Field and Flume Investigations of Bedload Transport and Bedforms in Sand-Bedded Rivers

by

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ABSTRACT

Worldwide, rivers and streams make up dense, interconnected conveyor belts of sediment—removing carved away earth and transporting it downstream. The propensity of alluvial river beds to self-organize into complex trains of bedforms (i.e. ripples and dunes) suggests that the associated fluid and sediment dynamics over individual bedforms are an integral component of bedload transport (sediment rolled or bounced along the river bed) over larger scales. Generally speaking, asymmetric bedforms (such as alluvial ripples and dunes) migrate downstream via erosion on the stoss side of the bedform and deposition on the lee side of the bedform. Thus, the migration of bedforms is intrinsically linked to the downstream flux of bedload sediment. Accurate quantification of bedload transport is important for the management of waters, civil engineering, and river restoration efforts. Although important, accurate qualification of bedload transport is a difficult task that continues to elude researchers. This dissertation focuses on improving our understanding and quantification of bedload transport on the two spatial scales: the bedform scale and the reach (∼100m) scale.

Despite a breadth of work investigating the spatiotemporal details of fluid dynamics over bedforms and bedload transport dynamics over flat beds, there remains a relative dearth of investigations into the spatiotemporal details of bedload transport over bedforms and on a sub-bedform scale. To address this, we conducted two sets of flume experiments focused on the two fundamental regions of flow associated with bedforms: flow separation/reattachment on the lee side of the bedform (Chapter 1; backward facing-step) and flow reacceleration up the stoss side of the next bedform (Chapter 2; two-dimensional bedform). Using Laser and Acoustic Doppler Velocimetry to record fluid turbulent events and manual particle tracking of high-speed imagery to record bedload transport dynamics, we identified the existence and importance of permeable splat events in the region proximal to flow reattachment.
These coupled turbulent and sediment transport events are integral to the spatiotemporal pattern of bedload transport over bedforms. Splat events are localized, high magnitude, intermittent flow features in which fluid impinges on the bed, infiltrates the top portion of bed, and then exfiltrates in all directions surrounding the point of impingement. This initiates bedload transport in a radial pattern. These turbulent structures are primarily associated with quadrant 1 and 4 turbulent structures (i.e. instantaneous fluid fluctuations in the streamwise direction that bring fluid down into the bed in the case of quadrant 1 events, or up away from the bed in the case of quadrant 4 events) and generate a distinct pattern of bedload transport compared to transport dynamics distal to flow reattachment. Distal to flow reattachment, bedload transport is characterized by relatively unidirectional transport. The dynamics of splat events, specifically their potential for inducing significant magnitudes of cross-stream transport, has important implications for the evolution of bedforms from simple, two dimensional features to complex, three-dimensional features.

New advancements in sonar technology have enabled more detailed quantification of bedload transport on the reach scale, a process paramount to the effective management of rivers with sand or gravel-dominated bed material. However, a practical and scalable field methodology for reliably estimating bedload remains elusive. A popular approach involves calculating transport from the geometry and celerity of migrating bedforms, extracted from time-series of bed elevation profiles (BEPs) acquired using echosounders. Using two sets of repeat multibeam sonar surveys from the Diamond Creek USGS gage station in Grand Canyon National Park with large spatio-temporal resolution and coverage, we compute bedload using three field techniques for acquiring BEPs: repeat multi-, single-, and multiple single-beam sonar. Significant differences in flux arise between repeat multibeam and single beam sonar. Multibeam and multiple single beam sonar systems can potentially yield comparable
results, but the latter relies on knowledge of bedform geometries and flow that collectively inform optimal beam spacing and sampling rate. These results serve to guide design of optimal sampling, and for comparing transport estimates from different sonar configurations.
To my mom, Cathy—
You are, and always have been, the greatest role model.

To my dad, Chris—
Thanks for the geology genes and the mind like steel wool.

To Beth and Laura—
Thank you for the endless laughter, inspiration, and support.

To Ryan—
You are my rock, pun intended.
“A creek, given its visual complexity, is a surprisingly simple construction.

Two nouns: Water and Land. One verb: Gravity.

Plant and animal life, growth and decay, the play of light on the water, the visual and liturgical improvisations of current, all obscure the simplicity. But the grammar of creeks is the antithesis of complex. The instant it alights on Earth, the first noun—Water—is turned by the verb, Gravity, into a ceaseless search for the lowest possible place while the second noun, Land, does all in its passive power to thwart that search. The result? Riffle; rapid; eddy; pool; souring sand; sculptured wood and rock; soil-making mud; insects; birds; fish; ar-ka; endless music; sustenance; life.”

—David James Duncan, My Story as Told by Water
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Chapter 1

INTRODUCTION

Rivers are the primary sculptors of Earth’s unglaciated landscapes despite widespread morphological variability in different geologic settings, climatic zones, and geographic locations. Worldwide, rivers and streams act as dense, interconnected conveyor belts that transport sediment from its weathering source to its ultimate archive in the sedimentary record. The mechanics of fluvial sediment transport have been a topic of scientific interest for centuries (Leslie, 1823; Hopkins, 1844; Lechalas, 1871; Gilbert, 1877; Gilbert and Murphy, 1914). Yet despite a rich history of scientific inquiry, many details of fluvial sediment transport remain unknown and/or difficult to quantify (Ancey and Heyman, 2014; Best, 2005).

Development of, and access to, reliable, quantitative approaches of calculating sediment transport impacts on how civil engineers, federal agencies, and land managers calculate and respond to sediment budgets within rivers. For example, an accurate characterization of bedload transport by the Colorado River in the Grand Canyon is essential to the National Park Service and Bureau of Reclamation in managing that waterway. Maintaining a minimum sediment flux in that system is vital to maintaining the river beaches essential to the outdoor recreation industry and riparian ecosystems. This dissertation focusses primarily on the details of bedload transport (sediment rolled or bounced in close proximity to the river bed) and associated bedforms on multiple spatial and temporal timescales and aims to establish a more comprehensive view of bedload transport in sand-bedded systems.
1.1 The Development, Role, and Dynamics of Bedforms

Organization of bed sediment into patterns is a virtually ubiquitous phenomenon in alluvial channels. A planar, alluvial-covered riverbed can deform into a wavey morphology due to pre-existing defects on the bed, such as isolated stone, woody debris, or protruding banks (Venditti et al., 2005, 2006). Flow separation over the downstream portion of the defect causes sand waves to propagate downstream (Raudkivi, 1963, 1966). Not all bedforms, however, originate due to pre-existing bed defects. Bedforms can also originate instantaneously over the entirety of the bed without an obvious initiating bed defect.

The dynamics of how bedforms develop without an obvious initiating bed defect is a topic of much debate. One possible explanation is that micro-turbulent structures generate small scale defects on the bed that are then amplified and propagated downstream to form larger waveforms (Grass, 1970; Williams and Kemp, 1971). Some researchers have argued (see Venditti et al. 2005, 2006) that this explanation seems unlikely, however, due to the highly variable spatial and temporal nature of turbulent flow (Nezu and Nakagawa, 1993; Ashworth et al., 1996). Additionally, bedforms can develop in laminar flow (Kuru et al., 1995; Coleman and Eling, 2000). A second possible explanation is that waveforms develop due to a phase-lag between near-bed shear stress and resulting bedload transport. This phase-lag generates an instability with a preferred wavelength that propagates downstream as waveforms (Engelund and Fredsoe, 1982; Charru, 2006; Kidanemariam and Uhlmann, 2014a). A third potential explanation, proposed by Coleman and Nikora (2009), is that seed waves (initial, regular bedforms) are caused by interacting patches of bed sediment. When interacting patches of sediment generate a sufficient bed disturbance, the disturbance will accumulate sediment and propagate downstream. A fourth explanation,
proposed by Venditti et al. (2006), states that when flow is sufficiently vigorous so as to entrain sediment over the entirety of the bed (i.e. transport is not spatially or temporally intermittent), the resultant bedload transport layer acts as a continuous medium and causes an interfacial hydrodynamic instability of Kelvin-Helmholtz type. This instability generates local erosion and deposition of sediment, which produces migrating waveforms that scale with the heights of both fluid layers. Over time, these waveforms develop into a field of bedforms (Venditti et al., 2006).

Regardless of the explanation of how waveforms/seed waves are initiated, this undulatory pattern grows to form ripples or dunes depending on the sediment and the flow (Venditti et al., 2005; Coleman and Nikora, 2009; Kidanemariam and Uhlmann, 2014a, 2017). In unidirectional flow, both ripples and dunes have a characteristic asymmetric geometry constructed of a long, low-angle stoss side and a short, high angle lee side (Figure 1.1A). Bedforms such as ripples and dunes migrate downstream via a combination of relative erosion and deposition, wherein sediment is eroded from the stoss side of the bedform and deposited on the lee side. This produces a downstream bedload flux that is dependent on the bedform migration rate and bedform geometry (Figure 1.1A).

In addition to conveying bedload downstream, bedforms fundamentally change the overriding turbulent fluid field (Figure 1.1B). As flow approaches the inclined stoss side of a bedform, near-bed streamwise flow accelerates reaching a maximum velocity near the crest of the bedform. This increase in fluid velocity is spatially coincident with region of the bedform that is eroding sediment and the interaction of the micro-turbulent structures within this accelerating flow with the bed are the mechanism by which sediment becomes entrained. At the crest of the bedform, flow separates from the bed and reattaches ∼4-6 step heights (distance downstream/bedform height; Engel, 1981). This generates a zone of fluid recirculation on the lee side of the
bedform, upstream of flow reattachment. This zone of de-accelerated fluid and fluid recirculation is spatially coincident with the portion of the bedform that is depositing sediment. Downstream of flow reattachment, fluid accelerates up the stoss side of the bedform and the process repeats.

Bedforms also play a pivotal role in stratigraphic record and in determining paleohyrdologic conditions. As bedforms translate downstream, scour on the lee side produces an erosional surface that is often preserved in the rock record (e.g. Sorby 1859, 1908; Allen 1963a,b, 1968, 1970; Brookfield 1977; Hunter 1977b,a; Rubin and Hunter 1982; Rubin 1987; Paola and Borgman 1991; Leclair 2002; Ganti et al. 2013). Preserved material between successive erosional surfaces produces cross-stratified units. Generally speaking, the thickness of cross-stratified units is dependent on the spatiotemporal variability in bedform geometry, bedform migration rate, and bed aggradation rate (Jerolmack and Mohrig, 2005a). As such, distributions of the thickness of cross-set beds can be used to infer water depth at the time of deposition (Yalin, 1964; Allen, 1970). Using this information, we can reconstruct estimates of paleochannel depth and width (Bridge and Tye, 2000).

Due to their ubiquity and their role in the downstream transport of sediment, understanding the spatiotemporal details of transport over bedforms is paramount to understanding and quantifying bedload transport in river systems. However, in a comprehensive review of the fluid dynamics over bedforms, Best (2005) demonstrated that our understanding of sediment transport over alluvial bedforms remains approximate at best. In part, this lack of understanding of sediment transport over bedforms stems from the fact that most studies investigating bedform dynamics focus almost entirely on the fluid dynamics rather than the sediment dynamics (McLean et al., 1994; Bennett and Best, 1995; Nelson et al., 1995; Venditti and Bennett, 2000; Venditti and Bauer, 2005; Fernandez et al., 2006; Venditti, 2007; Keylock et al., 2014;
Schmeeckle, 2015). These studies have produced a detailed, yet still incomplete, understanding of the micro-turbulent structures over two-dimensional (i.e. planar crest) bedforms, but the equivalent understanding of transport patterns remains relatively unexplored (Ancey and Heyman, 2014; Leary and Schmeeckle, 2017).

Characterization of micro-turbulent structures over bedforms is important in order to understand transport dynamics. A standard procedure for describing fluid flow is to decompose fluid velocities to fluctuations about the mean (i.e. $u'_i = u_i - \bar{u}_i$) in two-dimensions ($i = x$ and $i = z$) or in three-dimensions ($i = x$, $i = z$, and $i = y$). Fluid fluctuations are then paired to create quadrants (2D) or octants (3D; Table 1.1), where each octant/quadrant represents an instantaneous direction of fluid flow at the point of measurement (Madden Jr, 1997; Lu and Willmarth, 1973). Consider the two-dimensional case depicted in Figure 1.2: if a parcel of fluid located at the star in the center of the plot experiences a quadrant 1 event, that parcel of fluid would move up away from the bed in the streamwise direction. Conversely, if that parcel of fluid experienced a quadrant 4 event, it would fluctuate down towards to bed in the streamwise direction. Characterizing the flow as quadrants/octants allows us to investigate which micro-scale turbulent structures play the largest role in sediment transport.

It is well established that quadrant 1 and 4 events contribute significantly to sediment entrainment downstream of flow reattachment. Numerous investigations of the turbulence structure over fixed, two-dimensional bedforms observe the importance of quadrant 4 events near flow reattachment as significant contributors to the local Reynolds stress and sediment entrainment (McLean et al., 1994; Bennett and Best, 1995; Nelson et al., 1995; Robert and Uhlman, 2001; Ojha and Mazumder, 2008). Numerous studies also indicate that, in addition to quadrant 4 events, quadrant 1
events play an important role in entrainment near flow reattachment (McLean et al., 1994; Bennett and Best, 1995; Schmeeckle, 2015).

Although quadrant 1 and 4 events have been characterized as contributors to sediment entrainment, the pattern of the resulting transport has been relatively unexplored. Most studies investigating sub-bedform turbulent structures relate those turbulent structures to sediment transport on only the most basic of levels (i.e. do they contribute to the initiation/continuation of transport or not?). In their analysis of numerical simulations of turbulence in the ripple to dune transition, Robert and Uhlman (2001) remarked that turbulent field properties over dunes are highly dependent on location along the bed surface. Additionally, they noted that these fields are highly variable both spatially and temporally. If the flow field above bedforms varies spatially with distance along the bedform and temporally as bedforms migrate, should we not also see a similar complexity in entrainment and transport?

Significant advancements in our understanding of the grain-scale spatiotemporal details of bedload entrainment and transport over flat beds have been made in recent years (Roseberry et al., 2012; Furbish et al., 2012; Radice et al., 2013; Heyman et al.,

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**Table 1.1: Summary of Quadrants and Octants**

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</table>

*Modified from Keylock et al. [2014]*
2014; Aney and Heyman, 2014; Schmeeckle, 2014; Ballio and Radice, 2015; Fathel et al., 2015, 2016). These studies highlight that recent technological advancements improvements of high-speed imagery, development of semi-automatic and automated particle tracking, and improvements in numerical simulations of transport allow for more detailed investigations into grain-scale transport dynamics and patterns. Harnessing these technological advances to specifically investigate the spatiotemporal patterns of bedload transport over bedforms, rather than flat bed scenarios, and to correlate those patterns of transport with turbulent structures is necessary in order to generate more accurate theories and equations for bedload transport.

1.2 Reach Scale Bedload Transport

Field studies of alluvial rivers rarely focus on the bedform scale, but rather investigate sediment load on the reach scale. The spatial definition of a reach depends on the river, but is loosely defined as an uninterrupted (i.e. no rapids or riffles) portion of the river. In this dissertation, the term reach refers to a stretch of river ~100-150m long. The utility of bedload transport equations often rests on their applicability to the reach-scale. It is therefore important to relate sub-bedform scale bedload dynamics to reach-scale bedload calculations. In order to bridge this spatial resolution gap, synthesis of experimental and numerical data with high-resolution field data is necessary and, with new advancements in sonar-sampling systems for rivers, collecting data with requisite spatial and temporal resolution is now possible.

A current popular method for calculating bedload transport rates on the reach-scale relates bedform geometry and bedform celerity to calculate sediment flux (Simons et al., 1965). This method relies on the availability of bed elevation profiles (BEPs) and has grown in popularity recently with the rise of higher precision echosounders that allow for varying degrees of spatial and temporal observation of
the river bed. Repeat multi-beam sonar systems produce high-resolution bed elevation maps through time (Figure 1.3A) generating uniquely spatially and temporally detailed datasets. These systems are quite expensive, however, and are only effective on large rivers. Single beam echosounders in contrast record bed elevation at a single point through time (Figure 1.3B). These devices are relatively inexpensive and can be mounted to a permanent structure, such as a bridge, and left to collect data for long periods of time. Multiple single beam echosounders are similar to SB in that they record bed elevation through time but differ in that they have multiple beams for slightly increased spatial resolution (Figure 1.3C).

These types of high spatial and temporal resolution datasets could prove valuable in the effort to bridge the gap between bedform-scale observation and reach-scale calculations of bedload transport. It is unclear, however, whether these different sampling methodologies provide accurate estimates of bedload transport. Before we can begin assessing strategies to bridge the spatial scale gap using echosounder data, we need to first calibrate our sampling methodologies. In doing so, we can greatly improve our field measurements of bedload transport, which is of great import to civil engineers, federal and state agencies, and land managers.

1.3 Outline of Dissertation

This dissertation focuses on the details of bedload transport on two spatial scales—the sub-bedform scale and the reach scale—to shed light on elusive aspects of bedload transport. Chapters 2 and 3 zoom in to the sub-bedform scale and investigate turbulent structures and bedload transport patterns associated with flow-separation/reattachment (Chapter 2) and flow re-acceleration (Chapter 3) in two sets of flume experiments: downstream of a backward-facing step (Chapter 2) and over stationary ripples (Chapter 3). Combining high-speed imagery, semi-automated
particle tracking, acoustic and laser doppler velocimetry, and numerical simulations (Chapter 2; Schmeeckle, 2015), I aim to identify distinct patterns of transport along bedforms and couple those transport patterns with fluid flow fluctuations.

Chapter 4 is an investigation of bedload transport on the reach-scale. Bedload transport is notoriously difficult to calculate and even methodologies that use state-of-the-art instrumentation (i.e. repeat multibeam, single beam, and multiple single beam sonar) are un-tested in terms of their relative accuracy to one another. In this chapter, I use two repeat multibeam sonar data sets from the USGS Diamond Creek gage site on the Colorado River in Grand Canyon National Park to test the relative accuracy of each of the above types of sampling systems and provide practical guidelines for sampling using sonar systems in future investigations. Advancements in our ability to image the bed of a river through time have immense potential for bridging the gap between experimental (i.e. bedform and grain scale investigations) and field (i.e. reach scale) investigations. In this chapter, I establish the potential error introduced by different sonar sampling systems and suggest strategies for future investigations. This is an important first step towards applying this data toward multi-scale formulations of bedload transport.

Chapter 5 includes a summary of the major findings and contributions of chapters 2-4 followed by a discussion of unanswered questions and future directions of research.

1.4 Scientific and Practical Impact of Dissertation

Accurate quantification of bedload transport on the sub-bedform and reach-scales is paramount to scientific inquiries into the dynamics of river systems as well as to the management of waterways by civil engineers, federal and state agencies, and land managers. This dissertation impacts the scientific and waterway management communities in the following ways:
1. A more comprehensive understanding of bedload transport over bedforms is necessary in order to generate more accurate theories and equations for bedload transport that can be applied to larger scales.

2. Detailed observation of sub-bedform transport patterns provides insight into mechanisms driving the complex evolution of bedforms from two-dimensional to three-dimensional features. Establishing these mechanisms provides further understanding that can be applied to new theories and equations of bedload transport.

3. Establishing the potential error introduced by calculating bedload transport from different sonar sampling methodologies is necessary for accurate comparison of bedload transport estimates from site to site along a river system. Strategies suggested for future sonar system investigations allow for optimal data acquisition that can be reliably compared to bedload estimates from different sonar systems.

1.5 Publication Status and Contributing Authors

Chapter 2 was published in the Journal of Geophysical Research: Earth Surface (JGR:ES) in December 2017 with co-author Mark Schmeeckle (Leary and Schmeeckle, 2017). This publication can be found at https://doi.org/10.1002/2016JF004072. Chapter 3 is in preparation for submission to JGR:ES (estimated submission August 2018). Mark Schmeeckle is a co-author on this paper. Chapter 4 is currently in review at the Journal of Hydraulic Engineering. This paper is co-authored by Daniel Buscombe (Northern Arizona University). Matt Kaplinski, Bob Tusso, Erich Mueller, and Tom Ashley contributed significant field support. Dave Topping, Brandon McEl-
Flow and Sediment Dynamics
Over 2D Bedforms

Figure 1.1: Schematic of simplified flow dynamics over bedforms. Flow separates at the crest of each bedform and reattaches downstream. Recirculation of fluid occurs along the lee side of the bedform in the zone beneath the detached fluid. Upon reattachment, flow re-accelerates up the stoss side of the bedform.
Figure 1.2: Schematic of quadrant analysis.

