**Real time measurements of sediment transport and bed morphology during channel altering
flow and sediment transport events**

Joanna Crowe Curran^{1*}

Kevin A. Waters²

Kristen M. Cannatelli³

*Corresponding Author

¹Northwest Hydraulic Consultants, Inc.

16300 Christensen Road, Suite 350

Seattle, WA 98188

jcurran@nhcweb.com

²University of Virginia

Department of Civil and Environmental Engineering

PO Box 400742

Charlottesville, VA 22902

³Inter-Fluve, Inc.

220 Concord Av. 2nd Floor

Cambridge, MA 02138

Abstract

Real-time measurements of bed changes over a reach are a missing piece needed to link bed morphology with sediment transport processes during unsteady flows when the bed adjusts quickly to changing transport rates or visual observation of the bed is precluded by fine sediment in the water column. A new technique is presented that provides continuous measurement of sediment movement over the length of a flume. A bedload monitoring system (BLMS) was developed that makes use of pressure pillows under a false flume bottom to measure sediment and water weights over discrete flume channel sections throughout a flow event. This paper details the construction of the BLMS and provides examples of its use in a laboratory setting to reconstruct bed slopes during unsteady flows and to create a real-time record of sediment transport rates across the flume channel bed during a sediment transporting flow.

Data gathered from the BLMS compared well against techniques commonly in use in flume studies. When the BLMS was analyzed in conjunction with bed surface DEMs and differenced DEMs, a complete transport and bed adjustment picture was constructed. The difference DEMs provided information on the spatial extent of bed morphology changes. The BLMS supplied the data record necessary to reconstruct sediment transport records through the downstream channel, including locations and time periods of temporary sediment storage and supply. The BLMS makes it possible to construct a continuous record of the spatial distribution of sediment movement through the flume, including areas of temporary aggradation and degradation. Exciting implications of future research that incorporates a BLMS include a more informed management of river systems as a result of improved temporal

predictions of sediment movement and the associated changes in channel slope and bed morphology.

Keywords: Sediment transport; techniques; channel morphology; bedload monitoring

1. Introduction

An alluvial channel bed alters its topography in response to changes in flow rates and sediment supply through measureable changes in sediment transport rates and channel bed slope. Thus, alluvial channels are often characterized by spatially variable patterns of erosion and deposition, bed slope, and bedform morphology. During a single flood, the same bed areas may scour and fill, the surface layer may break and reform, and erosion and deposition volumes may be significant but spatially variable. The result can be a bed surface similar in appearance and volume to that prior to the flow event, masking much of the adjustment in bed morphology and sediment flux that occurred during the flood. These flood-induced adjustments may reduce total aquatic habitat (Wood and Armitage, 1997) or be beneficial if there is exchange between sediment in transport and the active layer of the bed (Brussock et al., 1985; Salant et al., 2006). Real-time measurements of changes in bed topography are needed to link bed morphology with sediment transport processes during flow events.

Sediment transport and bed morphology measurement techniques have evolved over time toward increased spatial and temporal resolution. Sediment transport rates have been determined using direct and indirect as well as active and passive measurement techniques (Gray et al., 2010). Direct measurements focus on individual cross sections from which bedload

63 flux data are extrapolated across a reach, necessarily limiting the spatial area that is measured.

64 Manual sampling has been through the use of either a suspended sampler like a Helley-Smith

65 (Kleinhans and Brinke, 2001) or through the placement of nets on the channel bed (Bunte et al.,

66 2004). Bedload sediment is captured at multiple but discrete locations across the channel width

67 and summed for a total transport rate. Continuous direct measurements of sediment transport

68 have been accomplished most effectively using pit traps in river beds (Garcia et al., 2000; Sear

69 et al., 2000). The amount of sediment moved over distinct time frames and the grain size

70 distribution of the transported sediment can be determined through repeat visits to the pit

71 traps (Leopold, 1992; Hassan and Church, 2001). The bedload trap design has been modified

72 through the addition of load cells and data recorders to refine the temporal measure of

73 bedload sediment transport (Reid et al., 1980; Sear et al., 2000; Bergman et al., 2007) and to

74 increase trap efficiency to near 100% (McMahon, 2013). Impact plates and geophones have

75 been installed in mountain streams (Rickenmann and McArdell, 2007; Rickenmann et al., 2012)

76 and bedrock channels (Richardson et al., 2003) where sediment movement can be episodic and

77 significant. The width of the channel bed is overlain with a plate to which either a piezoelectric

78 or geophone sensor is attached. Signals recorded as sediment passes over the plate create a

79 continuous measure of bedload movement. Magnetic detector strips have been similarly

80 installed across channel widths where they record the movement and magnetic content of

81 bedload (Gottesfeld and Tunnicliffe, 2003; Hassan et al., 2009). The use of impact and magnetic

82 sensors can be combined with large sediment traps or bed surveys for additional information

83 about the grain size distributions and spatial patterns of transport events. These methods

provide a robust record of bedload sediment flux but are limited to a single location in the channel.

