0.2 mm) (e.g., Marion et al., 2003; Ockelford and Haynes, 2013) but are only realistic during dry bed conditions before and after flume runs. Detailed bed topography can be used to characterize bed roughness instead of relying on a representative grain size as is commonly done in the field. The standard deviation and probability density function of bed elevations or one- and two-dimensional structure functions hold promise to better characterize bed roughness and structure (e.g., clusters of grains) (e.g., Marion et al., 2003). Green LiDAR, which has been used with success in the field to measure bed topography below water surfaces (McKean et al., 2014), has not been applied in laboratory flumes but might be applicable in future experiments. Sonar scans do not have the accuracy (often ≥ 1 mm) or resolution of laser scans (e.g., Singh et al., 2012; Venditti et al., 2012) but can measure bed topography during experiments when water is covering the bed. They

are also often attached to mobile carts and must be submerged just below the water surface. Sonar scans have been used successfully to better quantify dune migration rates and sediment fluxes (e.g., Martin and Jerolmack, 2013) (Fig. 3).

In laboratory flumes, traditional measurements of bed grain sizes include bulk samples (surface sediment, subsurface sediment or both combined) for subsequent sieving or pebble counts (Wolman or grid based) of the bed surface (Bunte and Abt, 2001). These methods partially modify the bed by removing sediment, can be extremely time consuming for characterizing large areas, and do not allow for measurements of bed changes during an experiment. Relatively recent alternatives are the use of photographs and high-resolution digital elevation models (usually from laser scans) for measuring bed surface grain sizes. Both of these techniques require a strong contrast between particle boundaries to fully isolate individual grains for accurate *b*-axis measurements. For high-resolution digital elevation models from laser scans, differences in elevation are used to derive the contrast between individual grains (Fig. 4) (McEwan et al., 2000; Nelson et al., 2010). With photogrammetry, the surface grain size is estimated from the two-dimensional projection of a three-dimensional structure (Buscombe et al., 2010). A variety of techniques such as autocorrelation (Rubin, 2004; Barnard et al., 2007; Warrick et al., 2009), semivariograms of image texture (Verdú et al., 2005), fractal dimension (Buscombe and Masselink, 2009), or spectral decomposition of image intensity (Buscombe et al., 2010) are used to estimate individual grain sizes.

Photogrammetry has a number of extra requirements for accurate grain size measurements such as photographs that are level and taken parallel to the bed. The camera distance to bed must be such that all grain sizes can be accurately captured and errors caused by perspective, especially at the edges of the photo, are minimized. Light sources must be vertically aligned to the camera and bed to minimize shadows around large particles, in which small particles could be undetectable. If the perspective error at the photo edges is insignificant, no overlap between neighboring images is required

– but they must be exactly adjacent (Bunte and Abt, 2001). To adequately characterize the complete grain size distribution, at least 300 grains must be analyzed from the photos (Fripp and Diplas, 1993; Rice and Church, 1996). The required sampling area (A) can be estimated with $A = n \cdot D_{50}^2$, where n is a coefficient (≥ 300) and D_{50} is the grain size for which 50% of the sediment is finer (Graham et al., 2005a)

Compared to traditional methods, photographs and high-resolution digital elevation models are non intrusive, do not disturb the bed, and could measure grain position and orientation coupled to individual grain coordinates. In particular, photographs can be used to measure bed grain sizes during an experiment, which eliminates the need to empty a flume of water and possibly alter the bed. Photogrammetry techniques can be up to 100 times faster than traditional methods (Rubin, 2004). In a field test with grain sizes ranging from sand to fine gravel (0.063 to 2.38 mm), the autocorrelation method had an accuracy of 96% in estimating mean and median grain sizes (Barnard et al., 2007). For coarser grain sizes (mean grain sizes of 1 to 200 mm), in which the grain orientation is not as uniform as in sand, this method has a lower accuracy in estimating grain short axes ($R^2 = 0.68$). However, long and intermediate grain axes are captured well with errors on the order of 14% (Warrick et al., 2009).

Automated grain size measurements in laboratory experiments have been used to characterize bed roughness, properties of armored gravel bed surfaces (Katul et al., 2002; Aberle and Nikora, 2006) and spatial variability in the median grain size (Nelson et al., 2010). A recent application is the automated delineation and identification of bed surface patches (areas of relatively narrow grain size distributions). Surface patches have been documented in laboratory experiments (Dietrich et al., 1989; Lisle et al., 1991, 1993; Buffington and Montgomery, 1999; Nelson et al., 2009, 2010) and in field studies (Lisle and Madej, 1992; Crowder and Diplas, 1997; Garcia et al., 1999; Laronne et al., 2000; Dietrich et al., 2005; Yager et al., 2012c). Patch boundaries are commonly delineated using visual observation combined with user judgment, which has problems of repeatability, transferability, and precision (Nelson et al., 2014). To overcome these problems and better delineate patch boundaries in an

objective manner, Nelson et al. (2014) tested different methods of defining patch edges using a spatial map of grain sizes created through photogrammetry.

Finally, photogrammetry has also been used to quantify detailed bed topography in the field and laboratory experiments. In this method, high resolution photographs, when combined with calibration points with known coordinates and elevations (or known camera locations), can provide relatively high precision digital elevation models ($\sim \pm 1$ mm) (e.g., Butler et al., 1998; Carbonneau et al., 2003; Carbonneau, 2005; Fonstad et al., 2013) . Paired cameras have been recently used to measure bed elevations in high resolution and to document topographic evolution during an experiment (Bouratsis et al., 2013)

3. The importance of bedload transport experiments

Laboratory flume experiments have been used to investigate a wide range of bedload transport processes in gravel-bed rivers. Most of the first experiments focused on quantifying bedload transport in general and the dimensionless critical shear stress (stress needed to initiate motion; critical Shields stress) for use in bedload transport equations (e.g., Gilbert, 1914; Shields, 1936; Meyer-Peter and Müller, 1948). Subsequent experiments have focused on wider grain size distributions to understand hiding effects, preferential transport of different grain sizes, bed roughness effects, and vertical sediment sorting (e.g., Wilcock and Southard, 1988; Kuhnle, 1993; Wilcock and McArdell, 1997; Yager et al., 2007). Many of the bedload transport equations, including critical Shields stress values and hiding functions, have been developed using laboratory flume data because of the difficulty of measuring bedload in the field (e.g., Gomez and Church, 1989). Laboratory experiments have not only been fundamental in developing empirical bedload equations, they have also been used to elucidate some of the more detailed processes and mechanics in bedload transport. Many other research topics on bedload transport have also significantly benefitted from laboratory flume experiments, such as the

formation of alternate bars, bedform dynamics, size-selective and equal mobility transport, and meandering channel stability. Here we focus on four key processes in gravel-bed rivers that have received recent attention and have many opportunities for future work: sediment supply impacts on bed conditions; armor layer formation and transport; flow hydrograph impacts; and grain scale mechanics of sediment motion.

3.1 Influence of sediment supply

Sediment supply, although long qualitatively recognized as a control of channel properties and bedload transport rates, has only been studied in detail in the past 25 years. Field studies on sediment supply have been relatively limited in extent because the upstream supply to a reach is difficult to quantify. In most cases it is estimated indirectly (e.g., pool filling, relative grain sizes) or qualitatively (Lisle and Hilton, 1999; Barry, 2004; Yager et al., 2012b), which precludes quantifying the exact linkages between sediment supply and bed grain size, channel slope, and channel morphology. Laboratory flume experiments are ideal for investigating sediment supply effects because the upstream input to the flume can be measured and controlled.

Laboratory studies have demonstrated that gravel-bed rivers primarily adjust their surface texture with changes in the sediment supply rate (Dietrich et al., 1989; Lisle et al., 1993, and Nelson et al., 2009). In most research, the focus has mainly been on limited sediment supply conditions, which are when the bedload transport capacity exceeds the sediment supply rate. Such conditions are often found immediately after dam construction or the formation of woody debris jams. With a restricted sediment supply, the bed surface coarsens in general (Dietrich et al., 1989) and may coarsen primarily by expansion of coarse, fixed patches (Nelson et al., 2009). Coarsening in response to sediment supply limitation is a key factor in armor layer development (see section 3.2). Bed surface texture is also sensitive to the grain size distribution of the sediment supply. For example, the coarse, relatively

immobile grains that compose armor layers will become more mobile (Venditti et al., 2010a, b) if relatively fine sediment is supplied upstream. Conversely, if the supplied sediment is coarser than the bed surface, armoring will remain intact (Cui et al., 2003).