Figure 1.3: Schematic of three common field methodologies for collecting bed elevation profiles (repeat multibeam, single beam, and multiple single beam) and the types of BEPs produced by each method.
Chapter 2

THE IMPORTANCE OF SPLAT EVENTS TO THE SPATIOTEMPORAL STRUCTURE OF NEAR-BED FLUID VELOCITY AND BEDLOAD MOTION OVER BEDFORMS: LABORATORY EXPERIMENTS DOWNSTREAM OF A BACKWARD-FACING STEP

Abstract

Flow separation/reattachment on the lee side of alluvial bedforms is known to produce a complex turbulence field, but the spatiotemporal details of the associated patterns of bedload sediment transported remain largely unknown. Here we report turbulence-resolving, simultaneous measurements of bedload motion and near-bed fluid velocity downstream of a backward-facing step in a laboratory flume. Two synchronized high-speed video cameras simultaneously observed bedload motion and the motion of neutrally buoyant particles in a laser light sheet 6 mm above the bed at 250 frames/s downstream of a 3.8 cm backward-facing step. Particle Imaging Velocimetry (PIV) and Acoustic Doppler Velocimetry (ADV) were used to characterize fluid turbulent patterns while manual particle tracking techniques were used to characterize bedload transport. Octant analysis, conducted using ADV data, coupled with Markovian sequence probability analysis highlights differences in the flow near reattachment versus farther downstream. Near reattachment, three distinct flow patterns are apparent. Farther downstream we see the development of a dominant flow sequence. Localized, intermittent, high-magnitude transport events are more apparent near flow reattachment. These events are composed of streamwise and cross-stream fluxes of comparable magnitudes. Transport pattern and fluid velocity data are consistent with the existence of permeable
“splat events”, wherein a volume of fluid moves toward and impinges on the bed (sweep) causing a radial movement of fluid in all directions around the point of impingement (outward interaction). This is congruent with flow patterns, identified with octant analysis, proximal to flow-reattachment.

2.1 Introduction

In low-gradient alluvial rivers, depositional bedforms (i.e. ripples and dunes) are ubiquitous—ranging in grain size from silt to gravel (Dinehart, 1992; Carling, 1999; Kleinhans, 2001; Kleinhans et al., 2002; Carling et al., 2005). These ubiquitous features can be quite complex, however, and this complexity helps further obfuscate our understanding of bedform dynamics. These complex dynamics are the result of, and a key boundary condition for, the bedload transport field.

The complexity of bedforms is apparent on large, multi-bedform scales in numerous ways. More often than not bedforms stray from the classically envisioned (i.e. simplified) two-dimensional, angle-of-repose bedform structure. Instead bedforms tend to manifest in more complex ways such as low-angle bedforms or with highly three-dimensional crescentic, barchanoid, or irregular planform geometries (Bagnold, 1941; Allen, 1966; Best, 2005; Venditti et al., 2005; Rubin, 2012). The presence of bedforms on a river bed causes mean flow characteristics, bed shear stresses, and turbulent flow structures to differ significantly from those over flat beds (Best, 2005). Low-angle dunes may have no, or intermittent flow separation (Kwoll et al., 2016). Adding to the complexity, bedforms are frequently changing in space and time due to translation and deformation. Translation refers to the mean streamwise movement of the bed, whereas, deformation is the change in the profile of a bedform in the translating frame of reference (McElroy and Mohrig, 2009). As bedforms deform spatially and temporally, so too do flow characteristics and near-bed shear stress distributions.
Thus, bedload transport in any natural system cannot be fully understood without a comprehensive understanding of near-bed velocity and bed shear stress distributions at the scale of a single bedform.

Even for the case of a non-deforming angle of repose bedform, the flow and bedload transport field is complex. The general features of flow over dunes (simplified from Best, 2005) is as follows: dune formation initiates flow separation on the lee side of the bedform; approximately 4-6 dune heights downstream, the flow reattaches (Engel, 1981). At this point, flow accelerates up the stoss side of the next bedform and reaches maximum streamwise velocity at the crest before separating and repeating the process (Figure 1A; Best, 2005).

Historically, these complexities of flow separation/reattachment and reacceleration have been dealt with by simply using spatial averages of mean flow characteristics (e.g. Smith and McLean, 1977) and standard bedload transport formulas that work best for uniform beds, such as the Meyer-Peter and Muller (MPM; 1948) equation (Wong and Parker, 2006). The MPM uses spatially averaged near-bed fluid velocities to calculate near-bed shear stress. This treatment of the inherent complexities of bedload transport over bedforms oversimplifies the problem and likely introduces sizeable error because mean flow characteristics change significantly spatially (Figure 1B).

Flow separation in the lee side of bedforms and flow reattachment and reacceleration on the stoss side of bedforms cause complex interactions between the flow, bedforms, and bedload sediment. Flow separation, re-attachment, and reacceleration change the overall spatial distribution of fluid velocities interacting with the bed (Best, 2005), which in turn changes the spatial distribution of shear-stress acting upon the bed (Figure 1B). Additionally, flow separation, re-attachment, and reacceleration change the temporal distribution of near-bed fluid velocities at any given distance
along the bedform profile (Figure 1C). Instead of being a narrow distribution that is characterized fairly well by the mean, flow separation and acceleration over bedforms increase the dispersion of the fluid velocity distribution and shear stress distributions (Figure 1C; Jovic and Driver 1994; Nelson et al. 1995; Le et al. 1997; Emadzadeh and Cheng 2016; Kwoll et al. 2016). Due to greater dispersion, it is possible to have both a mean shear stress that is below the critical shear stress as well as events that exceed that same critical shear stress (Figure 1C). This is a problem if one is using spatially or temporally averaged values and traditional bedload transport equations that rely on an average near-bed shear stress exceeding some theoretical critical shear stress to indicate initiation of transport. If we assume a steady flow and think of the profile of a bedform, as shown in Figure 1A, such an approach (i.e. near-bed shear stress exceeding the critical shear stress) only predicts transport on a portion of the stoss side of the bedform (Figure 1B).

Investigations into this oversimplification conducted by McLean et al. (1994, 1999) and Nelson et al. (1995), found that the spatial averaging approach was indeed misleading because bedload transport varied distinctly at different locations along the bedform. However, the alternative approaches presented, namely by McLean et al. (1999), suggested only using the portion of the dune where mean flow characteristics were similar to those of a uniform bed (i.e. at the dune crest) to estimate bedload transport. Although this kind of approach does eliminate some sources of error of spatial and temporal averaging methods, it does not provide a means of calculating the sediment transport rate at any location on a bedform. This local, sub-bedform sediment transport field is required to calculate the morphodynamics of bedforms using a suitable sediment continuity (Exner) equation.

Recent progress using turbulence- and particle-resolving numerical modeling of bedforms does not rely on bedload transport equations. Rather, only a force coupling
between particles and flow is needed. Finn et al. (2016) used a LES-DEM (large eddy simulation and distinct element method) to generate ripples under oscillatory waves. Kidanemariam and Uhlmann (2014a,b) used a fully resolved turbulence and DEM model to generate small ripples. As such their model did not require an empirical particle/fluid force relationship. Sun et al. (2016) used an LES-DEM model nearly identical to Schmeeckle (2014, 2015) model to generate bedforms in a unidirectional current. These important advances demonstrate that bedform generation directly from numerical simulation of turbulence and particle motion is now possible and a practical method for future investigations. However none of these studies provide a spatio-temporal analysis of the pattern of bedload transport.

Following the work of Nelson et al. (1995), we explore the sub-bedform scale by taking a piece-wise approach to understanding the complexities associated with bedload transport over bedforms. Rather than assessing both flow separation/reattachment and flow reacceleration simultaneously, the study outlined herein investigates only the effects of flow separation/reattachment on downstream fluid and sediment dynamics. Does flow separation and reattachment give rise to specific fluid and bedload characteristics that are distinct from those of flat beds? Nelson et al. (1995) first investigated the effects of flow separation and reattachment with a series of experiments that were conducted using a backward-facing step to initiate flow separation and in which bedload flux and flow velocities were measured at a series of distances downstream. Using quadrant analysis of flow velocity fluctuations, Nelson et al. (1995) demonstrated that near-bed shear stress could not fully account for the increase in transport downstream of the backward-facing step. However the mechanism responsible for this discrepancy remained unresolved.

The present study largely replicates the experiments of Nelson et al. (1995) using new technology and methodologies. In addition to comparing data to the results
of Nelson et al. (1995), experimental data are compared to numerical model results of Schmeeckle (2015) in which turbulence and bedload transport downstream of a backward facing step were modeled simultaneously using a LES-DEM. Our goal is to elucidate details of the temporal and spatial pattern of bedload transport downstream of reattaching flow.

2.2 Methods

2.2.1 Experimental

Experiments were conducted in an 8.5 x 0.3 m recirculating flume whose bed was lined with sheets of plastic upon which sand was glued. A slot was cut into the plastic sheet (approximately 40 x 25 cm) in which a mobile bed of sand was placed. The immobile and mobile sand was well sorted with a median diameter of 0.05 cm. Two synchronized high-speed video cameras operating at 250 frames/s simultaneously observed motion of the bedload, illuminated by high intensity LED lights, and the motion of neutrally buoyant particles illuminated by a laser light sheet parallel to and 6 mm above the mobile bed (Figure 2). The two high-speed cameras were synchronized so that the PIV camera triggered the bedload camera and the high intensity LED lights that illuminated the bed. This allowed for synchronous data acquisition of both the fluid and the bedload. The field of view for both cameras was approximately 36 cm$^2$ with a resolution of 1280 x 1024 pixels. Images were captured of the mobile bed area downstream of a 3.81 cm tall backward-facing step constructed of two 1.5 x 0.1905m steel plates placed on top of on another (Figure 2). The height of this backstep was chosen so as to produce flow separation at the scale of a ripple and to replicate, as near as possible, the experiments of Nelson et al. (1995). Synchronized cameras, LED lights, and the laser were held in a fixed position over
Table 2.1: Summary of experimental results.

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<th>Run</th>
<th>Distance Downstream (cm)</th>
<th>Distance Downstream (step heights)</th>
<th>$q_s$ (grains/cm²/sec)</th>
<th>$q_s$ (cm²/sec)</th>
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<td>15</td>
<td>3.93</td>
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</tr>
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</table>

the mobile bed section, while the backstep was moved varying distances upstream in the flume. Data were collected at 9 different distances downstream of the backward-facing step (Table 1). The flow depth over the test section ranged from 17.4-17.8 cm depending on the run. The 4 mm range in flow depths is most likely due to small disturbances on the water surface. Bedload consisted of uniform, medium-sized sand particles with the median grain size ($D_{50}$) of 0.05 cm. The sand used is filter grade such that all particle diameters are between 0.045 cm and 0.055 cm.

The following experimental procedure was used for each run: first, the backstep was set to the desired distance upstream of the field of view. With the flume off, sand was loaded to the mobile bed and screeded to be flush with the surrounding fixed bed. Once the mobile bed was planar, a sheet of Plexiglas with a centimeter ruler grid printed on it was placed on top the mobile bed so that the mobile bed would stay intact until the beginning of recording. The flume was turned on and the flow rate was gradually raised to approximately 0.015 m³/s. The speed of the electric motor pump is controlled by an inverter. The same volume of water was maintained in the tail tank to ensure that using an inverter rate of 54 Hz for each run would result in the same discharge. At the set discharge, a Plexiglas box was lowered within the flume to rest on the water surface above the mobile bed. This Plexiglas window provided
optimal image clarity by minimizing distortions caused by an irregular water surface. We do not expect this window to affect either the near-bed fluid flow or the bed itself because it was barely submerged in the water and was 17 cm above the area of interest. The cameras and LED lights, mounted to a stable platform, were then moved into place above this window. The bedload and PIV cameras were adjusted to maintain the same field of view and focused on the bedload grid and the neutrally buoyant particles, respectively. Once focused, an image of the Plexiglas grid was taken for the PIV post-processing. Once the computer interface was prepared for data acquisition, the Plexiglas grid was pulled from the mobile bed segment. As soon as the grid was completely removed from the mobile bed and the bed regained equilibrium, the PIV camera began recording; this triggered the bedload camera to begin recording. Run time ranged from 7.98 seconds (1997 images) to 19.65 seconds (4912 images) depending on the run.

One final run without mobile bedload was conducted in which Acoustic Doppler Velocimetry (ADV) data were collected at 25 distances downstream of the backstep at 5 cm intervals; each measurement was taken 1 cm above the bed for approximately 5 minutes. Data were recorded using a 200 Hz sampling rate, resulting in approximately 60,000 velocity readings per run. ADV correlation values, which are a measure of the signal quality in percentage, average 91.6%, 94.0%, and 91.0% for the velocities measured in the streamwise, cross-stream, and vertical directions, respectively. The mobile bed segment was replaced with an immobile bed (sheet of plastic upon which sand was glued) so as to avoid any scouring that may affect turbulence characteristics measured by the ADV. These data provide further streamwise, cross-stream, and vertical fluid velocity data. ADV was particularly useful in close proximity to the backstep where PIV was less accurate due to vertical fluid velocity fluxes moving neutrally buoyant particles in and out of the laser sheet.
Bedload movement analysis was conducted using bedload images and the open-source software ImageJ (discussed in detail in Section 2.3; Meijering et al. 2012). Bedload transport rates were acquired by manually tracking sand particles as they crossed a 6 cm line bisecting the field of view (discussed in detail in section 2.3). Particle imaging velocimetry (PIV) algorithms were applied to the laser sheet images to obtain two-dimensional field of two-dimensional vectors that describe fluid motions (discussed in detail in section 2.4).

To assess the effect of flow separation and reattachment on bedload transport, bedload transport is estimated as a function of near-bed shear stress and compared to measured values. Previous research has shown that common bedload transport equations, which are functions of boundary shear stress, work poorly in flows where the turbulence intensity is increased relative that found in flow over a flat boundary (Nelson et al., 1995; Sumer et al., 2003). Thus, agreement between these measured and calculated values of bedload transport are not expected, but the magnitude and spatial pattern of the discrepancy are expected to elucidate how transport differs downstream of the step relative to more simple flows.

In this subsection we compare measurements of bedload transport to bedload transport calculated using time-averaged measures of boundary shear stress. Experimentally observed bedload transport \(q_s\) was measured by tracking grains of sand as they passed over a 6 cm line in the middle of the field of view. For calculated bedload transport, we use the law of the wall to derive the temporally-averaged bed shear stress and a modified MPM equation from Wong and Parker (2006) to estimate bedload transport.
Does our technique work well using the law of the wall to relate mean velocity to stress? This technique does not rely on the profile from the bed to the point of measurement actually being logarithmic; rather the question is whether the relationship between mean velocity at the point of measurement and stress at the bed is nearly the same as that of the law of the wall. The DNS simulations of Le et al. (1997) and experiments of Jovic and Driver (1994) for flow over a backward-facing, smooth-walled step illustrate that the relationship between mean velocity and stress downstream of a backward-facing step is nearly the same as that of the law of the wall at certain points of measurement. Velocity profiles at varying distances downstream of a backward-facing step from Le et al. (1997) show a log-linear zone extending from approximately 10 to 100 wall units. Our estimates of \(u/u^*\) at 100 wall units (1 cm; Table 2) are in agreement with the log-linear zone outlined in Le et al. (1997). This log-linear zone, however, is somewhat suppressed below the standard law of the wall due to an adverse pressure gradient, with the percent error being approximately 17% (Le et al., 1997). We expect the possible percent error for the experiments presented herein to be similar to that of Le et al. (1997). Although there may be some error, using the law of the wall method for the experimental set-up presented herein should provide a reasonable estimate of the local, time-averaged boundary shear stress.

ADV data were used to predict bedload transport rates. ADV measurements yield time-averaged streamwise velocity values (\(\bar{u}\)) that can be used to derive near-bed shear stress using the following equations. Shear velocity (\(u^*\)) was calculated using the law of wall:

\[
\bar{u} = \frac{u^*}{k} \ln\left(\frac{z}{z_0}\right) \tag{2.1}
\]

where \(k\) is von Kármán’s constant (0.41), \(z\) is the distance above the bed (1 cm), and \(z_0\) is the distance from the boundary at which the idealized velocity given by the law of the wall goes to zero. The empirical fit of Duan (2004) to the data of Nikuradse
(1933) provides an estimate of this length scale:

\[ z_0 = D_{50} \left( 0.0275 - 0.007 \sqrt{\sin \left( \frac{R_e - 4}{4} \pi \right)} \right) \] (2.2)

where \( D_{50} \) is the median grain size (0.005 cm) and \( R_e \) is the boundary reynolds number. Equation 2 is applied to transitionally rough boundaries with \( R_e \) between 4 and 11. Equation (1) can be reorganized to solve for shear velocity:

\[ u_* = \frac{\bar{u} k}{\ln \left( \frac{z}{z_0} \right)} \] (2.3)

Using shear velocity acquired from equation (3), near bed shear stress \( (\tau_b) \) is calculated:

\[ \tau_b = \rho u_*^2 \] (2.4)

where \( \rho \) is fluid density. Near-bed shear stress is then non-dimensionalized:

\[ \tau_* = \frac{\tau_b}{(\rho_s - \rho)gD_{50}} \] (2.5)

Where \( \rho_s \) is the density of the sediment (2.65 g/cm\(^3\)), \( \rho \) is the density of the fluid (1 g/cm\(^3\)), and \( g \) is gravitational acceleration. Non-dimensional sediment transport \( (q_*) \) is solved for using a modified MPM equation from Wong and Parker (2006):

\[ q_* = 4.93(\tau_* - \tau_{*c})^{1.6} \] (2.6)

When, \( \tau_* > \tau_{*c} \). \( \tau_* \) is the non-dimensional near-bed shear stress and \( \tau_{*c} \) is the non-dimensional critical shear stress calculated from the Shield’s Diagram [Sheilds, 1936]. If \( \tau_* < \tau_{*c} \), \( q_* \) is expected to be zero. Calculated, dimensional bedload transport \( (q_{sm}; cm^2/sec) \) is calculated by:

\[ q_{sm} = q_* D_{50} \sqrt{\left( \frac{\rho_s - \rho}{\rho} \right)gD_{50}} \] (2.7)

Table 2 contains all values obtained through these calculations. Using data from Roseberry et al. (2012) in which bedload transport was observed over a flat bad in the
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<thead>
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<th>Distance Downstream (cm)</th>
<th>Distance Downstream (step heights)</th>
<th>$\bar{u}$ (cm/s)</th>
<th>$u_*$ (cm/s)</th>
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<th>$q_*$</th>
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<td>0</td>
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<td>26.25</td>
<td>26.53</td>
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<td>0.0311</td>
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<td>0</td>
</tr>
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<td>27.06</td>
<td>1.62</td>
<td>0.0323</td>
<td>0.000011</td>
<td>0.000004</td>
</tr>
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<td>28.87</td>
<td>27.44</td>
<td>1.64</td>
<td>0.0332</td>
<td>0.0001</td>
<td>0.0004</td>
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<td>115</td>
<td>30.18</td>
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<td>0.0321</td>
<td>0.00001</td>
<td>0.0000005</td>
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<tr>
<td>120</td>
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<td>1.69</td>
<td>0.0357</td>
<td>0.0006</td>
<td>0.00028</td>
</tr>
<tr>
<td>125</td>
<td>32.8</td>
<td>28.9</td>
<td>1.72</td>
<td>0.0366</td>
<td>0.0009</td>
<td>0.0004</td>
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<tr>
<td>130</td>
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<td>29.27</td>
<td>1.74</td>
<td>0.0375</td>
<td>0.0012</td>
<td>0.00054</td>
</tr>
</tbody>
</table>

$^a$Calculated bedload transport was predicted using Acoustic Doppler Velocimetry data and a modified MPM equation from Wong and Parker (2006). $\tau_{sc} = 0.032$.

same flume and using the same sediment used herein, we demonstrate that calculating sediment transport using the above methodology reasonably approximates observed bedload transport (Figure A.1).
2.2.3 Determining Patterns of Transport

Detailed streamwise and cross-stream bedload flux time series data, coupled with manual particle tracking of bedload sand grains, are used to assess changes in bedload transport patterns downstream of the region of flow separation. First, bedload flux time series were calculated by manually tracking grains that cross over a 2 cm vertical line (i.e. perpendicular to the direction of flow; herein reported as streamwise flux) and a 2 cm horizontal line (i.e. parallel to the direction of flow; herein reported as cross-stream flux) located in the middle of the field of view on the experimental bedload images at all 9 distances downstream of the backward-facing step included in Table 1. Particles were counted at 0.1 sec intervals for the first 8 seconds of each experimental run (Figure A.3).