Concerns about the spatial limitation of direct bed sampling has led to a number of indirect measurement methods. The Acoustic Doppler Current Profiler (ADCP) applies the Doppler principle to measure the movement of small particles in the water column. The method of application of an ADCP can be adjusted so that the signal records suspended sediment transport (Gaeuman and Jacobson, 2006) or the migration of sand waves over a channel bed (Rennie et al., 2002; Gaeuman and Jacobson, 2007). Application of the ADCP to measure changing bedload and bedform transport has been particularly useful in flood situations. When large flood waves pass through a channel quickly, the ADCP can provide a measure of sand and gravel transport that would otherwise not be possible because of the speed of the flood wave and the amount of sediment in transport (Rennie and Millar, 2007; Curran and Ables, 2009). High resolution bathymetry measurements, whether from ADCPs, sonar, or high density surveying, are used in photogrammetry analysis to create digital elevation models (DEMs) of channel beds. Where these measurements have been repeated over time, the sequential DEMs can be differenced to provide time-integrated estimates of net changes in the channel bed surface and to infer the amount of sediment movement (Zunic et al.; Ashmore and Church, 1998; Rumsby et al., 2008; Tsubaki et al., 2012). When used in a laboratory setting, repeated scanning can be performed to a high degree of accuracy and used to identify small movements of individual grains (Ockelford and Haynes, 2013). In a field situation, repeated bathymetry imaging provides bulk sediment mass transport information over a large spatial area. Bedform migration and changes in channel bed topography have been used to estimate bulk transport

rates occurring through a channel reach and to extend the area of channel over which bed changes are measured (e.g. Ashmore and Church, 1998; Chandler et al., 2002; Lane et al., 2003; Wheaton et al., 2010). These indirect methodologies have the advantage of covering large river reaches in a nonintrusive manner, but none provides a real-time measure of bed sediment movement through a channel reach. It is the high resolution temporal and spatial measurements of sediment flux that are necessary to relate the sediment movement to changes in bed morphology.

In this paper we present a new bedload monitoring system (BLMS) that provides continuous measurement of sediment movement over a flume-defined reach in a laboratory setting. The laboratory provides the advantage over the field case because a measurement system can be installed under the length of the flume making possible the collection of high resolution data. The BLMS directly measures sediment weights over the length of the flume, monitoring changes in mass that reflect spatial and temporal patterns of erosion and deposition. From the BLMS, sediment transport rates, changes in the channel bed slope, and intermediate fluctuations in bed morphology can be reconstructed for a flow event. We present the BLMS in detail with examples of how the BLMS has been used in laboratory experiments to further the interpretation of channel processes occurring during large flows. We evaluate the new method for use during sediment feed and sediment recirculation experiments where DEM differencing was also applied.

2. Bedload monitoring system

2.1. Background and setup

The BLMS design was inspired by sediment bedload transport monitoring methods that have been successful in field application. The most notable of these was the Reid sampler system by which a portion of the stream bedload is diverted into a concrete box buried in the river bed with top flush with the bed surface (Reid et al., 1980; Harris and Richards, 1995; Garcia et al., 2000; Sear et al., 2000; Laronne et al., 2003). A second box inside the concrete box rests on top of a water-filled rubber pressure pillow. Sediment in transport through the channel falls into and collects in the inner box. A pressure transducer attached to the pillow enables continuous measurement of the overlying weight of inner box, sediment, and water (Reid et al., 1980; Harris and Richards, 1995). Pressure changes associated with the changing water levels in the stream are accounted for using either a synchronous record of stream water stage or a pressure transducer (Garcia et al., 2000). The BLMS design presented here is a modification and expansion of the use of pressure pillows in a laboratory setting.

The BLMS consisted of measuring sections that extended over the 9-m channel bed length of a flume 11 m in total length, 0.6 m wide, and 0.5 m deep. The flume was divided into individual measurement sections, each 1.0 m long and 0.60 m wide. Each section consisted of a Plexiglas board 1.0 m long, 0.60 m wide, and 0.02 m thick resting on a circular tube that was connected to a pressure transducer recording in range 0-1 bar (Omegadyne, Inc., model no. PXM409-001BGV). With this design, each section was isolated and supported solely by the pressure tube (Fig. 1). The tubes were neoprene and filled with water to prevent compression and to provide a larger dynamic measurement range than was possible from air-filled tubes.

Once in place, the boards created a false bottom in the flume. To ensure that each Plexiglas board was supported solely by the pressure tube, it was essential that water and sediment be prevented from filling the space between the Plexiglas boards and the flume bottom. An abrasion-resistant latex rubber sheet with 0.152 mm thickness was laid over the boards and secured to the flume walls with clear tape. Flow discharge was controlled by a variable frequency motor capable of flows up to 0.12 m³/s. Honeycomb meshes at the inlet dampened turbulence to facilitate flow adjustment. In all tests water was recirculated. Locations in the flume were identified by the distance from the upstream end in meters. Because each transducer section was 1 m in length, flume locations corresponded to transducer sections.