In addition to grain size changes, flume experiments have shown that gravel-bed channels also adjust their morphology, bed elevation, slope, and roughness in response to changes in the sediment supply rate. When sediment supply is high (relative to the transport capacity), channel response includes increases in bed elevations (sediment deposition), water surface slopes, and reach-averaged sediment transport rates (Madej et al., 2009), whereas bed roughness declines (Yager et al., 2007; Madej et al., 2009). Sediment deposition occurs because the channel cannot carry the imposed load. Deposition also eventually increases the bed slope, which augments the transport capacity to approximately match the sediment input. Conversely, for low relative sediment supplies, there is a decrease in bed elevations (sediment erosion), water surface slopes, and reach-averaged sediment transport rates (Madej et al., 2009; Nelson et al., 2009; Venditti et al., 2012). Low sediment supply can also increase bed roughness because of surface coarsening or exposure of large roughness elements (Yager et al., 2007; Madej et al., 2009). Sediment supply can also impact alternate bar development and stability; reductions of sediment supply can cause bars to emerge and become stationary (Lisle et al., 1993) or completely disappear (Venditti et al., 2012).

Sediment supply can also impact long-term landscape evolution. For example, laboratory experiments have shown that bedrock erosion rates are highest at an intermediate sediment supply relative to the transport capacity (Sklar and Dietrich, 2001). At low sediment supplies, there are not enough tools to abrade bedrock surfaces; whereas at very high supplies, sediment will completely cover the bed and protect it from erosion. A model for bedrock erosion that includes tool and cover effects has been developed using these experimental observations (Sklar and Dietrich, 2004) and has been widely used and modified to include other processes (e.g., Lamb et al., 2008).

In steep, rough channels the sediment supply is particularly important because it is limited by the episodic delivery of material from landslides and debris flows. Bedload transport equations typically over predict sediment fluxes in steep channels by several orders of magnitude in part because of limited sediment availability. Experimental observations have demonstrated that the protrusion of relatively immobile boulders and the bed coverage by more mobile gravel may serve as proxies for sediment availability in steep channels (Yager et al., 2007). A bedload transport equation that indirectly accounts for sediment supply effects has improved sediment flux predictions in laboratory experiments and in a number of steep streams (Nitsche et al., 2011; Yager et al., 2012a).

3.2 Armor layer processes

Experiments conducted in laboratory flumes have also provided significant findings regarding the behavior of armor layers, a common phenomenon in gravel-bed channels in which the streambed surface is coarser than the subsurface material. The degree of armoring is typically measured by the ratio between the median grain sizes of the surface and subsurface ($D_{50}:D_{50s}$). Ratios greater than ~2 indicate armoring (e.g., Hassan et al., 2006), but ratios as large as 11 have been measured in natural channels (e.g., Ryan et al., 2002). Compared to field settings in which observing the armor during high flows is generally impossible and unsafe, laboratory flumes provide a much safer and more controlled environment for investigating armor dynamics and its impact on bedload transport. A variety of laboratory studies have highlighted the following: (i) mechanisms and influences on armor formation; (ii) differences between mobile and static armor; (iii) armor behavior during high flow events; and (iv) impacts on bedload transport.

Many flume-based studies have confirmed that armor forms primarily by the oft-cited mechanism of preferential transport of finer grains, leaving coarser grains at the surface (e.g., Dietrich et al., 1989; Hassan and Church, 2000; Madej et al., 2009; Sklar et al., 2009; Mao et al., 2011; Humphries et

al., 2012). Kinematic sieving, in which finer grains are shaken or settle to the subsurface through pores between larger grains, may also promote armoring (e.g., Parker and Klingeman, 1982). It has been hypothesized that low sustained flows are needed to develop bed armoring because they are more likely to preferentially transport fine sediment from the bed surface. However, most flume experiments employ a single, steady discharge per experiment and therefore cannot investigate the relative influences of different flow stages or their durations on armor layer formation. One exception is a set of flume experiments in which Hassan et al. (2006) investigated armor response to a variety of steady flows and hydrographs. They found that steady discharges and hydrographs with longer, gradually declining flow promoted more armoring than shorter, rapidly changing hydrographs. Further, experiments with approximately the same total stream power but differently shaped hydrographs produced varying degrees of armoring (Fig. 5).

Experiments have also shown relationships between the nature of the sediment supply (i.e., volume, grain size distribution, and particle shape) and the resulting armor. Sediment supply appears to be a primary influence (see section 3.1), with more significant armor development as supply decreases relative to the transport capacity of the channel (e.g., Dietrich et al., 1989; Lisle et al., 1993; Madej et al., 2009). This has also been indirectly demonstrated by studies that require an armored bed as the initial condition for subsequent experimental runs. In these flume experiments, an armor layer is always formed with a low (or zero) sediment supply (e.g., Sklar et al., 2009; Humphries et al., 2012). The grain size distribution of the sediment supply also impacts armoring. In particular, increasing the sand content reduces vertical sorting (Marion and Fraccarollo, 1997), surface grain sizes (Wilcock et al., 2001), and overall bed stability (Curran and Tan, 2013). Similarly, Sklar et al. (2009) and Venditti et al. (2010a, b) found that bed armor mobilized and fined with the addition of finer-grained gravel pulses. The shape of the particles in the bed and in the sediment supply may also influence the degree of armoring, with more rounded gravel resulting in greater armor ratios than flat or angular gravels (Gomez, 1994).

Work in flumes has also highlighted differences between static and mobile armor. Static armor tends to be coarser, with more developed structure and imbrication of grains compared to mobile armor (Mao et al., 2011). Further, formation of static armor occurs primarily by flows that preferentially transport only the finer, more mobile grains (e.g., Mao et al., 2011). Mobile armors, in contrast, can persist when all grain sizes are mobile (e.g., Parker et al., 1982; Mao et al., 2011), with kinematic sieving the primary mechanism of surface coarsening (e.g., Wilcock et al., 2001). Flume observations also indicate that the surface grain size of mobile armors tends to be insensitive to changes in shear stress, perhaps because of equal mobility of all grain sizes (e.g., Parker et al., 1982; Parker and Klingeman, 1982; Parker and Toro-Escobar, 2002).

Laboratory flumes have also provided some insight about the fate of armored surfaces during high flows, during which it is generally impossible and unsafe to make direct observations. In the field, bedload samples during high flows cannot provide direct information about changes in surface grain sizes. Further, comparing pre- and post-event data such as grain size distributions and armor ratios cannot determine if the original armor surface persisted intact, exchanged particles with the bedload, broke up and reformed, or was buried. Each of these possibilities has very different implications for local sediment availability, bed stability, and bedload transport rates. The majority of flume experiments have created mobile rather than static armor layers (e.g., Parker et al., 1982; Parker and Klingeman, 1982; Wilcock et al., 2001). For this bed condition, results indicate that while the original armor surface does not persist, vertical sorting endures because of kinematic sieving of the finer grains to the subsurface (e.g., Wilcock et al., 2001). However, this is an area for further investigation because few studies have tracked the fate of the original armor surface, whether static or mobile, during simulated high-flow hydrographs. Marking the armor surface or specific grain size classes of interest (Piedra et al., 2012) with paint or other materials could be used to facilitate observations of armor dynamics during runs.

Finally, experimentation in flumes has, to a limited extent, led to the incorporation of armor dynamics into bedload predictions. Using a variety of flume and field data sets, Bathurst (2007) accounted for the influence of the armor layer on transport rates through a modification to the excess-discharge based equation

$$g_s = a\rho(q - q_{c2}) \quad (1)$$

in which g_s is bedload transport per unit width, a is the rate of change of bedload with discharge, ρ is the density of water, q is unit discharge, and q_{c2} is the critical unit discharge for phase II transport (e.g., Ryan et al., 2002, 2005) when the coarse surface begins to break up and expose the finer subsurface. Applicable only to phase II transport, Bathurst (2007) suggested that the exponent a varied with the degree of bed armoring. Hiding functions (e.g., Ashworth and Ferguson, 1989; Wilcock and Crowe, 2003; Buscombe and Conley, 2012) can also indirectly incorporate the influence of an armored surface on bedload transport by adjusting for the reduced difference in mobility between fine and coarse grains, a condition often observed for armored beds (e.g., Parker et al., 1982; Parker and Klingeman, 1982; Parker and Toro-Escobar, 2002).