Although 8 seconds is a short sample time, obtaining these data of transport rates are laborious and tedious, requiring hundreds of hours. Direct estimates of standard errors of statistics obtained from these samples is difficult because of serial correlation. We can, however, reliably estimate standard errors of 8 second samples of the 3,000 second velocity measurements, as an indication of errors expected for the sediment transport rates. We calculate the mean and standard deviation of each 8 second window in the 3,000 second velocity time series. The standard deviation of these window means and standard deviations provides estimates of the standard errors of the mean and standard deviation. The standard error of the mean and the standard error of the standard deviation of the 8 second samples were both found to be less than or equal to 10% of the standard deviation of the 3,000 second velocity time series. Bedload concentration is more variable than near-bed velocity. Hence, we expect standard errors of measured sediment transport rates to be somewhat higher than 10% of the standard deviation.
Periods of high streamwise and cross-stream flux were then selected for detailed manual particle tracking analysis at distances 6.56, 14.44, and 30.18 step heights downstream of the backstep. Particle tracking of high flux events was conducted using the MTrackJ plugin for ImageJ (Meijering et al., 2012). This tool allows for manual particle tracking of individual grains through time by using a cursor to select the center of a grain at a given point in time. Once the center of the grain is selected, the tool advances to the next frame in time where the center of the grain is manually selected again. For each event, \(\sim 250-500\) grains were tracked from initiation of movement to completion of movement/exiting the field of view (Movies A.1, A.2, and A.3). Length of transport, average and instantaneous particle velocity, and average and instantaneous direction of particle transport were recorded for each grain. Direction of particle transport is defined in terms of degrees where 0 to \(-/+/+20\) degrees is streamwise transport, \(-/+/+ 20\) to \(-/+/+ 90\) degrees is left lateral and right lateral transport respectively, and \(-/+/+180\) is transport in the upstream direction. Directions of transport reported anywhere in between these values contain components of both streamwise and cross-stream transport.

2.2.4 Determining Flow Patterns

Bedload flux time series and manual particle tracking data were then coupled with fluid velocity data acquired by the ADV. Unfortunately the quality of PIV data collected are quite poor, especially for runs 1-4 (Table 1) near flow reattachment (Figure A.2). This reduction in PIV data quality is likely due to significant vertical fluid velocities moving neutrally buoyant particles in and out of the laser sheet. Significant exiting and entering of neutrally buoyant particles reduces the accuracy of the PIV algorithms because those particles cannot be tracked in the next time step. We thus rely primarily on the ADV data collected to analyze patterns of turbulence.
ADV fluid velocity data were analyzed qualitatively with Quantile-Quantile (Q-Q) plots (Figure A.4) and quantitatively using percentile differencing. Quantiles (similar to percentiles) are the proportion of data that fall below a certain point (i.e. 0.5 quantile is equal to the 50th percentile and indicates 50% of the data are less than that corresponding value). In a bell-curve standard normal distribution, the mean value is 0 and corresponds to the 0.5 quantile. A Q-Q plot is a graphical tool for comparing two distributions. For the analysis herein, fluid velocity distributions are compared to a theoretical normal distribution. Sample data (i.e. fluid velocities) are sorted in ascending order and then plotted versus a theoretical normal distribution. In this case, the normal distribution has a mean of 0 (0.5 quantile) and a standard deviation of 2. The solid, black line on each Q-Q plot in Figure A.4 indicates where the sample data should plot if the sample data are normally distributed. Any divergence from this line indicates that the distribution is not normal.

Q-Q plots shown herein show distinct changes in the distribution of streamwise, cross-stream, and vertical fluid velocities with increasing distance downstream from the backstep (Figure A.4). In all the Q-Q plots shown in Figure A.4, the distributions display heavy tails. However, the tails of each distribution became less heavy, compared to the normal distribution, with increasing distance downstream.

To quantify this change, we use the below percentile differencing for the positive tail:

\[
\frac{99th - 50th}{SD} \quad (2.8)
\]

and:

\[
\frac{1st - 50th}{SD} \quad (2.9)
\]

for the negative tail, where SD is the standard deviation of the distribution. This percentile differencing approach highlights changes in the tails of distributions. For
Table 2.3: Summary of Percentile Differencing Results$^a$

<table>
<thead>
<tr>
<th>Distance Downstream (cm)</th>
<th>Distance Downstream (Step heights)</th>
<th>$U_x$ 99th−50th SD</th>
<th>$U_x$ 1th−50th SD</th>
<th>$U_y$ 99th−50th SD</th>
<th>$U_y$ 1th−50th SD</th>
<th>$U_z$ 99th−50th SD</th>
<th>$U_z$ 1th−50th SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>3.94</td>
<td>2.62</td>
<td>-2.39</td>
<td>2.47</td>
<td>-2.44</td>
<td>2.17</td>
<td>-3.05</td>
</tr>
<tr>
<td>25</td>
<td>5.25</td>
<td>2.80</td>
<td>-2.13</td>
<td>2.65</td>
<td>-2.38</td>
<td>1.95</td>
<td>-2.99</td>
</tr>
<tr>
<td>40</td>
<td>10.5</td>
<td>3.02</td>
<td>-1.86</td>
<td>2.43</td>
<td>-2.40</td>
<td>1.95</td>
<td>-3.02</td>
</tr>
<tr>
<td>55</td>
<td>14.44</td>
<td>2.91</td>
<td>-1.90</td>
<td>2.65</td>
<td>-2.34</td>
<td>2.27</td>
<td>-2.78</td>
</tr>
<tr>
<td>70</td>
<td>18.37</td>
<td>2.88</td>
<td>-1.88</td>
<td>2.51</td>
<td>-2.48</td>
<td>2.54</td>
<td>-2.53</td>
</tr>
<tr>
<td>85</td>
<td>22.31</td>
<td>2.78</td>
<td>-1.86</td>
<td>2.42</td>
<td>-2.38</td>
<td>2.31</td>
<td>-2.73</td>
</tr>
<tr>
<td>100</td>
<td>26.25</td>
<td>2.67</td>
<td>-1.95</td>
<td>2.45</td>
<td>-2.32</td>
<td>2.35</td>
<td>-2.63</td>
</tr>
<tr>
<td>115</td>
<td>30.18</td>
<td>2.61</td>
<td>-1.96</td>
<td>2.48</td>
<td>-2.32</td>
<td>2.38</td>
<td>-2.67</td>
</tr>
<tr>
<td>130</td>
<td>34.12</td>
<td>2.55</td>
<td>-2.01</td>
<td>2.49</td>
<td>-2.30</td>
<td>2.39</td>
<td>-2.62</td>
</tr>
</tbody>
</table>

$^a$Percentile differencing (equations 8 and 9) of streamwise ($U_x$), cross-stream ($U_y$), and vertical ($U_z$) fluid velocities.

example, if the 1st and 99th percentiles of a distribution increase in magnitude (with respect to the mean) with increasing distance downstream from the backstep, the distribution would become more dispersed and we expect equations (8) and (9) to diverge from zero. If the 1st and 99th percentiles of a distribution decrease in magnitude (with respect to the mean) with increasing distance from the backstep, the distributions would become less dispersed and we expect equations (8) and (9) to approach zero. Table 3 contains values calculated using equations (8) and (9) for streamwise, cross-stream, and downstream fluid velocities.

2.2.5 ADV Octant Analysis

To analyze fluid velocity patterns in further detail, octant analysis was conducted at 3 distances downstream of the backstep: 6.56, 14.44, and 30.18 step heights. Octant analysis, the three-dimensional version of quadrant analysis, separates the flow into eight regions defined by fluid fluctuations in the streamwise, vertical, and cross-stream directions (Table 4; Madden Jr 1997; Keylock et al. 2014). Fluid velocity fluctuations
Table 2.4: Summary of Octants\textsuperscript{a}

<table>
<thead>
<tr>
<th>Quadrant Name</th>
<th>Quadrant Name</th>
<th>$U_x$</th>
<th>$U_z$</th>
<th>Octant</th>
<th>$U_y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Outward Interaction</td>
<td>&gt; 0</td>
<td>&gt; 0</td>
<td>+1</td>
<td>&lt; 0</td>
<td></td>
</tr>
<tr>
<td>2 Burst</td>
<td>&lt; 0</td>
<td>&gt; 0</td>
<td>+2</td>
<td>&lt; 0</td>
<td></td>
</tr>
<tr>
<td>3 Inward Interaction</td>
<td>&lt; 0</td>
<td>&lt; 0</td>
<td>+3</td>
<td>&lt; 0</td>
<td></td>
</tr>
<tr>
<td>4 Sweep</td>
<td>&gt; 0</td>
<td>&lt; 0</td>
<td>+4</td>
<td>&lt; 0</td>
<td></td>
</tr>
</tbody>
</table>

\textsuperscript{a}Modified from Keylock \textit{et al.} (2014)

are defined as:

$$u'_i = u_i - \bar{u}_i$$  \hspace{1cm} (2.10)

where $u'$ is the magnitude of the fluid velocity at a given point in time ($u_i$) deviates from the mean ($\bar{u}_i$). The subscript ‘i’ denotes the direction of flow (streamwise ($x$), cross-stream ($y$), or vertical ($z$)). Quadrants (two-dimensional) analysis and octants (three-dimensional) analysis can be conducted by pairing these downstream and vertical fluctuations (quadrant analysis) or downstream, cross-stream, and vertical fluctuations (octant analysis; Table 4). The analysis presented herein utilizes octants.

These octants describe the instantaneous direction of fluid movement at a given point in time and correspond to the traditional flow events: sweep, bursts, outward interactions, and inward interactions (Table 4). Keylock \textit{et al.} (2014) illustrated that octant analysis can be paired with Markovian transition probability analysis to identify significant fluctuation sequences in the flow. Markov transition analysis is dependent of the existence of a Markov Chain, which is defined as a series of states transitioning from one another such that $S = \{s_1, s_2, s_3, \ldots, s_n\}$, where $S$ indicates
Table 2.5: Octant Transition Probability Matrix at 6.56 step heights\textsuperscript{a}

<table>
<thead>
<tr>
<th>Octants</th>
<th>-4</th>
<th>-3</th>
<th>-2</th>
<th>-1</th>
<th>+1</th>
<th>+2</th>
<th>+3</th>
<th>+4</th>
</tr>
</thead>
<tbody>
<tr>
<td>-4</td>
<td>0.000</td>
<td>0.348</td>
<td>0.037</td>
<td>0.228</td>
<td>0.019</td>
<td>0.001</td>
<td>0.038</td>
<td>0.327</td>
</tr>
<tr>
<td>-3</td>
<td>0.391</td>
<td>0.000</td>
<td>0.291</td>
<td>0.045</td>
<td>0.003</td>
<td>0.014</td>
<td>0.213</td>
<td>0.043</td>
</tr>
<tr>
<td>-2</td>
<td>0.040</td>
<td>0.214</td>
<td>0.000</td>
<td>0.410</td>
<td>0.043</td>
<td>0.263</td>
<td>0.025</td>
<td>0.005</td>
</tr>
<tr>
<td>-1</td>
<td>0.238</td>
<td>0.040</td>
<td>0.413</td>
<td>0.000</td>
<td>0.224</td>
<td>0.046</td>
<td>0.006</td>
<td>0.032</td>
</tr>
<tr>
<td>1</td>
<td>0.040</td>
<td>0.004</td>
<td>0.042</td>
<td>0.232</td>
<td>0.000</td>
<td>0.328</td>
<td>0.044</td>
<td>0.309</td>
</tr>
<tr>
<td>2</td>
<td>0.004</td>
<td>0.020</td>
<td>0.278</td>
<td>0.054</td>
<td>0.330</td>
<td>0.000</td>
<td>0.263</td>
<td>0.051</td>
</tr>
<tr>
<td>3</td>
<td>0.039</td>
<td>0.185</td>
<td>0.015</td>
<td>0.004</td>
<td>0.032</td>
<td>0.263</td>
<td>0.000</td>
<td>0.462</td>
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<td>0.001</td>
<td>0.019</td>
<td>0.214</td>
<td>0.041</td>
<td>0.420</td>
<td>0.000</td>
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</table>

\textsuperscript{a}Rows are octant origins and columns are octant destinations. Bold indicates primary sequences, italic indicates secondary sequence, and bold underline indicates tertiary sequences.

Table 2.6: Octant Transition Probability Matrix at 14.44 step heights\textsuperscript{a}

<table>
<thead>
<tr>
<th>Octants</th>
<th>-4</th>
<th>-3</th>
<th>-2</th>
<th>-1</th>
<th>+1</th>
<th>+2</th>
<th>+3</th>
<th>+4</th>
</tr>
</thead>
<tbody>
<tr>
<td>-4</td>
<td>0.000</td>
<td>0.270</td>
<td>0.125</td>
<td>0.181</td>
<td>0.032</td>
<td>0.022</td>
<td>0.035</td>
<td>0.335</td>
</tr>
<tr>
<td>-3</td>
<td>0.325</td>
<td>0.000</td>
<td>0.412</td>
<td>0.082</td>
<td>0.010</td>
<td>0.049</td>
<td>0.079</td>
<td>0.042</td>
</tr>
<tr>
<td>-2</td>
<td>0.134</td>
<td>0.254</td>
<td>0.000</td>
<td>0.225</td>
<td>0.238</td>
<td>0.300</td>
<td>0.030</td>
<td>0.020</td>
</tr>
<tr>
<td>-1</td>
<td>0.365</td>
<td>0.102</td>
<td>0.299</td>
<td>0.000</td>
<td>0.095</td>
<td>0.055</td>
<td>0.014</td>
<td>0.070</td>
</tr>
<tr>
<td>1</td>
<td>0.061</td>
<td>0.013</td>
<td>0.044</td>
<td>0.084</td>
<td>0.000</td>
<td>0.313</td>
<td>0.081</td>
<td>0.403</td>
</tr>
<tr>
<td>2</td>
<td>0.024</td>
<td>0.031</td>
<td>0.273</td>
<td>0.044</td>
<td>0.296</td>
<td>0.000</td>
<td>0.196</td>
<td>0.135</td>
</tr>
<tr>
<td>3</td>
<td>0.050</td>
<td>0.077</td>
<td>0.071</td>
<td>0.013</td>
<td>0.093</td>
<td>0.384</td>
<td>0.000</td>
<td>0.312</td>
</tr>
<tr>
<td>4</td>
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<td>0.031</td>
<td>0.018</td>
<td>0.033</td>
<td>0.234</td>
<td>0.117</td>
<td>0.221</td>
<td>0.000</td>
</tr>
</tbody>
</table>

\textsuperscript{a}Rows are octant origins and columns are octant destinations. Bold indicates primary sequence.

the sequence and \( s_1 \) to \( s_n \) are the constantly transitioning states. Markov transition probabilities indicate the probability an object in the theoretical state ‘\( s_1 \)’ will transition to the theoretical state ‘\( s_2 \)’ (Grinstead and Snell, 2012). Applying this to a time series of octants, one can extract the probabilities of fluid flow transitioning from one octant to another. These probabilities are illustrated using Markov transition matrices (Tables 5-7).

ADV fluid velocity data at 6.56, 14.44, and 30.18 step heights were converted into time series of octants. These octant time series were then used to calculate Markov transition matrixes. Tables 5, 6, and 7 show the probability of each octant transitioning to each other octant at 6.56, 14.44, and 30.18 step heights respectively. These
Table 2.7: Octant Transition Probability Matrix at 30.18 step heights

<table>
<thead>
<tr>
<th>Octants</th>
<th>-4</th>
<th>-3</th>
<th>-2</th>
<th>-1</th>
<th>+1</th>
<th>+2</th>
<th>+3</th>
<th>+4</th>
</tr>
</thead>
<tbody>
<tr>
<td>-4</td>
<td>0.000</td>
<td><strong>0.361</strong></td>
<td>0.046</td>
<td>0.137</td>
<td>0.0237</td>
<td>0.008</td>
<td>0.055</td>
<td><strong>0.369</strong></td>
</tr>
<tr>
<td>-3</td>
<td>0.254</td>
<td>0.000</td>
<td><strong>0.458</strong></td>
<td>0.034</td>
<td>0.005</td>
<td>0.068</td>
<td>0.154</td>
<td>0.026</td>
</tr>
<tr>
<td>-2</td>
<td>0.056</td>
<td>0.220</td>
<td>0.000</td>
<td><strong>0.306</strong></td>
<td>0.051</td>
<td><strong>0.338</strong></td>
<td>0.022</td>
<td>0.008</td>
</tr>
<tr>
<td>-1</td>
<td>0.361</td>
<td>0.050</td>
<td>0.219</td>
<td>0.000</td>
<td>0.262</td>
<td>0.038</td>
<td>0.008</td>
<td>0.064</td>
</tr>
<tr>
<td>1</td>
<td>0.074</td>
<td>0.010</td>
<td>0.028</td>
<td>0.221</td>
<td>0.000</td>
<td>0.230</td>
<td>0.056</td>
<td><strong>0.380</strong></td>
</tr>
<tr>
<td>2</td>
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<td>0.033</td>
<td>0.308</td>
<td>0.053</td>
<td><strong>0.392</strong></td>
<td>0.000</td>
<td>0.146</td>
<td>0.055</td>
</tr>
<tr>
<td>3</td>
<td>0.043</td>
<td>0.171</td>
<td>0.062</td>
<td>0.009</td>
<td>0.045</td>
<td>0.421</td>
<td>0.000</td>
<td>0.250</td>
</tr>
<tr>
<td>4</td>
<td><strong>0.389</strong></td>
<td>0.053</td>
<td>0.009</td>
<td>0.026</td>
<td>0.196</td>
<td>0.046</td>
<td>0.281</td>
<td>0.000</td>
</tr>
</tbody>
</table>

*aRows are octant origins and columns are octant destinations. Bold indicates primary sequence.*

Probabilities were then used to identify primary, secondary, and tertiary (all three only at 6.56 step heights) octant sequences. Sequences are denoted with {...}. The highest probable sequences of transitions at each distance are classified as “primary sequences.” These sequences were identified by first identifying the most likely transition of all the octants. For example, lets say the most probable transition is {-3 -2} at 0.412. This would be the beginning of our sequence. We would then go to -2 and find the most probable transition it would take, in this case +2. We repeat this process until the sequence either repeats (in this case, comes back to -3) or stagnates by continuously repeating between two octants.

At 6.56 “secondary sequences” were identified by assuming the primary sequences did not occur but assuming the next highest probable transitions did. “Tertiary sequences” were identified in a similar manner: by assuming neither the primary nor secondary sequences occurred but that the next highest probable transition did occur. Using this Markovian transition probability analysis, we can see how the fluid flow evolves with increased distance downstream of the backstep.
2.2.6 Octant Analysis of Numerical Splat Events

Since experimental data reported herein does not contain sufficient coupled bedload and fluid velocity measurements (due to the poor quality of the PIV data), we aim to shed light on the potential coupling of data reported herein by utilizing data from the numerical simulations of Schmeeckle (2015) of nearly the same geometry reported here. Fluid flow and bedload movement over and downstream of a 4 cm high backward-facing step were modeled using the large eddy simulation (LES) and distinct element method (DEM), respectively. LES and DEM models are coupled in momentum. The computational domain began at the backward-facing step and extended 1.2m downstream (30 step heights). This domain extended 0.1m (2.5 step heights) in the cross-stream direction. Data were collected in 0.01m x 0.01m grid cells. Fluid velocities, shear stress, and particle movement were recorded at 40 Hz (every 0.025 seconds). For a complete description of this methodology, please refer to Schmeeckle (2015).

