

Bedload-Surrogate Monitoring Technologies



Scientific Investigations Report 2010–5091

U.S. Department of the Interior
U.S. Geological Survey

Cover: Impact plate array for measuring bedload transport in the Erlenbach stream, Switzerland (upstream view of the sediment retention basin, with plates visible in the left side of the curved check dam crest, and (inset) water falling into an automatically driven basket-type bedload sampler). Geophone sensors are mounted underneath the steel plates at the crest of the check dam. The movable bedload-collection basket provides calibration data for the acoustic data produced by the impact plates. See figures 12 and 13. Photographs courtesy of Dieter Rickenmann, Swiss Federal Research Institute.

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By John R. Gray, Jonathan B. Laronne, and Jeffrey D.G. Marr

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Conversion Factors

Multiply	By	To obtain
Length		
centimeter (cm)	3.937×10^{-1}	inch (in.)
millimeter (mm)	3.937×10^{-2}	inch (in.)
meter (m)	3.281	foot (ft)
Area		
square meter (m ²)	1.076×10^1	square foot (ft)
Flow/transport rate		
meter per second (m/s)	3.281	foot per second (ft/s)
kilogram per second per meter [(kg/s)/m]	2.903×10^1	tons per day per foot [(t/d)/ft]
Mass		
kilogram (kg)	2.205	pound avoirdupois (lb)
megagram (Mg)	1.102	ton, short (2,000 lb)
milligram (mg)	3.527×10^{-5}	ounce, avoirdupois (oz)
Power per unit area		
microwatt per square meter ($\mu\text{W}/\text{m}^2$)	1.246×10^{-10}	horsepower per square foot (hp/ft ²)
Force or mass per unit time and/or area		
Newtons per square meter (N/m ²)	1.44×10^2	pounds per square foot (lb/ft ²)
Megagrams per day per meter	1.024×10^{-1}	ton (short, 2,000 lb) per square foot (t/ft ²)

Acronyms and Abbreviations

ADCP	acoustic Doppler current profiler
AIH	American Institute of Hydrology
ASTM	American Society for Testing and Materials (now, “ASTM International”)
BLM	Bureau of Land Management
BRIC	Bedload Research International Cooperative
FISP	Federal Interagency Sedimentation Project
GPR	ground-penetrating radar
GTS	gravel-transport sensor
IAHS	International Association of Hydrological Sciences
IRTCES	International Research and Training Center on Erosion and Sedimentation
lidar	light detection and ranging
NCED	National Center for Earth-surface Dynamics
RFID	radio frequency identification tag
SAFL	St. Anthony Falls Laboratory, Minneapolis, Minnesota, United States
SOS	Subcommittee on Sedimentation of the Advisory Committee on Water Information
TLS	Terrestrial Laser Scanning
USGS	U.S. Geological Survey

Bedload-Surrogate Monitoring Technologies

By John R. Gray, Jonathan B. Laronne, and Jeffrey D.G. Marr

Abstract

Advances in technologies for quantifying bedload fluxes and in some cases bedload size distributions in rivers show promise toward supplanting traditional physical samplers and sampling methods predicated on the collection and analysis of physical bedload samples. Four workshops held from 2002 to 2007 directly or peripherally addressed bedload-surrogate technologies, and results from these workshops have been compiled to evaluate the state-of-the-art in bedload monitoring. Papers from the 2007 workshop are published for the first time with this report (see table 2). Selected research and publications since the 2007 workshop also are presented.

Traditional samplers used for some or all of the last eight decades include box or basket samplers, pan or tray samplers, pressure-difference samplers, and trough or pit samplers. Although still useful, the future niche of these devices may be as a means for calibrating bedload-surrogate technologies operating with active- and passive-type sensors, in many cases continuously and automatically at a river site. Active sensors include acoustic Doppler current profilers (ADCPs), sonar, radar, and smart sensors. Passive sensors include geophones (pipes or plates) in direct contact with the streambed, hydrophones deployed in the water column, impact columns, and magnetic detection. The ADCP for sand and geophones for gravel are currently the most developed techniques, several of which have been calibrated under both laboratory and field conditions.

Although none of the bedload-surrogate technologies described herein are broadly accepted for use in large-scale monitoring programs, several are under evaluation. The benefits of verifying and operationally deploying selected bedload-surrogate monitoring technologies could be considerable, providing for more frequent and consistent, less expensive, and arguably more accurate bedload data obtained with reduced personal risk for use in managing the world's sedimentary resources.

Introduction

Bedload—that part of total sediment load that is transported by rolling, skipping, or sliding on the streambed (ASTM International, 1998)—provides the major process

linkage between the hydraulic and material conditions that govern river-channel morphology (Gomez, 2006). An understanding of bedload-transport mechanisms and reliable data on bedload-transport rates are important to engineers, scientists, managers, and others interested in water resources to elucidate the causes and consequences of changes in channel form and to make informed management decisions that affect a river's function (Gomez, 2006). Additionally:

- Bedload is part of the river's total-sediment load that represents net erosion by water from watersheds (fig. 1).
- When accelerated, bedload transport can result in scour that can have catastrophic consequences, such as the failure of bridge piers or other hydraulic structures.
- When deposited as bed material, bedload can reduce the capacity of reservoirs and other water bodies, impede river navigation, impair aquatic habitat (Kuhnle, 2008), contribute to increased river flooding or, in extreme cases, result in channel avulsion.

Bedload monitoring is far less common than suspended-sediment monitoring. For example, in 2000 the U.S. Geological Survey (USGS) National Water Information System instantaneous-sample database contained about 50 times fewer sites with bedload data (a total of 238 sites) than sites with suspended-sediment data (12,185 sites). In 2002, none of the 36 States that responded to a questionnaire indicated that the responding State organization was collecting bedload data (Pruitt, 2003). However, 24 of the 36 States indicated that they were collecting either suspended-sediment or total-suspended-solids data.

The relative preponderance of suspended-sediment monitoring is in part due to the observation that suspended sediment:

- Accounts for at least 90 percent of sediment transported from uplands to continental margins (Meade and others, 1990); however, as Turowski and others (2009) show, the percentage of bedload to total load at selected measurement sites around the world is highly variable. In general, bedload makes up larger percentages of total load as drainage areas decrease and channel slopes increase.

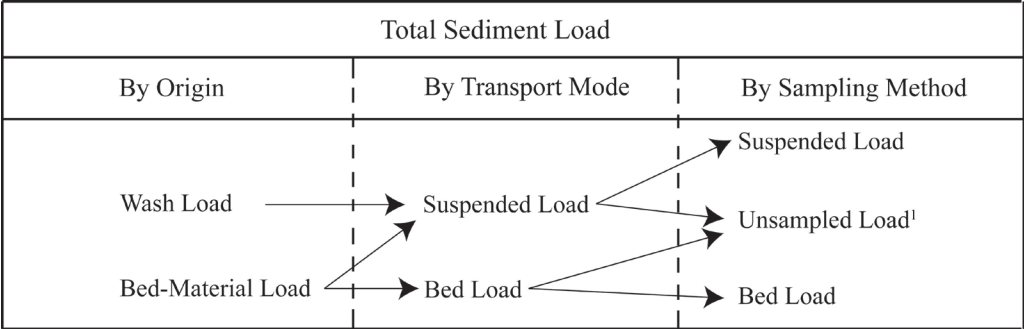


Figure 1. Components of total sediment load considered by origin, by transport, and by sampling method. Adapted from Diplas, Kuhnle, and others, 2008, p. 308.

¹That part of the sediment load that is not collected by the depth-integrating suspended-sediment and pressure-difference bedload samplers used, depending on the type and size of the sampler(s). Unsampled-load sediment can occur in one or more of the following categories: a) sediment that passes under the nozzle of the suspended-sediment sampler when the sampler is touching the streambed and no bedload sampler is used; b) sediment small enough to pass through the bedload sampler's mesh bag; c) sediment in transport above the bedload sampler that is too large to be sampled reliably by the suspended-sediment sampler; and d) material too large to enter the bedload-sampler nozzle.

• Is the easier of the two sedimentary phases to measure (fig. 1), but the more difficult to predict (Ergenzinger and De Jong, 2003).

Gomez (2006) observed that the collection of high-quality bedload-transport data with physical samplers is an expensive and time-consuming task, and for many practical purposes, the recourse is thus to use bedload-transport formulae. However, bedload-estimating formulae leave much to be desired. Gray and Simões (2008) present a number of factors that impinge on the reliability of estimates from such bedload-transport formulae in three categories: data issues, sediment-supply issues, and other technical issues. They conclude that use of formulae to estimate bedload-transport rates, particularly in gravel-bed rivers, remains problematic and is the focus of ongoing research.