3.3 Flow hydrograph impacts on bedload transport

Laboratory flumes have also been used to investigate the impacts of unsteady flows on bedload transport. Despite the fact that nearly all natural channels are subject to unsteady flow, experiments typically investigate single, steady discharges rather than using a series of discharges. Although the number of flume-based studies on bedload transport that employ unsteady flows is limited, their findings suggest that unsteady flows (or a particular sequence of flow stages or shear stresses) can impact bedload transport processes. Thus far, flume studies have investigated the effects of hydrograph

form on the following: (i) total volume of bedload transport; (ii) channel bed structure, including grain sorting and armoring; and (iii) hysteresis in transport rates and transported grain sizes.

Compared to an equivalent steady discharge, significant uncertainty exists regarding whether hydrographs increase, decrease, or do not change the total volume of bedload transported. Lee et al. (2004) and Bombar et al. (2011) found that compared to equivalent steady flows (usually defined as the mean of the unsteady discharges), hydrographs increased the total volume of material transported in straight channels. Further, these two studies demonstrated that the total bedload transport increased as the unsteadiness of the hydrograph (a measure of how rapidly flow is changing) increased, although each quantified unsteadiness differently. Similar results occurred when hydrographs were run over a forced bar that formed in a curved flume (Yen and Lee, 1995). In contrast, other studies have found that total bedload transport for hydrographs is less than that for an equivalent steady discharge (Griffiths, 1976; Bell, 1980; Young and Davies, 1991) or that there was no difference (Griffiths and Sutherland, 1977; Parker et al., 2007).

Flume studies suggest that one way in which hydrographs may influence bedload transport is by altering the bed grain size distribution, degree of grain sorting, armor development, and structure of the stream bed surface. The rate of change in flow during hydrographs (gradual vs. rapid or flashy) appears to be a second-order control (after sediment supply) on the degree armoring (see section 3.2); more gradual hydrographs result in greater sorting than flashy events (Hassan et al., 2006). Hydrographs may also influence the spatial sorting of sediment on point bars; flashier hydrographs caused more pronounced sorting (finer and coarser sediment on the inside and outside of a bend, respectively) (Yen and Lee, 1995). However, this result could also be impacted by differences in the peak flow rates between experimental hydrographs. In addition to bed sorting, hydrographs can drive changes in the structure or organization of the bed surface, which increases the reference shear stress and reduces sediment mobility during the falling limb (Mao, 2012). Such changes in bed armoring, spatial sorting,

and bed structure with different hydrographs have been used to partly explain the occurrence of hysteresis in bedload transport.

Hysteresis is defined as having different bedload transport rates for the same flow discharge on the rising and falling limbs of hydrographs in natural channels. The same phenomenon occurs during hydrograph runs in flumes (Fig. 6), with clockwise (transport higher on rising limb; Hassan et al., 2006; Humphries et al., 2012; Mao, 2012) and counterclockwise patterns observed (Lee et al., 2004; Bombar et al., 2011). Hysteresis has also been observed in the mobile and bed surface grain sizes (Fig. 6; Mao, 2012). However, different hysteresis patterns observed in experiments may result from differences in the experimental designs (i.e., grain sizes, applied shear stresses, hydrograph duration) that could impact the response time of the bed to changes in flow. Based on flume experiments, Mao (2012) suggested that clockwise hysteresis in gravel bed channels is driven by structural changes to the bed surface during the hydrograph falling limb (see above).

3.4 Grain scale transport mechanics

An increasing number of studies are focused on the detailed mechanics of sediment motion, including coupling between flow turbulence and the onset of movement or bedload transport rates. Such studies are needed because predictions of bedload transport generally are inaccurate (e.g., Gomez and Church, 1989; Yager et al., 2012b) and this partly stems from using reach-averaged parameters (e.g., grain size, shear stress) to predict a highly spatially variable and temporally stochastic process (e.g., McEwan et al., 2004). The mechanics of bedload transport are difficult to investigate in the field because they require measurements of grain scale turbulence and bed conditions (e.g., friction angles), continuously tracking individual particles, and/or eliminating natural variability (e.g., range of critical Shields stresses for a given grain size). From basic fluid mechanics, sediment entrainment is fundamentally driven by the momentum balance on a grain, which is partly a function of the fluctuating

flow velocity fields and pressure gradients around a grain (e.g., Schmeeckle and Nelson, 2003). In addition to flow turbulence, grain motion can be influenced by particle arrangement on the bed surface (e.g., Wiberg and Smith, 1987; Kirchner et al., 1990; Buffington et al., 1992). Once a particle is in motion, its transport can be characterized by particle velocities, step lengths, and rest times. Here, we highlight some of the key recent developments using laboratory experiments on flow turbulence, grain arrangement, and particle transport.

Laboratory flume experiments have been used to measure concurrent near-bed flow turbulence and bedload transport rates or detailed flow velocities immediately upstream of mobile and stationary grains. One area of investigation has focused on turbulence events as defined by the joint frequency distribution of streamwise and vertical velocity fluctuations from mean values. Numerous studies have demonstrated that sweeps and inward interactions are correlated with the initial entrainment of sediment (Fig. 7) and/or produce larger bedload fluxes than other events (bursts, inward interactions) of the same magnitude (e.g., Nelson et al., 1995; Dwivedi et al., 2011; Wu and Shih, 2012; Celik et al., 2013). It has been hypothesized that because bursts and outward interactions are associated with positive streamwise velocity fluctuations, the instantaneous streamwise velocity rather than the vertical velocity dictates particle motion. However, the velocity measurement location (relative to the grain of interest) can impact what turbulence events are assumed to be associated with grain movement (Wu and Shih, 2012), and this needs to be considered in future studies.

Although sediment motion may occur during specific turbulence events, such correlations do not necessarily explain the mechanics of particle motion at the grain scale. Drag and lift forces are often used to represent these mechanics and have been estimated on stable and on mobile grains. Direct measurements of drag and lift, or estimates of these forces from pressure sensors, have shown that mean forces, and temporal fluctuations in force, vary with particle protrusion into the flow (Hofland et al., 2005; Schmeeckle et al., 2007). In particular, vertical forces (similar to lift) decrease as grain

protrusion increases, which implies that lift forces may be relatively unimportant when grains protrude significantly above the mean bed elevation (Schmeeckle et al., 2007). Grain motion is not only dictated by the magnitude of instantaneous forces on a grain, but also by the duration of forces that exceed the grain's threshold of motion (e.g., vertical component of grain weight). For example, if a large force does not persist long enough to completely move a grain out of its pocket, the grain may wobble, but it will still remain immobile. Impulse, which includes the magnitude and duration of drag forces, may be better correlated to grain movement than drag force magnitude alone (e.g., Diplas et al., 2008) or an energy approach may better represent grain motion (Valyrakis et al. 2013).

In addition to the coupling between flow turbulence and grain motion, laboratory studies have demonstrated that bed arrangement can significantly impact the onset of sediment motion. Previous research has highlighted the importance of particle friction angles (angle through which a grain must pivot) and how these angles vary with the underlying bed grain size distribution (e.g., Kirchner et al., 1990; Buffington et al., 1992;). Recent laboratory experiments have also highlighted that bed arrangement also needs to be parameterized in terms of grain packing, imbrication, interlocking, or partial burial. For example, grain packing by other sediment can increase the critical Shields stress over what would be calculated by simply using grain weight and friction angles (e.g., Papanicolaou et al., 2002; Buxton et al., 2012). In addition, even for a constant bed grain size distribution, different sequences of applied shear stresses can influence the bed grain arrangement. The onset of motion may therefore vary through time depending on the flow history of a given bed (Haynes and Pender, 2007; Mao, 2012; Ockelford and Haynes, 2013).

After sediment entrainment, bedload transport rates are influenced by particle travel velocities, travel distances, and disentrainment rates. Until recently, knowledge of travel distances and velocities have been limited to field studies employing tracer particles. Although the movement of grains in natural channels have advantages over simplified flume experiments, unless those grains have radio-

tags or embedded accelerometers (see section 2.2) it is very difficult to know the exact travel distances, rest times, travel velocities, and shear stresses at entrainment or disentrainment. Laboratory experiments using videos or impact plates have allowed for such details to be accurately measured for relatively simple bed conditions (e.g., Heyman et al., 2013). For example, experimental observations have shown that the number of moving particles increases faster with excess shear stress than particle velocities or step lengths and suggests that bedload fluxes are largely driven by particle activity (e.g., Lajeunesse et al., 2010; Roseberry et al., 2012; Furbish and Schmeeckle, 2013).