Of particular interest are the presence and importance of spat events, as noted by Schmeeckle (2015). Perot and Moin (1995) were the first to discuss the process of splat events in which fluid impinges on an impermeable boundary. Impingement of fluid causes the boundary normal velocity to stagnate and causes the impinging fluid to be redirected parallel to the boundary (Perot and Moin, 1995). Because the boundary in question for these experiments (sand) is a porous medium, fluid infiltrates into the very top portion of the bed in addition to simply being redirected parallel to the bed (Schmeeckle, 2015). To accommodate the increase of fluid in the bed, fluid exfiltrates in all directions around the point of infiltration. Sediment is ejected in all directions from the bed during exfiltration, thus initiating bedload transport. This coupled outward interaction and sweep in addition to the radial bedload transport pattern is
Table 2.8: Summary of Numerical Splat Events

<table>
<thead>
<tr>
<th>Splat Event</th>
<th>$X_{beg}$ (m)</th>
<th>$X_{end}$ (m)</th>
<th>$Y_{beg}$ (m)</th>
<th>$Y_{end}$ (m)</th>
<th>$T_1$ (sec)</th>
<th>$T_2$ (sec)</th>
<th>Duration (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.2</td>
<td>0.27</td>
<td>0.06</td>
<td>0.09</td>
<td>1.625</td>
<td>1.775</td>
<td>0.15</td>
</tr>
<tr>
<td>2</td>
<td>0.4</td>
<td>0.45</td>
<td>0.06</td>
<td>0.09</td>
<td>3.1</td>
<td>3.35</td>
<td>0.25</td>
</tr>
<tr>
<td>3</td>
<td>0.21</td>
<td>0.27</td>
<td>0.07</td>
<td>0.09</td>
<td>3.5</td>
<td>3.85</td>
<td>0.35</td>
</tr>
<tr>
<td>4</td>
<td>0.18</td>
<td>0.24</td>
<td>0.06</td>
<td>0.09</td>
<td>4.2</td>
<td>4.35</td>
<td>0.15</td>
</tr>
<tr>
<td>5</td>
<td>0.27</td>
<td>0.33</td>
<td>0.03</td>
<td>0.05</td>
<td>9.375</td>
<td>9.55</td>
<td>0.175</td>
</tr>
<tr>
<td>6</td>
<td>0.31</td>
<td>0.37</td>
<td>0.04</td>
<td>0.09</td>
<td>17.45</td>
<td>17.6</td>
<td>0.15</td>
</tr>
</tbody>
</table>

known as a ‘permeable splat event’, herein referred to simply as splat events (Figure 3; Schmeeckle 2015). Stoesser et al. (2008) also noted the existence of splat events near flow reattachment in their numerical simulations of turbulence over dunes.

Six splat events from this numerical data were analyzed in detail (Table 8). Splat events were identified visually by noting localized areas of large streamwise and cross-stream transport 0-12 step heights downstream from the backstep. The spatial and temporal extent each splat event was identified. Fluid velocity fluctuations in the streamwise, cross-stream, and vertical directions were logged every 2 cm in the x direction and every centimeter in the y direction (Figure 4) at each time step. These fluctuations were then converted to octants. At each position and time step, near bed shear stress, streamwise transport, and cross-stream transport were also collected and paired with their respective octant for that position and time step. Using octants and bedload transport data from these splat events, we identify the octants responsible for bedload transport within a splat event.

2.3 Results

2.3.1 The Spatial Effects of Flow Separation and Reattachment

For the experiments described herein, flow reattachment occurs between 4.72 and 5.77 step heights. This was determined by the fact that bedload images collected
at 3.94 step heights and 6.56 step heights do not show a region of zero transport anywhere within their field of view. Additionally, the bedload images collected at 3.94 step heights capture only negative streamwise transport whereas the bedload images at 6.56 step heights capture only positive streamwise transport (Figure A.3). Since these distances refer to the center of the field of view on the bedload images, and the field of view is approximately $36 \ cm^2$, we can surmise that the reattachment point must be somewhere between the most downstream point of the 3.94 step heights measurement location (i.e. 4.72 step heights) and the most upstream point of the 6.56 step heights measurement location (i.e. 5.77 step heights). This is congruent with where we would expect to see flow reattachment based on Engel (1981).

Figure 5A shows bedload transport rates (Table 1) and fluid velocity downstream of a backward-facing step. Fluid velocity and bedload flux monotonically increase downstream of the backward-facing step. ADV fluid velocity data were used for this relationship rather than PIV fluid velocity data due to reduction in PIV data quality close to the backstep (Figure A.2). In contrast to the findings presented herein, the results of Nelson et al. (1995) show a peak in transport approximately 20 step heights downstream of the backward-facing step. In agreement with results presented herein, Schmeeckle (2015) LES-DEM simulations of the same geometry of the Nelson et al. (1995) experiments did not show a peak in bedload transport.

Comparison of calculated and observed bedload transport shows that using near-bed shear stress to predict bedload transport underestimates bedload transport at all sampling distances downstream of the backward-facing step (Figure 5B). In fact, the near-bed shear stress model predicts little to no bedload transport until approximately 27.5 step heights downstream, whereas observed bedload transport occurs at all distances downstream of the backstep. The discrepancy between calculated and observed bedload flux is most likely the result of the turbulent flow structures
associated with flow separation/reattachment. To explore how these turbulent flow structures, and therefore bedload transport characteristics, are evolving with distance downstream, we selected three distances downstream of reattachment for the detailed fluid and bedload analyses outlined in sections 2.3 and 2.5. The distances selected (6.56, 14.44, and 30.18) were chosen for their proximal, intermediate, and distal relationships with flow reattachment, respectively.

2.3.2 Fluid Velocity Patterns

Quantile-Quantile Analysis and Percentile Differencing

Temporal fluid velocity distributions show distinct differences with increasing distance downstream from the backstep (Figure 6 and Figure A.4). Quantile-Quantile plots of streamwise, cross-stream, and vertical velocity distributions display heavier tails near flow reattachment than fluid velocity distributions further downstream (Figure A.4). This indicates that large magnitude fluid velocity fluctuations (in all directions) are more likely near flow reattachment than further downstream.

In particular, near flow reattachment (0-14.44 step heights), 1\textsuperscript{st} percentile of the vertical velocity and 99\textsuperscript{th} percentile of the streamwise velocities are much larger than the median values of each (Figure 6A). Conversely, further downstream, these values are still larger than the median value, as to be expected due to the fact that they are 1\textsuperscript{st} and 99\textsuperscript{th} percentiles, however they are much closer in magnitude to the median value. Changes in 1\textsuperscript{st} and 99\textsuperscript{th} percentiles with respect to the mean suggest distinct changes in both vertical and streamwise velocity distributions (i.e. more dispersed distributions near flow reattachment).

Percentile differencing of streamwise fluid velocities (Figure 6B) shows that proximal to reattachment, large magnitude positive streamwise (99\textsuperscript{th} percentile) events
peak at 10.50 step heights and then gradually diminish with distance downstream. This indicates that flow separation and reattachment play a role in boosting large magnitude streamwise fluid events. Percentile differencing of vertical fluid velocity (Figure 6C) similarly shows an increase in large magnitude negative vertical fluid velocity events near flow reattachment that diminishes with increased distance downstream. In addition to boosting large magnitude streamwise velocity events, flow reattachment also appears to bring more fluid towards the bed proximal to reattachment (e.g. Bennett and Best, 1995).

This is congruent with our supposition that the quality of PIV data degrades near flow reattachment due to vertical fluid velocity moving particle in and out of the laser sheet. Where our PIV data quality is good (i.e. at 30.18 and 34.12 step heights) correlates to where vertical fluid velocity percentile differencing is lowest. In other words, where we see evidence for less negative vertical fluid velocity fluctuations we also see a higher quality in PIV data. Where high magnitudes of vertical fluid are coming down into the bed, we see very poor quality PIV data (Figure A.2).

**Octant Analysis**

Octant transition probabilities of fluid velocity octants at 6.56, 14.44, and 30.18 step heights (Table 5, 6, 7, respectively) show in detail the evolution of fluid flow at varying distances downstream of flow re-attachment. Similarly to Keylock *et al.* (2014), we see the development of a dominant, three-dimensional flow sequence: \{-3 -2 2 1 4 -4\}. This same sequence is identified by Keylock *et al.* (2014) as the second most probable 6-octant sequence. This flow sequence exists in temporally intermittent segments near flow reattachment (6.56 step heights) and develops into a more coherent, cyclical sequence with increased distance downstream.
At 6.56 step heights, three distinct “levels” of flow are apparent: primary, secondary, and tertiary sequences. The primary sequences are comprised of repeating fluctuations in the streamwise direction (Figure 7A; Table 5). The secondary sequences are comprised of a horizontal transition between the +4 and -4 octants. This horizontal transition can also be accompanied by a vertical transition (in the negative direction) from the +1 to +4 octants (\{1 4 -4\}; Figure 7A; Table 5). This sequence is equivalent to outward interactions and sweep events and was identified by Keylock et al. (2014) as the most probable 3-octant sequence. Keylock et al. (2014) also found that this sequence is extremely significant for bedload entrainment.

The tertiary sequence at 6.56 step heights is comprised of a vertical transition (in the positive direction) from the -3 to -2 octants followed by a horizontal transition from the -2 to +2 octants (\{-3 -2 2\}; Figure 7A; Table 5). This sequence is equivalent to inward interactions and burst events and was identified by Keylock et al. (2014) as the third most probable three-octant sequence. Both the secondary and tertiary sequences appear to stagnate in the horizontal direction (\{4 -4\} and \{-2 2\}, respectively). In other words, the \{1 4 -4\} and \{-3 -2 2\} sequences appear to be temporally intermittent flow features as opposed to continuously cyclical flow features (Figure 7A).

At 14.44 step heights we begin to see the development of the \{-3 -2 2 1 4 -4\} sequence. This is the primary octant sequence at this distance. Although this is the most probable sequence, it is not a repetitive sequence. Rather, the end of the sequence is likely to stagnate in the horizontal direction (\{-4 4\}) rather than continuing on in a cyclical manner from octant -4 to octant -3 (Figure 7B; Table 6).

At 30.18 step heights, the primary sequence is an almost fully developed dominant, three-dimensional flow sequence: \{-3 -2 2 1 4 -4\} (Figure 7C; Table 7). At this distance downstream, the probability of this sequence stagnating in the horizontal direction
between the -4 and 4 octants is still higher than the probability this sequence will move on in a cyclical manner from octant -4 to octant -3. However, the transition probabilities of \{-4 +4\} and \{-4 -3\} are very near even to one another at 0.369 and 0.361 respectively (Figure 7C; Table 7). This suggests that this primary sequence has almost fully developed into a cyclical, three-dimensional dominant flow sequence.

This more detailed analysis of fluid velocities at 6.56, 14.44, and 30.18 step heights is congruent with the Quantile-Quantile and percentile differencing analysis above. At 6.65 step heights, we see that the fluid velocity distributions in all three directions of flow have heavy tails. Additionally, it is around this distance that percentile differencing for negative vertical and positive streamwise fluid velocities peaks. Octant analysis in this region shows primary sequence fluctuations in the streamwise direction followed by a secondary sequence comprised of fluid fluctuations down, into the bed. The magnitude of percentile differencing in this region suggest that these fluctuation sequences have larger magnitudes than similar fluctuations occurring downstream.

As we move further downstream to 14.44 and 20.18 step heights, fluid velocity distributions (in all direction) become more normally distributed and therefore percentile differencing values are lower. This corresponds with the development of the \{-3 2 2 1 4 -4\} flow sequence. The magnitude of percentile differencing suggests that the fluid fluctuations in this region are smaller in magnitude than similar fluid fluctuations occurring upstream.

2.3.3 Bedload Transport Patterns

Bedload Transport Time Series

The pattern of bedload transport also appears to change with distance downstream of flow reattachment. Bedload flux time series data show that near flow reattachment,
cross-stream and streamwise fluxes are of more similar magnitudes (Figure 8, Figure 9A, and Figure A.3). In contrast, far downstream of flow reattachment, the magnitude of average streamwise flux is about five times greater than the magnitude of average cross-stream flux. While mean streamwise flux increases nonlinearly, mean cross-stream flux decreases nonlinearly with increased distance from the backstep. This suggests a diminishing role in cross-stream transport at distances farther from the backstep.

**Particle Tracking**

Bedload flux time series data coupled with particle tracking data show distinct differences in the overall pattern of transport with increasing distance downstream of flow reattachment (Figure 9). It is clear from bedload flux time series plots (Figure 9A) that transport in both the streamwise and cross-stream directions is intermittent even at distances far away from flow reattachment (i.e. 30.18 step heights). However, periods of high magnitude cross-stream flux are correlated with periods of high magnitude streamwise flux at distances proximal and intermediate to flow reattachment (6.56 and 14.44 step heights). We do not see this same correlation of high magnitude events at sampling locations distal to flow reattachment. Rather, at 30.18 step heights the magnitude of cross-stream transport events is much smaller than the magnitude of stream transport events.

This suggests that proximal to flow reattachment, transport events are intermittent and *multi-directional*. Distal to flow reattachment, transport events are still intermittent but largely unidirectional in the streamwise direction. Direction of transport data (Figure 9C) further supports the multi-directionality of transport near flow-reattachment. At 6.56 step heights, we see that grains in transport move in a wide
array of directions. The distribution of directions traveled by grains decreases with increasing distance downstream (Figure 9C).

Particle tracking videos suggest that not only is transport intermittent and multidirectional near flow reattachment, it is also localized. Movies A.1, A.2 and A.3 show the movement of sand grains during the large flux events highlighted in Figure 9A at 6.56, 14.44, and 30.18 step heights respectively. At 6.56 step heights (Movie A.1) particle tracking shows that the bulk of the sediment being transported through this event initiates in the bottom left-hand part of the field of view. At 14.44 step heights (Movie A.2) transport is still fairly intermittent, as evidenced by the fact that barely any transport occurs in the lower half of the field of view. At 30.18 step heights (Movie A.3), however, transport is initiated and occurring throughout the field view indicating that transport is no longer localized.

Combining bedload time-series data with particle tracking videos shows that within the proximal to flow reattachment, transport is localized, intermittent, and multi-directional. Distal to flow reattachment, transport is dispersed throughout the field of view, intermittent, and unidirectional. The extent of localized, intermittent, and multidirectional transport also corresponds to heavier tailed velocity distributions (Figure 9B and Figure A.4) and peak divergence from the mean in both streamwise and cross-stream velocities as indicated by percentile differencing (Figure 6B and C). Localized, intermittent, and multidirectional transport also spatially corresponds to where temporally intermittent octant sequences occur (Figure 7A).

2.3.4 Numerical Splat Analysis

The above analysis illustrates that bedload transport and fluid velocity patterns differ significantly near flow reattachment (i.e. 6.56 step heights) compared to further downstream (14.44 and 30.18 step heights). To connect patterns of bedload transport
with fluid velocity patterns, we turn to numerical data from Schmeeckle (2015). In these numerical simulations, Schmeeckle (2015) noted the presence and importance of splat events in the region just downstream of flow reattachment. We explore these numerical splat events in more detail for two reasons: (1) The region in which these events are dominant described in Schmeeckle (2015) is similar to the region in which we see distinctly different bedload transport and fluid velocity patterns in our flume experiments; and (2) The pattern of bedload transport (i.e. localized, intermittent, and multi-directional) observed in our bedload tracking analysis is congruent with the bedload transport patterns associated splat events, as described by previous investigations (Perot and Moin, 1995; Stoesser et al., 2008; Schmeeckle, 2015).

Detailed analysis of splat events in the numerical simulations of Schmeeckle (2015) is presented in Figure 10 and Figure A.5 and A.6. The single splat event shown in Figure 10 highlights that although the fluid flow during a splat event does generally include all octants (Figure 10A) transport (in both the cross-stream and downstream directions) is primarily associated with -1, 1, 4, and -4 octants (Figure 10C and D). Further, Figure A.6 and A.7 show that all six splat events analyzed show peaks in streamwise and cross-stream transport during -1, 1, 4, and -4 octant events. Additionally, high near-bed shear stress is often, but not always, associated with -1, 1, 4, and -4 octant events (Figure 10B, Figure A.6 and A.7).

2.4 Discussion

Results reported here are in agreement with results presented by Nelson et al. (1995) and Schmeeckle (2015). As noted by Nelson et al. (1995), near-bed shear stress cannot accurately account for the increase in bedload transport downstream of flow reattachment. We report similar findings here, but did not identify a peak in transport ~20 step heights downstream of the backstep as Nelson et al. (1995)
did. Rather, we report a nonlinear increase of bedload transport with increasing distance downstream. Octant analysis conducted herein is in agreement with the quadrant analysis completed by Nelson et al. (1995) in that we see outward interactions (Quadrant 1; Octants -1 and 1) and sweep events (Quadrant 4; Octants -4 and 4) playing a key role in transport, particularly near flow reattachment. Schmeecle (2015) reported similar findings to this effect.

As previously mentioned, Schmeecle (2015) also noted the presence and importance of splat events. In the numerical simulations of Schmeecle (2015), splat events manifested within larger sweep structures of the flow and were prevalent closest to the backstep and diminished in frequency and size with increasing distance from the backstep. The numerical experiments exhibited low-frequency fluid pressure fluctuations, wherein high pressure was associated with high-transport splat events and sweeps and outward interactions (i.e quadrant 4 and 1 events). Whereas, low pressure fluctuations where associated with low transport and bursts and inward interactions (i.e quadrant 2 and 3 events). Although, fluid pressure and vertical fluid velocity was not measured simultaneously with sediment movement in the present study, the radiating pattern of transport from intermittent events near flow reattachment (see Figure 9c and Movie A.1) is consistent with numerical results of Schmeecle (2015).

Additionally, new analyses investigating the dynamics of splat events from the numerical simulations reported herein indicate further that the transport initiated during a splat event is primarily associated with outward interactions and sweep events (i.e. octants -1, 1, 4, and -4). These same octants form a secondary flow sequence at 6.56 step heights (i.e. the region in which we see transport patterns similar to those of splat events). Given this new analysis, in conjunction with data presented in Schmeecle (2015) and the previously documented assertion that splat events are the combination of a sweep and an outward interaction, we suggest that
the secondary sequence observed at 6.56 step heights, \{1 4 -4\} is the octant sequence responsible for splat events (Figure 3). This sequence of octants paired with the distinct pattern of localized, intermittent, multi-directional bedload transport at 6.56 step heights indicates a high possibility that splat events are the primary mechanism responsible for bedload transport in the region just downstream of flow reattachment in the flume experiments presented herein. Octant sequence probabilities and pattern of bedload transport results reported here indicate that this zone does not extend past 14.44 step heights.

The existence of splat events and their importance to the initiation and pattern of bedload transport near flow reattachment cannot be neglected from future modeling that focuses on bedload transport over bedforms on the bedform scale. By looking at the sub-bedform scale, we see that not only are splat events important to initiating the movement of sediment near flow re-attachment, they heavily influence where sediment goes. As indicated by bedload transport pattern data reported here, near flow reattachment bedload transport has a large cross-stream component. This is significant when considering the evolution of bedforms through time.

Cross-stream transport has been assumed to be a secondary, diffusive process, depending linearly on cross-stream bed slope (Murray and Paola, 1997; Jerolmack and Mohrig, 2005b). Results reported here, however, prompt the question: is the lateral movement of bedload only a diffusive process dependent on slope? Each splat event causes considerable cross-stream transport. In the case of these backward-facing step experiments, net cross-stream transport is most likely zero due to the back and forth motion of multiple events. However, this is a product of a straight, undeforming backward-facing step upstream. In the case of complex, evolving, three-dimensional bedforms however, the flow field changes depending on the geometry of the upstream form (Venditti, 2007). In such circumstances, it seems reasonable to assume that
the number and intensity of splat events will vary laterally, leading to net lateral
transport from a gradient in grain transport activity (Furbish et al., 2012). It is also
probable that splat events are asymmetric in their net transport when the bedform
crestline varies in position and height in the cross-stream direction. In order to better
model and understand bedload transport over and evolution of bedforms, splat events
and their role in initiating entrainment needs to be accounted for.