Additionally, the ability of formulae to predict bedload-transport rates under given flow conditions is predicated on the assumption that it is possible to describe the rate at which bedload is transported in terms of measurable hydraulic and sedimentological quantities. Even under the assumption that sediment supply is unlimited, the task is complicated: movement of heterogeneous sediment is governed by absolute and relative size effects, so that local transport rates depend on the population of particles immediately available at the bed surface. Although progress is being made toward a better understanding of the processes and factors by which the composition of the bed surface changes over time (Topping and others, 2000; Wilcock and DeTemple 2005; Clayton and Pitlick 2007; Parker and others, 2008), Gomez (2006) concludes that despite more than a century of effort, it is not yet possible to make reliable predictions of bedload-transport rates.

The international river research community continues to strive for a better understanding of the processes of erosion, transport, and deposition in rivers with the goal of developing the ability for reliable modeling, estimating, and predicting of sediment transport in rivers. Progress in this regard

is predicated on technological advancement at local and channel-reach scales.

Local-scale bedload research, sponsored largely by academic and government institutions, tends to focus on grain-scale processes involved in the transport of non-cohesive fluvial sediment. New methods for controlled and more detailed observation and quantification of bedload processes that show promise toward a much improved—and needed—understanding of these processes are sought. In addition to quantifying transport rates, these might include other metrics such as:

- bed-material grain-size distributions,
- grain-hiding and protrusion,
- effects of larger bedforms such as bars,
- incipient motion, and
- bed, and near-bed turbulence.

Examples of research in this regard include Papanicolaou and others (2002), Bogen and others (2003), Ryan and others (2005), Gaeuman and Jacobson (2007), Schmeeckle and others (2007), Diplas, Dancey and others (2008), Nittrouer and others (2008), Rickenmann and McArdell (2008), Barton and Pittman (2010), and Gaskin and Rennie (2010).

Research on transport processes in the channel cross-section and reach scales focuses on the spatial and temporal characterization of bedload transport. The spatial and temporal variability of bedload has been characterized as part of many studies (for example, Carey, 1985; Gray and others, 1991; Leopold and Emmett, 1997; Childers, 1999; Gomez and others, 2006; Kuhnle, 2008). However, the capability to model and forecast bedload-transport rates at the channel or reach scale needed for river management and restoration purposes remains elusive.

In light of the often substantial expense, difficulty, and deficient temporal and spatial resolution associated with physical bedload measurements, and of inadequacies associated

with predictive formulae, efforts to develop new approaches for monitoring bedload have expanded, particularly since the early 1990s. Development of bedload-surrogate technologies—instruments and methodologies for measuring or continuously monitoring characteristics of bedload transport at dense time and (or) spatial scales without the routine need for collection and analyses of physical bedload samples other than for calibration purposes—has been enabled by advances in computing and sensing capabilities. Technological innovation capable of continuous, spatially and (or) temporally dense monitoring of channel- and reach-scale sediment-transport processes is an active area of research for suspended sediment (Gray and Gartner, 2009; Gray and Gartner, 2010a) and for bedload (Bogen and others, 2003; Ryan and others, 2005; Barton and Pittman, 2010; Gaskin and Rennie, 2010; Gray and Gartner, 2010b). Even with the continued need for site-specific calibrations over a wide range of transport rates, these surrogate-monitoring technologies show promise to enable relatively safe, quantifiably reliable and continuous monitoring of bedload transport in rivers. Such information should provide a better understanding of the rates and mechanics of sediment transport which, in turn, may lead to development of better bedload-modeling and -prediction capabilities for fluvial systems.

The following four workshops have convened since 2002 on selected aspects of sediment-transport research and monitoring needs, including the means to provide reliable information on bedload-transport rates and related metrics:

- *Federal Interagency Sedimentation Workshop on Turbidity and Other Sediment Surrogates*, April 30–May 2, 2002, Reno, Nevada, United States, sponsored by the Federal Interagency Subcommittee on Sedimentation (Gray and Glysson, 2003).
- *Erosion and Sediment Transport Measurements in Rivers: Technological and Methodological Advances*, June 19–21, 2002, Oslo, Norway, convened by the International Commission of Continental Erosion of the International Association for Hydrological Sciences, and sponsored by the Norwegian Water Resources and Energy Directorate (Bogen and others, 2003).
- *Federal Interagency Sediment Monitoring Instrument and Analysis Research Workshop*, September 9–11, 2003, Flagstaff, Arizona, United States, sponsored by the Subcommittee on Sedimentation of the Advisory Committee on Water Information (Gray, 2005).
- *International Bedload Surrogate Monitoring Workshop*, April 11–14, 2007, Minneapolis, Minnesota, United States, sponsored by the Subcommittee on Sedimentation of the Advisory Committee on Water Information (Gray and others, 2007a; Laronne and others, 2007). Workshop attendees are listed in appendix 1 and workshop sponsors are listed in appendix 2.

These workshops, which were instrumental in bringing disparate sediment-surrogate research activities into focus, have led to new collaborations in field- and laboratory-sediment-surrogate research. Although none of the bedload-surrogate technologies described herein are broadly accepted for use in large-scale monitoring programs, several are under evaluation. The benefits of verifying and operationally deploying selected bedload-surrogate monitoring technologies could be enormous, providing for more frequent and consistent, less expensive, and arguably more accurate bedload data obtained with reduced personal risk for use in managing the world's sedimentary resources.

In addition to information gleaned from these workshops, novel bedload-measurement and monitoring systems rely on the considerable historical research on both direct and surrogate bedload-measurement techniques. For example, bedload discharge was monitored on semi-continuous temporal scales and consistent spatial scales by Mühlhofer (1933) using a basket-type sampler in the Inn River, Austria, 1931–1932. Figure 2 shows the variability in bedload transport sequentially in time and across the river width (Mühlhofer, 1933). Bedload discharge increased with stage as part of the spring snowmelt runoff, and with local shear stress toward the channel centerline. Not only was bedload monitored—albeit with an unknown sampling efficiency—but it was also sampled at relatively short time intervals, elucidating a phenomenon that later became known as the stochastic behavior of bedload discharge (fig. 3). The temporally varying bedload texture (fig. 4) was also demonstrated by Mühlhofer (1933).

Not only was bedload sampled with physical samplers in the previous century, bedload-surrogate monitoring was initiated as early as the 1980s. Thorne (1985, 1986) undertook a variety of experiments on the acoustic response of a hydrophone due to collisions or movements of single spheres or natural particles in the laboratory and natural particles in the sea. Thorne's (1985, 1986) research included attempts to calibrate acoustic signals (acoustic intensity) with physical measurements of individual grains (fig. 5). Bursts of sediment transport in places coincided with local-flow velocity, Reynolds stress, and acoustic intensity (for example, see shaded area between 4 and 5 minutes, fig. 5). Quantifying bedload texture from the acoustic signal, a difficult task, was also attempted (fig. 6).

This report provides an overview of selected characteristics of bedload-surrogate technologies in development, testing, and application, along with background information on the more common traditional instruments and methods for measuring bedload transport. To this end, the outcomes from the four aforementioned workshops germane to advancing the science of bedload-surrogate monitoring are summarized. An evaluation of the state-of-the-art and applicability of selected bedload-surrogate technologies for potential use in monitoring programs concludes these summaries, with a summary of relevant developments that have taken place since the 2007 International Bedload Surrogate Monitoring Workshop.

