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Large-Scale Laboratory Testing of Bedload-Monitoring Technologies: Overview of the StreamLab06 Experiments

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ABSTRACT

A 3-month-long, large-scale flume experiment involving research and testing of selected conventional and surrogate bedload-monitoring technologies was conducted in the Main Channel at the St. Anthony Falls Laboratory under the auspices of the National Center for Earth-surface Dynamics. These experiments, dubbed StreamLab06, involved 25 researchers and volunteers from academia, government, and the private sector. The research channel was equipped with a sediment-recirculation system and a sediment-flux monitoring system that allowed continuous measurement of sediment flux in the flume and provided a data set by which samplers were evaluated. Selected bedload-measurement technologies were tested under a range of flow and sediment-transport conditions.

The experiment was conducted in two phases. The bed material in phase I was well-sorted siliceous sand (0.6-1.8 mm median diameter). A gravel mixture (1-32 mm median diameter) composed the bed material in phase II. Four conventional bedload samplers – a standard Helley-Smith, Elwha, BLH-84, and Toutle River II (TR-2) sampler – were manually deployed as part of both experiment phases. Bedload traps were deployed in study Phase II. Two surrogate bedload samplers – stationary-mounted down-looking 600 kHz and 1200 kHz acoustic Doppler current profilers – were deployed in experiment phase II.

This paper presents an overview of the experiment including the specific data-collection technologies used and the ambient hydraulic, sediment-transport and environmental conditions measured as part of the experiment. All data collected as part of the StreamLab06 experiments are, or will be available to the research community.

INTRODUCTION

Bedload transport is the mechanism by which alluvial rivers change form. Hence, for alluvial rivers with active bed-material transport, reliable estimation of bedload-transport rates is required for a wide range of assessments, including those for river restoration, channel stability, and the long-term viability of reservoirs and hydraulic structures.

Deficiencies associated with traditional instruments and techniques used to quantify bedload and potential solutions to address those deficiencies have been identified as part of two workshops sponsored by the Advisory Committee on Water Information's Subcommittee on Sedimentation (2007): The Federal Interagency Sediment Monitoring Instrument and Analysis Workshop (Ryan et al., 2005) and the International Bedload-Surrogate Monitoring Workshop (Laronne et al. 2007; Gray et al. 2007). Both workshops identified a fundamental need for ground-truth in bedload measurements and for reliable surrogate technologies to provide a continuous time-series of bedload-transport rates. These needs serve as the motivation for the work presented herein, in which we conducted an intense, 3-month set of research experiments using five conventional and two surrogate bedload-monitoring technologies at the St. Anthony Falls Laboratory (SAFL) in Minneapolis, Minnesota, USA.

This paper presents a description of the facility, an overview of the instrumentation, and a summary of the salient conditions occurring during the experiment, e.g. sediment fluxes, water discharges and other experimental conditions. Specific results pertaining to the performance of bedload-monitoring technologies are presented in selected papers in these proceedings.

MAIN CHANNEL FACILITY

The experiments were conducted in the Main Channel facility (flume) at SAFL, which is capable of conveying field-scale flows and recirculating known quantities of sand- to medium-gravel-sized sediment for days at a time. The flume has a rectangular cross-section with a width and height of 2.74 and 1.80 m, respectively, and a length of 80 m (Figure 1). Water from the Mississippi River is diverted through the flume via a screened intake by exploiting the head differential from St. Anthony Falls. A sluice gate controls flows to the Main Channel at rates ranging from 0 to 8.5 m^3/s.

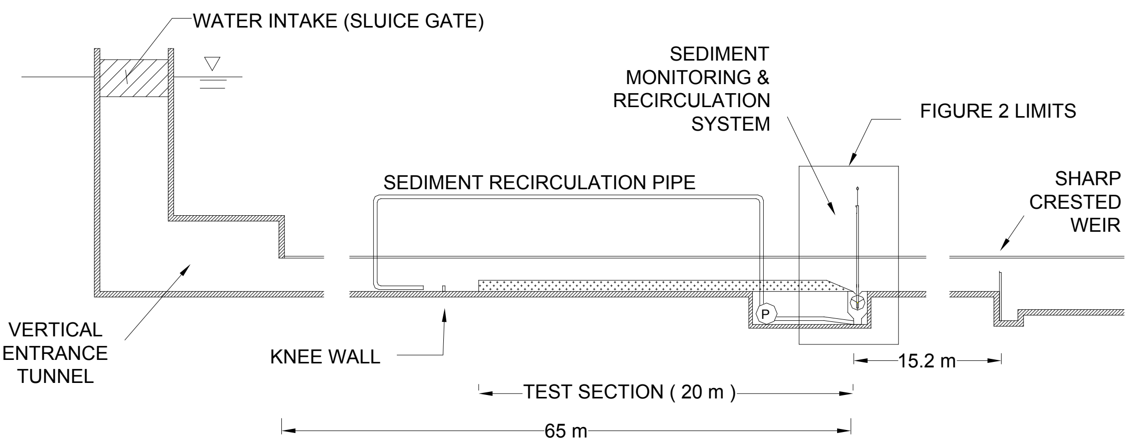

Figure 1. Section schematic of the St. Anthony Falls Laboratory Main Channel facility.

A key characteristic of the Main Channel is the Sediment Monitoring and Recirculation System (SMRS). Located 65 m from the upstream end of the flume, the SMRS has the following principal components:

1. A cross-channel slot (bedload trap) into which bedload particles fall,

2. A sediment-flux monitoring component that spans the full width of the bedload trap below the flume's floor and continuously collects and weighs entrapped bedload (see next section), and
3. A pumping system that returns the trapped sediments as large as 76-mm median diameter to the upstream part of the flume via a 20-cm-diameter steel pipe.