2.5 Conclusion

Flume experiments modeled after Nelson et al. (1995) assess the affects of flow
separation and reattachment due to a backward-facing step on downstream turbulent
structures and bedload transport. Fluid velocities were analyzed qualitatively using
PIV and Quantile-Quantile plots and quantitatively using percentile differencing tech-
niques. Fluid velocity patterns were assessed using octant analysis and Markovian
transition probabilities. Bedload transport patterns were assessed using time series
analysis and manual particle tracking techniques. Splat events from numerical simu-
lations (Schmeeckle, 2015) were analyzed to assess the role of different fluid velocity
fluctuations to splat event dynamics. These numerical results were then compared
to experimental fluid velocity fluctuation and bedload transport pattern data to as-
ssess the potential role of splat events in real (i.e. non-numeric) situations. Results
reported here show that:

1. Flow separation/reattachment and associated downstream turbulent structures
play a significant role in the pattern of transport downstream.

2. Traditional bedload transport equations underestimate observed bedload trans-
port at all distances downstream of the backward-facing step.
3. Fluid velocity distributions also differ at distances proximal, intermediate, and distal to flow reattachment. Proximal to flow reattachment, we see large magnitude streamwise velocity events, relative to the mean streamwise velocity. Additionally, there is an increase in large magnitude negative vertical velocity events (irrespective of the mean).

4. Octant analysis at 6.56, 14.44, and 30.18 step heights show distinct differences of flow patterns. Proximal to flow reattachment (6.56 step heights), flow is comprised of segmented primary, secondary, and tertiary fluid sequences. At intermediate distances from flow reattachment (14.44 step heights), we see the development of a dominant, three-dimensional flow sequence: \{-3 -2 2 1 4 -4\}. This sequence becomes fully formed at locations distal to flow reattachment (30.18 step heights and greater).

5. Distances proximal to flow reattachment show distinct differences in bedload transport pattern compared to sampling locations farther downstream. While streamwise bedload transport increases nonlinearly with distance downstream, cross-stream transport decreases nonlinearly. Bedload transport proximal to flow reattachment consists of intermittent, localized, multi-directional transport events that move sediment comparable magnitudes in both the streamwise and cross-stream directions. Distal to flow reattachment, transport events move sediment primarily in the streamwise direction.

6. Analysis of numerical splat events (Schmeeckle, 2015), coupled with patterns of bedload transport and octant analysis data, strongly suggests the flow sequence \{1 4 -4\} is associated with splat events.
7. Bedload transport pattern and fluid velocity fluctuation data are both consistent with the existence of permeable splat events. Splat events play a large role in bedload transport close to flow reattachment and should be considered in future models of bedload transport over bedforms. Additionally, splat events should be explored in more detail to investigate their potential role in bedform evolution.
Figure 2.1: (A) Schematic of simplified flow dynamics over bedforms. Flow separates at the crest of each bedform and reattaches downstream (blue dashed line). Upon reattachment, flow accelerates up the bedform (red and yellow dashed line) before detaching at the crest of the next. (B) Schematic of temporally averaged streamwise velocity and shear stress values with distance along the bedform profile illustrated in (A). Horizontal dashed line shows region of predicted transport if temporally average values are used for transport equations that rely on average shear stress exceeding a critical shear stress. Vertical dashed line shows flow separation point. (C) Schematic of temporal distributions of streamwise fluid velocity for a flat bed and a bed with bedforms at a given point along the bed.
**Figure 2.2:** Schematic of experimental set up.

**Figure 2.3:** Schematic of fluid and bedload dynamics associated with a permeable splat event. (A) Flow characterized by positive streamwise velocity fluctuations and negative vertical velocity fluctuations (sweep turbulent structure) impinges on and penetrates into the bed. This causes exfiltration in all directions around the point of infiltration, characterized by flow with both positive vertical and streamwise velocity fluctuations (outward interaction, O.I., turbulent structure). This initiates bedload transport by ejecting grains from the bed in all directions (B).
Figure 2.4: Schematic of sampling methodology for numerical splat analysis. (A) Map view of cross-stream transport (m2/s) of splat event 6. (B) Grid of sampling locations (black circles with stars) for Splat Event 6. Each splat event was sampled using a similar grid: every 2 cm in the x-direction and every 1 cm in the cross-stream direction. Octants, near-bed shear stress, streamwise transport, and cross-stream transport were collected at each location every 0.025 seconds (40 Hz).
Figure 2.5: (A) Bedload flux and ADV flow velocity data (measured at 5 mm above the bed). Bedload flux covaries with fluid velocity, increasing nonlinearly downstream of a backward-facing step. Dashed lines are fits to the data. (B) Calculated bedload transport compared to experimentially observed bedload transport. Calculated bedload transport underestimates observed bedload transport at all sample distances downstream of the backward-facing step. Negative bedload flux values indicate transport in the upstream direction.
Figure 2.6: (A) Velocity vectors downstream of the backstep. Bottom row of vectors represents the median (50th percentile) values for both streamwise and vertical fluid velocities. The top row of vectors contains 99th percentile streamwise fluid velocities (i.e. large magnitude positive streamwise velocity events) and 1st percentile vertical fluid velocities (i.e. large magnitude negative vertical velocity events). (B) Percentile differencing (as defined in section 2.4) for the positive tail of streamwise velocity distributions. (C) Percentile differencing (as defined in Section 2.4) for the negative tail of vertical velocity distributions.
Figure 2.7: Schematic of primary (red), secondary (blue), and tertiary (green) octant transitions (modified after Keylock et al. 2014) for 6.56 (A), 14.44 (B), and 30.2 (C) step heights. The grey sequence shown in A, B, and C is the primary octant transition sequence \{-3 -2 2 1 4 -4\} observed by Keylock et al. (2014). Portions of this sequence exist at all locations but are only primary transitions at 14.44 and 30.2 step heights. This sequence only repeats, however, at 30.2 step heights, where the probability of the \{-4 -3\} transition and the stagnating transition of \{-4 4\} are comparable (0.361 and 0.369 respectively). These two transitions are noted with blue and red arrows at the transition from octant -4 to octant -3.
Figure 2.8: Mean streamwise and cross-stream bedload flux. Cross-stream transport shown above is the magnitude of both positive and negative cross-stream flux. Notably, mean streamwise and cross-stream flux are of similar magnitudes at distances proximal to flow reattachment.
Figure 2.9: (A) Bedload transport (streamwise in purple and cross-stream in green) time series data for distances 6.56, 14.44, and 30.18 step heights downstream of the backstep. Red boxes indicate timing of transport events used for particle tracking analysis in panel (c). (B) Quantile-Quantile plots of streamwise (u, red), cross-stream (v, blue), and vertical (w, green) fluid velocities. The solid black line represents where the data should plot if it were normally distributed. (C) Pattern of bedload transport particle tracking data and sample images. Rose diagrams show average direction each grain travels while in transport, where 0 indicates purely streamwise transport.
Figure 2.10: Cumulative spatiotemporal octant (A), near-bed shear stress (B), streamwise transport (C), and cross-stream transport (D) for a single splat event (E). Red diamonds and bars in the violin plots of B, C, and D are the mean and the extent of 2 standard deviations, respectively. Negative streamwise transport indicates transport in the upstream direction. Transport, both in the streamwise and cross-stream directions, corresponds primarily with -1, 1, -4, and 4 octants, which are the octant equivalent of outward interactions and sweep quadrant events. This is congruent with the secondary octant sequence identified in the ADV data at 6.56 step heights.
SPATIOTEMPORAL BEDLOAD TRANSPORT PATTERNS OVER BEDFORMS

Abstract

Despite a rich history of studies investigating transport over ripples and dunes in rivers, the spatiotemporal details of the pattern of transport over bedforms remain largely unknown. Previous experiments assessing the effects of flow separation on downstream fluid turbulent structures and bedload transport suggest that localized, intermittent, high-magnitude transport events, called permeable splat events, play an important role in both downstream and cross-stream transport near flow reattachment. Here we report results from a set of flume experiments that assess the combined effects of flow separation/reattachment and flow reacceleration up the stoss side of the bedform. The flume was lined with 17 concrete ripples that had a 2 cm high crest and were 30 cm long. A high-speed camera observed bedload transport along the entirety of the bedform at 250 f/sec. Downstream and vertical fluid velocity was observed at 1mm and 3 mm above the bed using Laser Doppler Velocimetry (LDV) at 15 distances along bedform profile. As observed in the experiments of Leary and Schmeecckle (2017), mean downstream fluid velocity increases nonlinearly with increasing distance along the ripple. Observed bedload transport, however, increases linearly with increasing distance along the ripple with an exception at the crest of the bedform, where both mean downstream fluid velocity and bedload transport decrease significantly. Quadrant analysis was used to assess fluid fluctuations and patterns along the length of the bedform. Near reattachment, quadrant 2 and 4 events dominate the flow. Bedload transport time-series and manual particle tracking data show a zone of high-magnitude
cross-stream transport near flow reattachment, suggesting that permeable splat
events are still playing an important role in the pattern of bedload transport.

3.1 Introduction

Although bedload transport has been a subject of scientific inquiry for over a
century (Gilbert, 1877; Gilbert and Murphy, 1914), our understanding of bedload
transport mechanics on a sub-bedform scale remains limited (Leary and Schmeeckle,
2017). Sub-bedform transport mechanics potentially play an important role in calcula-
tions of bedload transport as well as our understanding of the three-dimensionality
of bedform evolution. However, relatively few studies have focused on sediment trans-
port patterns on a sub-bedform scale. Due to the dearth of studies on this subject,
it is important to start at first principles and assess bedload transport dynamics
associated with the two primary and fundamental fluid regimes of bedforms: flow
separation/reattachment and flow reacceleration.

An abundance of experiments of this nature were conducted in the later half of the
20th century (Vanoni and Nomicos, 1960; Raudkivi, 1963, 1966; Vanoni and Hwang,
1967; Rifai and Smith, 1971; Vittal et al., 1977; Itakura and Kishi, 1980; Van Mierlo
and De Ruiter, 1988; Nelson and Smith, 1989; Wiberg and Nelson, 1992; Lyn, 1993;
Nelson et al., 1993; McLean et al., 1994; Nelson et al., 1995; Bennett and Best, 1995).
These studies primarily focused on the sub-bedform spatiotemporal patterns of fluid
turbulent structures but were limited in their analyses of sediment transport. Rather
than looking at the spatiotemporal patterns of sediment transport, these studies were
limited to whether certain turbulent structures induced entrainment or not.

Bennett and Best (1995) found that the turbulence structure over bedforms is in-
trinsically linked to the development, magnitude, and extent of the flow separation
zone. Notably, they observed the importance of quadrant 4 events near flow reattach-
ment as significant contributors to the local Reynolds stress and sediment entrainment. In agreement with McLean et al. (1994), Bennett and Best (1995) also indicate that, in addition to quadrant 4 events, quadrant 1 events may play an important role in entrainment near flow reattachment. Investigations such as those conducted by Bennet and Best [1995] provide important sub-bedform scale observations regarding fluid turbulence and bedload transport over bedforms. However, the advent of new technologies and methods, particularly semi-automated particle tracking techniques and higher precision numerical models, suggest the need for experimental replication.

The flume and numerical experiments of fluid and bedload dynamics downstream of a backward-facing step by Leary and Schmeeckle (2017) and Schmeeckle (2015) assessed the effect of flow separation and reattachment to downstream bedload and fluid dynamics. These studies largely replicated the experiments of Nelson et al. (1995) but with upgraded technologies and methodologies. Schmeeckle (2015) and Leary and Schmeeckle (2017) found distinct fluid turbulent structures near flow reattachment called splat events. Splat events are localized, high magnitude, intermittent flow features in which fluid impinges on the bed, infiltrates the top portion of bed, and then exfiltrates in all directions surrounding the point of impingement. This initiates bedload transport in a radial pattern (Perot and Moin (1995); Figure 3.1). These turbulent structures are primarily associated with quadrant 1 and 4 events (Schmeeckle, 2015; Leary and Schmeeckle, 2017). Splat events generate a distinct pattern of bedload transport compared to transport dynamics distal to flow reattachment. Distal to flow reattachment, bedload transport is characterized by unidirectional transport Leary and Schmeeckle (2017).

The investigations described above indicate that splat events play an important role in the initiation and pattern of bedload transport proximal to flow reattachment. It is unclear, however, if these events remain an important factor in bedload transport.
when full bedforms are present. Do splat events continue to play a role in bedload transport when both flow reattachment and flow reacceleration are present? To assess the potential importance of splat events to bedload transport dynamics over bedforms, a series of flume experiments were run in which bedload motion and fluid velocities were observed over stationary ripples.

3.2 Methods

3.2.1 Experimental Methods

Experiments were conducted in the sediment transport research flume at the US Geological Survey’s Geomorphology and Sediment Transport Laboratory in Golden, CO. This recirculating flume is approximately 6m x 0.25m. The flume was lined with 17 cement ripples, each 30 cm long and 2 cm high at the crest. The stoss side of the ripple was characterized by a half sine function. The lee side of the ripple was characterized by a linear function intersecting the bed at 30 degrees. The size and geometry of these cement ripples were informed by the flume experiments presented in Nelson et al. (2011). The experiments of Nelson et al. (2011) were run in the same flume with the same sediment as the experiments presented herein and assessed fluid and sediment dynamics over live bedforms. The cement ripples in the present study were scaled to replicate the live ripples from Nelson et al. (2011). We then used the same discharge as Nelson et al. (2011).

One ripple was designated as the test ripple and was loaded with live sediment for every experimental run. Mobile sand was well sorted with a median diameter ($D_{50}$) of 0.05cm. The discharge for each run was determined using an inline vortex flow meter and was consistently $0.01\ m^3/s$. Motion of the bedload, illuminated by high-intensity LED lights, was observed with a high-speed camera operating at 250
frames/s. The camera was angled so that the lens was parallel to the sloped bed to minimize distortion due to bed slope, and thus depth, differences. The field of view was approximately 36 \text{ cm}^2 with resolution of 1280 x 1024 pixels. Images were captured at 6 distances along the stoss side of the test ripple (Runs 2-7; Table 3.1). Each run overlapped with the previous run by 1 cm (Figure 3.2). The flow depth was 9.5 cm.

The experimental procedure was as follows: With the flume off, sand was loaded to the test ripple and screed as best as possible into a planar surface. Once the mobile bed was planar, a Plexiglas sheet with a centimeter rules grid printed on it was placed on the mobile bed so that it would stay intact until the beginning of recording. The flume was then turned on and the recirculation rate was raised gradually to recirculation speed of 17.3 Hz. Once at 17.3 Hz, a Plexiglas window was lowered into the flume to rest on the water surface above the mobile bed so as to provide optimal image clarity by minimizing distortions from an irregular water surface. The camera, mounted on a stable platform, was then moved into position above this window. The camera was focused and then an image was taken of the Plexiglas grid for post-processing scaling. For runs 2 and 3, the Plexiglas grid was pulled and then recording of bedload motions began. For runs 4-7, due to high transport rates, recording began while the Plexiglas grid was still on the bed. The

\begin{table}
\centering
\small
\begin{tabular}{c|ccc|cc}
\hline
Run & Distance & Distance & \( \frac{q}{s} \) (grains cm\(^{-1}\) s\(^{-1}\)) & \( q_s \) (cm\(^2\)/sec) \\
 & Downstream & Downstream & & \\
 & (cm) & (step heights) & & \\
\hline
2 & 3 & 1.5 & 28.21 & 0.083 \\
3 & 8 & 4 & 78.75 & 0.23 \\
4 & 13 & 6.5 & 135.16 & 0.39 \\
5 & 18 & 9 & 178.08 & 0.52 \\
6 & 23 & 11.5 & 282.23 & 0.83 \\
7 & 26 & 13 & 212.08 & 0.62 \\
\hline
\end{tabular}
\caption{Experimental Overview}
\end{table}
Plexiglas grid was pulled at the beginning of recording. For these runs, the first 3 seconds of recording are ignored to account for the Plexiglas grid being pulled and the bed equilibrating.

Two additional runs without live sediment were conducted to collect fluid velocity data. Streamwise and vertical fluid velocity data were collected using Laser Doppler Velocimetry (LDV). Velocity data were collected for 3 minutes at 15 positions along the test bedform at 2 cm intervals (Figure 2); measurements were taken at 1mm and 3mm above the bed.

### 3.2.2 Bedload Transport Rate and Patterns

Bedload transport analysis was conducted using bedload images and the open-source software ImageJ. Bedload transport rates were acquired by manually tracking sand particles as they crossed a 6 cm line bisecting the field of view. Patterns of transport were determined for each run using the same methods presented in (Leary and Schmeecle, 2017).

### 3.2.3 Determining Flow Patterns

LDV fluid velocity data were analyzed as a distribution using basic statistics and as fluid velocity fluctuations using quadrant analysis. LDV yields time-averaged streamwise ($u_x$) and vertical ($u_z$) velocity values. Fluid velocity fluctuations are defined as:

$$u'_i = u_i - \bar{u}_i$$

where $u$ is the magnitude of the fluid velocity and a given point in time ($u_i$) deviates from the mean ($\bar{u}_i$). The subscript $i$ denotes the direction of flow (streamwise ($x$) or vertical ($z$)). The covariance of streamwise and vertical fluid velocity fluctuations
is equal to the Reynolds stress $(-\rho \overline{u_x' u_z'})$. Reynolds Stress was calculated for all LDV sampling locations.

Quadrant analysis is a two dimensional analysis wherein fluid velocity fluctuations, calculated by equation (3.1), are paired to produce 4 quadrants that describe the instantaneous movement of the flow (Table 3.2). Quadrant plots provide a visual representation of the quadrant activity that dominates the flow. Quadrant plots herein include all data points but are binned to illustrate the spatial density of the data. Significant quadrant observations were derived from only observations that exceed a threshold ($H$) value of one standard deviation of the Reynolds stress (Table 3.3; Lu and Willmarth, 1973).

Flow exuberance, EXFL, was calculated at all LDV sampling locations along the bedform using only significant quadrant observations. Exuberance describes the shape of the quadrant distribution by using a ratio of the total Q1 and Q3 events to Q2 and Q4 events (Shaw et al., 1983; Yue et al., 2007; Chapman et al., 2012, 2013). In other words, exuberance is the ratio between positive and negative contributions to the Reynolds stress. If exuberance is near or equal to 1, there is an even distribution of events in all quadrants and the resulting quadrant plot is roughly circular. If exuberance values are approaching zero, however, that indicates a dominance of quadrant 2 and quadrant 4 events and the resulting quadrant plot will be skewed toward those quadrants.
3.3 Results

Mean streamwise fluid velocities increase nonlinearly along the majority of the bedform, the exception being right at the crest where mean streamwise fluid velocity decreases slightly (Figure 3.3). Streamwise fluid velocity data and bedload videos indicate flow reattachment occurs at approximately 1 step height downstream from the trough (approx. 3 step heights downstream of flow separation). Mean vertical fluid velocities increase along the bedform up to 10 step heights, where they begin to decrease (Figure 3.3). The mean vertical fluid velocity is negative at, and just downstream of, flow reattachment in addition to at the crest. In these two zones, the fluid is primarily moving toward the bed. Positive vertical fluid velocities dominate the middle portion of the bedform. In this region, fluid is primarily moving away from the bed.

Observed sediment transport increases linearly along the bedform with the exception at the crest where transport decreases slightly (Figure 3.3). This pattern of bedload transport is in contrast to results from Leary and Schmeeckle (2017) in which bedload transport downstream of a backward-facing step (i.e. only responding to flow-reattachment) increased nonlinearly (Figure 3.3), with flow increasing rapidly just downstream of flow reattachment and leveling out with increased distance along the bedform. However, this linear increase in transport with increasing distance along the stoss side of the bedform is necessary for two-dimensional bedforms to sustain their two-dimensional geometry. Thus this result is both expected and interesting in that the difference in flow and sediment transport in the presence of bedforms is precisely the difference required for self-sustaining migration of bedforms. We will discuss this point in detail in the discussion section.
3.3.1 Fluid Patterns

Although average streamwise and vertical fluid velocities increase nonlinearly with increased distance along the bedform, the standard deviations of streamwise and vertical velocity distributions reflect a different pattern (Figure 3.4A and B). Both streamwise standard deviations and vertical standard deviations peak just downstream of flow reattachment. With increased distance along the bedform, standard deviations of fluid velocities decrease. Near flow reattachment the distributions of streamwise and vertical fluid velocities have greater dispersion and have higher magnitude fluid fluctuations. In particular, this suggests the potential for large magnitude positive streamwise and negative vertical fluid velocity fluctuations. Fluctuations of this type have been observed to be important factors in splat events (Stoesser et al., 2008; Schmeeckle, 2015; Leary and Schmeeckle, 2017).