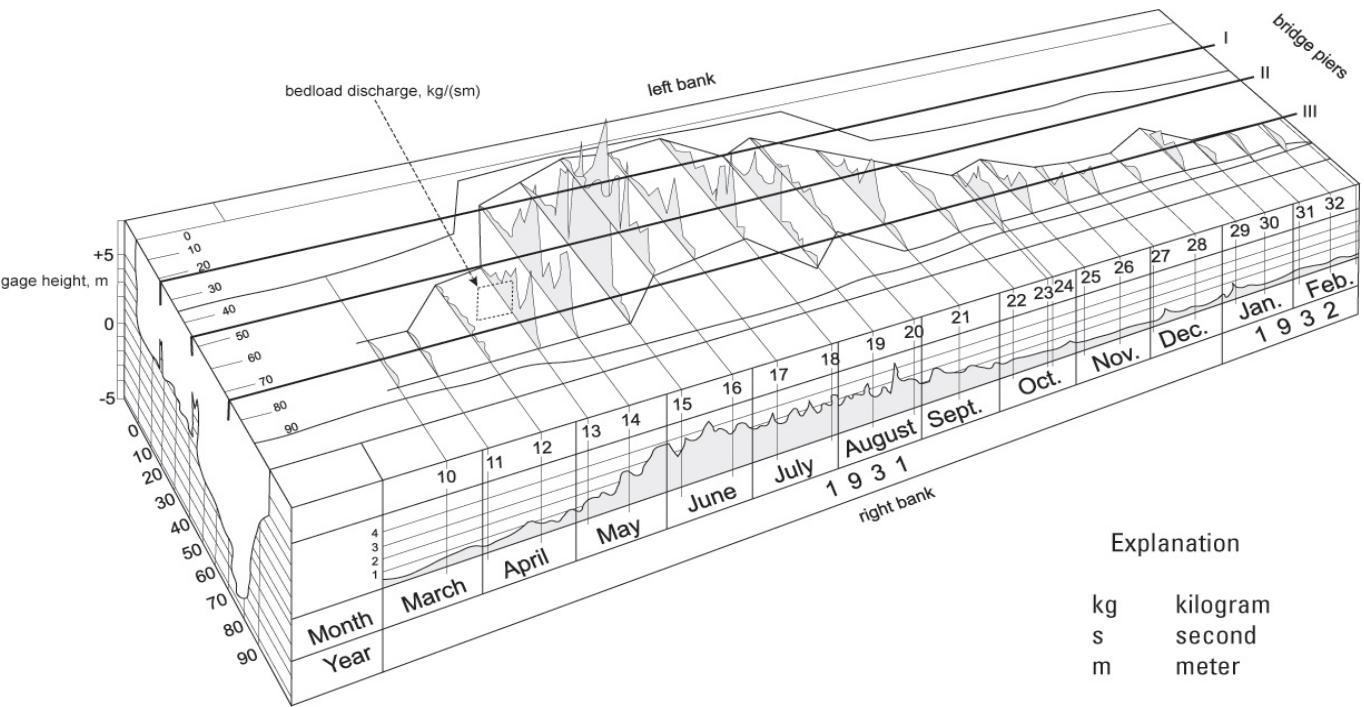


Figure 2. Bedload discharge obtained on the Inn River, Austria, 1931–32 (bedload discharge for the period was reported as 485.90 kg/(sm)). Modified from Mühlhofer, 1933.

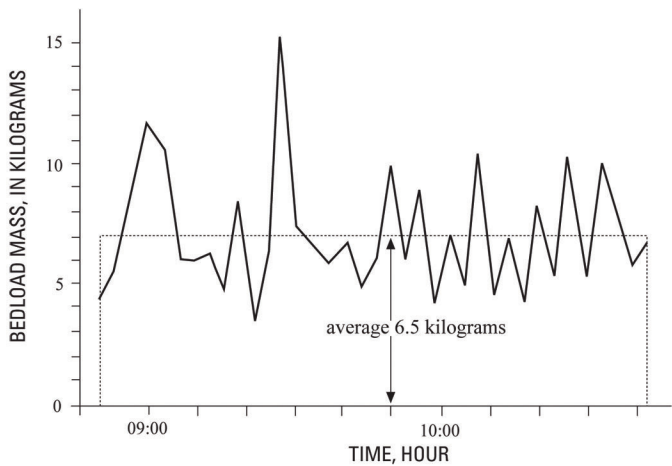


Figure 3. Hourly variations in bedload discharge, Inn River, Austria. Modified from Mühlhofer, 1933.

Selected research endeavors and publications since the 2007 workshop are also included.

Background

Most bedload data historically were, and continue to be, derived from physical samplers. Records of bedload-sampler use date back to at least the late 1800s, and attempts at bedload-sampler calibrations date to at least the early 1930s

(Mühlhofer, 1933; Federal Interagency Sedimentation Project, 1940; Hubbell, 1964; Carey, 2005). As with the development of isokinetic suspended-sediment samplers (Davis, 2005), the Federal Interagency Sedimentation Project (FISP) (Federal Interagency Sedimentation Project, 2008) endeavored to address problems and needs related to bedload-data collection in the latter 1930s (Federal Interagency Sedimentation Project, 1940). However, development and calibration of reliable portable bedload samplers capable of sampling a wide range of both particle sizes and transport rates remains a work in progress. All portable bedload samplers have some deficiencies that restrict their use and prevent widespread acceptance as the standard method for monitoring bedload (Ryan and others, 2005). A similar conclusion was drawn by the International Standards Organization (1992), observing that no single apparatus or procedure has been universally accepted as adequate for the determination of bedload discharge over the wide range of the sedimentological and hydraulic conditions found in nature.

Traditional Bedload Samplers

Traditional bedload samplers fall under one or a combination of the following four categories: Box or basket samplers, pan or tray samplers, pressure-difference samplers, and trough or pit samplers (Federal Interagency Sedimentation Project, 1940; Hubbell, 1964). Box samplers retain intercepted particles due to a reduction in flow velocity, while

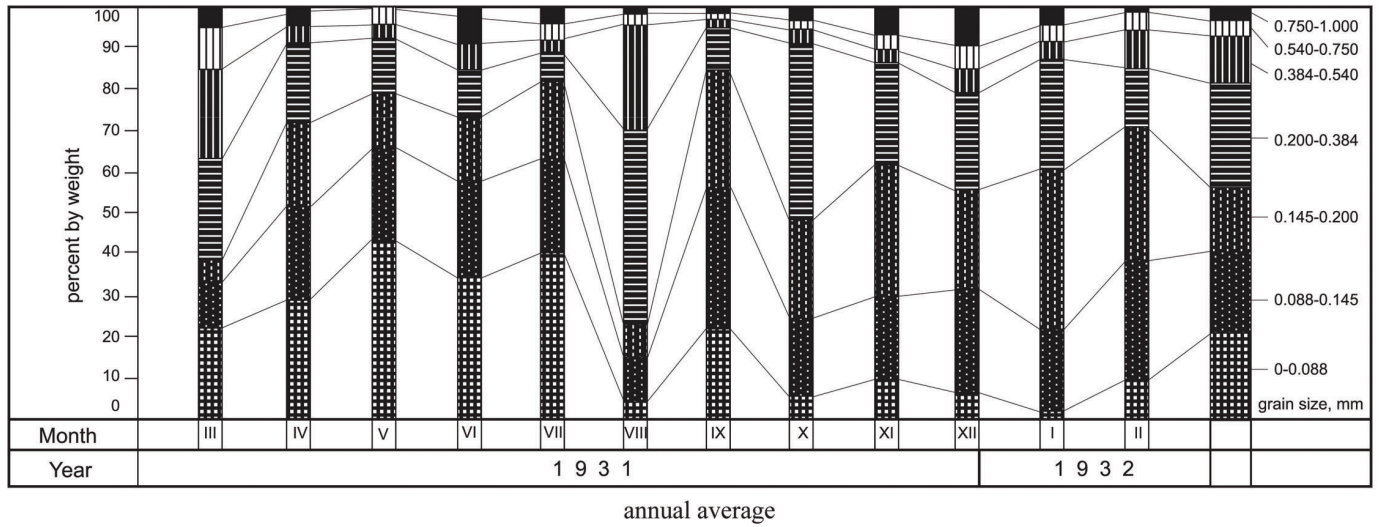


Figure 4. Grain size detail in millimeters (mm) of sampled bedload, Inn River, Austria. From Mühlhofer, 1933.

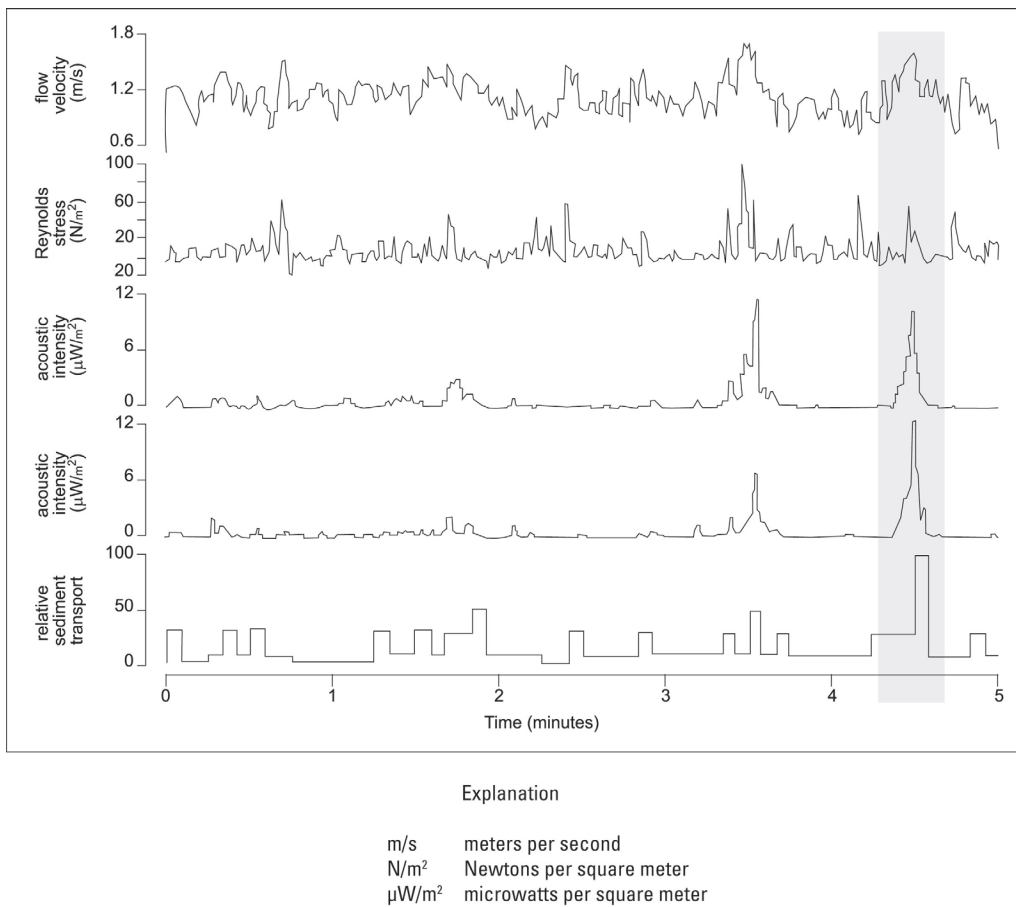


Figure 5. An early example of an attempt to calibrate a bedload-surrogate monitoring technology in the 1980s. The shaded area identifies a burst of sediment transport in places coinciding with local-flow velocity, Reynolds stress, and acoustic intensity. From Thorne, 1986.