Each transducer continuously recorded voltages that corresponded with the total weight acting on the pressure tube, which included the weight of the Plexiglas board, sediment, and water. The consistent board size ensured a constant board weight at each segment. Water depth fluctuated during the experiments and required direct measurement. A transducer was placed in the sediment trap at the downstream end of the flume. The water signal was measured continuously and subtracted from the signal recorded from the other transducers, leaving the weight of the sediment. Longitudinal changes in water depth over the 9-m flume channel were assumed to be minimal. A data acquisition program in LabVIEW Signal Express 2012 (version 6.0.0) stored data at a frequency of 1000 Hz, which corresponded to a pressure measurement every 0.02 min.

2.2. Calibration

The BLMS was calibrated to develop a relation between overburden weight and recorded voltage. Weights were placed on each section in 27-kg increments from 0 to 272.2-kg,

and voltages were recorded. Two measurements were recorded for each weight and each transducer, one while increasing the weights and one while decreasing the weights. Voltages from each measurement pair were averaged. A quadratic calibration relation between weight and voltage was developed for each transducer with the calibration coefficients determined through least squares non-linear regression. In all cases the calibration curve fits were very high (Table 1). The section 5 m from the upstream end of the flume provides a representative calibration curve (Fig. 2). Transducer variability was evaluated using the pair of measurements to define a lower and upper bounds for each transducer. These bounds were used to approximate the error associated with the range of weights tested at each section. Mean voltage signals from the transducers predicted the weights in the overlying system to within $\pm 0.55\%$ of the actual weights for the first calibration. This was reflective of the strong fit of the calibration curves to the mean data points. When the lower and upper voltages were applied to the calibration curves, the results were weights that were $\pm 5.3\%$ of the actual weight in a single section. Calibration predictions improved as the weight on a given transducer increased (Fig. 3A). For weights over 56 kg, which was roughly equal to the initial weight of sediment in the flume at each segment, the calibration curves showed strong predictive ability indicating reliable readings from the transducers. This was true for the mean signals used to develop the calibration curves as well as for the upper and lower signals used to quantify predictive variability (Figs. 3B and 3C). For weights over 56 kg, the error from the first transducer calibrations was -0.25% using the mean output values, or between -2.5% and $+2.0\%$ according to the uncertainty bounds. Error analysis from a second set of calibrations was -0.30% for the

mean calibration curves and a range between -3.0% and +2.5% for the low and high signal predictions.

2.3. *Laser profiler*

Bed morphologies and volumes were measured before and after each experiment by generating DEMs of the flume bed. The DEMs were created from laser scans of the flume bed collected using a Micro-Epsilon scanCONTROL laser profiler (Model LLT2800-100). This profilometer uses laser triangulation to determine distance to the bed, registering 1024 points per profile in the cross-stream direction. The profilometer was operated to maintain a vertical resolution of 40 μm (Micro-Epsilon, 2008) ensuring bed measurements detailed enough to develop high resolution DEMs for bed analysis and calculation of changes in sediment volume. The profiler was mounted on a carriage platform above the flume which was controlled by two stepper motors operated through LabVIEW, allowing for accurate placement in the streamwise and cross-stream directions. Five longitudinal scans were required to span the full flume width with ~ 1 cm of overlap between adjacent scans. All five scans were combined to create each DEM of the flume channel bed. Because the laser did not measure through the water column, the flume was carefully drained prior to each scan. Each scan represented the bed surface before or after a flow event. Sequential scans were differenced to measure the volume and spatial distribution of morphological change over the flume channel bed. The differenced DEMs are used here to evaluate how the BLMS added to information concerning channel adjustments during the flow.

3. Slope calculation with bedload monitoring system

3.1. Experiment details

The bed slope of an alluvial channel fluctuates during any large flow as sediment is eroded and deposited in a spatially nonuniform manner. A traditional method for monitoring these changes in a laboratory setting has been to read the bed level from rulers attached to the clear sides of a flume. While this information is useful, it is subject to errors from wall effects and choices made by the person recording concerning where to measure the bed. The BLMS provides an alternative. By measuring the weight over the flume length, the transducer readings can be manipulated to provide channel bed slope.

An example of how the BLMS has been applied to calculate bed slope comes from a series of experiments measuring sediment transport and bed changes during unsteady flow sequences (Waters and Curran, accepted). Alluvial bed surfaces alter under flood situations, and the BLMS was tested for its ability to replicate the expected rise and fall during the unsteady flow. The channel bed was comprised of well-mixed sediment with 70% sand and 30% gravel (median grain size of 0.55 mm). The bed was screeded flat prior to each experiment, and sediment was recirculated. The experiments used two different stepped hydrographs to simulate large and small flood events. Stepped hydrographs, which are commonly used to simulate unsteady flows in flumes (De Sutter et al., 2001; Hassan et al., 2006; Parker et al., 2008; Mao, 2012; Martin and Jerolmack, 2013), were constructed with 19 flow intervals of constant flow rate: six intervals on the rising limb, one at the peak flow, and 12 intervals on the falling limb. Each flow interval lasted for 4 min, and the unsteady flow hydrographs had a total duration of 76 min with a time to peak of 26 min. (Fig. 4). Short flow duration intervals ensured