Located 15 m downstream from the bedload trap is an adjustable-elevation sharp-crested weir, which has the dual purpose of controlling flume tailwater elevation and, with continuous stage data and a stage-discharge relation, metering water discharge. A schematic of the SAFL's Main Channel Facility is shown in Figure 1.

Sediment Flux Monitoring System

The sediment-flux monitoring component of the SMRS, which was designed, fabricated, and installed by the SAFL in 2005, is an essential component of the Main Channel flume. The SMRS is capable of continuously monitoring bedload flux during an experimental run.

The monitoring system is composed of five adjacent, identical aluminum drums that span the width of the flume and cumulatively measure the submerged weight of the bedload intercepted by the bedload trap. Hence, each weigh drum measures bedload transport occurring in the one-fifth interval (0.55-m-wide section) of the flume that the drum occupies (Figure 2). The drums, like the sediment recirculation system, can accommodate up to 76-mm-median-diameter particles.

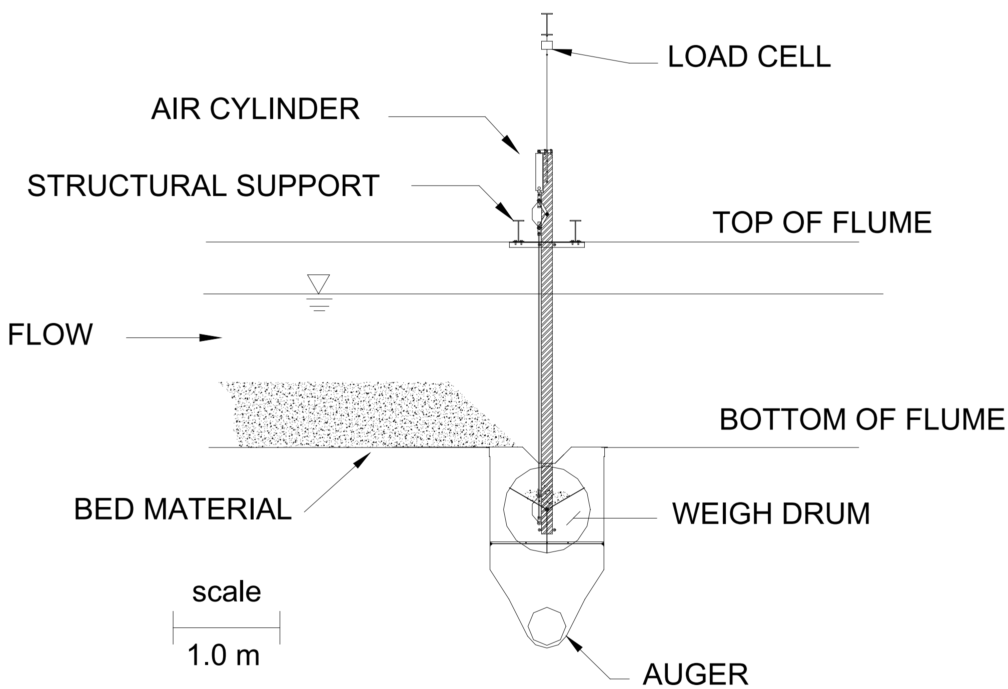

Figure 2. Schematic section of a weigh-drum viewed perpendicular to the direction of flow.

Each drum hangs from an aluminum frame that extends from its sides to a load cell connected to the ceiling above the Main Channel. The system uses load cells manufactured by Interface Advanced

Force Measurement[1] (SM-250) that have a capacity of 113 kg and are accurate to ±45 gram-force[2]. As a safety margin to avoid exceeding the capacity of the weigh-drum system, the drum rotation that voids each bin's contents is triggered at user-specified net weights, typically 20-40 kilogram-force (kg-f).

Removable stainless steel cover plates with 45.2-cm by 15.2-cm slots located under the bed trap serve to funnel the intercepted bedload downward into the drums. The drums, which can accommodate particles up to 76-mm median diameter, are constructed of aluminum and have three radial baffles welded to a common 3.8-cm-diameter hub and to two 81.3-cm-diameter end plates. They are oriented horizontally and transverse to the flume under the sediment trap. The three radial baffles form two adjacent 120-degree "V"-shaped bins, each of which has a capacity of 62 liters. The submerged weight of sediment in a bin at maximum capacity is 62 kg-f. Each drum operates independently using a tipping-bucket arrangement with "tips" consisting of alternating clockwise and counterclockwise 120-degree rotations. When the sediment mass in a weigh drum reaches a specified threshold, a pneumatic piston either extends or retracts, causing the drum to rotate 120 degrees. This action results in dumping the contents of one bin and repositioning the adjacent, empty bin under the funnel to continue collecting the captured bedload. In this manner, all bedload is continuously captured and weighed in the five independently operating drums.

The submerged weights of each drum measured continuously by the respective load cell are monitored by a central data-acquisition (CDAQ) system. Data on water temperatures and water-surface elevations (stage) measured by sensors located 6 m upstream from the weir, along with the weir elevation, are also continuously monitored. All data acquired by the CDAQ system are automatically recorded and stored as an ASCII-formatted file. The measurements are recorded by the CDAQ system at 5000 Hz for a user-specified period of time. Typically, 4000 values of mass-force are measured in a 0.8-second interval. A mean value from the 4000 measurements is computed and stored in the ASCII file. Each measurement, processing, and recording cycle, the duration of which is user-defined, took about 1.1 seconds to complete during the StreamLab06 experiments.