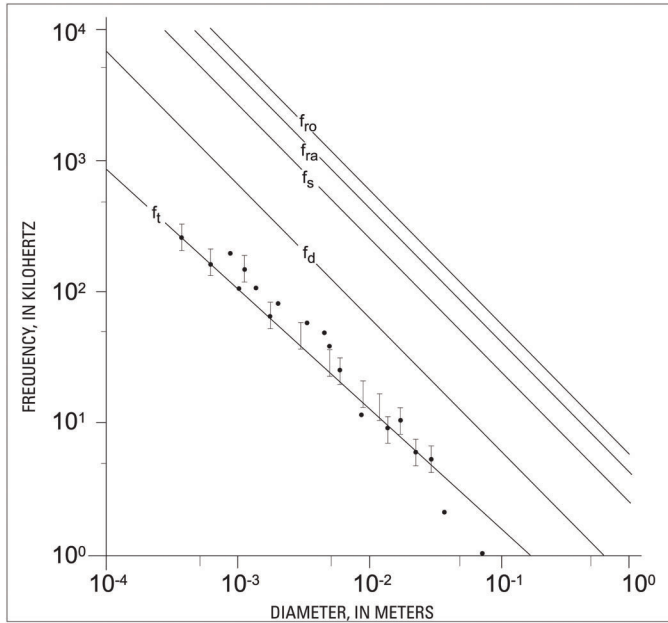


Figure 6. Bedload-texture monitoring using acoustics: the effect of particle size on the dominant frequency due to a collision (modified from Thorne, 1985). The symbols f_{ra} , f_{ro} , and f_s denote the respective lowest natural resonance frequencies of a sphere due to radial, rotary, and spherical vibrations; f_d is the damped frequency of vibration of the transient sound, and f_t is the frequency arising from twice the duration time of contact. The observations show that f_t is the dominant frequency due to collisions of particles of different size.

basket samplers capture particles by the sampler screen (e.g., netframe samplers and bedload traps). Pan or tray samplers retain the sediment that drops into one or more slots after the sediment has rolled, slid, or skipped up an entrance ramp. Pressure-difference samplers are designed so that a sampler's entrance velocity is about the same as the ambient stream velocity. Figure 7 shows selected hand- and cable-deployed pressure-difference bedload samplers. They collect sediment small enough to enter the nozzle but too large to pass through the mesh collection bag. Troughs or pits are rectangular cavities constructed in the streambed into which bedload particles drop. Troughs are usually continuous across the stream width (e.g., vortex and conveyor belt samplers), whereas pits only span part of the streambed (e.g., Reid-type (Birkbeck) samplers and pit-type samplers that normally lack in situ weighing apparatus). Unlike basket-type bedload samplers, which collect suspended particles exceeding the mesh size, pit- and trough-type bedload samplers are particularly efficient at sampling bedload and inefficient at sampling suspended sediment (Poreh and others, 1970).

Troughs and pits tend to produce the most reliable bedload data, provided that they are not full, have slots that span the channel, are capable of capturing the largest bedload particles, and possess a slot length that exceeds the maximum saltation length. However, there can be substantial differences

in calibration between the trough-type and other types of bedload samplers. The trough-type samplers are the most difficult to construct and operate. In contrast, no universally agreed-upon method has been developed for calibrating portable bedload samplers, but they are the easiest to deploy (Carey, 2005). The Reid-type (formerly termed Birkbeck-type) automatic and continuously operating slot sampler may be used in a variety of environments to calibrate physical samplers or surrogate samplers (Bergman and others, 2007; Mizuyama and others, listed in table 2 of this report). Portable bedload traps mounted on ground plates anchored to the bed are a logistically simple option in wadeable (i.e., small), coarse gravel and cobble headwater streams up to moderately low shear stresses and where collection of discrete physical samples is important (Bunte and others, listed in table 2 of this report).

Bedload-Sampler Calibration Efforts

The sampling efficiency of a bedload sampler is the ratio of the sampled bedload mass divided by the mass that would have been transported in the same section and time in the absence of the bedload sampler. Unlike FISP isokinetic suspended-sediment samplers, which have hydraulic efficiencies within about 10 percent of unity and hence exhibit negligible bias in sedimentological efficiency (Gray and others, 2008), known or potential bias in bedload-sampler efficiency can cast doubt upon the reliability of their derivative data. Bedload-sampler calibrations are complicated by a fundamental dichotomy, to wit: an innate inability to quantify the bedload-transport rate that would have occurred in a stream section in the absence of a deployed bedload sampler, unless the bedload sampler's sedimentological efficiency is known a priori.

Most calibration studies have been performed in laboratory flumes in which bedload-transport rates can be controlled. Although flume bedload-transport-rate measurements (often considered to be "ground truth" measurements) can be quite accurate, they do not closely represent natural river conditions. Leopold and Emmett (1997) observed that a river's ability to adjust its cross section to a variety of flows is a characteristic not shared by a fixed-wall flume. Riverine sediment transport is determined by the geological and physical setting of the river and river basin; thus, sediment is not a controllable variable. In summary, the variety of conditions controlled in a laboratory experiment cannot be established in a natural river.

At least two serious problems impinge on flume bedload-sampler calibrations: temporal and spatial variability of transport rates (see Bunte and others, listed in table 2). Even with a stable mean bedload-transport rate, the instantaneous rate at a given point (discrete width) can vary widely about the mean at that point (Hamamori, 1962; Hubbell and others, 1985; Gomez and others, 1990; Carey, 2005; Gray and Simões, 2008). Figure 8 shows the temporal variability in bedload transport with two types of pressure-difference bedload samplers deployed 2 meters apart near the middle of the sand-bedded Colorado River at the USGS streamgage above National Canyon near Supai, Arizona (Gray and others, 1991).

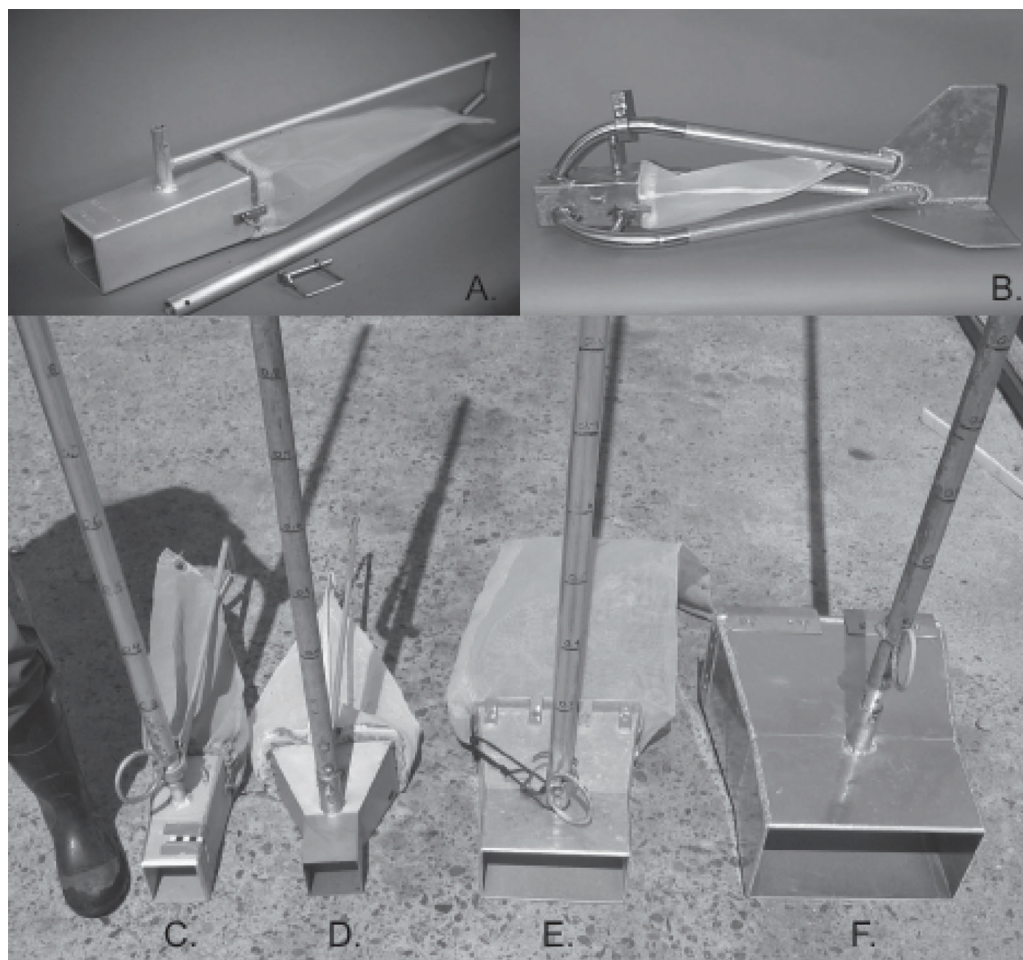


Figure 7. Pressure-difference bedload samplers: *A* and *C*, Hand-held US BLH-84; *B*, Cable-suspended US BL-84; *D*, Hand-deployed Helley-Smith; *E*, Hand-deployed Elwha; and *F*, Hand-deployed TR-2 (although only one cable-suspended sampler is shown, all the bedload samplers shown are also available in cable-suspension configurations). Lower photograph courtesy of Kristin Bunte, Colorado State University.