This pattern of standard deviations with increased distance along the bedform is congruent with increased Reynolds stresses in the region proximal to flow reattachment (Figure 3.4). Reynolds stress is a measure of the covariance of fluid fluctuations in the streamwise and vertical directions. Reynolds stress decreases in magnitude with increasing distance along the bedform, except for at the crest where it is slightly higher than immediately upstream (Figure 3.4C). This pattern of Reynolds stress is in agreement with previous studies findings (Bennett and Best, 1995; Venditti and Bennett, 2000; Robert and Uhlman, 2001; Venditti and Bauer, 2005; Fernandez et al., 2006), wherein this pattern is credited to the development of the internal boundary layer such that measurements near flow reattachment and on the lee side are in the wake region of flow reattachment and therefore have elevated Reynolds stress values. Measurements made along the stoss side of the bedform are within the internal boundary layer and therefore have greatly reduced Reynold stress values.
Quadrant analysis conducted at 2, 7, and 12 step heights is also congruent with the above statistical analysis of the flow (Figure 3.5; Table 3.3). At 2 step heights (proximal to flow reattachment) we see the dominance of quadrant 2 and 4 events, which are composed of high magnitude streamwise and vertical fluctuations. At 7 and 12 step heights, however, all quadrants are roughly equally represented. Additionally, whereas at 2 step heights the data are oriented towards quadrants 2 and 4, quadrant plots at 7 and 12 step heights are oriented elongate in the \( U_x' \)-direction and narrower in the \( U_z' \)-direction. This change in pattern with increased distance along the bedform indicates that at distances medial and distal to reattachment, the fluid is experiencing larger magnitude fluctuations in the streamwise direction compared to the vertical direction.

Flow exuberance also captures this change in quadrant distribution with increasing distance along the bedform (Figure 3.6). Exuberance is nearest to 0 in the region near flow reattachment, indicating that region is most dominated by quadrant 2 and 4 events. With increasing distance along the bedform, however, exuberance increases towards 1 indicating an increase in frequency of quadrant 1 and 4 events. Chapman et al. (2012) identified this exuberance effect over coastal eolian dunes and observed that where exuberance was low (near the toe and lower stoss region) Reynolds stress was increased. This is expected as low exuberance indicates a dominance of Quadrant 2 and 4 events that contribute positivity to the Reynolds stress.

### 3.3.2 Patterns of Bedload Transport

Streamwise and cross-stream bedload transport time series data at 1.5, 6.5, and 11.5 step heights show similar patterns to those observed by Leary and Schmeeckle (2017). At all distances along the bedform, transport is intermittent (Figure 3.7A; Movies B.1-B.3). Near flow reattachment (1.5 step heights) streamwise and cross-
Table 3.3: Summary of Significant Quadrant Events and Exuberance (EXFL)

<table>
<thead>
<tr>
<th>Distance (step heights)</th>
<th>Distance (cm)</th>
<th>Q1</th>
<th>Q2</th>
<th>Q3</th>
<th>Q4</th>
<th>Total</th>
<th>% Q1</th>
<th>% Q2</th>
<th>% Q3</th>
<th>% Q4</th>
<th>Q2:Q4</th>
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<td>70</td>
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<td>1291</td>
<td>6</td>
<td>54</td>
<td>5</td>
<td>47</td>
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<td>0.13</td>
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<td>45</td>
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<td>0.14</td>
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<td>719</td>
<td>1631</td>
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<td>42</td>
<td>7</td>
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<td>518</td>
<td>188</td>
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<td>39</td>
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</table>
stream transport are of similar magnitudes. With increased distance along the bedform, however, streamwise transport increasingly outweighs cross-stream transport (Figure 3.7A). Direction of transport data from manual particle tracking supports these observations (Figure 3.7B). Near flow reattachment, transport occurs in a wide range of directions (+90 to -90 degrees). With increased distance along the bedform, direction of transport narrows to just the streamwise direction (within the range of +22.5 to -22.5 degrees).

Near flow reattachment, transport is much more localized than further downstream (Figure 3.8; Movies B.1, B.2, B.3). At 1.5 step heights (Figure 3.8A; Movie B.1), almost all the transport observed is initiated in the upper left hand corner of the field of view at the beginning of the transport event. At 7 and 12 step heights (Figure 3.8B and 3.8C; Movie B.2 and B.3), however, transport is initiated and occurring throughout the field of view and throughout the transport event. Leary and Schmeeckle (2017) contributed these localized, intermittent, high-magnitude, multidirectional transport events, observed near flow reattachment, to bedload patterns associated with splat events. The localized initiation and radial pattern of transport observed in Figure 3.8A and Movie B.1 reflects the pattern expected of a spat event (Perot and Moin, 1995; Stoesser et al., 2008; Schmeeckle, 2015; Leary and Schmeeckle, 2017).

3.4 Discussion

3.4.1 Linear Pattern of Transport Rates

The pattern of sediment transport rates downstream of flow reattachment presented herein is in contrast with Leary and Schmeeckle (2017). When flow reacceleration is present in addition to flow separation/reattachment, bedload transport rates
increase linearly with increased distance along the bedform (Figure 3.3). A linear increase in transport is necessary for bedforms to retain a two-dimensional geometry while translating downstream. Consider conservation of mass of the bed in which there is no exchange of suspended sediment with the bed:

\[
- \frac{\delta z}{\delta t} = \left( \frac{\delta q_s}{\delta x} - \frac{\delta q_s}{\delta y} \right) \frac{1}{1 - \lambda_p}
\]

(3.2)

Where \( q_s \) is the sediment transport rate in the streamwise direction, \( \delta z/\delta t \) is the erosion rate, and \( \lambda_p \) is the porosity of the sediment. Let's first assume that \( \delta q_s/\delta y = 0 \). If \( q_s \) increases with respect to \( x \), erosion occurs. If \( q_s \) decreases with respect to \( x \), deposition occurs. This is in agreement with the classical formulation that as bedforms migrate, sediment is eroded along the stoss side of the bedform (where sediment transport rates increases due to increasing mean streamwise fluid velocities) and deposited on the lee side (where sediment transport rate decreases due to flow separation).

There remains a conundrum, however. If erosion is occurring along the stoss side of the bedform, why are bedforms long-lived features? Why do they not simply erode away? The pattern of bedload transport presented in this study suggests that deposition is initiated at the crest of the bedform (where \( q_s \) begins to decline; Figure 3.3) and continues over the lee side of the bedform. This pattern of peak \( q_s \) located upstream of the crest is integral to maintaining bedforms because it initiates deposition at the crest rather than continuing to erode the bedform away. Why does a decrease in \( q_s \) occur at the crest? The crest represents the region of the bedform in which the zone of fluid acceleration transitions to flow separation. At this transition, near-bed fluid velocities decrease (Figure 3.3). Additionally, flow separation does not occur at a fix point in space and time. This variability creates a flow separation “zone” at
the crest that is characterized by decreases in near-bed fluid velocities (Figure 3.3) resulting in a decrease in $q_s$ at the crest.

The rate of change of $q_s$ along the stoss side of the bedform also has important implications for the geometric evolution of bedforms. For erosion to occur on the stoss side of the bedform only an increasing pattern of transport is necessary (i.e. it is not necessary for transport rate to increase linearly). A linear increase in transport rate is necessary, however, to maintain a constant erosion rate and therefore the two-dimensionality of the bedform. Substituting a linear equation for $q_s$ into equation (2) results in:

$$\frac{\delta z}{\delta t} = \frac{\delta(a x + b)}{\delta x} \frac{1}{1 - \lambda}$$

(3.3)

where $a$ and $b$ are constants. Solving the derivative for change in sediment transport rate with respect to $x$ thus produces a constant rate of erosion independent of distance along the bedform:

$$\frac{\delta z}{\delta t} = \frac{a}{1 - \lambda}$$

(3.4)

In this case of a linear increase in sediment transport rate, in which there is no cross-stream variability ($\delta q_s/\delta y = 0$), the bedform will erode an equal amount at all distances along the stoss side and, assuming all that sediment is then deposited on the lee side (i.e. no suspension), therefore retain a two-dimensional geometry (Figure 3.9A). Any nonlinear increase in sediment transport rate could result in deformation (i.e. when the sum of all changes in elevation of the bed does not equal zero; McElroy and Mohrig (2009)) and potentially cause a shift to a more three-dimensional geometry, especially if variability in the cross-stream direction exists ($\delta q_s/\delta y \neq 0$).

Venditti et al. (2005) reported the development and importance of ‘crest defects’ in the transition from two-dimensional to three-dimensional bedforms. Small excesses or deficiencies of sediment at the crest line cause these crest defect features (Ven-
ditti et al., 2005). As time elapsed and flow conditions remained constant, Venditti et al. (2005) observed that the field of bedforms (originally two-dimensional) became overwhelmed by crest defect features and transitioned to a field of three-dimensional bedforms.

Based on results from this study, crest defects could be caused by a spatially non-uniform increase in transport rates along the bedform in the cross-stream direction (i.e. linear increase in some regions, nonlinear increase in other regions). For example, if sediment transport rates increase exponentially (i.e. $q_s = x^a$; where $a > 1$), the erosion rate will increase along the stoss side causing a deficiency in sediment near the crest where the erosion rate is highest (Figure 3.9C). In contrast, if sediment transport rates increase logarithmically (i.e. $q_s = \log(x)$), erosion rates will decrease with distance along the stoss side resulting in an excess of sediment near the crest where erosion rate is lowest (Figure 3.9B). The spatiotemporal changes in bedload transport rate over bedforms need to be examined in more complex conditions than that of a fixed, two-dimensional ripple (as presented in this study) in order to determine the validity of the above hypotheses.

3.4.2 The Dynamics of Splat Events

In addition to changes in the magnitude of transport occurring along the stoss side of the bedform, changes in the pattern of transport and turbulent structures also occur. In the region just downstream of flow reattachment, the fluid is dominated by large magnitude streamwise and vertical fluid fluctuations that take the form of either quadrant 2 or 4 events. The dominance of these events decreases with increased distance along the stoss side of the bedform. Notably, quadrant 4 events are integral to splat events (Schmeekle, 2015; Leary and Schmeekle, 2017) and the increase in these events near flow-reattachment indicates that splat events may be occurring in
the region. Bedload transport time series and manual particle tracking indicate that in this zone just downstream of flow reattachment, transport is localized, intermittent, high-magnitude, and multidirectional—the same characteristics previously attributed to particles transported by splat events (Leary and Schmeeckle, 2017). These results indicate that splat events still play a significant role in the pattern of transport in the zone immediately downstream of flow reattachment even when flow reacceleration is present. The majority of transport occurring at 1.5 step heights is the result of a splat event, we can use particle tracking data to assess the transport characteristics of splat events. For the splat event observed at 1.5 step heights, length of transport and particle velocity are investigated in relation to direction of transport.

Although splat events initiate transport in a radial pattern, transport velocity (both mean and instantaneous) and transport length (both cumulative and instantaneous) vary with direction of transport (Figure 3.10). Instantaneous refers to transport dynamics (length, velocity, and direction) at each time step. Mean velocity is the average speed the particle moves throughout the period of active transport. Cumulative transport length is the distance traveled by the particle during the entire time it is in motion. Instantaneous and cumulative data show that particles moving in the streamwise direction have a much larger distribution of velocity and length of transport. At a maximum, particles traveling in the streamwise direction have a velocity and transport length approximately double that of a particle moving in a cross-stream direction. This indicates that splat events do not transport particles equally in all directions. Despite this, splat events do actively transport sediment in the cross-stream direction indicating that cross-stream transport may play a more active role in bedload transport over bedforms than previously thought.

It is also worth noting that at all locations in which particles were tracked, particles are not observed saltating in a classical sense. That is to say, with these coarser
sediments, particles are not observed being ejected into the flow or saltating with large hop distances. Rather, particles appear to almost trundle along the surface of the bedform. This is in agreement with Fathel et al. (2015) where in streamwise and cross-stream particle motions over a flat bed exhibited predominantly small hop distances.

There remain some biases in this method of particle tracking. The first is that particles that are moving slowly are much easier to track and although effort was made to randomly track particles regardless of speed, this unintended bias is potentially still present. For this reason, particle velocities may be greater than those presented in Figure 3.10. Secondly, length of transport is of course biased by the size of field of view. Once a particle leaves the field of view, its track is terminated but it may continue to be transported. Therefore, the lengths of transport reported in Figure 3.10 should be taken as minimum estimates. Lastly, small particle displacements, in which particles are in transport on very short timescales, are often not taken into account during manual particle tracking (Fathel et al., 2015, 2016). Fathel et al. (2015; 2016) found that these small particle displacements tend to dominate bedload motions over a flat bed. The bedload tracking analysis conducted herein did not expressly address this and therefore the lower end of transport length and velocity distributions may not be represented.

3.4.3 The Importance of Splat Events

The dynamics of splat events not only inform our understanding of the importance of cross-stream transport proximal to flow reattachment, they also potentially provide insight into the three-dimensionality of bedforms. Rubin and Rubin and Ikeda (1990) and Rubin and Hunter (1987) demonstrated that bedform alignment in multidirectional flows is dependent on the maximum gross bedform normal transport, which is
dictated by the resultant vector of two flow vectors. Although these studies did not
investigate flows with more than two flow vectors, the concept of shifting dominant
transport directions depending on flow geometry, and by extension bedform geometry,
is intriguing.

Building on the experiments of Allen (1966), Venditti (2007) investigated the
patterns of flow over non-planform dune geometries and found that flow over a lobe
shape tended to converge downstream whereas flow over a saddle shape would diverge.
Splat events may become concentrated in these regions of flow convergence or diver-
gence, which would potentially shift the direction of maximum gross bedform normal
transport. The convergence and divergence of flow over lobe/saddle features could
potentially cause an along-dune variability in the intensity of splat events. Along-
dune variability in the intensity of splat events could very well produce a gradient
of sediment transport with respect to $y$ (i.e. $\delta q_s/\delta y \neq 0$). As noted in the above
discussion, variability in transport rates in the cross-stream direction would enable
deformation of the downstream crest and induce bedform three-dimensionality. Splat
events maybe a key mechanism for producing three-dimensional bedforms and should
be considered in future investigations.

3.5 Conclusions

The results presented herein demonstrate two potential mechanisms promoting the
three-dimensionality of bedforms: (1) localized, nonlinear increases in bedload trans-
port rates along the stoss side of the bedform and (2) the existence of splat events
near flow reattachment. The existence and importance of splat events is congruent
with previous studies that lacked the detailed bedload tracking analysis included in
this study but that recognized the importance of quadrant 1 and 4 events in the en-
trainment of bedload near flow reattachment (Bennett and Best, 1995; McLean et al.,
Results reported herein and by Leary and Schmeeckle (2017) and Schmeeckle (2015) indicate that splat events are (1) the primary mechanisms entraining sediment near flow reattachment, (2) comprised of quadrant 1 and 4 events (or the octant sequence \{1 \ 4 \ 4\} in the case of Leary and Schmeeckle (2017)), and (3) entrain sediment in both the streamwise and cross-stream directions. Although splat events transport sediment at greater velocities and greater distances in the streamwise direction, their transport dynamics in the cross-stream direction remain significant. Further work needs to be done investigating the spatiotemporal patterns of transport rates over live bedforms and the bedform-scale effect splat events have on along-dune transport.

**Figure 3.1:** Schematic of fluid and bedload dynamics associated with a permeable splat event from Leary and Schmeeckle (2017). (A) Flow characterized by positive streamwise velocity fluctuations and negative vertical velocity fluctuations (sweep turbulent structure) impinges on and penetrates into the bed. This causes exfiltration in all directions around the point of infiltration, characterize by flow with both positive vertical and streamwise velocity fluctuations (outward interaction, O.I., turbulent structure). This initiates bedload transport by ejecting grains from the bed in all directions (B).
Figure 3.2: Schematic of experimental set-up and measurement locations. Crest of bedform is 4 cm upstream from trough.
Figure 3.3: Mean streamwise fluid velocities, mean vertical fluid velocities, and observed bedload transport with distance along the bedform. Dashed line indicates the location of flow reattachment (1 step height along the bedform).
**Figure 3.4:** Standard deviation of streamwise (A) and vertical (B) fluid velocity distributions. Higher standard deviations near flow reattachment indicate the potential for high magnitude fluid fluctuations. (C) Reynold Stress with distance along the bedform. Reynold stress was calculated from LDV velocity data collected 3mm above bed.
Figure 3.5: Quadrant analysis at three different distances along the bedform. Data are hexagonally binned (nbins=50 in each direction) to display varying density of data.
Figure 3.6: Exuberance at all 14 LDV sampling locations along the bedform. In the region proximal to reattachment, Quadrant 2 and 4 events are dominant as indicated by exuberance estimates near 0. Farther along the ripple, exuberance estimates increase as Quadrant 1 and 3 become more prevalent.

Figure 3.7: (A) Times series of streamwise (purple) and cross-stream (green) bedload transport with increasing distance along the bedform. Streamwise transport is characterized by particles being transported within the directional range of -22.5 to 22.5 degrees. Cross-stream transport is characterized by particles moving in the directional range of 22.5 to 90 degrees or -22.5 to -90 degrees. Anything higher than 90 degrees is considered upstream transport. (B) Rose diagrams indicating the direction of transport form manual particle tracking of the transport event outline is the black, dashed box for each distance along the bedform. Direction of transport becomes more dominated by streamwise transport with increased distance along the bedform. Near flow reattachment, sediment has a wide range of directions in which it is transported.
Figure 3.8: Sand grains in transport through time at 1.5, 6.5, 11.5 step heights. Grains were tracked during the transport events outlined in figure 7A. At 1.5 step heights, a majority of grains in transport during the transport event are entrained at a localized position in the upper right hand corner of the field of view at the beginning of the transport event and continue to be in transport until the end of the transport event. At 6.5 and 11.5 step heights, however, particles are being entrained and transport at all location and times.
Figure 3.9: Schematic of different patterns of erosion along the stoss side of a bedform based on linear (A), logarithmic (B), and exponential (C) increases in bedload transport.
Figure 3.10: Instantaneous (A) and cumulative (B) transport characteristics of a splat event. Vertical dashed lines indicate +/130 degrees, transport between which is classified as streamwise. (A) Instantaneous length of transport (LI) and instantaneous transport velocity (VI) referenced to direction of transport. The data is binned hexagonally to illustrate the density of the data (nbins = 25; n = 11,091). (B) Cumulative track length (total distance particle travels) and mean particle velocity during over the entire period of transport.
Chapter 4

PRACTICAL GUIDELINES FOR ESTIMATING SAND BEDLOAD IN RIVERS
BY TRACKING DUNES

Abstract

Quantifying bedload transport is paramount to the effective management of rivers with sand or gravel-dominated bed material. However, a practical and scalable field methodology for reliably estimating bedload remains elusive. A popular approach involves calculating transport from the geometry and celerity of migrating bedforms, extracted from time-series of bed elevation profiles (BEPs) acquired using echosounders. Using two sets of repeat multibeam sonar surveys from the USGS Diamond Creek gage site on the Colorado River in Grand Canyon National Park, with large spatio-temporal resolution and coverage, we compute bedload using three field techniques for acquiring BEPs: repeat multi-, single-, and multiple single-beam sonar. Significant differences in flux arise between repeat multibeam and single beam sonar. Multibeam and multiple single beam sonar systems can potentially yield comparable results, but the latter relies on knowledge of bedform geometries and flow that collectively inform optimal beam spacing and sampling rate. These results serve to guide design of optimal sampling, and for comparing transport estimates from different sonar configurations.

4.1 Introduction

Bedload is usually a significant proportion of total load in rivers with sand and/or gravel-dominated bed material, and the relative importance of suspended load and bedload often changes with flow and the location within the channel (e.g. Gomez,
1991). Whereas instrumentation and protocols for sampling suspended sediment loads are relatively well established (e.g. Edwards and Glysson, 1999; Wren et al., 2000; Nolan K.M. and Glysson, 2005), reliable estimates of bedload are more difficult to obtain, because bedload in transport is difficult to sample directly (e.g. Emmett, 1980; Gomez, 1991), define (e.g. Church, 2006), or estimate with empirical formulas (e.g. Van Rijn, 1984; Martin and Church, 2000). Therefore, the effectiveness of sediment management in river systems is often predicated on the accuracy and representativeness of available bedload measurements.