that the stepped flow approach realistically modeled the unsteady nature of a natural hydrograph. The flow rates for the hydrographs were chosen to ensure a range of sediment transport conditions in which fine gravel was partially mobile at the low flow peak and the larger gravel fractions were partially mobile at the high flow peak. Relative flow magnitudes of each 4-min interval were derived to mimic the asymmetrical shape of the NRCS curvilinear dimensionless unit hydrograph (NRCS 2007) based on peak flow rates that were 2.5 times and 4.5 times the base flow rate. Hydrographs of the same flow magnitude were applied in repetition, with 2-hour base flow periods in between to form unsteady flow sequences. The base flow depth was set at 8 cm by a tailgate at the downstream end of the flume. During the unsteady flows, the depth was able to adjust freely.

3.2. *BLMS application*

Transducer readings from the BLMS were continuously recorded during the unsteady flow experiments. The signals were converted to weight, and the time series of weight measurements were broken into 4-min intervals to correspond with each constant flow interval. Data collected from 2.83 to 3.83 min within each 4-min interval were used to obtain a representative average weight for that interval while allowing for flow and bed adjustment. Total weights for each flume section and time interval were adjusted to account for overlying water weight and were then converted to mean sediment depth using sediment density and flume width. A linear regression of sediment depths over the downstream 6-m flume distance provided an estimate of bed slope for that flow interval, and a record of changes in bed slope during the unsteady flow hydrograph was reconstructed (Fig. 5). The flume reach adjusted throughout the flow event with variable adjustment rates on the rising and falling limbs of the

hydrograph. The resolution in bed slope changes recorded using the BLMS illustrated the variability occurring during a flood when direct measurements are rarely possible.

BLMS-measured bed slopes were compared against results from the more traditional method of taking measurements with clear rulers along the side of the flume (Fig. 6). During the experiments, at the midpoint of each 4-min hydrograph flow interval, bed elevations were recorded at every meter of the flume using rulers on the clear flume walls. The bed slope record from these measurements did not exhibit the increase and decrease that was expected, and many slope values were unrealistically similar. The method of reading rulers led to underestimated and overestimated slope values. The poor quality of ruler-derived measurements was attributed at least in part to the error from the person recording the data who may not have recorded level with the ruler and in this way underestimated the bed thickness or and may have focused on the highest point on the bed surface cross section coincident with the ruler and overestimated the bed level. In contrast, the data from the BLMS yielded consistently improved bed slope measurements that replicated the temporal variability in flume reach slope during an unsteady flow.

4. Sediment transport rates from BLMS

4.1. Experiment details

Sediment transport rates are known to fluctuate and are averaged over discrete time periods to capture mean transport rates. In the laboratory, sediment transport has been traditionally measured through interval sampling from either the downstream end of the flume channel or from the sediment recirculation system. The DEM differencing of sequential flume beds has been used to determine bulk sediment transport from morphology changes but not

transport rate. The BLMS was designed to measure spatial variability in the transport rate across the flume length during sediment transporting flows. To test the BLMS, flume runs were performed during which the sediment was measured with multiple methods: through collection in a sediment trap at the downstream end of the flume, through the BLMS, and indirectly through differencing DEMs created from laser scans of the bed surface before and after each experiment.

Three experiments were conducted to provide a test of the BLMS under low and high flows and for sediment beds with and without silt. The flow rates were $0.012 \text{ m}^3/\text{s}$ and $0.036 \text{ m}^3/\text{s}$, respectively. The first sediment was a graded mixture of 70% sand and 30% gravel with $D_{16} = 0.43 \text{ mm}$, $D_{50} = 0.66 \text{ mm}$, $D_{84} = 5.70 \text{ mm}$, and was applied to both flow rates. The second mixture, which was tested with $Q = 0.036 \text{ m}^3/\text{s}$, included a silt fraction and had $D_{16} = 0.10 \text{ mm}$, $D_{50} = 0.55 \text{ mm}$, $D_{84} = 5.15 \text{ mm}$. The sediments are referred to as the sand/gravel and sand/gravel/silt mixtures. In all experiments a sediment bed 12 cm thick was created that extended over the length and width of the flume. A low flow was run over this bed to create a water-worked surface. Additional sediment was then added to the upstream 2 m of flume length such that the first 2 m had a sediment bed 22 cm thick and the downstream 7 m had a bed $\sim 12 \text{ cm}$ thick. The upstream 2 m of the bed acted as a sediment source for the downstream area, allowing for a test of potentially erosional and depositional processes in the same experiment. Each experiment was continued until the transport rate out of the flume had diminished to near zero.