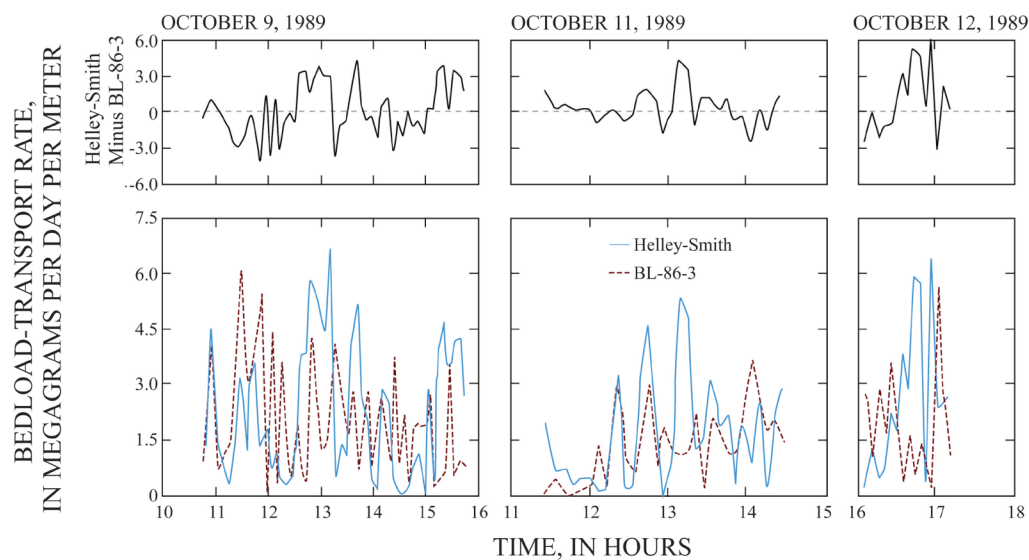


Figure 8. Variability in sand bedload-transport rates measured 2 meters apart by a Helley-Smith bedload sampler and a BL-86-3 bedload sampler (the latter is identical to the US-BL-84 bedload sampler), at the USGS streamgage on the Colorado River above National Canyon near Supai, Arizona, United States, October 1989. Modified from Gray and others, 1991.

Additionally, Fienberg and others (listed in table 2) deduced that mean sediment-transport rates measured in a flume at moderate flows decreased with increasing sampling time, indicating dependence.

Sampler calibrations are also hampered by spatial variability. Transport rates in the section of the flume in which the bedload sampler is deployed may differ from those at the flume ground-truth measuring location, such as a slot.

Emmett (1980) concluded that a solution to these problems was to construct a concrete trough across the bed of the East Fork River, Wyoming, United States. A conveyor belt transported the bedload that dropped into the trough to the right stream bank for weighing and sampling, and returned it to the river downstream from the trough. Thus, the spatial component was addressed by the streamwide slot-conveyor system, and the temporal component was addressed by the continuity of the apparatus' operation. This apparatus was used to collect bedload data for 7 years and to field-calibrate the portable Helley-Smith bedload sampler (Helley and Smith, 1971). This work is as notable for its considerable success in quantifying the bedload characteristics of the East Fork River and calibrating the Helley-Smith bedload sampler as it is in highlighting the difficulties and considerable expense of obtaining reliable bedload data (Gray and Simões, 2008).

Field-based comparisons between bedload samplers lacking ground-truth data can only be used to infer differences in deployed bedload-sampler efficiencies. However, such comparisons are useful for inferring the relative efficiency of a given bedload sampler. Childers (1999) compared the relative

sampling characteristics of six pressure-difference bedload samplers in high-energy flows at the USGS gaging station on the Toutle River at the Coal Bank Bridge near Silver Lake, Washington, United States. The sampling ratio of each pair of tested samplers was computed by dividing the mean bedload-transport rate determined for one sampler by the mean rate for a second sampler. Ratios of bedload-transport rates between measured bedload pairs ranged from 0.4 to 5.7, or more than an order of magnitude in differences of sampling efficiencies. Gray and others (1991) demonstrated that two pressure-difference bedload samplers exhibited divergent sampling efficiencies when deployed simultaneously 2 meters apart in the middle of the 76-meter-wide sand-bedded Colorado River above National Canyon, near Supai, in Grand Canyon, Arizona, United States, under steady low-flow conditions (fig. 9). Bunte and Abt (2009) compared bedload transport rates of particles larger than 4 millimeters (mm) collected with bedload traps to those collected with a thin-walled 7.6-centimeter (cm) -square Helley-Smith sampler in numerous mountain streams. Transport rates measured by the Helley-Smith sampler were substantially larger than those measured by the bedload trap at 50 percent bankfull, whereas the samplers produced similar transport rates at flows above bankfull. The technology was approved for use in wadeable coarse-bedded streams by the Federal Interagency Sedimentation Project (2009).

The accuracy of data produced by any bedload-surrogate technology cannot be better than that of its calibration data. Because surrogate technologies require empirical calibration with data analyzed from physical samples collected by

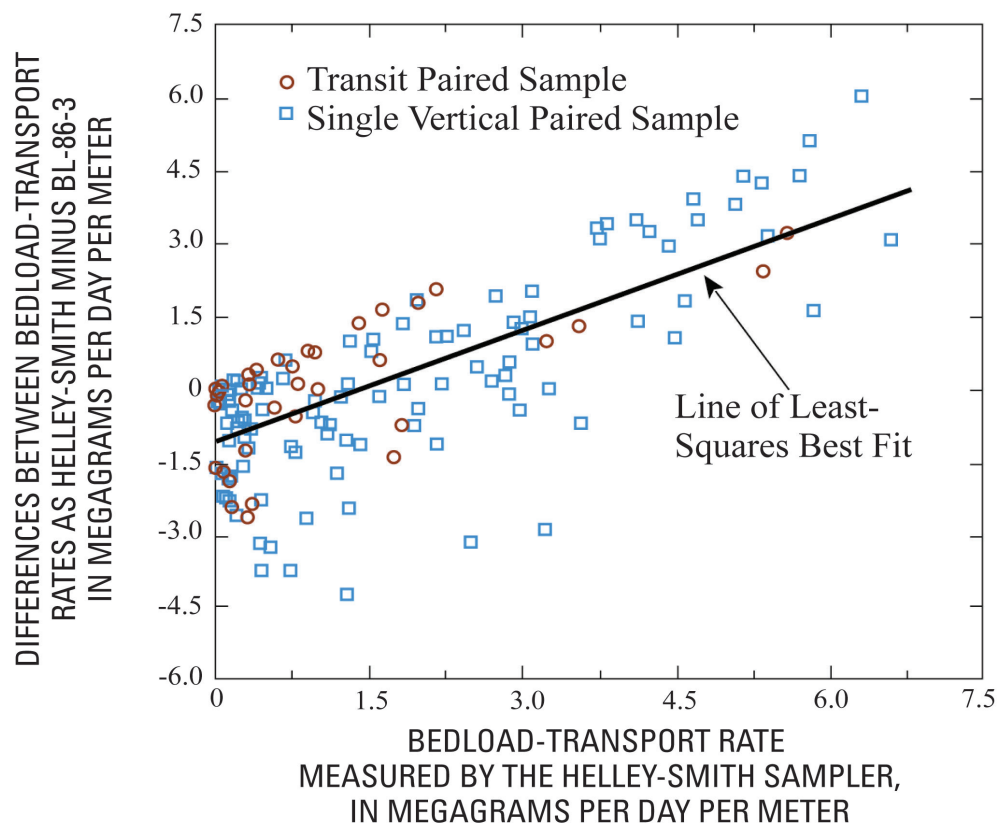


Figure 9. Relation between sand bedload-transport rates measured 2 meters apart by a Helley-Smith bedload sampler and a BL-86-3 bedload sampler (the latter is identical to the US-BL-84 bedload sampler), at the USGS streamgaging station on the Colorado River above National Canyon near Supai, Arizona, United States, October 1989. From Gray and others, 1991.

bedload samplers, it is evident that careful calibration with the most appropriate bedload sampler is a prerequisite for reliable bedload-transport surrogate monitoring in rivers. This is true for applications in a range of rivers, from small to large and coarse-bedded to fine-bedded.