The drum-weight data are used to estimate bedload mass flux by providing data on the rate of change of the submerged weight of sediment trapped in each drum. As bedload is transported from the test section and falls into an initially empty drum bin, the load cell records an increasing weight of material in the drum. The data include some high frequency noise (positive- and negative-value oscillation about the correct weight) resulting from vibration in the weigh drums due to water turbulence around the SMRS intake induced by the dumped sediment. The recorded data during and immediately after a drum tip, as the water around the drum becomes relatively quiescent once again, are also spurious. Post-processing of the data, including removal of spurious data resulting from bin dumps and applying averaging techniques on the data to remove the oscillation noise, is required for computation of reliable sediment-flux values at 1 Hz at each of five distinct lateral locations across the flume.

The first step for post-processing these data is to rectify data recorded during tipping events and to convert the data to a continuous cumulative dataset. An algorithm was written to identify and correct for the spurious data recorded as part of a tipping event. Based on examination of the data, it was determined that no more than eight consecutive mass-force values recorded in the 8.8-second period following a tipping event are compromised. To estimate mass-force accumulation values for these intervals, the algorithm performs a linear regression on the 30 mass-force accumulation values leading

[1] The use of firm, brand, or product names does not imply endorsement by the U.S. Government or SAFL.
[2] The uncertainty associated with mass-force measurements is a function of the resolution of the analog-to-digital converter board and that of the load cells. The accuracy of the latter, being an order of magnitude less than the resolution associated with the converter board, is the limiting factor. The combined uncertainty is about 0.04 percent, which for the 113.4-kg load cells is equivalent to 45 gram-force.

up to the tipping event. The slope and offset associated with the regression relation are used to estimate mass-force accumulations during the tipping event, and to replace the spurious data in that interval with the regression-computed values. The normal accumulation algorithm is continued following the removal of the tipping event. The combined duration of tipping events was rare compared to the total run time of the experiments (less than 1% of data points were associated with tipping events) and, therefore, likely contribute a relatively small error in the computation of continuous bedload transport. For example, with the drum net weight limit set at 40 kg-f and a typical mean full channel submerged flux rate of 0.17 kg-f/sec (0.1 kg-f/sm – dry weight), tips occur on average every 19.5 minutes, and the 8.8 seconds-per-tip of lost data comprise only 0.7% of the full data set. A diagram of a tipping event and the procedure for removing these events from the data are shown in Figure 3.

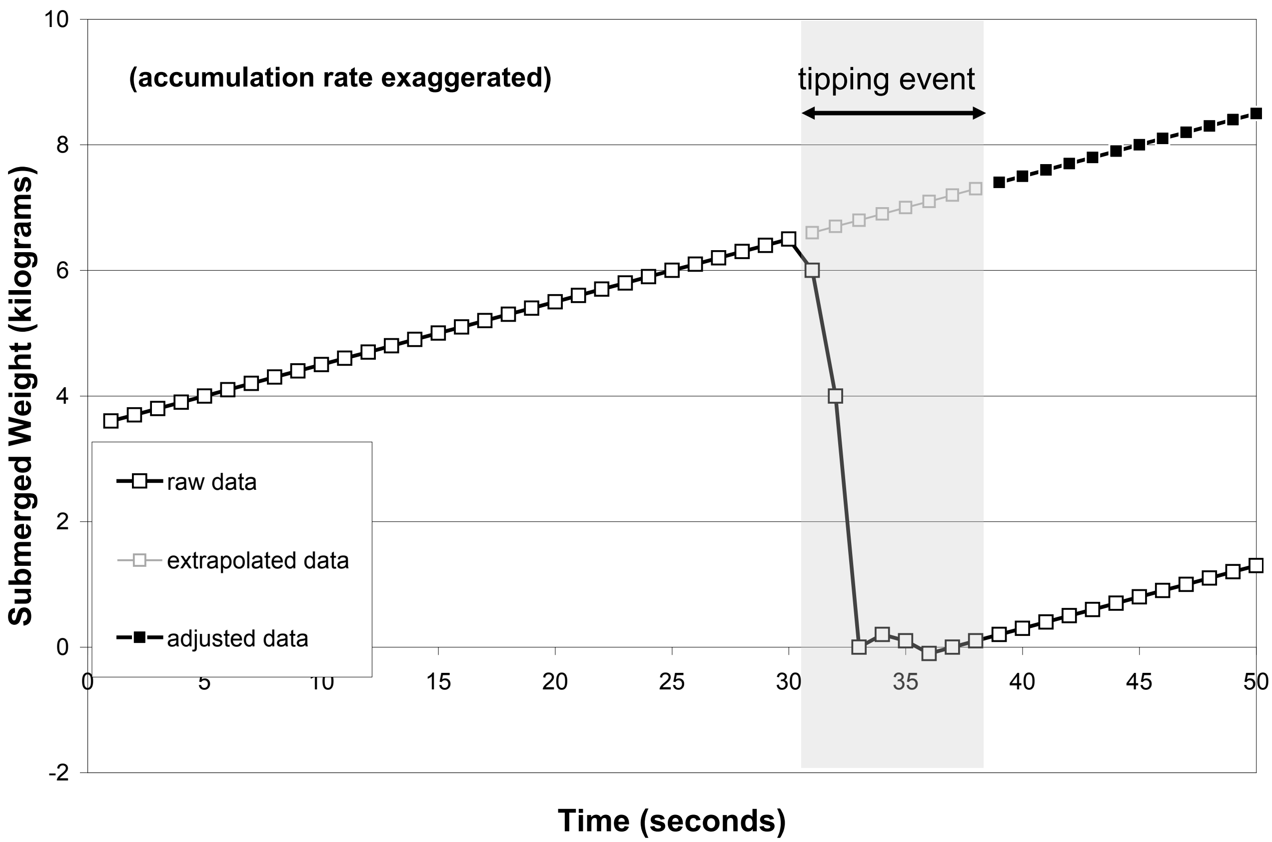

Figure 3. Illustration of weigh-drum accumulation data and removal of spurious data caused by drum-tipping events. Note: accumulation rate is idealized and exaggerated for clarity of method.