Sediment was not recirculated or fed during the experiments. As the sediment exited the flume, the majority was collected in a sediment trap. However, there remained the

possibility that some suspended sediment would bypass the trap and either deposit in the water tank or transport through the water recirculation system. To account for this sediment, suspended sediment samples were collected at the upstream and downstream ends of the flume throughout each experiment. Suspended sediment concentrations were negligible for the sand/gravel sediment, but averaged 0.06 g/mL at the upstream and downstream ends of the flume during the sand/gravel/silt experiment with minimal variation. The difference between the total suspended sediment concentrations at the upstream and downstream ends of the flume provided an indirect measurement of the amount of suspended sediment that deposited in the water tank.

4.2. *BLMS application*

The BLMS records were converted to weights using calibrations performed prior to the experiments, and the water signal was subtracted from each record. Weights were recorded every 0.2 min and demonstrated the ability of the transducers to capture a dynamic bed surface (Fig. 7). Despite variability in each record, it was possible to identify periods of erosion or deposition at each flume section. In all experiments, the BLMS recorded erosion from the upstream transducer, which was located under the area of added sediment, and erosion and deposition over the downstream bed during each experiment (Fig. 7). Upstream rates of erosion were initially high and reduced quickly. The downstream transducers generally registered increases in weight, indicating deposition over the downstream 7 m of flume channel. Within these general trends, records from the BLMS captured variability in the sediment transport rates that corresponded to flow rate and sediment mixture.

Under the high flow rate and the sand/gravel sediment, a steady rate of deposition was indicated by increases in weight recorded over the first half of the experiment followed by a steady rate of erosion at 4, 5, 6, 8, and 9 m (Fig. 7A). In contrast, the transducer immediately downstream of the added sediment, at the 3-m section, recorded channel bed erosion over the first half of the run with deposition not occurring until the latter part of the experiment. Erosion of the thicker sediment at sections 1 and 2 occurred quickly with 90% of the reduction in weight occurring during the initial 20% of the experiment. Further erosion from the upstream 2 m occurred much slower and were coincident with increases in sediment weight immediately downstream at the 3-m section.

The BLMS record from the low flow rate experiment demonstrated the influence of flow rate and the ability of the BLMS to capture small changes in the channel bed (Fig. 7B). The same sand/gravel sediment under a low flow rate experienced deposition downstream at 3 m, immediately downstream of the thicker upstream sediment bed. For the majority of the experiment, erosion from the upstream sections occurred at a similar rate as deposition over the sections 3-5 m downstream. The section at 7 m increased in weight, indicating deposition at this location over the first half of the experiment. The sediment bed sections farthest downstream, at 8 and 9 m, adjusted to the imposed flow regime and sediment supply quickly, within the first 20% of the experiment time. There was net flume channel bed aggradation over sections 3-9 m under the low flow rate, and the BLMS captured variability in deposition rates over the downstream flume bed.

The addition of a silt fraction to the sediment tested the ability of the transducers to capture changes in bed weights when a sand/gravel/silt sediment moved both as bedload and

in suspension under a high flow rate. Immediately following erosion from the upstream sections, increases in sediment weight were recorded at the 3- and 4-m sections. Deposition at these two sections occurred quickly, over the first 20-40% of the experiment time. An increase in weight at 5 m was measured over 30-45% of the experiment. These same three bed sections eroded over the second half of the experiment as the sections at 8 and 9 m downstream experienced a smaller increase in weight over 60-80% of the experiment time. The BLMS captured the pattern of deposition and erosion through the downstream part of the flume channel, quantifying temporary sediment storage during the experiment.

The DEM differencing provided the volume and spatial distribution of net erosion and deposition during each experiment (Fig. 8). After the high flow rate was applied to the sand/gravel sediment, DEM differencing showed that the final bed surface had experienced a loss of 4.5-12.9% of its initial sediment volume at all the downstream sections except for the section at 4 m, which increased in volume by 1.1% (Fig. 8A). These percentages corresponded to a maximum erosion of 10.8 kg and maximum deposition of 7.4 kg. Changes in the bed surface were not uniform, and there were areas of deposition and areas of erosion within each bed section. Net deposition and erosion were near equal within the section at 3 m, but farther downstream the erosional areas within each section were greater than the deposition areas. In contrast, the same sand/gravel sediment under a low flow rate experienced net aggradation over all sections downstream of the thicker sediment bed (Fig. 8B). Increases in sediment volume were between 4.8% at the 4-m section and 29% at the 3-m section for a maximum aggradation of 17.1 kg at a single section. Spatial variability identified from the differenced DEM showed that while sections from 3-9 m experienced net aggradation, there were limited areas

of net erosion along flume channel sides within the 3-m section and offset from the center of the 8-m section. Patterns of erosion and deposition were most variable in the differenced DEM from the experiment using the sand/gravel/silt sediment (Fig. 8C). The channel sections immediately downstream of the added sediment, 3 and 4 m, aggraded by 39% and 13% from their initial bed volumes, respectively. Over the same time, sections farther downstream lost between 4.5% and 12.8% of their initial volumes. These percentages translated to a range of maximum net aggradation of 17.7 kg to a maximum net erosion of 12.3 kg at an individual section. These weights were similar to the values measured following the experiment with the sand/gravel sediment and same high flow rate.