Synopses of Four Sediment-Surrogate Workshops from 2002 through 2007

Largely due to the well-established need for advanced sediment-monitoring technologies, four substantive topical workshops have been held since 2002, all sharing goals of increased communication, technology transfer, and development of new collaborations toward advancing promising sediment-surrogate technologies. Summaries from these workshops are available and references are provided herein. Below are synopses of the four workshops with an emphasis on outcomes germane to bedload-surrogate research.

I. Federal Interagency Sedimentation Workshop on Turbidity and Other Sediment Surrogates, April 30–May 2, 2002, Reno, Nevada, United States

Summary

Sponsored by the Federal Interagency Subcommittee on Sedimentation of the Advisory Committee on Water Information (SOS) (<http://acwi.gov/sos/>), this workshop was held with the primary goals of developing an unambiguous definition of turbidity, to propose a means for estimating suspended-sediment concentration from continuous in situ turbidity data, and to identify capabilities and limitations of surrogate methods for monitoring suspended sediment (Gray and Glysson, 2003a). Although bedload monitoring was not explicitly addressed in this workshop, four of its recommendations are indirectly germane to bedload monitoring:

Technology transfer and communication.—Increase technology transfer between groups and individuals with interests in sediment-surrogate technologies. A steering committee should be formed that includes a coordinator and topical expert advisors on sediment-surrogate technologies. Resources associated with the steering committee may include publication of a newsletter, creating and maintaining a Web-based compilation of information, supporting user groups and online help, documenting methods, transferring industrial technology to the environmental field, and otherwise providing guidance to the SOS.

Stakeholder and peer review.—Keep the public and users of sediment-surrogate data informed about the issues involved in producing these data, including assumptions, limitations, methods, and applicability.

Test and development program for instruments.—

Develop a program to foster research, testing, and evaluation of instruments and methods for measuring, monitoring, and analyzing selected characteristics of fluvial sediment by cost-effective, safe, and quantifiably accurate means. Technically supportable and widely available standard guidelines for sensor deployment, calibration, and data processing, including real-time data, are needed. Acceptance criteria for data from a given parameter should be developed, endorsed by the SOS, and widely advertised to encourage methods and instrumentation development.

Collection and computation of sediment-surrogate measurements.—Develop standardized procedures for the collection of sediment-surrogate data. This should include protocols for instrument calibration and criteria for acceptance of the derivative sediment data. A standard procedure for computation of sediment-discharge records should be developed for all sediment-surrogate records utilizing the fullest set of data.

Submitted Papers

The papers from this workshop were published in Gray and Glysson (2003), and are available at: <http://water.usgs.gov/osw/techniques/TSS/listofabstracts.htm>.

II. Erosion and Sediment Transport Measurement in Rivers: Technological and Methodological Advances, June 19–21, 2002, Oslo, Norway

Summary

Sponsored by the International Association of Hydrological Sciences [IAHS (<http://iahs.info/>)], this workshop followed up on a 1992 IAHS-sponsored symposium dealing with erosion and sedimentation (Bogen and others, 1992) and directed particular attention to the development of new sediment-measurement technologies. Of the 24 published papers (Bogen and others, 2003), 13 focused on bedload measurements, monitoring, and associated transport processes.

Bogen and others (2003) wrote that “It is hoped that publication of these presentations...will stimulate further discussion and draw attention to recent advances in erosion and sediment transport measurement involving new methods and new technologies.”

Submitted Papers

The papers from this workshop are available in Bogen and others (2003).

III. Federal Interagency Sediment Monitoring Instrument and Analysis Research Workshop, September 9–11, 2003, Flagstaff, Arizona, United States

Summary

Sponsored by the Subcommittee on Sedimentation, this workshop was held as a follow-up to the four recommendations listed under the summary for the 2002 Federal Interagency Sedimentation Workshop on Turbidity and Other Sediment Surrogates (Gray and Glysson, 2003a). It also was held in recognition of a convergence of advanced instrument technologies and analytical capabilities that provide the capability to measure and (or) monitor one or more phases of fluvial sediment with a heretofore unprecedented continuity, temporal density, and known accuracy. The workshop's theme was posed as the question, "What are the fluvial-sediment-data needs of the United States, and how can these needs be met with:

- a substantially increased temporal and (or) spatial resolution,
- a better and quantifiable accuracy,
- an expanded suite of measurement characteristics,
- reduced costs, and (or)
- a greater margin of safety?"

The workshop's overarching goals were to exchange information and provide a forum in which to develop a vision on how to attain the critical fluvial-sediment data needed for the United States. The workshop scope focused on the means for measuring, storing, analyzing, and disseminating data for the following sedimentary phases: suspended sediment, bedload, bed material, and bed topography. The degree of uncertainty in the production of fluvial-sediment data was considered with respect to each of the sedimentary phases, including their storage and computational treatment (Gray, 2005).

Seven papers focusing on bedload were included among the workshop's 22 published papers (Gray, 2005). Additionally, 8 surrogate technologies (in addition to 5 types of in-stream bedload-monitoring installations and 7 types of portable physical samplers) were identified (Ryan and others, 2005).

Four primary recommendations resulted from the 2003 workshop (Ryan and others, 2005):

- The development of nationally recognized sites for field calibration of bedload sampling technologies should be given high priority to bring "better" (less costly, certifiably accurate, safer) technologies to operational use. These should be sites where bedload transport ground-truth rates are known, and the accuracy of sampling technologies can be evaluated.

- There should be a federally based oversight organization responsible for the field-calibration sites, such as the FISP or a similar-type organization. This could be part of an organized bedload-research program such as the Sediment Instrument and Analysis Research Program operated informally by the USGS, the components of which are described by Gray and Glysson (2003b) and Gray and Simões (2008).
- Additional discussion is needed on selecting the candidate sites for field testing bedload sampling technologies and the types of devices to be used in determining accurate rates of bedload transport. A separate workgroup that focuses solely on bedload issues should be convened to develop recommendations on how this might be done.
- A white paper is needed to provide an unbiased evaluation of all existing technologies and potential surrogate technologies. This paper would describe the state of the art in bedload measurement, offer recommendations on the use of devices in different types of stream environments, and provide guidance on desired sampler accuracy requirements for commercial developers.

Additionally, a matrix was produced by the workshop comparing selected characteristics of different bedload-sampling technologies (Ryan and others, 2005). The parts of that matrix that include traditional in-stream, and portable/physical bedload-sampling technologies are reproduced here as table 1.

Submitted Papers

The papers from this workshop were published in Gray (2005), and are available at: <http://pubs.usgs.gov/circ/2005/1276/pdf/Appendix4.pdf>.

Table 1. Comparison of characteristics of traditional in-stream and portable/physical bedload-sampling technologies.—Continued

[Modified from Ryan and others (2005). See the original table for all annotations. <, less than; ~, approximately; %, percent; N/A, not applicable]

Bedload sampling technology	Stream type	Requires wading or retrieval during high flows	Physical sample obtained for sieving	High percentage of channel width sampled	Large opening relative to grain size	Relatively long sampling duration	Stream excavation required	Relative ease of use	Disruptive to flow fields	Status of development	Potential use as calibration standard
1. In-stream installations											
Reid-type (Birkbeck) pit sampler (weighable trap)	Narrow gravel bed channel	No	Yes, requires time-split sampling	Typically not	Depends on slot width	Continuous	Yes	Easy	Not when pit <~80% full	Completed	High.
Vortex sampler	Gravel bed channel	No	Yes	Yes	Yes	Continuous	Yes	Depends on flow conditions	Depends on experimental setup	Additional testing and modifications	High.
Pit traps, non-weighable	Gravel bed channel	Yes	Yes	Typically not	Possibly	Possibly	Yes, small scale	Depends on flow conditions	Slightly	Additional testing	Probably not.
Net-frame sampler	Gravel bed channel	Wading at low-medium flows; not serviceable when unwadeable	Yes	Yes	Yes	Yes	Depends on experimental setup	Can be difficult	Depends on experimental setup	Completed	Possible for low flows and medium flows.
Sediment detention basins/weir ponds	Sand-gravel bed channels	No	Upon excavation	Yes	Yes	Period of runoff	Yes	Relatively easy with adequate personnel	No	Completed	Low, relevant as flood-composite only.
2. Portable/physical devices											
Pressure-difference samplers (small openings)	Sand-gravel bed channel	Yes	Yes	No	No for medium and larger gravel	No	No	Usually not excessively difficult	Somewhat	Completed, but calibration issues persist	Moderate.
Pressure-difference samplers (larger openings)	Gravel bed channel	Yes	Yes	No	Yes	No	No	Depends on flow conditions	Somewhat	Additional verification pending	Moderate.
Baskets (suspended or in-stream)	Gravel bed channel	Yes	Yes	No	Depends on design	Yes	No	Depends on flow conditions	Depends on hydraulic and field conditions	Completed	Low.