Bedload transport can be classified into three different characteristic time scales as suggested by Nikora et al. (2002). Short time scales represent intervals between particle and bed collisions. Intermediate time scales include entire particle flights from entrainment to disentrainment and can include a number of bed and particle collisions. At long time scales, particles have experienced many flights and periods of rest during which no motion occurs (Nikora et al., 2002). A number of recent laboratory investigations have measured heavy tailed distributions of travel distances at intermediate time scales. These measurements support the occurrence of superdiffusion of bedload transport, which implies that finite sample times may not be representative of actual bedload fluxes and many bedload transport equations may not be correctly formulated (e.g., Nikora et al., 2002; Hill et al., 2010; Martin et al., 2012). Other recent laboratory experiments and theoretical analyses (Furbish et al., 2012; Roseberry et al., 2012) suggest that the observed superdiffusive behavior at intermediate time scales may be driven by periodicities in grain motion (correlated random walks).

4. Conclusions and next steps

Laboratory data on bedload transport can fill in the gap between more natural but highly complex (and difficult to understand) field experiments and relatively simple but very detailed numerical modeling. Unlike field measurements, laboratory experiments can easily isolate the importance of

510 different parameters (e.g., sediment supply, roughness) and allow for detailed measurements (e.g.,
511 near-bed turbulence, bed grain size) during active bedload transport. Numerical models such as large
512 eddy simulation (LES) coupled with discrete element method models (DEM) can also provide detailed
513 insight into the coupling between flow turbulence, bedload transport, and channel bed evolution.
514 However, many numerical models still need some validation using detailed flow measurements, employ
515 relatively simple grains (e.g., spheres), and/or can have limited spatial extents given available
516 computational resources. Future studies that employ field, laboratory, and numerical modeling to
517 understand different scales of processes may provide more insight into bedload transport mechanics
518 than those that just use one method in isolation.

519 The advance of instrumentation in laboratory experiments has made detailed measurements of
520 bedload transport rates, bed topography, grain sizes, flow turbulence, particle entrainment, and travel
521 properties (distance, velocities) possible. The use of accelerometers in particles to pinpoint exact times
522 of entrainment and disentrainment and of high-speed video cameras to record grain motion and
523 bedform migration both hold great promise for future experiments. Simple and fast ways to measure
524 bed topography and grain size will significantly improve our understanding of how bedload transport
525 and channel bed conditions co-vary. Structure from motion techniques, which use photographs from
526 multiple angles to obtain topography, are particularly promising to easily and quickly obtain bed
527 topography and grain size in laboratory flume experiments. In addition to better instrumentation,
528 future experiments on armor layer formation, unsteady flows, and the mechanics of grain motion could
529 elucidate ways to improve bedload transport predictions in the field.

530 Any additional insight into armor dynamics could further improve predictions of bedload
531 transport for river channels in general because the majority of gravel-bed rivers have some level of
532 armor development. Whether armor is immobile, mobile and slowly exchanging particles with bedload,
533 or breaks up and then reforms will impact local sediment availability and bedload transport rates in very

different ways. Accurate predictions for when certain armor behaviors will occur are needed. Flumes allow for detailed observations and data collection *during* simulated high flow events, not just comparisons of pre- and post-event data, which often cannot indicate what happened to the original armored surface. The original coarse surface can be marked in some way (i.e., paint) to facilitate observations during runs. Similarly, specific grain sizes of interest can be marked, such as the use of ultraviolet paint for coarse grains by Piedra et al. (2012) to facilitate during-run observations. Still images and high speed video in particular can be used to observe and quantify armor response and the impact of armor on local sediment availability and transport rates.

Although previous studies on the impacts of unsteady flow on bedload transport have provided interesting insights, many uncertainties remain. Key areas for further investigation include the following: (i) scaling of experimental hydrographs; (ii) isolating the influence of different hydrograph characteristics (e.g., peak flow, rising and falling limbs) on bedload transport processes; and (iii) estimating conditions under which it is necessary to consider hydrograph form for predicting bedload transport. At present, there appears to be little consensus in the literature regarding appropriate scaling of experimental hydrographs, particularly the duration (Lee et al., 2004). Durations have been as short as 36 s (e.g., Song and Graf, 1995) and as long as ~15 hr (Mao, 2012). It remains unclear how the temporal scale of these experiments relates to, or can be extended to, natural channels. Appropriate scaling of experimental hydrographs is also needed to properly isolate the influence of different hydrograph characteristics. Many past studies have simultaneously varied both the rate of change and peak flow between runs, making it difficult to isolate the influence of hydrograph form from peak discharge. Finally, flume investigations can be used to systematically investigate under which conditions hydrograph form needs to be considered in bedload transport predictions and when steady state assumptions are appropriate.

A growing number of studies have been devoted to understanding the details of grain mechanics, but the fundamental coupling between grain motion and flow turbulence requires further research (Schmeeckle and Nelson, 2003; Coleman and Nikora, 2008; Schmeeckle et al., 2007). Better direct measurements of forces at grain motion or the use of an array of micropressure sensors in mobile grains may improve estimates of the flow conditions necessary to entrain grains. In addition, image diffraction matching techniques coupled with PIV and high-speed videos hold promise for documenting the detailed turbulence in the immediate vicinity of mobile grains. Such techniques have not been broadly applied to the field of bedload transport, but we expect them to grow in popularity. Further, determination of how turbulence at the grain scale relates to reach-averaged conditions, the scale at which most researchers measure, is also needed. Even if the flow turbulence around single grains is well understood, grain arrangement will still complicate predictions of motion in the field and the laboratory. Additional studies that quantify grain packing, burial, and interlocking would significantly improve our understanding of the forces that resist sediment entrainment. In particular, the variation of grain arrangement with flow history and grain size distribution may be important considerations.

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References

- Aberle, J., Nikora, V., 2006. Statistical properties of armored gravel bed surfaces. *Water Resour. Res.* 42, W11414, doi:10.1029/2005WR004674
- Adrian, R.J., 2005. Twenty years of particle image velocimetry. *Exp Fluids* 39, 159–169. doi:10.1007/s00348-005-0991-7
- Adrian, R.J., Westerweel J., 2011. *Particle Image Velocimetry*. Cambridge University Press, New York.
- Ashworth, P. J., Ferguson, R. I., 1989. Size-selective entrainment of bed load in gravel bed streams. *Water Resour. Res.* 25, 627-634.
- Barnard, P.L., Rubin, D.M., Harney, J., Mustain, N., 2007. Field test comparison of an autocorrelation technique for determining grain size using a digital 'beachball' camera versus traditional methods. *Sediment. Geol.* 201, 180–195.
- Barry, J.J., 2004. A general power equation for predicting bed load transport rates in gravel bed rivers. *Water Resour. Res.* 40. doi:10.1029/2004WR003190
- Bathurst, J.C., 2007. Affect of coarse surface layer on bed-load transport. *Journal of Hydraulic Engineering* 133, 1192-1205.
- Bell, R. G., 1980. *Non-Equilibrium Bedload Transport by Steady and Non-steady Flows*. Report No. 80-23, University of Canterbury, Christchurch, New Zealand, 237 pp.
- Bhattacharyya, A., Ojha, S.P., Mazumder, B.S., 2013. Evaluation of the saltation process of bed materials by video imaging under altered bed roughness: video capturing of the saltation process. *Earth Surface Processes and Landforms.* 38, 1339–1353. doi:10.1002/esp.3370
- Bombar, G., Ş. Elçi, Tayfur, G., Şükrü Güney, M., Bor, A., 2011. Experimental and Numerical Investigation of Bed-Load Transport under Unsteady Flows. *Journal of Hydraulic Engineering* 137, 1276-1282.