Sediment-Recirculation System

Another feature of the SAFL Main Channel is its capability to recirculate large quantities (0-20 kg/s) of medium-gravel-sized sediments up to 55 m upstream from the SMRS, which enables continuous, long-duration sediment-transport research. The system was designed in the early 1980s by the Federal Interagency Sedimentation Project as part of a program for ground-truth testing of several configurations (selected nozzle sizes and ratios of intake-to-outlet nozzle area) of the Helley-Smith bedload sampler (Hubbell et al., 1987).

The recirculation system is capable of entraining and recirculating particles up to 76 mm median diameter. The recirculation system's intake is in the bed trap below the weigh-drum system, where a horizontal auger, driven by a variable-speed motor, spans the full width of the channel (Figure 4). The rotating auger conveys sediments accumulated from weigh-pan dumps toward an outlet recessed in the right side of the flume and into the recirculation-pump (dredging-pump) intake. A large 3-phase recessed-impeller centrifugal pump transports the sediments and a small amount of water via a 20 cm diameter steel recirculation pipe at an elevation about 4 m above the floor of the flume to an upstream location, where the water-sediment mixture is discharged back to the flume. The water required for the pump's operation, about 0.25 m^3/s, is not obtained from the flume but from an independent source. This is because use of flume water for pump operation would induce a net downward flow of water into the bed trap that would (1) potentially result in the suction of sediment into the weigh drums, and (2) generate a false loading onto the weigh drums, thus potentially resulting in spurious bedload-transport calculations.

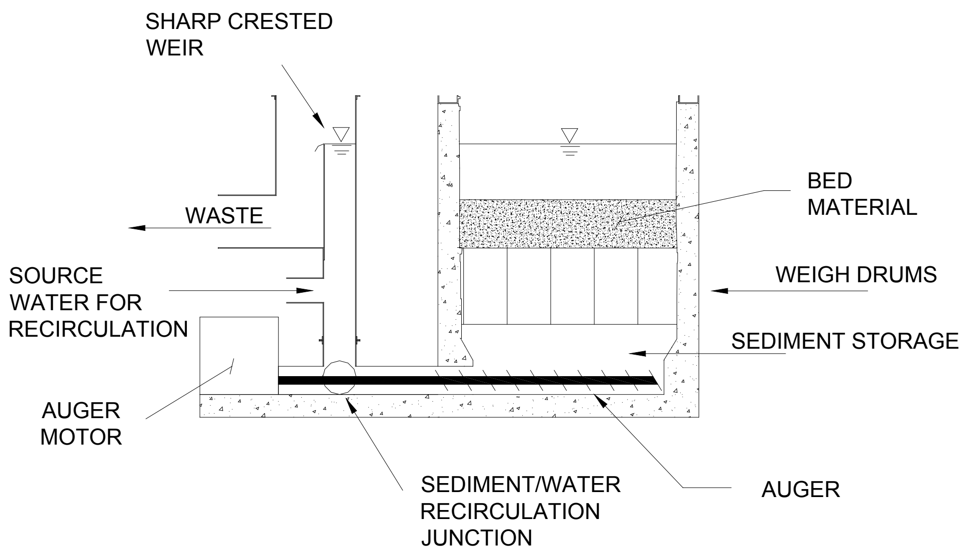

Figure 4. Cross-section detail (not to scale) of the sediment flux and recirculation system.

The maximum test section length in the Main Channel is 55 m. However, to minimize the total sediment mass required for the StreamLab06 experiments, the length of the test section during the experiments was shortened to 20 m. The 20-cm recirculation pipe extended to a point 10 m upstream from the test section (i.e. 30 m upstream from the SRMS). The outlet configuration is shown in Figure 5. The recirculation pipe was aligned longitudinally along the centerline of the channel bottom with the outlet oriented downstream. Located 1 m downstream from the outlet pipe was a 0.3-m-high knee wall installed across the width of the channel to dissipate the relatively high water- and sediment-exit velocities of the recirculation pipe. We estimate from bathymetric surveys that the entrance effects caused by the knee wall and the recirculation pipe affected the upstream-most 3-5 m of the test section, and therefore we do not consider this part of the flume in subsequent data analyses.

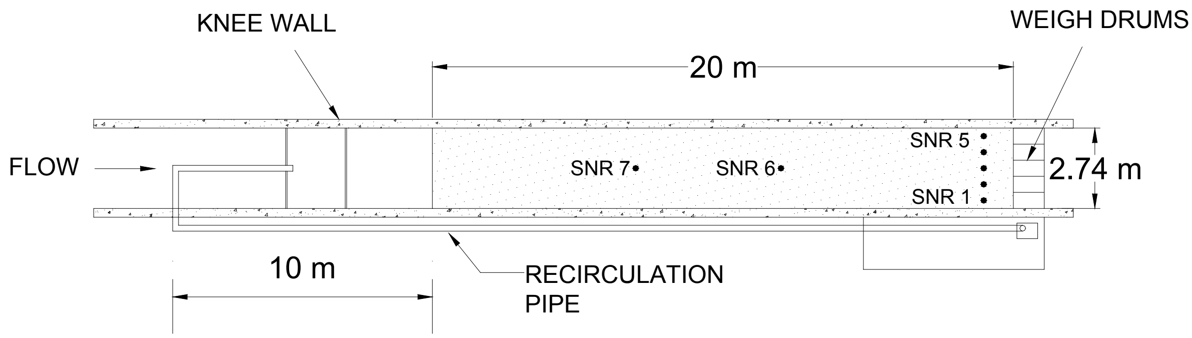

Figure 5. Plan view of the experimental set-up for the bedload technology research in the Main Channel. "SNR" indicates the location of submersible sonar probes.