Table 1. Comparison of characteristics of traditional in-stream and portable/physical bedload-sampling technologies.—Continued

[Modified from Ryan and others (2005). See the original table for all annotations. <, less than; ~, approximately; %, percent; N/A, not applicable]

Bedload sampling technology	Stream type	Requires wading or retrieval during high flows	Physical sample obtained for sieving	High percentage of channel width sampled	Large opening relative to grain size	Relatively long sampling duration	Stream excavation required	Relative ease of use	Disruptive to flow fields	Status of development	Potential use as calibration standard
Bedload traps	Gravel bed channel	Yes	Yes	Depends on number of traps deployed	Yes	Yes	Minor	Only in wadeable conditions	Unknown	Completed except efficiency; testing of modifications	Moderate for wadeable streams, low discharges.
Tracer particles (painted, magnetic, signal-emitting rocks)	Gravel bed channel	Possibly	No	Depends on tracer placement, inapplicable for larger streams	N/A	Yes	Not generally, sometimes locally	Easier in ephemeral streams; relatively time consuming	No	Completed	Low.
Scour chains; scour monitor; scour core	Sand-gravel bed channel	Possibly	No	No	N/A	Yes	Yes locally	Easy in ephemeral streams	No	Completed	Low.
Bedload collector (streamside systems)	Sand-gravel bed channel	No	Yes	Depends on number and size of devices deployed	Depends on design of device	Yes	Yes	Operation is easy once installed	Unknown	Needs verification	Needs to be tested.
3. Surrogate technologies											
ADCP – acoustic Doppler current profiler	Sand bed rivers, experimental in larger gravel bed channels	No	No	Yes when deployed in cross section	N/A	Continuous when used in single vertical	No	Logistics and data reduction are complex	No	Moderate (sand systems) early (gravel systems)	Verification for sand and gravel bed systems.
Hydrophones (passive acoustic sensors)	Gravel bed channel	No	No	Potentially yes	N/A	Continuous	No	Easy	No	Early	Additional development needed.
Geophones (gravel impact sensors placed on riverbed, passive acoustic sensors)	Gravel bed channel	No	No	Potentially yes; function of instrument deployment	N/A	Continuous	No	Easy under many conditions	No	Moderate	Additional development needed.

Table 1. Comparison of characteristics of traditional in-stream and portable/physical bedload-sampling technologies.—Continued

[Modified from Ryan and others (2005). See the original table for all annotations. <, less than; ~, approximately; %, percent; N/A, not applicable]

Bedload sampling technology	Stream type	Requires wading or retrieval during high flows	Physical sample obtained for sieving	High percentage of channel width sampled	Large opening relative to grain size	Relatively long sampling duration	Stream excavation required	Relative ease of use	Disruptive to flow fields	Status of development	Potential use as calibration standard
Magnetic tracers	Gravel bed with naturally magnetic particles	No	No	Yes	N/A	Continuous	Yes	Relatively easy	Depends on experimental setup	Additional testing	Low.
Magnetic sensors	Gravel bed channel	No	No	Yes in small streams	N/A	Continuous	Yes	Easy under many conditions	Minor; flush with stream bottom	Early	Additional verification needed.
Topographic differencing	Sand-gravel bed channel	No	No	Yes	N/A, inclusive of all grain sizes	Episodic	No	Easy	No	Advanced	Relevant only for entire floods.
Sonar-measured debris basin	Gravel bed channel	No	No	Yes	N/A, inclusive of all grain sizes	Continuous	No	Requires periodic debris basin sampling and dredging	N/A	Early	High only for longer time span.
Underwater video cameras	Relatively clear-flowing streams	Used from bridges or boats	No	No	N/A	Continuous	No	Easy under right lighting conditions	Slightly	Early	Additional verification needed.

IV. International Bedload-Surrogate Monitoring Workshop, April 11–14, 2007, Minneapolis, Minnesota, United States

Summary

This workshop, attended by about 50 geomorphologists, sedimentologists, hydraulic engineers, hydrologists, and others with expertise and (or) interest in bedload monitoring representing 11 countries (appendix 1), took place at the St. Anthony Falls Laboratory, Minneapolis, Minnesota, United States. Others from around the world participated via live webstream on April 11–13, and the webstream was permanently archived (National Center for Earth-surface Dynamics, 2007). Workshop sponsors are listed in appendix 2.

Laronne and others (2007) and Gray and others (2007b) summarized initial workshop outcomes. These and the ensuing technology summary sections constitute the final summary of this workshop. The objectives of the workshop were threefold:

- Determine the extent to which available bedload-surrogate technologies have progressed toward potential operational applications based on calibrations under laboratory and field conditions.
- Further the development and verification of novel bedload-surrogate technologies and methodologies toward their routine application in large-scale monitoring programs.
- Identify needs related to international standards for bedload data-collection, -storage, and -dissemination protocols.

The workshop was predicated on recognition of the research community's longstanding inability to resolve a variety of difficulties in measuring and monitoring bedload transport, particularly in gravel and mixed gravel-sand bedded rivers. Direct bedload measurements, particularly during the higher flows at which most bedload occurs, tend to be time-consuming, expensive, and potentially hazardous. Surrogate technologies developed largely over the last decade and used at a number of research sites around the world show considerable promise toward providing relatively dense, robust, and quantifiably reliable bedload datasets. However, information on the relative performance, scope of applicability, and ultimate efficacy of selected technologies for use in monitoring programs is needed, as is identifying methods for bringing the most promising and tractable of the technologies to fruition.

Three principal recommendations emanated from the workshop:

1. *Summarize the status of progress in bedload-surrogate technologies.*—A primary thrust of the workshop was to compile and evaluate information on bedload-surrogate technologies and to identify those that show the most promise for monitoring bedload as part of operational programs in a quantifiably reliable manner. Papers pre-

sented at the workshop—all of which are published with this report, in addition to several relevant invited papers germane but not presented at the workshop—addressed a number of bedload-surrogate technologies. Each technology operates on one of several principles, with active or passive acoustic techniques predominating. Surrogate technologies based on magnetic and radar sensing presently are less developed for use in the near future.

2. *Provide access to bedload and ancillary data worldwide.*—The desire for access to a broad spectrum of bedload data from around the world was unanimous among workshop participants. Anticipated limitations in resources seem to preclude development, population, and maintenance of a central database. An alternate approach to bedload-data access was described as follows:

- a. Form an ad hoc committee to define the objectives and approach toward accessing bedload and ancillary data worldwide. Identify potential partners in this effort.
- b. Locate and post online static (historical) bedload and ancillary databases that do not require refreshment and maintenance.
- c. Identify and access dynamic databases with bedload and ancillary data worldwide, such as the USGS National Water Information System. Provide metadata on each database, including protocols by which the data were collected and analyzed.
- d. Develop sequential query language or other script-type language that can extract data on request from the static and dynamic databases.
- e. Enable access or make available information related to access to the suite of bedload and ancillary databases through the Bedload Research International Cooperative (Gray and others, 2007a) Web site, free of charge.

This concept has been articulated in some detail by Gray and Osterkamp (2007). Collaborators that have expressed some level of interest include the National Center for Earth-surface Dynamics and the World Association for Sedimentation and Erosion Research. A questionnaire designed to identify useful, quality-assured databases is online at the Subcommittee on Sedimentation of the Advisory Committee on Water Information Web site (<http://acwi.gov/sos/>).

3. *Form and implement a Bedload Research International Cooperative (BRIC) benchmark network.*—A number of bedload researchers have developed novel techniques for intermittently or continuously monitoring bedload transport. Recognizing this need and the potential availability of a number of facilities capable of providing

bedload-transport ground truth, the workshop attendees were unanimous in their recommendation for the BRIC to develop a Bedload Benchmark Network. Such a network would consist of sites and facilities that:

- Possess the facilities and capabilities that enable reliable computations of bedload transport.
- Will be an active collaborator in the BRIC Benchmark Network.
- Are coordinated by a BRIC-organized committee to help researchers in the selection of an appropriate bedload-research venue.

At least 20 such venues have already been identified as potential BRIC Benchmark Network research sites. A list of venues is available from the National Center for Earth-surface Dynamics Web page at www.bedloadresearch.org.

Submitted Papers

Table 2 lists papers associated with the International Bedload-Surrogate Monitoring Workshop, April 11–14, 2007, St. Anthony Falls Laboratory, Minneapolis, Minnesota, United States. Papers by USGS authors were reviewed and approved for publication by the USGS. Although papers by other authors were submitted for peer review and edited by the workshop organizers, they did not go through the USGS review process, and therefore may not adhere to USGS editorial standards or stratigraphic nomenclature.