601 Bouratsis, P.P., Diplas, P., Dancey, C.L., Apsilidis, N., 2013. High-resolution 3-D monitoring of evolving
 602 sediment beds: High-Resolution 3-D Monitoring of Evolving Sediment Beds. *Water Resources*
 603 *Research* 49, 977–992. doi:10.1002/wrcr.20110
 604 Boutier, A., 2012. *Laser Velocimetry in Fluid Mechanics*. John Wiley & Sons, London.
 605 Buffington, J.M., Montgomery, D.R., 1999. Effects of hydraulic roughness on surface texture of gravel-
 606 bed rivers. *Water Resour. Res.* 35 (11), 3507-3521.
 607 Buffington, J.M., Dietrich, W.E., Kirchner, J.W., 1992. Friction Angle Measurements on a Naturally
 608 Formed Gravel Streambed: Implications for Critical Boundary Shear Stress. *Water Resources*
 609 *Research* 28, 411-425.
 610 Bunte, K., Abt, S.R., 2001. Sampling surface and subsurface particle-size distributions in wadable gravel-
 611 and cobble-bed streams for analyses in sediment transport, hydraulics, and streambed
 612 monitoring. Gen. Tech. Rep. RMRS-GTR-74. U.S. Department of Agriculture, Forest Service,
 613 Rocky Mountain Res Station, Fort Collins, CO.
 614 Bunte, K., Abt, S.R., Potyondy J.P., Ryan S.E., 2004. Measurement of Coarse Gravel and Cobble Transport
 615 Using Portable Bedload Traps. *Journal of Hydraulic Engineering* 130.
 616 Buscombe, D., Masselink, G., 2009. Grain Size Information from the Statistical Properties of Digital
 617 Images of Sediment. *Sedimentology* 56, 421-438.
 618 Buscombe, D., Conley, D.C., 2012. Effective shear stress of graded sediments. *Water Resour. Res.* 48,
 619 W05506, doi:10.1029/2010WR010341.
 620 Buscombe, D., Rubin, D. M., Warrick, J. A., 2010. A universal approximation of grain size from images of
 621 noncohesive sediment, *J. Geophys. Res.* 115, F02015, doi:10.1029/2009JF001477.
 622 Butler, J.B., Lane, S.N., Chandler, J.H., 1998. Assessment of DEM Quality for Characterizing Surface
 623 Roughness Using Close Range Digital Photogrammetry. *The Photogrammetric Record* 16, 271–
 624 291. doi:10.1111/0031-868X.00126

625 Buxton, T., Yager, E.M., Buffington, J.M., Fremier, A.K., Hassan M.A. 2012. The Influence of Salmonid
 626 Spawning on Grain Architecture, Critical Bed Shear Stress, and Bed Load Transport in Streams,
 627 Eos, Transactions, American Geophys. Union, Fall Meeting Supplment.
 628 Carbonneau, P.E., 2005. The threshold effect of image resolution on image-based automated grain size
 629 mapping in fluvial environments. *Earth Surf. Process. Landforms* 30, 1687–1693.
 630 doi:10.1002/esp.1288
 631 Carbonneau, P.E., Lane, S.N., Bergeron, N.E., 2003. Cost-effective non-metric close-range digital
 632 photogrammetry and its application to a study of coarse gravel river beds. *International Journal*
 633 *of Remote Sensing* 24, 2837–2854. doi:10.1080/01431160110108364
 634 Celik, A.O., Diplas, P., Dancey, C.L., 2013. Instantaneous turbulent forces and impulse on a rough bed:
 635 Implications for initiation of bed material movement: Instantaneous Turbulent Forces and
 636 impulse on A Rough Bed. *Water Resources Research* 49, 2213–2227. doi:10.1002/wrcr.20210
 637 Celik, A. O., Diplas, P., and Dancey, C. L., 2014. Instantaneous pressure measurements on a spherical
 638 grain under threshold flow conditions. *Journal of Fluid Mechanics*, 741, 60-97.
 639 doi:10.1017/jfm.2013.632.
 640 Chatanantavet, P., Whipple, K.X., Adams, M.A., Lamb, M.P., 2013. Experimental study on coarse grain
 641 saltation dynamics in bedrock channels. *Journal of Geophysical Research: Earth Surface* 118,
 642 1161–1176. doi:10.1002/jgrf.20053
 643 Coleman, S.E., Nikora, V.I., 2008. A unifying framework for particle entrainment. *Water Resour. Res.* 44.
 644 doi:10.1029/2007WR006363
 645 Comiti, F., Mao, L., Wilcox, A., Wohl, E., Lenzi, M.A., 2007. Field-derived relationships for flow velocity
 646 and resistance in high-gradient streams. *J. of Hydrol.* 340, 48-62.
 647 Crowder, D.W., Diplas, P., 1997. Sampling heterogeneous deposits in gravel-bed streams. *J. of Hydraul.*
 648 *Eng.* 123 (12), 1106-1117.

649 Cui, Y., Parker, G., Lisle, T. E., Gott, J., Hansler-Ball, M. E., Pizzuto, J. E., Allmendinger, N. E., Reed, J. M.,
650 2003. Sediment pulses in mountain rivers: 1. Experiments, *Water Resour. Res.* 39(9), 1239,
651 doi:10.1029/2002WR001803.

652 Curran, J.C., Tan, L., 2013. Effect of bed sand content on the turbulent flows associated with clusters on
653 an armored gravel bed surface. *Journal of Hydraulic Engineering* 140, 137-148.

654 Dietrich, W.E., Kirchner, J.W., Ikeda, H., Iseya, F., 1989. Sediment supply and the development of the
655 coarse surface layer in gravel-bedded rivers. *Nature*. 340, 215-217.

656 Dietrich, W.E., Nelson, P.A., Yager, E., Venditti, J.G., Lamb, M.P., Collins, L., 2005. Sediment patches,
657 sediment supply, and channel morphology, in G. Parker and M.H. Garcia (eds.), *Proceedings of*
658 *the 4th IAHR Symposium on River, Coastal and Estuarine Morphodynamics*, pp. 79-90.

659 Diplas, P., Dancey, C.L., Celik, A.O., Valyrakis, M., Greer, K., Akar, T., 2008. The Role of Impulse on the
660 Initiation of Particle Movement Under Turbulent Flow Conditions. *Science* 322, 717–720.
661 doi:10.1126/science.1158954

662 Drake, T., Shreve, R., Dietrich, W., Leopold, L., 1988. Bedload transport of fine gravel observed by
663 motion-picture photography. *J. Fluid Mech.* 192, 193–217.

664 Dwivedi, A., Melville, B., Shamseldin, A.Y., 2010. Hydrodynamic Forces Generated on a Spherical
665 Sediment Particle during Entrainment. *Journal of Hydraulic Engineering* 136, 756–769.
666 doi:10.1061/(ASCE)HY.1943-7900.0000247

667 Dwivedi, A., Melville, B.W., Shamseldin, A.Y., Guha, T.K., 2011. Flow structures and hydrodynamic force
668 during sediment entrainment. *Water Resources Research* 47, W01509.
669 doi:10.1029/2010WR009089

670 Durst, F., A. Melling, J.H. Whitelaw, 1981. *Principles and practices of laser-doppler anemometry*.
671 Academic, San Diego.

672 Ferguson, R., 2007. Flow resistance equations for gravel- and boulder-bed streams. *Water Resour. Res.*
 673 43, W05427. doi: 10.1029/2006WR005422.

674 Fernandez-Luque, R., Van Beek, R., 1976. Erosion and transport of bedload sediment. *Journal of*
 675 *Hydraulic Research* 14, 127–144.

676 Fonstad, M.A., Dietrich, J.T., Courville, B.C., Jensen, J.L., Carbonneau, P.E., 2013. Topographic structure
 677 from motion: a new development in photogrammetric measurement. *Earth Surface Processes*
 678 *and Landforms* 38, 421–430. doi:10.1002/esp.3366

679 Fripp, J. B., Diplas, P., 1993. Surface sampling in gravel streams. *J. Hydraul. Eng.* 119 (4), 473–490.

680 Furbish, D.J., Schmeeckle, M.W., 2013. A probabilistic derivation of the exponential-like distribution of
 681 bed load particle velocities. *Water Resources Research* 49, 1537–1551. doi:10.1002/wrcr.20074

682 Furbish, D.J., Ball, A.E., Schmeeckle, M.W., 2012. A probabilistic description of the bed load sediment
 683 flux: 4. Fickian diffusion at low transport rates. *Journal of Geophysical Research* 117. F03034
 684 .doi:10.1029/2012JF002356

685 Garcia, C., Laronne, J.B., Sala, M., 1999. Variable source areas of bedload in a gravel-bed stream. *J. of*
 686 *Sediment. Res.* 69(1), 27-31.

687 Gilbert, G. K., 1914. The transportation of debris by running water. USGS Professional Paper No. 86. U.S.
 688 Geological Survey, Washington, D.C.

689 Gomez, B., 1994. Effects of particle shape and mobility on stable armor development. *Water Resources*
 690 *Research* 30, 2229-2239.

691 Gomez, B., Church, M., 1989. An assessment of bed load sediment transport formulae for gravel bed
 692 rivers. *Water Resources Research* 25, 1161–1186. doi:10.1029/WR025i006p01161

693 Graham, D.J., Reid, I., Rice, S.P., 2005a. Automated sizing of coarse-grained sediments: image-processing
 694 procedures. *Mathematical Geol.* 37, 1–28.

695 Graham, D.J., Reid, I., Rice, S.P., 2005b. A transferable method for the automated grain sizing of river
696 gravels. *Water Resour. Res.* 41, W07020, <http://dx.doi.org/10.1029/2004WR003868>.