The ability of the BLMS and DEM differencing to measure net change in the sediment bed was evaluated through comparison to the sum of the sediment collected from the sediment trap and in the water tank after the experiment. In each case, the weight measured represented the amount of sediment that left the flume channel into either the sediment trap or tank (Table 1). For the BLMS, this was the difference between initial and final bed weights. With DEM differencing it was the measured net loss in sediment bed volume converted to weight. The difference between the weight of sediment collected in the downstream trap and tank and the loss in sediment bed weight calculated by the BLMS and DEMs quantified the ability of each method to provide an accurate measure of the change in the channel bed. The differences between trap and BLMS or DEM sediment weights were divided by the initial weight of each sediment bed. The accuracy with which the BLMS and DEM differencing measured the changes in channel sediment bed and closed the sediment mass balance was compared through this percent difference. For the low flow rate experiment with the

sand/gravel sediment, the BLMS and DEM analysis gave similar results with respective net sediment losses within 7.1 and 6.9 kg of the 46.2 kg accumulated in the downstream trap and tank. These weights represented <1% of initial sediment bed weights. The high flow experiment mobilized a greater amount of sediment, and 144 kg accumulated in the downstream trap and tank from the sand/gravel bed and 131.1 kg from the sand/gravel/silt bed. For both experiments, the results from the BLMS were more accurate than the DEM differencing. Results from the BLMS were within 1.5 kg or 0.20% of the initial bed weight for the sand/gravel sediment bed and within 14.8 kg or 2.81% for the sand/gravel/silt sediment. In contrast, the DEM analysis underestimated the net erosion by 59.9 kg or 8.0% of the initial bed weight for sand/gravel sediment and by 47 kg or 8.9% with the sand/gravel/silt sediment. Overall, the BLMS demonstrated a high degree of accuracy in accounting for sediment movement during low and high flow rate experiments and for beds with and without a significant suspended sediment component. The greater accuracy of the BLMS data may be attributed in part to the ability of the BLMS to capture continuous weight data, while DEM differencing relied on time-integrated data to measure net bed volume change.

4.3. Sediment transport rates from BLMS data

Data from the BLMS were used to re-create the sediment transport during each experiment. Because the BLMS measured sediment and water weights longitudinally down the length of the flume, we were able to use the measured change in sediment weight between time steps and re-create records of sediment deposition and erosion across the flume bed and over the duration of each experiment. These data were used to quantify the amount of sediment in transport at each measurement step. Sediment transport records were averaged into one-

407 minute intervals to produce the transport rate in kg/min throughout each experiment (Fig. 9).
408 The patterns from the three experiments show the dependence of transport rate on sediment
409 size distribution and flow rate.

410 The sand/gravel sediment transported at a rate between 0.1 and 1.9 kg/min under the high
411 flow rate (Fig. 9A). Sediment transport during the first minutes of the experiment reached a
412 maximum of 1.2 kg/min and quickly decreased to between 0.1 and 0.6 kg/min over the first half
413 of the experiment. Transport rates and variability in the transport rate increased during the
414 second half of the experiment over the length of the flume. Transport rates were slightly larger
415 within the area of added sediment at the 1- and 2-m sections when compared with the sections
416 farther downstream. While this spatial difference in transport rates was maintained throughout
417 the experiment, the difference between the transport rates over 3-4 and 8-9 m increased as
418 volatility in the sediment transport rates increased.

419 The same sand/gravel sediment subjected to a low flow rate experienced its largest transport
420 rates at the start of the experiment. A peak in transport rate occurred at minute 5 when
421 transport across the flume averaged 2.0 kg/min. Before and after minute 5, the transport was
422 within the range of 0.05-0.25 kg/min. Similar to the transport pattern from the high flow
423 experiment, there were larger sediment transport rates in the area near the downstream end
424 of the added sediment bed when compared to farther downstream in the flume. Unlike the
425 record from the high flow rate experiment, the sediment transport rates under the low flow
426 were larger early in the experiment. The disparity between upstream and downstream
427 transport rates was also greater during the first half of the experiment. During the second half

of the experiment, transport rates equalized across the flume and remained within a narrow band between 0.10 and 0.17 kg/min.

The addition of silt to the sediment bed dramatically altered the sediment transport record and dampened most of the volatility in transport rates despite being measured during a high flow rate. High transport rates were measured during the first 3 min of the experiment when transport rates peaked at 0.95 kg in minute 1, 2.59 kg in minute 2, and 1.07 kg in minute 3. After 3 min, transport rates quickly decreased and remained low. Over the remainder of the experiment the maximum transport rate was 0.57 kg/min. Transport rates were maintained between 0.10 and 0.20 kg/min with the exception of isolated increases in transport rate across the flume at minutes 17 and 24, but each was limited to a single minute in duration. The addition of silt to the bed sediment also increased the suspended sediment transport rates, which clouded the water and precluded direct observation of the flume bed.

