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

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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.

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

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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 (ADVs) 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 (ADCPs) can provide flow measurements that are relatively close to the bed, although many 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.

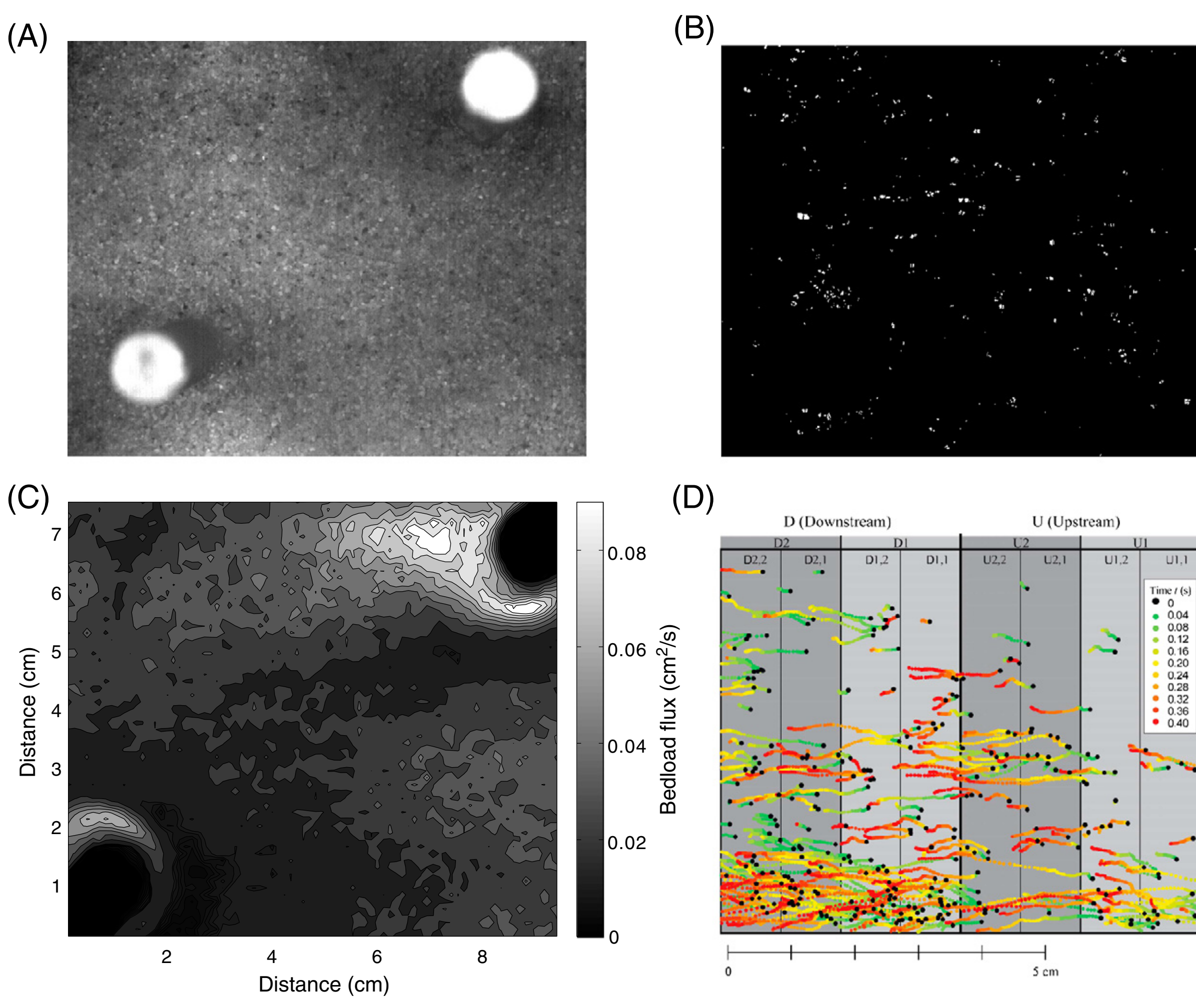

Fig. 1. (A) Image from one frame of a high-speed video of sand transport through cylinders. Flow is from the right to left. (B) Corresponding difference between two frames in the video where white areas represent the locations in which sand grains have moved. (C) Total bedload fluxes from the video measurements 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.
Panel D has been reproduced from Roseberry et al. (2012).