Reliable estimates of bedload transport have been shown to result from application of the Exner equation (Simons et al., 1965; Engel and Lau, 1980) to time-series of BEPs (Van Den Berg, 1987; Dinehart, 2002; Villard and Church, 2003; Wilbers and Ten Brinke, 2003; Nittrouer and Campanella, 2008; Claude et al., 2012; Guala et al., 2014) acquired with an echosounder. Simons et al. (1965) show that bedload flux can be estimated by tracking the average celerity, $V_c$, of the downstream migration of dunes with a known average height, $H$, and average length, $\lambda$. In practice, this might be achieved in three ways using echosounders: repeat multibeam (Fig. 4.1A), single-beam (Fig. 4.1B), and multiple single-beam (4.1C) sonar. Repeat multibeam sonar measures a spatially extensive three-dimensional bed, $z(x,y,t)$, from a moving vessel, from which it is possible to independently and simultaneously estimate $V_c$, $H$, and $\lambda$. Single beam sonar measures a one-dimensional bed, $z(t)$, at a single $(x,y)$ location using a stationary (fixed reference frame) sonar. Multiple single beam sonar measures a spatially limited three-dimensional bed, $z(x,y,t)$, at a few $(x,y)$ locations using stationary sonar.

There are practical benefits and drawbacks to each data collection method. For example, repeat multibeam is spatially extensive, but relatively expensive, only practical in relatively deep, safely navigable rivers, and limited in temporal coverage.
Therefore, the use of in situ stationary echosounders (also called altimeters) is becoming an increasingly popular alternative (Gray et al., 2010), especially in shallow water, being less expensive, and generating longer time-series (e.g. Moulton et al., 2014). However, only measuring the bed elevation at a single location means it is not possible to resolve V, H, and $\lambda$ simultaneously (Fig. 4.1A), with implications for bedload estimates that are explored in this paper.

Since different methodologies may be employed to collect BEPs, it is important that resulting bedload flux estimates are compared, particularly with respect to the sensitivities of transport estimates on the degree to which the assumptions made by Simons et al. (1965) are violated (McElroy and Mohrig, 2009; Shelley et al., 2013). Presently, it is unclear how differences in bed elevation data acquired with different methods translate to the fidelity with which dune migration is captured, and finally to bedload transport estimates. In order to examine these issues, we compare bedload estimates from the three different field survey methods outlined above.

We use an extensive repeat multibeam dataset consisting of bed elevation from a large area of migrating dunes at high spatio-temporal resolution. Data come from a 300 m reach upstream of the Diamond Creek USGS gage site on the Colorado River in Grand Canyon National Park (Fig. 4.2A, B), where flows are regulated by releases through Glen Canyon Dam 385 km upstream. This is an ideal location for repeat multibeam sonar sampling because of its proximity to a USGS gage and the straight, trapezoidal channel morphology. We simulate data from simultaneous single beam and multiple single beam deployments by extracting time-series of bed elevations from the repeat multibeam datasets (Fig. 4.2C). This ‘virtual echosounder’ experiment allows us to directly compare flux estimates from all three methods. We assess the relative accuracy of the single beam and multiple single beam techniques at estimating bedload transport compared to repeat multibeam-derived bedload, and
suggest practical guidelines for developing sampling and processing protocols that maximize accuracy.

4.2 Methods

4.2.1 Study Area and Survey Data

Repeat multibeam surveys were collected at two different discharges (Fig. 4.3A) from just upstream of the Diamond Creek USGS gage site (Fig. 4.2A). All bathymetric data were collected using a Teledyne-Reson 7125 multibeam echosounder, with sensor attitudes provided by a vessel-mounted inertial navigation system, and positions telemetered to the survey vessel at 20 Hz using a robotic total station situated onshore on monumented control. Data were collected with a 50% overlap between adjacent sweeps, providing up to 1000 individual soundings per $m^2$. Each sounding was edited manually. Further details of this system, survey, and processing methods are given by Buscombe et al. (2014, 2017) and Kaplinski et al. (2017). The channel bed was entirely composed of fine to medium sand with no gravel patches (Buscombe et al., 2017). At each discharge, data were collected every 6-10 minutes for 12 hours. A digital elevation model of the riverbed was produced for each survey, using coincident 0.25x0.25 m grids. The March 2015 repeat multibeam survey (around 283 $m^3 s^{-1}$) consists of 68 DEMs capturing the evolving bed during mostly increasing flow discharge (Fig. 3A). The July 2015 survey (around 566 $m^3 s^{-1}$) consists of 88 DEMs, capturing the bed during a decreasing hydrograph (Fig. 4.3A). The precision of the repeat surveys was very high (mean cell elevation standard deviation of 0.012 m computed over rocks known to be immobile).

In response to changes in discharge (Fig. 4.3A), bedform size almost doubled over the course of the survey in March and almost halved over the course of the survey.
in July (Fig. 4.3B). Due to the greater discharge, the bedforms in July were much larger and longer (Fig. 4.3C) compared to those in March.

4.2.2 Extraction of single beam and multiple single beam BEPs

A 35 x 30 m subsection in approximately the middle of the area surveyed by the repeat multibeam (approx. 300 m long by 40 m wide) was selected for detailed bedload analyses using repeat multibeam, single beam, and multiple single beam bed elevation profiles (Fig. 4.2C, D). This subsection was then divided into 40 different repeat multibeam BEP locations (8.67 m in length, 3.67 m spacing) for March and 20 different repeat multibeam BEP locations for July (17.34 m in length, 3.67 m spacing). The length of the BEPs was determined by considering the maximum dune wavelength (Fig. 4.3C). All repeat multibeam BEPs were detrended using the bedform tracking tool (BTT) described by Van der Mark et al. (2008). This tool detrends each BEP using a weighted moving average and extracts bedform height and wavelength data. This produced 2,760 individual repeat multibeam bedload transport estimates (and daily averages from the 40 BEPs) for March and 1,740 individual bedload transport estimates (and 20 daily averages) for July. Whereas repeat multibeam analyses can be carried out in two dimensions, analyses were deliberately carried out using one-dimensional transects oriented with flow direction, so any anisotropic effects in flux (caused by dunes not aligned perpendicular to the flow) affected repeat multibeam, single beam, and multiple single beam results equally.

Virtual single beam and multiple single beam echosounders were placed at the downstream end of each repeat multibeam BEP (Fig. 4.2D). Multiple single beam systems have four virtual beams, one of which is the same beam location as the single beam virtual echosounders. Two different beam spacings were explored: 1) 0m-0.56m-1.16m-1.74m and 2) 0m-1.74m-3.48m-5.22m. By conducting this virtual
experiment, we can explore the unlikely scenario in which multibeam, single beam, and multiple single beam BEPs are collected at the same exact time and in the same exact place. In this scenario, all three types of echosounders are observing the same exact bedforms and should theoretically yield similar bedload transport estimates.

4.2.3 Calculating Bedload Transport

Bedload transport, $q_b$ (m$^3$s$^{-1}$), was calculated using the Shelley et al. (2013) modification to the Simons et al. (1965) formulation based on the two-dimensional Exner equation Paola and Voller (2005) for bed sediment mass conservation, assuming triangular dunes:

$$q_b = (1 - p) V_c \frac{H^2}{2} - q_e - q_0 \quad (4.1)$$

where $p$ is the porosity of the sand (0.35 was used here) and $q_0$ is a constant of integration (set to zero here; see McElroy and Mohrig (2009) for a discussion of the potential physical meaning of this term). The original formulation of (4.1) has been validated and extended by numerous studies (e.g. Willis and Kennedy, 1975; Engel and Lau, 1980; Havinga, 1983), most recently by Shelley et al. (2013) who proposed the $q_e$ term, defined as:

$$q_e = \frac{V_c \Delta t H}{2\lambda} \quad (4.2)$$

where $\Delta t$ is the change in time between successive surveys. Note that Eq. (1) is averaged over a field of dunes to satisfy the necessary assumptions that suspended sediment load, $q_s$, is in equilibrium ($d_{qs}/dx = 0$), and with continuity of mass ($d_{qb}/dx + d\eta/dt = 0$), where $x$ and $\eta$ are downstream distance and bed elevation, respectively (Simons et al., 1965). It quantifies only the first-order bedload flux due to dune translation, not accounting for any exchanges in bed material load between suspended and bedload fractions that deform the dune and may contribute to net transport (McElroy and Mohrig, 2009).
The primary variables in the above equations are calculated differently for each BEP measurement system. For repeat multibeam, $H$ and $\lambda$ of a BEP are calculated directly using the BTT. $V_c$ is calculated using a cross-correlation of two consecutive BEPs (Engel and Lau, 1980).

Single beam data consists of time-varying elevation only (Fig. 4.1B) therefore $\lambda$ must be estimated independently. This might be done by measuring dune wavelengths in the field (for example, by wading, SCUBA, or using a boat-mounted sonar or ADCP) while installing or maintaining the echosounder. To simulate such an exercise, we use the daily average wavelength calculated by the BTT from the repeat multibeam survey directly upstream of the virtual single beam echosounder. Celerity ($V_c$) is:

$$V_c = \frac{\lambda'}{T} \quad (4.3)$$

where $T$ is the period, and $\lambda'$ is the estimated average wavelength. For multiple single beam data, average period and height can be measured directly from the BEPs, whereas ($V_c$) may be estimated in one of three different ways. The first, “original method”, is the same as Eq. (4.3), in which each beam is treated as a separate BEP to produce four estimates of transport that are then averaged. The second “cross-correlation method” is to use a cross-correlation of BEPs measured by two different beams to find the spatial offset or ‘lag’, $l$, between translated dunes:

$$V_c = \frac{D}{l\Delta t} \quad (4.4)$$

where $D$ is the distance between sensors. In a field situation, this is constrained by practical considerations, but here we are free to vary $D$ to evaluate its effects. This method produces six estimates of bedload transport (from six pairs of four beams), as does the third, “manual method”, in which velocity is:

$$V_c = \frac{D}{t_{m2} - t_{m1}} \quad (4.5)$$

where $t_{m1}$ and $t_{m2}$ are manually picked times at which a crest appears at each beam.
4.3 Results

4.3.1 Repeat Multibeam v. Single Beam

We consider the repeat multibeam-derived bedload estimates to be the most accurate because the superior spatio-temporal coverage of these data allow for simultaneous resolution of $V_c$, $H$, and $\lambda$. Single beam-derived daily bedload transport rates are underestimated relative to repeat multibeam in March, and overestimated in July (Fig. 4.4). This could have been caused either by mischaracterization of $V_c$, $H$, or $\lambda$ in either repeat multibeam or single beam calculations, or in both.

The most likely source of error in the repeat multibeam calculations occurs when calculating $V_c$. To investigate whether cross-correlation correctly measured translation of dunes, $l$ was manually calculated from repeat multibeam BEPs and then used to calculate bedform celerity. This showed that cross-correlation-derived $V_c$ were underestimated in both March and July (Fig. 4.5). This underestimation is much larger in July, when dunes were larger and deforming at a greater rate, indicating that caution should be exercised when using cross-correlation to derive $V_c$, especially during higher transport stages.

Using the linear regressions between manual and cross-correlation computed $V_c$ (Fig. 4.5) a lag-corrected bedload transport rate can be calculated for repeat multibeam (Fig. 4.4). Correcting repeat multibeam estimates for cross-correlation lag errors results in 1.6% and 33.9% error for March and July, respectively. Percent error will be expressed relative to repeat multibeam-corrected lag flux estimates for the remainder of this paper.

Even with the lag-correction applied, discrepancies exist between repeat multibeam and single beam data due to errors estimating $V_c$ from estimated wavelength and observed period. In March, period computed from single beam data is overes-
timated relative to repeat multibeam period, causing $V_c$, and therefore transport, to be underestimated. The opposite is true for the July data (Fig. 4.6A).

These discrepancies in observed period are likely linked to the bed responding rapidly to unsteady flows during each survey (Fig. 4.3A), with changes in discharge causing commensurate changes in $H$ (Fig. 4.3B) and $\lambda$ (Fig. 4.3C). This suggests that growing/shrinking dunes apparently distort the period observed in the single beam data, which would invalidate the assumption made in Eq. (4.3) that the daily average wavelength (or any invariant measure of wavelength) is representative.

### 4.3.2 Sinusoid Model of Growing and Shrinking Bedforms

To test the above hypothesis, a simple sinusoid model was used to simulate time-varying dune height and wavelength. Each detrended bed elevation series was approximated by:

$$\eta = A \sin(B + Cx)$$

(4.6)

Dune growth/shrinkage was controlled by varying $A$ (amplitude) and $C$ (wavelength). Dune translation was controlled by $B$ (shift). Dune wavelength $C$ was estimated from $A$ according to the regressions presented in Fig. 3C that represent scaling relationships between bedform height and wavelength for each day. Using Eq. (4.6), sinusoid single beam BEPs are constructed from the synthetic elevation series, $\eta$, at a single location, $x$. Synthetic repeat multibeam bedload transport rates are then calculated using Eq. (4.1).

Single beam BEPs of growing and shrinking sinusoids display significantly different distributions of periods compared to the assumption of constant bedform wavelength (Fig. 6B). As dunes grow or shrink, the ratio of synthetic repeat multibeam to synthetic single beam bedload transport increased or decreases, respectively. The maximum synthetic repeat multibeam to single beam ratio from growing (shrinking)
dunes is 1.2 (0.75). Applying these ratios as correction factors to the single beam data generates sine-corrected single beam transport estimates (Fig. 4), resulting in a decrease of the discrepancy between repeat multibeam and single beam derived bedload from 45.3% to 27.7% in March and from 38.9% to 10.7% in July.

### 4.3.3 Repeat Multibeam v. Multiple Single Beam

Another potential practical solution to minimizing the distortion of period in single beam surveys caused by ambiguity in $(\lambda')$ is to use a multiple single beam (spatial array of echosounders). By increasing the spatial resolution of bed elevation data, multiple estimates of bedload may be obtained, as well as multiple options for computing $V_c$ (Eq. (4.3) through (4.5)), two of which (Eq. (4.4) and (4.5)) do not require a priori estimation of $(\lambda')$. We expect the period recorded by each beam to be similarly affected by growing/shrinking dunes as were the single beam periods. We therefore apply the same sine correction from above to multiple single beam flux estimates calculated with the “original method”. Fig. 7A shows these results for the beam spacing of 0, 0.56, -1.16, and -1.74 m for the three methods for computing celerity, and Fig. 7B shows the bedload transport estimates using a larger beam spacing and Eq. (4.5) only.

The original method of calculating celerity (Eq. (4.3)) produces an average percent error of 13.3% and 15.8% in March and July, respectively; suggesting that increasing the number of beams and incorporating a sinusoid correction can mitigate discrepancies with repeat multibeam estimates. The cross-correlation method (Eq. (4.4)) systematically over-estimates bedload transport in both March (43.4% error) and July (108.4% error), suggesting that the lag is systematically underestimated, and hence overestimating celerity. The manual method (Eq. (4.5)) yields a small
mismatch between multiple single beam and repeat multibeam derived bedload in March (1.3% error) but a 62.9% error in July.

This disparity in performance of the manual method for March and July could be related to beam spacing, because the bedforms (and bedload mismatches) in the July data are much larger than those in March. This could cause greater celerity because only between 10 and 30% of the dune wavelength is being captured by the multiple single beam with the smaller sonar spacing, increasing to 30-100% with the larger spacing of 0-1.74-3.48-5.22 m (Fig. 4.6B). Increasing beam spacing does not resolve discrepancies between repeat multibeam and multiple single beam bedload estimates (36.6% error; Fig. 4.7B), suggesting another factor is contributing to the observed discrepancies, most likely temporal resolution.

Using a linear interpolation we increase the temporal resolution of the data from 6 to 3 minutes. At this new sampling frequency, the original method yields a 2% error in March, but continues to overestimate bedload transport in July (67.5% error; Fig. 4.8A). Increasing the temporal resolution of the data results in more accurate estimates of lag. The cross-correlation method yields a 6.8% error in March and a 16.3% error in July (Fig. 4.8B). These results suggest that the temporal resolution of the multiple single beam data will cause variation in cross-correlation-derived estimates of $V_c$.

4.4 Discussion and Conclusion

Bed elevation profiles (BEPs) recorded by repeat multi-, single-, and multiple single-beam sonar methodologies produce different estimates of bedload transport, but practical steps can be taken to reduce the mismatch. Significant errors in fluxes computed using single beam BEPs could arise for two main reasons: (1) cross-correlation derived repeat multibeam bedform celerity estimates can show systematic
bias, and (2) dunes can grow/shrink in response to non-stationary flow or sediment supply (Martin and Jerolmack, 2013).

Caution should be exercised when using cross-correlation to derive dune celerity measurements, especially during higher transport stages and for relatively large time increments between successive measurements. It is good practice to check lags estimated using cross-correlation with manual measurements in order to compile a relationship that can be used to correct for systematic bias in estimated lag (Fig. 4.5).

Using single beam BEPs, as dunes grow, transport is underestimated because period is overestimated. As dunes shrink, transport is overestimated because period is underestimated (Fig. 4.6). It is therefore important to understand the time scales over which dunes size is responding to flow in order to assess the relative effect period distortion may be having on the bedload estimates. A sinusoidal growth model is proposed that accounts for geometric effects on bedload flux in unsteady flows, using measured dune heights and translations and a scaling relationship to predict dune wavelength from its height (Fig. 4.3C). Such a scaling relationship could be compiled over time for a specific single beam deployment and applied retroactively to entire time-series of BEPs. The sinusoid model could be applied in any operational setting where temporal variations in dune wavelength and a dune height-wavelength scaling relationship exist. A less generally applicable extension to this procedure could involve modeling the spatio-temporal evolution of the bed more explicitly using Fourier series (e.g. Guala et al., 2014).

In this study, accounting for changes in dune geometry accounted for 28.9 (March) and 134.8 (July) tons/day in daily bedload rates computed using single beam, or 17.6% (March) and 28.3% compared to lag corrected repeat multibeam-derived rates.
Increasing the spatial resolution of the bed elevation data by using a multiple single beam system does not necessarily improve upon single beam transport estimates. Multiple single beam transport estimates do not suffer from distortions in period caused by changing dune wavelength but are sensitive to both beam spacing and sample frequency (Fig. 4.7). Ideally, sonar beams should be spaced such that a large proportion of the dune wavelength is sampled (Fig. 4.7B), although this is not always practical, especially in shallow water. If dune wavelengths change significantly according to flow, designing sampling to be optimal for a particular wavelength would not be recommended. A more effective approach to maximizing multiple single beam-derived bedload accuracy is to adjust sampling rate (Fig. 4.8), calibrated in relation to a known range of dune migration rates. This is especially helpful for dune celerity estimates based on cross-correlation (Fig. 4.8B). We found the most accurate way to measure dune celerity from multiple single beam data is to measure time elapsed between successive dune crests.

In summary, repeat multibeam-derived elevation time-series are a more accurate means with which to estimate bedload than using single beam or multiple single beam, because the superior spatio-temporal coverage of these data allow for simultaneous resolution of \(V_c\), \(H\), and \(\lambda\). However, there are significant practical advantages to using single beam or multiple single beam systems over repeat multibeam, and their capacity to monitor bedload over long periods may in some situations outweigh any disadvantages to do with greater errors in instantaneous bedload flux. We have offered a case study and practical guidelines to maximizing the efficacy of comparing bedload transport estimates derived from different sampling methodologies, which collectively will guide design of optimal bed sampling strategies for tracking dunes in rivers.
**Figure 4.1:** Schematic of three common field methodologies for collecting bed elevation profiles (repeat multibeam, single beam, and multiple single beam) and the types of BEPs produced by each method.
Figure 4.2: (A) Location of study area on the Colorado River in Grand Canyon National Park. (B) Map of study reach. Yellow line indicates the location of the Diamond Creek USGS gage. Grey section indicates area mapped with single multibeam survey. Colored area indicates area over which repeat multibeam surveys were collected (colors indicate elevations where red is high and blue is low). The blue lines that bisect the repeat multibeam survey area indicate the track lines the boat drove along in order to obtain each survey. Black rectangle indicates area in which BEPs were extracted. (C) Schematic of repeat multibeam BEP locations. (D) Schematic of single beam and multiple single beam virtual-echosounder locations.
Figure 4.3: (A) Discharge during the sample time period. Dashed line is July data, solid line is March data. (B) Example of bedform height varying with time from BEP 5.2. Open circles indicate July data, closed circles indicate March data. (C) Height versus wavelength. Red line indicates linear regression of the data.