697 Grass, A. J., 1970. Initial instability of fine bed sand. *Journal of Hydraulics Division, Proceedings of ASCE*
698 96, 619–632.

699 Griffiths, G. A., 1976. Transport of bed load by translation waves in an alluvial channel. Report No. 76-1,
700 Dept. of Civil Engineering, University of Canterbury, Christchurch, New Zealand, 152 pp.

701 Griffiths, G. A., Sutherland, A.J., 1977. Bedload transport by translation waves. *Journal of Hydraulic*
702 *Division, American Society of Civil Engineers* 103, 1279-1291.

703 Hardy, R.J., Best, J.L., Lane, S.N., Carbonneau, P.E., 2009. Coherent flow structures in a depth-limited
704 flow over a gravel surface: The role of near-bed turbulence and influence of Reynolds number.
705 *Journal of Geophysical Research* 114. F01003. doi:10.1029/2007JF000970

706 Hassan, M. A., Church, M., 2000. Experiments on surface structure and partial sediment transport on a
707 gravel bed. *Water Resour. Res.* 36, 1885-1895.

708 Hassan, M. A., Egozi, R., Parker, G., 2006. Experiments on the effect of hydrograph characteristics on
709 vertical grain sorting in gravel bed rivers. *Water Resources Research* 42, W09408,
710 doi:10.1029/2005WR004707.

711 Haynes, H., Pender, G., 2007. Stress History Effects on Graded Bed Stability. *Journal of Hydraulic*
712 *Engineering* 133, 343–349. doi:10.1061/(ASCE)0733-9429(2007)133:4(343)

713 Heyman, J., Mettra, F., Ma, H. B., and Ancely C., 2013. Statistics of bedload transport over steep slopes:
714 Separation of timescales and collective motion. *Geophysical Research Letters* 40, 128-133.
715 doi:10.1029/2012GL054280.

716 Hill, K.M., DellAngelo, L., Meerschaert, M.M., 2010. Heavy-tailed travel distance in gravel bed transport:
717 An exploratory enquiry. *Journal of Geophysical Research* 115. doi:10.1029/2009JF001276

718 Hofland, B., Battjes, J.A., Booij, R., 2005. Measurement of Fluctuating Pressures on Coarse Bed Material.
 719 Journal of Hydraulic Engineering 131, 770–781. doi:10.1061/(ASCE)0733-9429(2005)131:9(770)
 720 Humphries, R., Venditti, J.G., Sklar, L., Wooster, J.K., 2012. Experimental evidence for the effect of
 721 hydrographs on sediment pulse dynamics in gravel-bedded rivers. Water Resources Research 48,
 722 W01533, doi:10.1029/2011WR010419.
 723 Johnson, JP, 2011. Using accelerometer-embedded cobbles to relate the initiation of motion by lift or
 724 drag to near-bed turbulent structures, Coherent Flow Structures in Geophysical Flows at Earth's
 725 Surface conference, August 3-5, 2011, Simon Fraser University, Burnaby, BC, Canada.
 726 Katul, G., Wiberg, P., Albertson, J., Hornberger, G., 2002. A mixing layer theory for flow resistance in
 727 shallow streams. Water Resour. Res. 38(11), 1250, doi:10.1029/2001WR000817.
 728 Keylock, C.J., Nishimura, K., Peinke, J., 2012. A classification scheme for turbulence based on the
 729 velocity-intermittency structure with an application to near-wall flow and with implications for
 730 bed load transport. Journal of Geophysical Research 117. doi:10.1029/2011JF002127
 731 Kirchner, J.W. Dietrich, W.E., Iseya, F., Ikeda, H., 1990. The variability of critical shear stress, friction
 732 angle, and grain protrusion in water-worked sediments. Sedimentology 37.
 733 Kuhnle, R. A., 1993. Incipient motion of sand-gravel sediment mixtures. Journal of Hydraulic
 734 Engineering. 119(12), 1400-1415.
 735 Lajeunesse, E., Malverti, L., Charru, F., 2010. Bed load transport in turbulent flow at the grain scale:
 736 Experiments and modeling. Journal of Geophysical Research 115. doi:10.1029/2009JF001628
 737 Lamb, M.P., Dietrich, W.E., Sklar, L.S., 2008. A model for fluvial bedrock incision by impacting suspended
 738 and bed load sediment. Journal of Geophysical Research 113. doi:10.1029/2007JF000915
 739 Laronne, J.B., Garcia, C., Reid, I., 2000. Mobility of patch sediment in gravel bed streams: Patch character
 740 and its implications for bedload. In Gravel-Bed Rivers V. Edited by M.P. Mosley 249–290. New
 741 Zeland Hydrol. Soc., Wellington, pp. 249-289.

742 Lee, K. T., Y.L. Liu, Cheng, K.H., 2004. Experimental investigation of bedload transport processes under
 743 unsteady flow conditions. *Hydrological Processes* 18, 2439-2454.

744 Lisle, T.E., Hilton, S., 1999. Fine bed material in pools of natural gravel bed channels. *Water Resources*
 745 *Research* 35.

746 Lisle, T.E., Madej, M.A., 1992. Spatial variation in armouring in a channel with high sediment supply. In P.
 747 Billi, R.D. Hey, C.R. Thorne, and P. Tacconi (eds). *Dynamics of Gravel-Bed Rivers*. New York: John
 748 Wiley.

749 Lisle, T. E., Ikeda, H., Iseya, F., 1991. Formation of stationary alternate bars in a steep channel with
 750 mixed-size sediment: A flume experiment. *Earth Surfaces Processes Landforms*. 16(5), 43–469.

751 Lisle, T. E., Iseya, F., Ikeda, H., 1993. Response of a channel with alternate bars to a decrease in supply of
 752 mixed-size bed load: A flume experiment. *Water Resour. Res.* 29(11), 3623 – 3629.

753 Madej, M.A., Sutherland, D.G., Lisle, T.E., Pryor, B., 2009. Channel responses to varying sediment input:
 754 A flume experiment modeled after Redwood Creek, California. *Geomorphology*. 103, 507-519.
 755 doi:10.1016/j.geomorph.2008.07.017

756 Mao, L., 2012. The effect of hydrographs on bed load transport and bed sediment spatial arrangement.
 757 *J. Geophys. Res.*, 117, F03024, doi:10.1029/2012JF002428.

758 Mao, L., Cooper, J.R., Frostick, L.E., 2011. Grain size and topographical differences between static and
 759 mobile armour layers. *Earth Surface Processes and Landforms* 36, 1321-1334.

760 Marion, A., Fraccarollo, L., 1997. Experimental investigation of mobile armor development. *Water*
 761 *Resources Research* 33, 1447-1453.

762 Marion, A., Tait, S.J., McEwan, I.K., 2003. Analysis of small-scale gravel bed topography during armoring.
 763 *Water Resources Research* 39. doi:10.1029/2003WR002367

764 Martin, R.L., Jerolmack, D.J., 2013. Origin of hysteresis in bed form response to unsteady flows. *Water*
 765 *Resources Research* 49, 1314–1333. doi:10.1002/wrcr.20093

766 Martin, R.L., Jerolmack, D.J., Schumer, R., 2012. The physical basis for anomalous diffusion in bed load
 767 transport. *Journal of Geophysical Research* 117. doi:10.1029/2011JF002075
 768 McEwan, I.K., Sheen, T.M., Cunningham, G.J., Allen, A.R., 2000. Estimating the size composition of
 769 sediment surfaces through image analysis. *Proceedings of the Institute of Civil Engineers, Water
 770 and Maritime Eng.* 142, 189–195.
 771 McEwan, I., Sørensen, M., Heald, J., Tait, S., Cunningham, G., Goring, D., Willetts B., 2004. Probabilistic
 772 Modeling of Bed-Load Composition. *Journal of Hydraulic Engineering* 130.
 773 McKean, J., Tonina, D., Bohn, C., Wright, C.W., 2014. Effects of bathymetric lidar errors on flow
 774 properties predicted with a multi-dimensional hydraulic model: Lidar bathymetry and hydraulic
 775 models. *Journal of Geophysical Research: Earth Surface* 119, 644–664.
 776 doi:10.1002/2013JF002897
 777 Meyer-Peter, E., Müller, R., 1948. Formulas for bed-load transport, in: *Proc., 2nd Meeting, IAHR,*
 778 *Stockholm, Sweden*, pp. 39–64.
 779 Nakagawa, H., Nezu, I., 1977. Prediction of the contributions to the Reynolds stress from bursting events
 780 in open-channel flows. *Journal of Fluid Mechanics* 80, 99–128. doi:10.1017/S0022112077001554
 781 Nelson, J.M., Shreve, R.L., McLean, S.R., Drake, T.G., 1995. Role of Near-Bed Turbulence Structure in Bed
 782 Load Transport and Bed Form Mechanics. *Water Resources Research* 31, 2071.
 783 doi:10.1029/95WR00976
 784 Nelson, J.M., Logan, B.L., Kinzel, P.J., Shimizu, Y., Giri, S., Shreve, R.L., McLean, S.R., 2011. Bedform
 785 response to flow variability. *Earth Surface Processes and Landforms* 36, 1938–1947.
 786 doi:10.1002/esp.2212
 787 Nelson, P.A., 2010. Bed Surface Patchiness in Gravel-Bed Rivers. Ph.D. thesis, University of California,
 788 Berkeley, California.