5. Discussion

The BLMS was designed for laboratory use and may be applied to a wide variety of experiments where there is a need to improve understanding of the movement of sediment and associated changes in bed slope, especially during complicated flow regimes or when fine sediments transport in suspension. The study of river systems has matured over time toward increased accuracy and detail. For example, studies of incipient motion from gravel-bed rivers have evolved from spherical grains on an inclined plane (Shields, 1936) to unisize (Wiberg and Smith, 1987) and then graded sediments (Wilcock and Southard, 1988). At the same time, the number of parameters found to affect incipient motion has also increased to include relative degree of exposure (Shvidchenko and Pender, 2000; Armanini et al., 2005), grain shape (Gogus

and Defne, 2005), sediment mixture modality (Wilcock and McArde, 1993), the fines content of the mixture (Wilcock and Crowe, 2003), the antecedent flows in the channel (Ockelford and Haynes, 2013), and the magnitude and duration of turbulent flow bursts (Valyrakis et al., 2010; Valyrakis et al., 2013). With each level of detail, work from flume studies provides further insight into the forces shaping natural channels.

The BLMS can be utilized in laboratory experiments to improve an understanding of how a channel bed changes in response to a change in flow rates and sediment supply. Experiments with the BLMS in place will be able to focus on how an event, such as a dam removal or prescribed flow hydrograph, will transport sediment and redistribute it over the channel bed in the flume. In the experiments presented here, the combination of BLMS and DEM enabled an accurate reconstruction of bed slopes during the passage of unsteady hydrographs. When BLMS results were combined with DEM differencing, preferred areas of degradation and aggradation were identified and tied to the record of sediment movement through the flume for a more complete understanding of how the sediment transport and bed surface changed during an experiment. For example, BLMS data from the experiment applying a low flow rate to the sand/gravel sediment were characterized by sediment transport rates that were initially greater at the upstream end of the flume and decreased during the experiment. Data from the BLMS indicated increased deposition on the bed surface as the transport rate that decreased over time, and this was confirmed by DEM differencing that illustrated net bed aggradation. However, the associated differenced DEM also illustrated isolated areas of limited net bed scour. While the BLMS provided information on sediment transport rates over the flume channel, the differenced DEM illustrated the impact of sediment transport on the spatial

distribution of net deposition and bed scour. During the experiment using the sand/gravel/silt sediment, the suspended sediment precluded direct observation of bed changes, making the combination of BLMS and DEM especially useful. The DEM record showed the bed surface generally smoothed during the experiment such that the final bed surface had few extremes in topographic variability. Data from the BLMS indicated the progressive movement of the transport peak downstream during the experiment. The BLMS provided insight into the rate of topographic change that was captured as overall bed aggradation by the DEMs. The BLMS added the high resolution spatial and temporal sediment flux measurements that were previously not possible.

Combined application of BLMS and DEMs in scaled physical model experiments may be most beneficial when real time changes in the bed can have a direct effect on ecosystems or where the stability of a bed feature is desirable. If there are specific areas of a channel where the ecosystem is highly sensitive to change, the BLMS can provide the additional information needed to evaluate the potential for temporary scour or burial of the sensitive area, thereby linking temporal changes in sediment supply and storage that impact channel adjustments. An estimate of the time duration over which a particular bed section will be disturbed is also possible with this system. The BLMS provides insight into real time channel changes during unsteady flows that were previously unattainable in cases where high suspended sediment concentrations precluded observation. The BLMS can be adjusted for different experiments by changing the size of the Plexiglas plates. Reducing the size of the plates will increase the spatial resolution of the BLMS and enable analysis over specific bed features. Increasing the spatial resolution of BLMS measured bed changes will also increase the sensitivity of the system to

small topographic changes as they will encompass a greater fraction of the bed area measured by a single transducer. Exciting implications of future research that incorporates a BLMS include a more informed management of river systems as a result of improved temporal predictions of sediment movement and the associated changes in channel slope and morphology.

6. Summary

Methods for nonintrusive sediment flux measurements in either a flume or a field site have been limited and focused primarily on individual particle tracking and downstream bedload sediment trapping. The BLMS was developed to add to the information gathered during a sediment transport event in a laboratory flume. With the BLMS we were able to identify the time lag for bed adjustment, compare the relative amounts of deposition and erosion during flume runs, quantify longitudinal sediment transport rates during the experiments, and quantify rapidly changing bed slopes during an unsteady flow. The system was especially helpful in experiments with finer sediments in which the amount of silt in suspension prevented direct observation of the bed and during flood hydrographs during which bed adjustments occurred quickly.

The examples presented here focused on the additional information gained by using the BLMS and how that information can be combined with existing techniques to enhance an overall understanding of real-time changes in bed morphology. Existing methods for measuring sediment transport rate and changes in the bed surface morphology work on discrete time intervals defined by the operator. They can be used to infer changes occurring over the channel bed during a sediment transport event but they do not provide a direct measurement of the fluctuations in bed aggradation and degradation. The spatial intervals over which the BLMS

measures were set by the size of the Plexiglas boards. The temporal measurements from the BLMS were continuous. When the BLMS was analyzed in conjunction with bed surface DEMs and differenced DEMs, a complete transport and bed adjustment picture was constructed. The difference DEMs provided information on the spatial extent of bed morphology changes. The BLMS supplied the data record necessary to reconstruct sediment transport records through the downstream channel, including locations and time periods of temporary sediment storage and supply.