INSTRUMENTATION

In addition to data obtained continuously by the sediment-monitoring system, several other types of measurements were made during the experiments. Details on the specific instrumentation and data-collection techniques employed in the experiments are given below.

Water Temperature – Water temperature was recorded at the SRMS using a YSI thermistor having an accuracy of ±0.1 degree C. The thermistor was mounted on the right SRMS pier (nearest weigh-drum 5) at the bottom of the channel.

Water-Surface Elevation (Stage) – The downstream tailwater surface elevation was measured using a sonic range finder, Model M5000/220 manufactured by Massa Products Corporation. The sensor, located 6 m upstream from, and referenced to the elevation of the sharp-crested weir at the flume's tailwater section, has a measurement accuracy of 0.5 mm.

Water Discharge – Discharge was computed by the CDAQ software using a calibrated sharp-crested weir equation, stage data, and weir-crest data. The weir-crest elevation was monitored by a potentiometer connected to a float via a wheel and tape. The measured discharge was the total flow passing the bed trap, comprised of Mississippi River diversions plus the relatively minor contributions from the sediment-recirculation system.

Bottom Tracking Sonar – During most of the experimental runs, temporal point measurements of bed elevation were obtained at seven locations using a submersible pulse-echo sonar system. Five of the transducers were located 1 m upstream from the centerline of each of the five weigh drums. The other two transducers were located near the flume centerline at 8 m and 13 m upstream of the weigh drums. Data from these probes were used to periodically determine bed elevations under each probe. One data point for each probe was recorded to an ASCII output data file every 10 seconds. The location of the seven bottom-tracking sonar probes is shown in Figure 5 and tabulated in Table 1.

Table 1. Location of submersible sonar probes in the Main Channel.

Transducer	Longitudinal position (m)	Lateral position (m)
Sonar 1	18.98	2.615
Sonar 2	18.98	2.075
Sonar 3	18.98	1.635
Sonar 4	18.98	1.005
Sonar 5	18.98	0.475
Sonar 6	12	1.41
Sonar 7	7	1.50

Note: distances are measured from upstream limit of test section and the left wall of the flume.

Water and Bed Slopes – Mean water-surface slope was calculated by measuring the water-surface elevation at two locations upstream from the weigh drums and dividing the difference in elevation by the distance between the measuring points. Water-surface slope measurements were made manually with point gages (Rickly Hydrological Company, accuracy +/- 0.1 mm) referenced to a common datum. Bed slope was similarly calculated by measuring the difference in bed elevation at zero flow and two locations within the test section and dividing by their separation distance. Manual bed-elevation measurements were obtained using staff rods (accuracy +/- 1 mm) at the sonar probes. In addition, bed slope was computed from the 0.1 Hz bed elevation time-series data recorded by the submersible bed-sonar system.

RESEARCH EXPERIMENTS

The research presented here was conducted during January-June 2006 and altogether involved 25 researchers and volunteers from academia, federal and private agencies, and industry. Participants and their respective affiliations are listed in Table 2. The research involved ground-truth testing of physical bedload samplers and surrogate bedload technologies over a range of flow and transport conditions and two compositions of bed material. Phase I of the project (January 3 -February 14) was performed with a sand bed and Phase II (March 3-29) with a gravel bed. The sand bed consisted of well-sorted siliceous sand in the particle size diameter range 0.8-1.8 mm median diameter. The gravel material size was a comparatively broad distribution (2-32 mm; D_{50} = 11.2 mm median diameter). The sieved grain-size distributions for the sand-bed and gravel-bed materials are shown in Figure 6.

Table 2. Participants and institutions involved in the bedload monitoring research program (StreamLab06) (NCED is the National Center for Earth-surface Dynamics).

StreamLab06: Bedload Monitoring Research Participants	
Project Managers	**Institution**
Jeff Marr	NCED, University of Minnesota
John R. Gray	US Geological Survey
NCED Partners and Visitors	**Institution**
Steven Abt	Colorado State University
Kristin Bunte	Colorado State University
Broderick Davis	Federal Interagency Sedimentation Project
Dave Gaeuman	US Geological Survey
Robert Hilldale	US Bureau of Reclamation
Andreas Krause	Trinity River Restoration Program
Johnny McGregor	Federal Interagency Sedimentation Project
John Pitlick	University of Colorado, Boulder
Smokey Pittman	Graham Mathews and Associates
John Potyondy	US Forest Service
Rauf Ramooz	University of Ottawa
Colin Rennie	University of Ottawa
Kurt Swingle	Independent Contractor, Boulder Colorado
Wes Smith	Graham Mathews and Associates
Staff	**Institution**
Richard Christopher	St. Anthony Falls Laboratory
Dave Dean	NCED, University of Minnesota
Chris Ellis	NCED, University of Minnesota
Ben Erickson	St. Anthony Falls Laboratory
Sara Johnson	NCED, University of Minnesota
Students	**Institution**
Travis Kluthe	NCED[1], University of Minnesota
Adam Markos	NCED[1], University of Minnesota
Nick Olson	NCED[1], University of Minnesota
Andrew Sander	NCED[1], University of Minnesota