789 Nelson, P.A., Venditti, J.G., Dietrich, W.E., Kirchner, J.W., Ikeda, H., Iseya, F., Sklar, L.S., 2009. Response
790 of bed surface patchiness to reductions in sediment supply. *J. of Geophys. Res.* 114, F02005,
791 <http://dx.doi.org/10.1029/2008JF001144>.

792 Nelson, P. A., Dietrich, W. E., Venditti, J. G., 2010. Bed topography and the development of forced bed
793 surface patches. *J. Geophys. Res.* 115, F04024, doi:10.1029/2010JF001747

794 Nelson P.A., Bellugi, D., Dietrich, W.E., 2014. Delineation of river bed-surface patches by clustering high-
795 resolution spatial grain size data. *Geomorphology*. 205, 102-119.

796 Nezu, I., Rodi, W., 1986. Open-channel flow measurements with a laser doppler anemometer. *Journal of*
797 *Hydraulic Engineering* 112, 335–355.

798 Nezu, I., Sanjou, M., 2008. Turbulence structure and coherent motion in vegetated canopy open-channel
799 flows. *Journal of Hydro-environment Research* 2, 62–90. doi:10.1016/j.jher.2008.05.003

800 Nikora, V., Habersack, H., Huber, T., McEwan, I., 2002. On bed particle diffusion in gravel bed flows
801 under weak bed load transport. *Water Resources Research* 38, 17–1–17–9.
802 doi:10.1029/2001WR000513

803 Nitsche, M., Rickenmann, D., Turowski, J.M., Badoux, A., Kirchner, J.W., 2011. Evaluation of bedload
804 transport predictions using flow resistance equations to account for macro-roughness in steep
805 mountain streams. *Water Resources Research* 47. doi:10.1029/2011WR010645

806 Ockelford, A.M., Haynes, H., 2013. The impact of stress history on bed structure. *Earth Surface Processes*
807 *and Landforms* 38, 717–727. doi:10.1002/esp.3348

808 Papanicolaou, A.N., Diplas, P., Dancey, C.L., Balakrishnan, M., 2001. Surface Roughness Effects in Near-
809 Bed Turbulence: Implications to Sediment Entrainment. *Journal of Engineering Mechanics* 127,
810 211–218. doi:10.1061/(ASCE)0733-9399(2001)127:3(211)

811 Papanicolaou, A., Diplas, P., Evaggelopoulos, N., and Fotopoulos, S., 2002. Stochastic Incipient Motion
812 Criterion for Spheres under Various Bed Packing Conditions. *J. Hydraul. Eng.* 128, 369-380.

813 Parker, G., 1990. Surface-based bedload transport relation for gravel rivers, *J. of Hydraul. Eng.* 28, 417–
814 436.

815 Parker, G., Klingeman, P.C., 1982. On why gravel bed streams are paved. *Water Resour. Res.* 18,
816 1409– 1423.

817 Parker, G., Toro-Escobar, C.M., 2002. Equal mobility of gravel in streams: The remains of the day. *Water*
818 *Resour. Res.* 38, 1264, doi:10.1029/2001WR000669.

819 Parker, G., Dhamotharan, S., Stefan, H., 1982. Model experiments on mobile, paved gravel bed streams.
820 *Water Resources Research* 18, 1395-1408.

821 Parker, G., Hassan, M., Wilcock, P., 2007. Adjustment of the bed surface size distribution of gravel-bed
822 rivers in response to cycled hydrographs. In: Habersack, H., Piégay, H., Rinaldi, M. (Eds.), *Gravel*
823 *Bed Rivers* 6. Elsevier, Amsterdam, The Netherlands, pp. 241-289.

824 Piedra, M.M., Haynes, H., Hoey, T.B., 2012. The spatial distribution of coarse surface grains and the
825 stability of gravel river beds. *Sedimentology* 59, 1014-1029.

826 Rice, S. P., Church, M., 1996. Sampling fluvial gravels: Bootstrapping and the precision of size
827 distribution percentile estimates. *J. Sediment. Res.* 66 (3), 654–665.

828 Rickenmann, D., 1994. An alternative equation for the mean velocity in gravel-bed rivers and mountain
829 torrents. In Cotroneo, V and Rumer, R.R., editors. *Proceedings of Hydraulic Engineering '94*, Vol.
830 1, American Society of Civil Engineers, New York, pp. 672-676.

831 Rickenmann, D., Recking, A., 2011. Evaluation of flow resistance in gravel-bed rivers through a large field
832 dataset. *Water Resour. Res.* 47, W07538. doi: 10.1029/2010WR009793.

833 Roseberry, J.C., Schmeeckle, M.W., Furbish, D.J., 2012. A probabilistic description of the bed load
834 sediment flux: 2. Particle activity and motions. *Journal of Geophysical Research* 117.
835 doi:10.1029/2012JF002353

836 Rubin, D. M., 2004. A simple autocorrelation algorithm for determining grain size from digital images of
837 sediment. *J. Sediment. Res.* 74, 160–165.

838 Ryan, S. E., Emmett, W.W., 2002. The nature of flow and sediment movement in Little Granite Creek
839 near Bondurant, Wyoming, U.S. Forest Service General Technical Report, RMRS-GTR-90, 46 pp.

840 Ryan, S.E., Porth, L.S., and Troendle, C.A., 2002. Defining phases of bedload transport using piecewise
841 regression. *Earth Surf. Process. and Landforms* 27, 971–990. DOI: 10.1002/esp.387

842 Ryan, S.E., Porth, L.S., Troendle, C.A., 2005. Coarse sediment transport in mountain streams in Colorado
843 and Wyoming, USA. *Earth Surf. Process. and Landforms* 30, 269-288.

844 Schmeeckle, M.W., Nelson, J.M., 2003. Direct numerical simulation of bedload transport using a local,
845 dynamic boundary condition. *Sedimentology* 50, 279–301. doi:10.1046/j.1365-
846 3091.2003.00555.x

847 Schmeeckle, M.W., Nelson, J.M., Shreve, R.L., 2007. Forces on stationary particles in near-bed turbulent
848 flows. *J. Geophys. Res.* 112. doi:10.1029/2006JF000536

849 Schott, H.E., Yager, E.M., 2012. An investigation into the turbulence parameter responsible for the onset
850 of grain motion, *Eos, Transactions, American Geophys. Union*, Fall Meeting Suppl.

851 Shields, A., 1936. Anwendung der Aehnlichkeitsmechanik und der Turbulenzforschung auf die
852 Geschiebebewegung. *Mitteilungen der Preußischen Versuchsanstalt für Wasserbau* (in German)
853 26. Berlin.

854 Singh, A., Foufoula-Georgiou, E., Porté-Agel, F., Wilcock, P.R., 2012. Coupled dynamics of the co-
855 evolution of gravel bed topography, flow turbulence and sediment transport in an experimental
856 channel. *Journal of Geophysical Research* 117. doi:10.1029/2011JF002323

857 Sklar, L.S., and Dietrich, W.E., 2004. A mechanistic model for river incision into bedrock by saltating bed
858 load. *Water Resour. Res.* 40. doi:10.1029/2003WR002496

859 Sklar, L.S., Dietrich, W.E., 2001. Sediment and rock strength controls on river incision into bedrock.
860 Geology 29, 1087-1090.

861 Sklar, L. S., Fadde, J., Venditti, J.G., Nelson, P., Aleksandra Wydzga, M., Cui, Y., Dietrich, W.E., 2009.
862 Translation and dispersion of sediment pulses in flume experiments simulating gravel
863 augmentation below dams. Water Resour. Res. 45, W08439.