Figure 4.4: Cumulative density plots (CDFs) of single beam and repeat multibeam bedload transport estimates. Additionally CDFs of single beam and repeat multibeam transport rates with added corrections for mis-characterized lag (repeat multibeam) and period (single beam).
Figure 4.5: Bedform celerity calculated using a manually picked lag versus a lag produce using a cross-correlation algorithm. The best linear regression of the data for each survey day serves as a correction factor for this under-prediction of lag. Dashed line represents x=y relation.
Figure 4.6: (A) CDFs of period measured from single beam and repeat multibeam BEPs. (B) Sinusoid model showing what the single beam BEP would look like if dunes were growing/shrinking or if dunes remained the same size through time. The dune geometry chosen for the green curves uses the average height and wavelength from the duration of the model.
**A** *MSB Spacing: 0.56, 1.16, 1.74 m downstream*

**Original Method**

![Graphs showing CDFs for different methods and dates](image)

**Xcorr Method**

![Graphs showing CDFs for different methods and dates](image)

**Manual Method**

![Graphs showing CDFs for different methods and dates](image)

**B** *MSB Spacing: 0.56, 1.16, 1.74 m downstream (March)*

*1.74, 3.48, 5.22 m downstream (July)*

**Manual Method**

![Graphs showing CDFs for different methods and dates](image)

*Figure 4.7:* CDFs of lag corrected repeat multibeam and multiple single beam bedload transport estimates using the original, cross-correlation, and manual methods to calculate bedform celerity for the multiple single beam profiles. Dashed lines are sine-corrected estimates. (A) multiple single beam beam spacing of 0 - 0.56 - 1.16 -1.74 meters. (B) multiple single beam beam spacing of 0 - 1.74 - 3.48 - 5.22 meters.
Figure 4.8: CDFs of lag corrected repeat multibeam and multiple single beam bedload transport estimates. (A) multiple single beam estimates if the bed is sampled every three minutes, using the original method to calculate bedform celerity. Dashed lines are sine-corrected estimates. (B) multiple single beam estimates if three-minute sampling frequency is employed along with the cross-correlation method for calculating celerity.
Chapter 5

CONCLUSION

5.1 Pattern of Bedload Transport on the Sub-Bedform Scale

Recent advancements in technology has enabled more detailed and comprehensive investigations of bedload transport on multiple scales. This dissertation focused on applying several new approaches to the bedform- and reach-scales in order to assess the dynamics of bedforms and their relation to downstream transport of sediment. On the sub-bedform scale (Chapters 1 and 2), flume and numerical experiments were used to assess how the two primary flow regimes over bedforms (i.e. flow separation/reattachment and flow reacceleration) impact the spatiotemporal patterns of transport. High-speed imagery, manual particle tracking, and various high frequency acoustic instruments were used to document and evaluate the sediment and fluid dynamics associated with the two primary flow regimes over bedforms (i.e. flow separation/reattachment and flow reacceleration). On the reach-scale, repeat multibeam sonar data was used to test the relative effectiveness of three different approaches often employed for observing the migration of bedforms: repeat multibeam, single-beam, and multiple single-beam echosounders.

5.1.1 The Effect of Flow Separation/Reattachment

The first aim on this study was to examine the effects of flow separation and reattachment on downstream patterns of bedload transport. Flow separation and reattachment on the lee side of bedforms in rivers is known to produce a complex turbulence field, but the spatiotemporal details of the resulting sediment transport
remain largely unknown. Flume experiments were conducted in which fluid and bedload dynamics were recorded downstream of a 4cm high backward-facing step. Analysis of PIV, ADV, and high-speed video shows distinct differences in both fluid turbulent structures and patterns of sediment transport near flow reattachment compared to farther downstream.

ADV velocity data was used to conduct octant analysis. Markovian sequence probability analysis of octants highlights differences in the flow near reattachment compared to farther downstream. Near reattachment we see three distinct levels of octant flow sequences comprised of high magnitude fluid fluctuations but that are inherently intermittent. Farther downstream we see the development of a dominant octant flow sequence \((\{-3 -2 2 1 4 -4\})\) that comprise smaller magnitude fluid fluctuations. Additionally, localized, intermittent, high-magnitude transport events are more apparent near flow reattachment than farther downstream. These events are composed of streamwise and cross-stream sediment transport of comparable magnitudes.

The observed patterns of transport and turbulent structures in the region proximal to flow reattachment are consistent with the existence of permeable splat events, wherein a volume of fluid moves toward and impinges on the bed (sweep) causing a radial movement of fluid in all directions around the point of impingement (outward interaction; Schmeeckle, 2015; Perot and Moin, 1995). Using numerical simulation data from Schmeeckle (2015), we assessed which octant components of splat events generate the most cross-stream and streamwise sediment transport. We found that despite all octant events exerting similar magnitudes of shear stress on the bed, octants -1, 1, 4, and -4 octant events generate the most transport in both streamwise and cross-stream directions. Analysis of numerical simulation data from Schmeeckle
(2005) is congruent with the octant sequence \{1 4 -4\}, which was found to be a secondary octant sequence in the region just downstream of flow reattachment.

The potential of splat events to move significant quantities of sediment in the cross-stream direction suggests that they may play a pivotal role in the evolution of bedform from two-dimensional to three-dimensional features. Investigations into whether splat events still manifest when flow reacceleration is present need to be conducted in order to confirm their role in bedload transport over bedforms.

5.1.2 The Effect of Flow Acceleration

Previous experiments assessing the effects of flow separation on downstream fluid turbulent structures and bedload transport (chapter 1, Leary and Schmeeckle, 2017) suggest that permeable splat events, play an important role in both downstream and cross-stream transport of sediment near flow reattachment. The primary aim of this study was to investigate flow and sediment patterns over fixed, two-dimensional bedforms and determine whether splat events still play a pivotal role in transport near flow reattachment when flow reacceleration is present. Flume experiments were conducted wherein the flume was lined with 17 concrete ripples that had a 2 cm high crest and were 30 cm long. A high-speed camera observed sediment transport along the entirety of the bedform at 250 Hz. Downstream and vertical fluid velocity was observed at 1mm and 3 mm above the bed using Laser Doppler Velocitmetry (LDV) at 15 distances along bedform profile.

As observed in our previous backward-facing step experiments and simulations, mean downstream fluid velocity increases nonlinearly with increasing distance along the ripple. Observed sediment transport, however, increases linearly with increasing distance along the ripple with an exception at the crest of the bedform, where both mean downstream fluid velocity and sediment transport decrease slightly. We
contribute this decrease in velocity to the spatiotemporal fluctuation in the point of flow separation at the crest. The resulting decrease in sediment transport is therefore suggestive of the initiation of sediment deposition at the crest.

The linear increase in bedload transport rates with increased distance along the stoss side of the bedform is distinct from the nonlinear increase in transport rates we observed downstream of the backward-facing step (i.e. just flow separation/reattachment). Considering conservation of mass, a linear increase sediment transport is necessary for equal amounts of erosion to occur at all distances along the stoss side of the bedform. Assuming all eroded sediment is deposited on the lee side of the bedform (i.e. no suspension) and that this linear increase in transport is laterally consistent, the bedform should migrate at a constant rate downstream and retain a two-dimensional geometry. Lateral variability in transport rates could potentially result in bedform deformation and three-dimensionality.

Sediment transport time-series data, manual particle tracking data, and LDV velocity data indicate that permeable splat events still play an important role in the magnitude and pattern of sediment transport just downstream of flow reattachment. We suggest that splat events could be the primary contributors to lateral variability in streamwise sediment transport along the stoss side of the bedform and therefore could be a integral part to bedform deformation and three-dimensionality. More studies investigating mobile bedforms with more complex geometries need to be conducted to explore this further.

5.2 Estimating Sand Bedload from Migrating Dunes

The aim of this field study was critically assess various methodologies by which bed elevation profiles are extracted and determine the relative effectiveness of each methodology at measuring bedload transport. Repeat multibeam, single-beam, and
multiple single-beam echosounders were considered. Using repeat multibeam data as the "gold standard" approach, we compared single and multiple single-beam bedload flux estimates and found that significant differences in bedload flux estimates arise depending on the type of echosounder deployed. We attribute a majority of the difference between single beam and repeat multibeam flux estimates to (1) systemic bias in the cross-correlation derived repeat multibeam bedform celerity; and (2) changes in bedforms geometry in response to non-stationary flow or sediment supply. We suggest future studies always use caution when using cross-correlation to derive bedform celerity. We also provide a sinusoid growth model that can be applied to any single-beam set with extensive bedform wavelength and height data are available. Increasing the spatial resolution of your data by using a multiple single-beam system does not necessarily improve upon single-beam estimates. Both sampling rate and beam spacing need to be carefully calibrated for the river stretch in question and we provide some guidelines for doing so.

5.3 Future Research: Bedload Transport Patterns over Three-Dimensional Bedforms

5.3.1 Fixed Bedform Experiments

Chapters 2 and 3 of this dissertation contain a comprehensive analysis of bedload transport patterns over fixed two-dimensional bedforms and suggest that splat events play a pivotal role in initiation and pattern of transport near flow reattachment. The presence of these splat events, their concentration in a zone just downstream of flow reattachment, and their ability to induce cross-stream transport provokes the question, “Do splat events (and their associated cross-stream transport) affect the
three-dimensional geometry and evolution of bedforms?" Three general hypotheses are outlined below:

1. The Null Hypothesis: Splat events do not affect the three-dimensional evolution of bedforms. This process is primarily dictated by fluid-bed interactions in which bedload sediment is suspended and/or suspended sediment integrates into the bed (McElroy and Mohrig, 2009).

2. Hypothesis 1: Splat events positively affect the three-dimensional evolution of bedform (i.e. they augment three-dimensional geometries). Field and flume investigations (Allen, 1966; Parsons et al., 2005; Venditti, 2007) show that fluid flow patterns change depending on upstream crest geometry. These investigations found that flow converges or diverges depending on whether the upstream crest is concave or convex (in the downstream direction), respectively. These flow patterns could potentially concentrate splat events, induce more cross-stream transport in those regions, and initiate a positive feedback that accentuates three-dimensional geometry.

3. Hypothesis 2: Splat events negatively affect the three-dimensional evolution of bedforms (i.e. they augment 2D geometries). In a review of two-dimensional, alluvial bedforms, Rubin (2012) suggests that along crest flow and sediment transport produce a physical coupling along the crest of the bedform that produces straight crest. He noted that Aeolian ripples are more two-dimensional that their fluvial counterparts because of ballistic impacts that eject grains laterally (parallel to the crest line). Splat events could be the fluvial equivalent of this aeolian process and could therefore promote straighter crest lines.

More experimentation is needed to establish the role of splat events over three-dimensional bedforms. Specifically, sediment transport dynamics need to be observed
over more complex geometries that the geometries presented herein. I propose a set of experiments of bedload transport over fix three-dimensional bedforms similar in geometry to those of Venditti (2007). Bedload transport patterns and associated fluid dynamics would be observed using similar methods outlined in chapters 2 and 3. Comparing these results to those of simple, two-dimensional geometries could help distinguish between the above hypotheses. This same geometric set-up could also be used in numerical simulations, similar to that used by Schmeckle (2014, 2015).

5.3.2 Live Bedform Experiments

The next level of complexity would be to experimentally observe bedload transport patterns with manual particle tracking over live, three-dimensional bedforms. The objective of these experiments would be to assess the amount of cross-stream transport that occurs along migrating bedforms and the effect that intra-dune transport has on the three-dimensional evolution of bedforms. Experiments would be conducted using a single bed sediment grain size distribution and at a single, uniform flow. Fluid and bedload observations could be made on two main spatial scales: the sub-bedform scale using high-speed photography (field of view \(\sim12\text{cm} \times 12\text{cm}\)) and the bedform scale using repeat scans of the bed over 5-10 bedforms (dependent on the size of the bedforms).

Experimental observations would be made of:

1. Omni-directional transport of individual grains at timescales associated with both turbulent and fluid motions. A high-speed camera to measure grain movement on a sub-bedform scale over a portion of the bed (a methodology developed for Leary and Schmeckle, 2017).
2. Time-series of three-dimensional bedforms translating and evolving through time using repeat scanning of the bed

3. Total bedload measurements via weigh pans at the end of the flume.

Results from these experiments would establish the potential importance of cross-stream transport on dune evolution and bedload flux, as well as a methodology for relating cross-stream transport events to dune translation and deformation in the immediate vicinity. Additionally, by conducting repeat sonar scans of the bed co-eval with sub-bedform high speed imaging, we can begin to bridge the gap between the sub-bedform and reach scales. Can we link bedform scale morphodynamics to sub-bedform scale patterns of transport using repeat sonar surveys and high speed imagining in the lab? Further, can we link bedform-scale morphodynamics to reach-scale bedload estimates using lab sonar surveys and field repeat multibeam surveys? By combining high resolution flume data with high resolution field data, we can begin to more comprehensively understand how different scales of observation affect the quantification of bedload transport.


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Contents

1. Text S2.1 to S2.7
2. Figures S2.1 to S2.7
3. Captions for Movies S1 to S3

Introduction

This supporting information includes figures and movies similar to those presented in the main paper but for all sampling distances downstream of the backstep. Additional statistical analysis for Acoustic Doppler Velocimetry (ADV) fluid velocity data is also provided. Figures for numerical splat events not shown in the main article (Splat Events 1-5) is presented herein. Particle tracking videos (Movie S1-S3) show complete time span of selected bedload transport event at the 3 distances downstream of the backstep as presented in the main paper.

Text A.1. Observed and calculated near-bed shear stress and bedload transport data. Observed data is from Roseberry et al. [2012] in which bedload transport was observed over a flat bed in the same flume and using the same sediment used in the experiments presented in the main manuscript. Observed transport was compared to a bedload transport rate calculated using the methodology outlined in section 2.2 of the main manuscript. Using such a method reasonably approximates bedload transport over a flat bed.

Text A.2. Particle imaging velocimetry (PIV) algorithms were applied to the laser sheet images to obtain a two-dimensional field of two-dimensional vectors that describe fluid motions. The quality of PIV data degrades near flow reattachment due to vertical velocity fluctuations bringing neutrally buoyant particles in and out of the laser sheet.

Text A.3. Complete set of sediment flux time-series data for all 9 distances downstream of the backstep. Cross-stream transport reported here is the total magnitude of cross-stream transport.

Text A.4. Complete set of fluid velocity quantile-quantile plots for all 9 distances downstream of the backstep. Quantile-Quantile plots were used to compare observed fluid velocity distributions to a normal distribution representing that of a flat bed.

Text A.5. In this study, we compare experimentally observed fluid velocity distributions to a normal distribution representing fluid velocities over a uniform bed to assess how flow separation affects fluid turbulent structures. A Kuiper test can be used to assess the goodness of fit of two distributions are in cumulative density function space, with the null hypothesis being that they are the same. The Kuiper test (Kuiper, 1960) was designed to assess the maximum deviation above and below the proposed cumulative distribution function (a normal distribution for this study). The Kuiper test differs from other goodness of fit tests, such as the Kolmogorov-Smirnov test (K-S test), in that it is as sensitive to deviations of the tails as it is to deviations of the median. A Kuiper test measures the maximum distance between the two distributions both above and below the normal distribution in cumulative density function space. These are called the D+ and D- values respectively, where large D+ or D- values mean considerable deviation. Generally, the absolute value of D+ and D- are added together and used as the test statistic (V). In this study we choose to report D+ and D- values separately, as they represent the deviation of each tail from the normal distribution (i.e. the deviation from a uniform bed).
Fluid velocity data show distinct differences with increasing distance downstream from the backstep (Supplemental 4). Kuiper test values show large deviations from normal for both positive downstream and negative vertical fluid velocity distributions at distances closer to reattachment (Supplemental 4). Near flow reattachment, large downstream and negative vertical velocity events occur more frequently whereas further downstream, fluid velocities begin conforming to a normal distribution. Changes in bedload transport pattern and fluid velocity with increasing distance downstream correspond with the zone of underestimate transport.

**Text A.6.** Histogram of octants and violin plots of shear-stress, streamwise transport, and cross-stream transport associated with Numerical Splat Events 1-3 (see table 8 in main text for times and locations of each splat event). Violin plots are read similar to box plots, with the exception that violin plots are comprised of rotated kernel density functions. For this reason, violin plots show the probability density of data at a given value in addition to the overall distribution of the data.

**Text A.7.** Histogram of octants and violin plots of shear-stress, streamwise transport, and cross-stream transport associated with Numerical Splat Events 4 and 5 (see table 8 in main text for times and locations of each splat event).

**Movie A.1.** Particle tracking video at 25 cm downstream of the backstep. Particles were tracked during the large transport event at 0.4-1.5 seconds shown in Figure 6A. This movie can be found at: https://www.youtube.com/watch?v=VZzTokoSA64.

**Movie A.2.** Particle tracking video at 55 cm downstream of the backstep. Particles were tracked during the large transport event at 5.9-6.5 seconds shown in Figure 6A. This movie can be found at: https://www.youtube.com/watch?v=V1_ZVoBAuxg.

**Movie A.3.** Particle tracking video at 115 cm downstream of the backstep. Particles were tracked during the large transport event at 2.4-3.1 seconds shown in Figure 6A. This movie can be found at: https://www.youtube.com/watch?v=bo0NPgxH59E.
Figure A.1: Experimentally observed and calculated near-bed shear stress and bedload transport. Data are from Roseberry et al. [2012] in which bedload transport and fluid dynamics were observed over a flat bed. These experiments were conducted in the same flume and using the same sediment as used in the study presented herein. They therefore provide a reasonable case with which to compare our data. Near-bed shear stress was calculated using the law of while and sediment transport was calculated using modified Meyer-Peter Müller equation from Wong and Parker [2006]. We see that these methods of calculating near-bed shear stress and bedload transport reasonably approximate experimentally observed shear-stress and bedload transport over a flat bed.
Reduction in PIV Data Quality as a Result of Vertical Fluid Fluctuations

Figure A.2: Particle Imaging Velocimetry data at varying distances downstream of the backstep. Note degradation of data quality at distances near flow reattachment.
Figure A.3: Bedload transport time series data for downstream and cross-stream transport. Cross-stream transport is reported as the absolute value of positive and negative cross-stream transport.
Figure A.4: Acoustic Doppler Velocimetry (ADV) velocity data collected 1 cm above the bed. Quantile-Quantile plots of downstream (red), cross-stream (blue), and vertical (green) fluid velocities. Black line indicates where data should plot if it was normally distributed.
Kuiper Analysis For Streamwise and Vertical Fluid Velocities

![Graph showing Kuiper test results for downstream and vertical fluid velocities. Positive Tail (D+) and Negative Tail (D-) are indicated. Zones of underestimated transport are also marked.]

Figure A.5: Kuiper test results for downstream and vertical fluid velocities.
Figure A.6: Histogram and violin plots of octants, near-bed shear stress, downstream bedload transport, and cross-stream bedload transport associated with Numerical Splat Events 1-3.
**Figure A.7:** Histogram and violin plots of octants, near-bed shear stress, downstream bedload transport, and cross-stream bedload transport associated with Numerical Splat Events 4 and 5.
Contents

1. Captions for Movies B.1 to B.3

**Movie A.1.** Particle tracking video at 1.5 step heights downstream of the backstep. Particles were tracked during the large transport event shown in Figure 3.7B. This movie can be found at: https://youtu.be/L2fe3qlDM5w.

**Movie A.2.** Particle tracking video at 6.5 step heights downstream of the backstep. Particles were tracked during the large transport event shown in Figure 3.7B. This movie can be found at: https://youtu.be/NDwFzx4Pqro.

**Movie A.3.** Particle tracking video at 11.5 step heights downstream of the backstep. Particles were tracked during the large transport event shown in Figure 3.7B. This movie can be found at: https://youtu.be/VvWqUzw3oHU.