[1]National Center for Earth-surface Dynamics

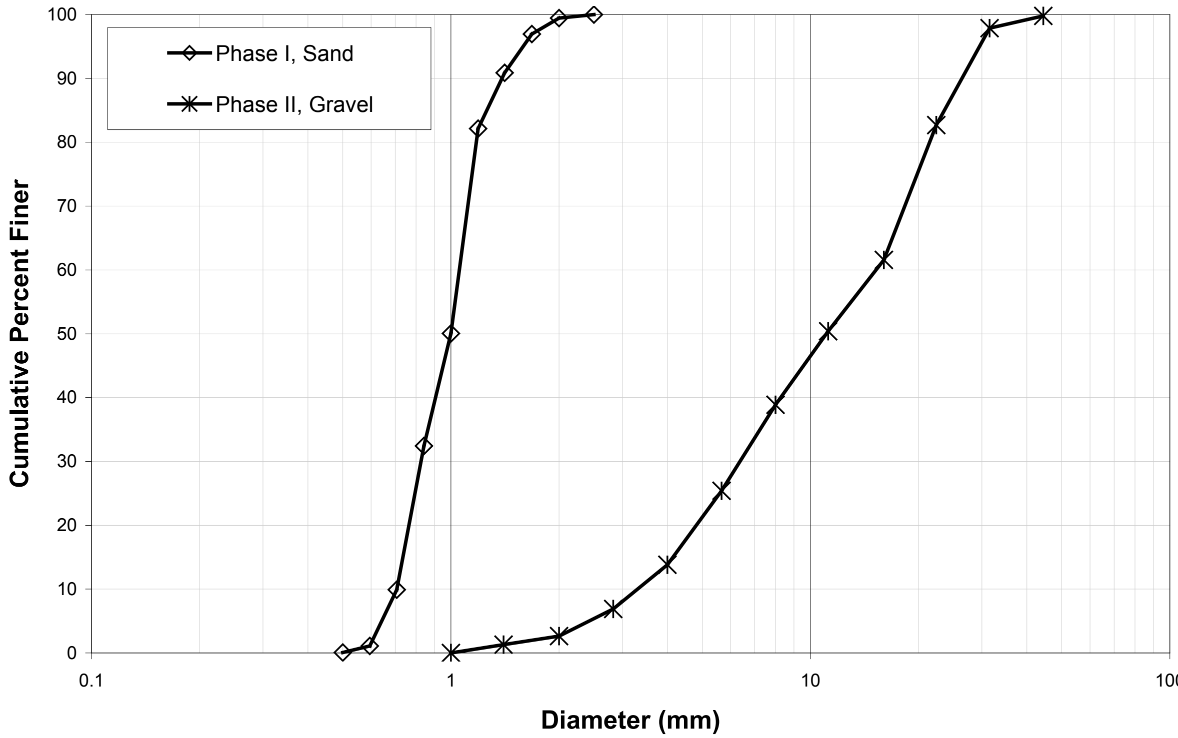

Figure 6. Grain size distributions of the original sand- and gravel-bed material.

Five water discharges were selected for Phase I sand-bed conditions and four discharges for Phase II gravel-bed conditions to span a range of low to high sediment-transport conditions. A summary of the conditions for each run is presented in Table 3. For each new discharge and for a shorter period of time at the beginning of each sampling session, it was necessary to operate the flume and recirculation system to establish a dynamic bed equilibration. Achievement of dynamic equilibrium in bedload-transport rates was inferred by observing stabilization of the computed 60-minute mean sediment flux rates, which were continuously computed and displayed by CDAQ software. Table 3 lists the total duration of the run as well as the duration of the run after equilibrium was achieved.

Table 3. Summary table of experimental conditions[1].

$Q_{w,design}$ (m^3/s)	Bed	$Time_{total}$ (hrs)	$Time_{eq}$ (hrs)	T_{mean} (C)	$Q_{w,mean}$ (m^3/s)	$q_{s,mean}$ (kg/(ms)-dry)	$q_{s\text{-}equil,\ mean}$ (kg/(ms)-dry)
2.0	Sand	12.3	11.7	0.4	2.02	0.013	0.013
2.5	Sand	15.8	14.2	0.5	2.70	0.045	0.047
2.9	Sand	34.3	22.3	2.3	2.95	0.077	0.077
3.2	Sand	8.5	NA	0.6	3.20	0.126	NA
3.6	Sand	11.6	10.3	1.0	3.69	0.180	0.176
4.0	Gravel	56.0	43.0	2.2	4.01	0.003	0.002
4.3	Gravel	36.3	13.0	3.5	4.32	0.011	0.015
4.9	Gravel	33.9	24.2	4.7	4.90	0.161	0.168
5.5	Gravel	29.0	28.2	2.7	5.51	0.785	0.782

Variables: $Q_{w,design}$ = Design water discharge for the run

Bed = Bed material type

$Time_{total}$ = Total duration of time at the design discharge including equilibration period

$Time_{eq}$ = Total duration time of at equilibrium bed condition

T_{mean} = Mean water temperature

$Q_{w,mean}$ = Mean water discharge

$q_{s,mean}$ = Mean sediment transport rate computed over total duration

$q_{s\text{-}equil,mean}$ = Mean sediment transport rate computed for period after equilbration was reached

[1]q_{mean} is computed using a 90-second moving average

Calibration and Comparison of Physical Samplers

Pressure-Difference Bedload Samplers: The original-type Helley-Smith bedload sampler and three other manually deployed samplers of the Helley-Smith type, all of which operate on the pressure-difference principle, were calibrated as part of the experiments (Table 4). The expansion of the nozzle area from the entrance to the exit of pressure-difference-type samplers results in an acceleration of flow through the nozzle. This acceleration theoretically compensates for the flow resistance resulting from the physical presence of the sampler on the bed. The hydraulic efficiency value for a given sampler is a function of a number of factors, including the sampler's expansion ratio, its entrance nozzle size, the ambient flow velocity in the vicinity of the sampler, the bag mesh size, the degree to which the bag is filled, and the presence of particles of the same approximate size as the mesh that might clog the bag. The bedload samplers tested in StreamLab06 experiments had hydraulic efficiencies of 1.35-1.54 (Hubbell et al., 1987). The primary motivation for this experiment was to calibrate the Elwha Sampler (Childers, 1999) and to compare the Elwha Sampler's sedimentological efficiency in gravel- and sand-bed conditions to those for up to 3 other bedload samplers. These experiments took place during January-March 2006.