864 Song, T., and Graf, W. H., 1995. Velocity and turbulence distribution in unsteady open-channel flows. J.
865 Hydraul. Eng. 122, 141-154.

866 Underwood, E., 2012. How to Build a Smarter Rock. Science 338, 1412–1413.
867 doi:10.1126/science.338.6113.1412

868 Valyrakis M., and Pavlovskis E., 2014. "Smart pebble" design for environmental monitoring
869 applications. EGU General Assembly 2014, Vienna, Austria, id.13731.

870 Valyrakis, M., Diplas, P., and Dancey C.L., 2011. Prediction of coarse particle movement with adaptive
871 neuro-fuzzy inference systems. Hydrological Processes 25 (22),3513-3524.
872 doi:10.1002/hyp.8228.

873 Valyrakis, M., Diplas, P., and Dancey C. L. (2013), Entrainment of coarse particles in turbulent flows: An
874 energy approach. J. Geophys. Res. Earth Surf. 118, 42-53. doi:10.1029/2012JF002354.

875 Venditti, J.G., Dietrich, W.E., Nelson, P.A., Wydzga, M.A., Fadde, J., Sklar, L., 2010a. Effect of sediment
876 pulse grain size on sediment transport rates and bed mobility in gravel bed rivers. Journal of
877 Geophysical Research 115. doi:10.1029/2009JF001418

878 Venditti, J. G., Dietrich, W. E., Nelson, P. A., Wydzga, M. A., Fadde, J., Sklar, L., 2010b. Mobilization of
879 coarse surface layers in gravel-bedded rivers by finer gravel bed load. Water Resour. Res. 46,
880 W07506, doi:10.1029/2009WR008329

881 Venditti, J.G., Nelson, P.A., Minear, J.T., Wooster, J., Dietrich, W.E., 2012. Alternate bar response to
882 sediment supply termination. *Journal of Geophysical Research* 117. doi:10.1029/2011JF002254

883 Verdú, J.M., Batalla, R.J., Martínez, J.A., 2005. High-resolution grain-size characterization of gravel bars
884 using imagery analysis and geo-statistics. *Geomorphology*. 72, 73-93.

885 Warrick, J.A., Rubin, D.M., Ruggiero, P., Harney, J.N., Draut, A.E., Buscombe, D., 2009. Cobble cam: grain-
886 size measurements of sand to boulder from digital photographs and autocorrelation analyses.
887 *Earth Surface Processes and Landforms*. 34, 1811–1821.

888 Wiberg, P.L., Smith, J.D., 1987. Calculations of the Critical Shear Stress for Motion of Uniform and
889 Heterogeneous Sediments. *Water Resources Research* 23.

890 Wilcock, P. R., Crowe, J. C., 2003. Surface-based transport model for mixed-size sediment. *J. of Hydraul.*
891 *Eng.* 129, 120–128

892 Wilcock, P.R., McArdell, B.W., 1997. Partial transport of a sand/gravel sediment. *Water Resources*
893 *Research* 33, 235–245. doi:10.1029/96WR02672

894 Wilcock, P.R., Southard J.B., 1988. Experimental Study of Incipient Motion in Mixed-Size Sediment.
895 *Water Resources Research* 24.

896 Wilcock, P. R., Kenworthy, S.T., Crowe, J.C., 2001. Experimental study of the transport of mixed sand and
897 gravel. *Water Resour. Res.* 37, 3349-3358.

898 Wu, F.-C., Shih, W.-R., 2012. Entrainment of sediment particles by retrograde vortices: Test of
899 hypothesis using near-particle observations. *Journal of Geophysical Research* 117.
900 doi:10.1029/2011JF002242

901 Yager, E.M., Kirchner, J.W., Dietrich, W.E., 2007. Calculating bed load transport in steep boulder bed
902 channels. *Water Resources Research* 43. doi:10.1029/2006WR005432

903 Yager, E.M., Dietrich, W.E., Kirchner, J.W., McArdell, B.W., 2012a. Prediction of sediment transport in
904 step-pool channels. *Water Resources Research* 48. W01541. doi:10.1029/2011WR010829

905 Yager, E.M., Dietrich, W.E., Kirchner, J.W., McArdell, B.W., 2012c. Patch dynamics and stability in steep,
906 rough streams. *Journal of Geophysical Research* 117. F02010. doi:10.1029/2011JF002253
907

908 Yager, E.M., Turowski, J.M., Rickenmann, D., McArdell, B.W., 2012b. Sediment supply, grain protrusion,
909 and bedload transport in mountain streams. *Geophysical Research Letters* 39.
910 doi:10.1029/2012GL051654

911 Yager, E.M., Schmeeckle, M.W., 2013. The influence of vegetation on turbulence and bed load transport.
912 *Journal of Geophysical Research: Earth Surface* 118, 1585–1601. doi:10.1002/jgrf.20085

913 Yen, C., Lee, K.T., 1995. Bed Topography and Sediment Sorting in Channel Bend with Unsteady Flow.
914 *Journal of Hydraulic Engineering* 121, 591-599.

915 Young, W. J., Davies, T. R. H., 1991. Bedload transport processes in a braided gravel-bed river model.
916 *Earth Surface Processes and Landforms* 16, 499-511.

917 Zimmermann, A., 2010. Flow resistance in steep streams: an experimental study. *Water Resour. Res.* 46:
918 W09536. doi: 10.1029/2009WR007913.

919 Zimmermann, A.E., Church, M. and Hassan, M.A., 2008. Video-based gravel transport measurements
920 with a flume mounted light table, *Earth Surface Processes and Landforms*. 33: 2285–2296. doi:
921 10.1002/esp.1675

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List of Figures

Fig. 1. (A) Image from one frame of a high-speed video of sand transport through cylinders. Flow is from right to left. (B) Corresponding difference between two frames in the video where white areas represent locations in which sand grains have moved. (C) Total bedload fluxes from the video measurements that have been calibrated to individual counts of mobile sand grains. (D) Example of travel paths of individual sand grains that were recorded in a high-speed video. Figure 1D has been reproduced from Roseberry et al. (2012). Copyright 2012 American Geophysical Union. Reproduced/modified by permission of the American Geophysical Union.

Fig. 2. (A) Example of the three different components of acceleration measured with an accelerometer embedded in a mobile particle. The time of grain motion through rolling is when all sensors change from static conditions. (B) A test particle that is instrumented with seven micropressure sensors and sits on three force sensors. (C) Example differences between upstream and downstream pressure ports ($\sim$ drag force) and between bottom and top pressure ports ($\sim$ lift force) installed in a mobile test grain. Fluctuations in pressure are driven by turbulence around the grain.

Fig. 3. Repeat sonar scans of a sand bed in the outdoor stream lab at Saint Anthony Falls Laboratory. Each different figure represents a successive scan through time. Approximate locations of a dune crest at each time step are identified by black lines.

Fig. 4. (A) Hillshade DEM obtained from laser altimeter scans, (B) and individual grain outlined from the DEM. Figure partially reproduced from Nelson et al., 2014. Copyright © 2014 Elsevier Ltd. All rights reserved.

Fig. 5. Results from Hassan et al. (2006) showing varying armor response to symmetrical and asymmetrical hydrographs and steady flows. Circled data points highlight experiments with similar effective total stream power but differing final armor ratios. Copyright 2006 American Geophysical Union. Reproduced/modified by permission of the American Geophysical Union.

Fig. 6. Impacts of experimental hydrographs on bedload transport rates (q_s) and transported grain sizes (D_t) (top row) and grain size of the bed surface (D_s) (bottom row) for higher peak (left side) and lower peak hydrographs (right side). Rising and falling limbs are differentiated. Stars in (A) and (B) are transport rates from steady flow experiments of Mao et al. (2011). Bedload transport rates are higher on the rising limb of the hydrographs than steady flow. Transport rates show clockwise hysteresis while grain sizes show counterclockwise hysteresis. Reproduced/modified by permission of the American Geophysical Union.

Fig. 7. Cumulative quadrant fractions before and after grain motion (defined at shifted time = 0). Note that the peak in outward interactions occurs immediately before movement, whereas the spike in sweeps occurs immediately after. Figure reproduced from Wu and Shih (2012). Copyright 2012 American Geophysical Union. Reproduced/modified by permission of the American Geophysical Union.

Figure 1 (color)

Figure 2 (color)

Figure 3 (color)

Figure 7

Figure 1 (black and white)

Figure 2 (black and white)

Figure 3 (black and white)

Figure 4

Figure 5

Figure 6 (Black and White)

Figure 7 (black and white)

Figure 8