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Fig. Captions

Fig. 1. Bedload monitoring system without sediment. View is looking down the flume. The plexiglas plates and pressure tubes underneath are visible. The latex sheet and sediment have not yet been added.

Fig. 2. Transducer calibration curve for flume segment 5 m (second calibration). Error bars are determined by minimum and maximum signal measurements. Dashed line represents calibration curve given by equation: $w_l = 56,153(volt)^2 + 8949.5(volt) - 119.2$.

Fig. 3. Transducer calibration errors for (A) mean signals; (B) low signals; (C) high signals.

Fig. 4. Stepped experimental design hydrographs for (A) low flow and (B) high flow. The red dashed line indicates baseflow.

Fig. 5. Example of the bed slope estimates from BLMS during unsteady flow events of varying flow magnitude. Respective peak flows occurred at hydrograph run time of 26 minutes.

Fig. 6. Comparison of ruler-read bed slopes to those from the DEM+BLMS system. Comparisons are made relative to bed slope after an unsteady flow event.

Fig. 7. Weight records from BLMS transducers. Each line in the graph is the record from one transducer and shows the changes in weight over a 0.6 m^2 area of the flume bed over time. The darkest line represents the flume section at 1 m where there was a thicker sediment bed and the lightest line the section at 9 m. (A) Record from experiment with sand/gravel sediment transport and $Q=0.036 \text{ m}^3/\text{s}$. (B) Record from experiment with sand/gravel sediment and $Q=0.012 \text{ m}^3/\text{s}$. (C) Record from experiment with sand/gravel/silt sediment and $Q=0.036 \text{ m}^3/\text{s}$.

Fig. 8. Differenced DEMs illustrating the change in bed elevation before and after each experiment. Flow is from left to right. In each image, red indicates net aggradation and blue net erosion. The scale is adjusted in each Fig. to the difference in elevations. (A) Sand/gravel sediment transport with $Q=0.036 \text{ m}^3/\text{s}$. The elevation scale is from 0.03 to -0.10 m. (B) Sand/gravel sediment transport with $Q=0.012 \text{ m}^3/\text{s}$ over 55 min. The elevation scale is from 0.20 to -0.05 m. (C) Record from experiment with sand/gravel/silt sediment and $Q=0.036 \text{ m}^3/\text{s}$. The elevation scale is from 0.04 to -0.05 m.

Fig. 9. Sediment transport rates calculated from BLMS data. In each graph a single line represents the transport rate across the length of the flume averaged over a minute. The first minute of the experiment is the darkest line and the final minute the lightest. The bed is thicker over the upstream 2 m, and this is marked on the figures. (A) Sand/gravel sediment transport with $Q=0.036 \text{ m}^3/\text{s}$ over 55 min. (B) Sand/gravel sediment transport with $Q=0.012 \text{ m}^3/\text{s}$ over 55 min. The average transport rate at minute 5

675 was 2.0 kg/min, and this time step has been removed for graphing. (C) Record from experiment with
676 sand/gravel/silt sediment and $Q=0.036 \text{ m}^3/\text{s}$.

677

Table 1

Table 1. BLMS calibration results.

Flume section	1st Calibration				2nd Calibration			
	A	B	C	R ²	A	B	C	
3m	38,674	9,175	-79.2	0.9997	-4,466	11,162	-119.8	
4m	48,093	9,040	-80.7	0.9998	59,579	8,958	-91.1	
5m	72,319	8,393	-69.7	0.9999	56,153	8,950	-119.2	
6m	22,328	9,994	-118.8	0.9998	35,514	9,573	-124.3	
7m	64,866	8,144	-99.4	0.9998	56,033	8,305	-121.0	
8m	41,550	9,533	-88.4	0.9999	35,010	9,638	-133.3	

Table 2

Table 2. Comparison of sediment lost from the flume as measured through accumulation in the do

Flow rate, m ³ /s	Sediment mixture	Direct measurement			DEM	
		Amount in sediment	Amount in tank, kg	Combined trap+tank, kg	Sediment loss, DEM,	Δ DEM- (trap+tank)
0.012	Sand/ gravel	45.98	0.27	46.20	39.20	7.10
0.036	Sand/ gravel	143.78	0.23	144.00	84.10	59.90
0.036	Sand/ gravel/ silt	129.10	1.97	131.10	84.10	47.00

Figure (Color)

Figure (Color)

Figure (Color)

Figure (Color)

Figure (Color)

Figure (Color)

Figure (Color)

Figure (Color)

Figure (Color)

Figure (Greyscale)

Figure (Greyscale)

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Figure (Greyscale)

(A)

-0.010 m 0.03 m

(B)

-0.05 m 0.20 m

(C)

-0.05 m 0.04 m

Figure (Greyscale)