Table 4. Bedload samplers used in the study and tested grain sizes.

Sampler identity	Nozzle dimensions (width x height) (cm x cm)	Nozzle outlet-to-inlet area ratio	Bag mesh size (mm)	Bed composition (mm)
Toutle River 2 (TR-2)*	30.5 x 15.2	1.4	0.5	Gravel, D_{50} = 11
Elwha *	20.3 x 10.2	1.4	0.5	Gravel, D_{50} = 11
BLH-84**	7.62 x 7.62	1.4	0.25	Sand, D_{50} = 1 Gravel, D_{50} = 11
Helley-Smith***	7.62 x 7.62	3.22	0.25	Sand, D_{50} = 1 Gravel, D_{50} = 11

*Developed by Dallas Childers, U.S. Geological Survey (Childers, 1999)

**Currently the only bedload sampler that is accepted – albeit "provisionally" – as the standard sampler for U.S. Federal Agencies (Edwards and Glysson, 1999, p. 25).

***Data will continue to be accepted by the U.S. Geological Survey Water Resources Discipline until additional testing is done (Edwards and Glysson, 1999, p. 25).

Bedload samplers with larger nozzle outlet to inlet ratios tend to have higher hydraulic efficiencies. However, hydraulic efficiency is of interest only in how it influences a sampler's sedimentological efficiency, derivation of which was the focus of this experiment. Generally, a higher hydraulic efficiency brings rise to higher sedimentological efficiency in supply-unlimited conditions.

Only hand-held bedload samplers were used for testing during the StreamLab06 experiments. Each bedload sampler was composed of a nozzle, a bag affixed to the rear of the nozzle, a deployment rod affixed to the top of the nozzle, and a rear-extending rod that supported the bag. Cable-suspended versions of these samplers were designed for use in non-wadeable streams and are constructed with substantial frames with tail fins that comprise most of the samplers' weight and serve to orient the intake upstream when submerged. The rod-deployed version was essentially the sampler nozzle with a bag affixed to the outlet and a rod extending from the top of the nozzle.

The bedload samplers were manually deployed 8.5 m upstream from the weigh drums at up to five lateral cross sectional locations centered at 0.27, 0.82, 1.37, 1.92, and 2.47 m from the left flume wall, i.e. directly upstream from the center of each weigh-drum. Each sampler was deployed by a vertically held rod with a tether line extending from the bottom of the rod to a cross-brace several meters upstream from and atop the flume, which served to stabilize the sampler and ensure a consistent longitudinal location in the measurement cross section. Each sampler was held stationary on the bed during a given run for 15, 30, 45, 60, 75, or 90 seconds. The duration that the sampler remained on the bed was, with rare exception, constant for a given bed type, sampler, flow rate, based on how quickly bedload accumulated in the bag, permitting bedload to fill, at most, half of the capacity of the sampler bag.

A crew of two was required to operate a single bedload sampler. One person operated the sampler and measured the water depth on the graduated-sampler rod, while the other timed the sample duration, prepared the sample bags, helped to empty the sampler of accumulated bedload material, and served as recorder. After the bedload sample was collected, it was emptied into a labeled bag. Most of the bags were immediately transferred to a weigh station and wet-weighed (Carey, 1984). The wet-weighing process involved suspending the bagged samples from a digital scale in a bucket of water. The fully submerged mass, W_{ss}, was recorded and entered into a spreadsheet, where it was automatically converted to an equivalent dry mass, W_{ds} according to the equation:

$$W_{ds} = \frac{SG_s}{SG_s - 1} * W_{ss} \quad (1)$$

where SG_s is the mean specific gravity of the sediment material (e.g. 2.65 for quartz). Samples were subsequently sealed and stored, some for later sieving to compute grain-size distribution statistics. Several samples that had been wet-weighed were dried in an oven to determine the dry weight, thereby enabling comparison to the value computed by equation 1, thus confirming the applicability of the wet-weighing system.

Depth-averaged suspended-sediment samples were collected upstream and downstream from the weigh drums before and after each episode of bedload-sampler deployment to determine whether sand-size material was being introduced from the Mississippi River, or if any sand-size material was bypassing the bed trap as suspended sediment or as saltating bedload. A US DH-48 suspended-sediment sampler (Davis, 2005) was used to collect these samples by methods described by Nolan et al. (2005). The U.S. Geological Survey Cascade Volcano Observatory Sediment Laboratory analyzed the suspended-sediment samples for concentrations and, in some cases, the amount and percentage of sand (>0.062 mm) in these samples.

Bedload-Trap Samplers: A second component of the research involved testing a bedload trap technology developed by Bunte et al. (2006). The motivation for this research was to develop calibration coefficients for the bedload traps.

The bedload trap is a simple technology for measuring bedload in gravel-bedded mountain streams during low-to-moderate flows and has been developed during many years of experience in field sampling of bedload. This research, which took place in April-May after the data for calibrating the manually deployed bedload samplers were collected. This involved placing two bedload traps into the Main Channel under various flow rates and operational configurations. Trap capture rates were compared to flux recorded from the weigh-drum system. A full report on this research is provided in Bunte and Swingle (2007).

Calibration of the Bottom-Tracking Function, Acoustic Doppler Current Profiler:

The testing location for acoustic Doppler current profilers (ADCPs) was 2 m upstream from the SMRS. Two ADCPs were tested: 600 kHz and 1200 kHz Rio Grande ADCP units made by Teledyne RD Instruments (RDI). Both devices require a minimum water depth of about 1 m. For this reason, all of the runs in both Phase I and Phase II were performed at the maximum allowable depth for the main channel. The motivation for this research was to utilize the large-scale test facility to determine the measured bedload bias and precision under sand- and gravel-transport conditions, and to study in detail small-scale flow and particle interactions during bedload transport. In addition to the ADCP, the research involved a number of other technologies including acoustic Doppler velocimeters, underwater video cameras, and suspended-sediment samplers. Details about this related research effort and preliminary results can be found in Ramooz and Rennie (2010).

RESEARCH OUTCOMES

Specific results and performance evaluations of the conventional and surrogate technologies are not covered here and the reader is referred to selected papers contained in this publication and other sources (Ramooz et al., 2010; Bunte et al., 2010). Herein we present a summary of the experimental conditions from the run, which includes summaries of sediment accumulation, sediment flux, water temperature and water discharge.

Water Temperature

Experiments were conducted in relatively cold water that ranged from just above 0 ºC to 7ºC. Water-temperature variations during an experimental run were minimal, with the largest standard deviation equaling 1.5ºC. Such experimental-run specific water-temperature variations are hydraulically insignificant. Table 3 provides a summary of water temperatures for all the experimental runs including the mean and standard deviation of the water temperatures for each of the discharge conditions.

Water Discharge

Water discharge was measured and recorded continuously at 1 Hz during the experimental runs. Table 3 summarizes the mean water discharge for all runs. The data indicate that discharge fluctuated minimally during the runs.

Sediment Accumulation and Flux

The bedload fluxes measured by each of the five weigh drums were the key data used to evaluate the physical and surrogate bedload-measurement technologies. There are many possible methods for computing flux from the accumulation data, the most appropriate of which depends on the time scale of fluxes sought by the user. For this reason, only the most basic form of the data, weight accumulation in each weigh drum, is provided by SAFL, and researchers are free to choose their own method of computing fluxes. SAFL does, however, correct the accumulation data for all weigh-drum tipping events using the method described below.

Detailed sediment-accumulation data from the StreamLab06 experiments are or will be available at no charge. An estimate of mean sediment flux for the nine experimental runs is provided in Table 3. Sediment flux was computed by (1) filtering the equivalent dry sediment accumulation data with a 90 s moving average window, and (2) computing flux by subtracting filtered weights lagged in time and dividing by the lag time (90 s) (Eq. 2). A summary of the mean and standard deviation for dry sediment flux Q_s computed for the nine runs is provided in Table 3.

$$\mathrm{Qs}(t) = \frac{accumulation}{time} = \frac{\frac{1}{n}\sum_{i=t}^{t+n} weight(i) - \frac{1}{n}\sum_{i=t-n}^{t} weight(i)}{n} \tag{2}$$

Where,

n = selected averaging window size and differencing period (typically 90 s)

EXPERIMENTAL CAVEATS

Future research programs with the SAFL SMRS should consider the following issues:

1. Test section entrance condition – The entrance condition into the test section near the discharge end of the recirculation pipe was altered several times at the beginning of the sand runs. Various issues including air entrained by plunging inflow complicated the sonar measurements, and jet plumes and secondary circulation resulted in scour along the sidewalls in the upper 3-5 m of the 20 m test section. The final configuration shown in Figure 5 provided the most natural entrance condition.
2. Test section exit condition – The sand and gravel at the end of the test section terminated in a slope at an angle of repose terminating at the cross-channel bedload slot. Movement of sediment down this sloping face was often episodic, occurring as sloughing events that were inconsistent with bedload movement. Similar observations were made in the earlier Hubbell et. al. (1987) experiments. These slough events may influence the sediment accumulation measurements and should be considered when selecting a time step for computing sediment flux.
3. Transport equilibration – The flume was run for periods ranging from 0.5 to 23 hours prior to sampler collection in order to "equilibrate" the transport in the flume. Determination of (dynamic) equilibrium in bedload-transport rates was inferred by observing continuous plots of sediment accumulation and computed 60 min averages of sediment flux on the CDAQ computer. Future experiments should adopt more rigorous methods of determining when the flume is in transport equilibrium.
4. Water-surface slope estimates were made using relatively infrequent point measurements of stage at multiple points in the section of the flume upstream from the weigh pans. Water-surface slope is a key variable in the flow-energy calculation, which in turn has a direct bearing on estimates of bedload-transport capacity (Meerovich et al., 1998). Future experiments should take advantage of state-of-the-art continuous recording technologies for stage at multiple points in the flume to provide more accurate water-surface slope values. The measurements might benefit from inclusion of a physical means for damping short-term water-surface elevation fluctuations, such as by enclosing the sensor in a static tube.

CONCLUSIONS

A major facility upgrade to the main channel at the St. Anthony Falls Laboratory provided the opportunity for an intense series of experiments focused on ground-truth testing of physical and surrogate bedload-monitoring technologies. The research took place in the winter and spring, 2006, and involved a total of 25 researchers and volunteers. Because accurate measurement of bedload characteristics in rivers and streams is vital to successful management of watercourses, this effort to document the accuracy of existing monitoring tools and to develop new tools is needed by the scientific and river-management community. Hence, additional ground-truth testing in this facility is planned for the years ahead. The channel is equipped with advanced technologies that allow continuous monitoring of fundamental environmental conditions such as water temperature, water-surface slope, bed slope and bedload flux. The relatively large flow capacities (8.5 m^3/s) and ability to recirculate gravel up to 76-mm median diameter make the SAFL Main Channel a useful and desirable facility for testing and developing bedload technologies.

Summaries of the principal hydraulic conditions in the flume and estimates of mean sediment flux from the experiments are provided herein. Experimental results for specific measurement technologies are being published separately by the principal researchers. All data acquired in this study including water discharge, sediment flux, water surface slopes, bed surface slopes and other environmental conditions will be made freely available to any interested researcher by contacting National Center for Earth-surface Dynamics Administrative Offices in Minneapolis, Minnesota, United States (www.nced.umn.edu) or SAFL (www.safl.umn.edu).

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