Most of the papers listed in table 2 were presented at the 2007 workshop. All of the listed papers are germane to the thrusts of the workshop, and are published here for the first time. They may be accessed by clicking the desired paper in table 2, or by accessing them from <http://bedloadresearch.org/content/2007-workshop>.

Summary of Activities on Bedload-Surrogate Monitoring Technologies

Syntheses and Progress from the 2002–2007 Sediment-Technology Workshops

Sustained, international research and development is underway on developing advanced surrogate technologies for use in bedload monitoring. The four workshops held since 2002 have played a large role in shaping the conversations and collaborations involving this research. In aggregate, the workshops have led to three areas of activity:

1. *Collaboration.*—The workshops provided opportunities for ongoing contact between members of the research community involved in developing surrogate technolo-

gies, which has resulted in better communication and coordination within this relatively small field. New collaboration, technology exchange, coordinated ground-truth testing campaigns, and new field deployments are all examples of these new activities. Examples of collaboration that derived from the 2007 International Bedload Surrogate Workshop follow:

- The project “Sediment Transport in Steep Streams” has been funded by the Swiss Science Foundation to Dieter Rickenmann (Swiss Federal Research Institute), principal investigator. The project involves the use of plate geophones as surrogate bedload monitoring techniques to study bedload transport, and includes collaboration and deployment of plate geophones also in Israel (project manager Jonathan Laronne, Ben Gurion University of the Negev) and Austria (project manager Helmut Habersack, Universität für Bodenkultur–BOKU, Vienna).
- Collaboration has taken place between the U.S. Bureau of Reclamation, the Norwegian Water Resources and Energy Directorate (see Møen and others, listed in table 2), and the National Center for Earth-surface Dynamics (NCED) regarding the use of geophones to monitor bedload-transport rates across the Elwha River, Washington, United States, before, during, and after removal of two upstream high-head dams.

2. *Organization.*—The Bedload Research International Cooperative (BRIC) was developed (Laronne and Gray, 2005; Gray and others, 2007a) with the goal of introducing a point of contact and information resource center for bedload-related data, activities, resources, publications, and expertise. BRIC currently has its own Web site (www.bedloadresearch.org), with plans for expansion in part due to outcomes from the aforementioned 2007 workshop.
3. *Information Outreach and Advocacy.*—The important role that bedload plays in many river-management issues is often underrepresented and (or) underappreciated, and thus financial support for research and technology development and for field monitoring is limited. The activities resulting from the workshops serve to raise awareness about the importance of bedload in river management and the needs that exist for improving, understanding, and developing management tools through research and monitoring.

Table 2. Papers submitted as part of the International Bedload-Surrogate Monitoring Workshop, April 11–14, 2007, St. Anthony Falls Laboratory, Minneapolis, Minnesota, United States. [The papers listed in this table are available only online at <http://pubs.usgs.gov/sir/2010/5091/papers/>.]—Continued

[Listed in alphabetical order by first author]

Authors	Title
Barton, Jonathan S., Slingerland, Rudy L., Pittman, Smokey, and Gabrielson, Thomas B.	Monitoring Coarse Bedload Transport with Passive Acoustic Instrumentation: A Field Study (http://pubs.usgs.gov/sir/2010/5091/papers/)
Batalla, Ramon J., Vericat, Damià, Gibbins, Chris N., and Garcia, Celso	Incipient Bed-Material Motion in a Gravel-Bed River: Field Observations and Measurements (http://pubs.usgs.gov/sir/2010/5091/papers/)
Belleudy, Philippe, Valette, Alexandre, and Graff, Benjamin,	Passive Hydrophone Monitoring of Bedload in River Beds: First Trials of Signal Spectral Analyses (http://pubs.usgs.gov/sir/2010/5091/papers/)
Bunte, Kristin	Measurements of Gravel Transport Using the Magnetic Tracer Technique: Temporal Variability Over a Highflow Season and Field-Calibration (http://pubs.usgs.gov/sir/2010/5091/papers/)
Bunte, Kristin, Swingle, Kurt W., and Abt, Steven R.	Necessity and Difficulties of Field Calibrating Signals from Surrogate Techniques in Gravel-Bed Streams: Possibilities for Bedload Trap Samplers (http://pubs.usgs.gov/sir/2010/5091/papers/)
Diplas, Panayiotis, Celik, A.O., Valyrakis, Manousos, and Dancy, C.L.	Some Thoughts on Measurements of Marginal Bedload Transport Rates Based on Experience from Laboratory Flume Experiments (http://pubs.usgs.gov/sir/2010/5091/papers/)
Downing, John	Acoustic Gravel-Momentum Sensor (http://pubs.usgs.gov/sir/2010/5091/papers/)
Emmett, William W.	Observations of Bedload Behavior in Rivers and Their Implications for Indirect Methods of Bedload Measurement (http://pubs.usgs.gov/sir/2010/5091/papers/)
Fienberg, Kurt, Singh, Arvind, Fofoula-Georgiou, Efi, Jerolmack, Doug, and Marr, Jeffrey D.G.	A Theoretical Framework for Interpreting and Quantifying the Sampling Time Dependence of Gravel Bedload Transport Rates (http://pubs.usgs.gov/sir/2010/5091/papers/)
Froehlich, Wojciech	Monitoring of Bed Load Transport Within a Small Drainage Basin in the Polish Flysch Carpathians (http://pubs.usgs.gov/sir/2010/5091/papers/)
Gaeuman, David, and Pittman, Smokey	Relative Contributions of Sand and Gravel Bedload Transport to Acoustic Doppler Bed-Velocity Magnitudes in the Trinity River, California (http://pubs.usgs.gov/sir/2010/5091/papers/)
Gray, J.R., Laronne, J.B., Osterkamp, W.R., and Vericat, Damià	Bed Load Research International Cooperative—BRIC (http://pubs.usgs.gov/sir/2010/5091/papers/)
Habersack, Helmut, Seitz, Hugo, and Liedermann, Marcel	Integrated Automatic Bedload Transport Monitoring (http://pubs.usgs.gov/sir/2010/5091/papers/)
Holmes, Robert R., Jr.	Measurement of Bedload Transport in Sand-Bed Rivers: A Look at Two Indirect Sampling Methods (http://pubs.usgs.gov/sir/2010/5091/papers/)
Mao, Luca, Comiti, Francesco, and Lenzi, Mario Aristide	Bedload Dynamics in Steep Mountain Rivers: Insights from the Rio Cordon Experimental Station (Italian Alps) (http://pubs.usgs.gov/sir/2010/5091/papers/)
Marr, Jeffrey D.G., Gray, John R., Davis, Broderick E., Ellis, Chris, and Johnson, Sara	Large-Scale Laboratory Testing of Bedload-Monitoring Technologies: Overview of the StreamLab06 Experiments (http://pubs.usgs.gov/sir/2010/5091/papers/)
McLelland, Stuart J.	Observing Bedload/Suspended Load Using Multi-Frequency Acoustic Backscatter (http://pubs.usgs.gov/sir/2010/5091/papers/)

Table 2. Papers submitted as part of the International Bedload-Surrogate Monitoring Workshop, April 11–14, 2007, St. Anthony Falls Laboratory, Minneapolis, Minnesota, United States. [The papers listed in this table are available only online at <http://pubs.usgs.gov/sir/2010/5091/papers/>.]—Continued

[Listed in alphabetical order by first author]

Mizuyama, Takahisa, Laronne, Jonathan B., Nonaka, Michinobu, Sawada, Toyoaki, Satofuka, Yoshifumi, Matsuoka, Miwa, Yamashita, Shintaro, Sako, Yoichi, Tamaki, Shohei, Watari, Masaaki, Yamaguchi, Shinji, and Tsuruta, Kenji	Calibration of a passive acoustic bedload monitoring system in Japanese mountain rivers (http://pubs.usgs.gov/sir/2010/5091/papers/)
Mizuyama, Takahisa, Oda, Akira, Laronne, Jonathan B., Nonaka, Michinobu, and Matsuoka, Miwa	Laboratory Tests of a Japanese Pipe Geophone for Continuous Acoustic Monitoring of Coarse Bedload (http://pubs.usgs.gov/sir/2010/5091/papers/)
Møen, Kurt M., Bogen, Jim, Zuta, John F., Ade, Premus K., and Esbensen, Kim	Bedload Measurement in Rivers Using Passive Acoustic Sensors (http://pubs.usgs.gov/sir/2010/5091/papers/)
Papanicolaou, Athanasios (Thanos) N., and Knapp, Doug	A Particle Tracking Technique for Bedload Motion (http://pubs.usgs.gov/sir/2010/5091/papers/)
Ramooz, Rauf, and Rennie, Colin D.	Laboratory Measurement of Bedload with an ADCP (http://pubs.usgs.gov/sir/2010/5091/papers/)
Reid, Ian, Graham, David, Laronne, J.B., and Rice, Stephen	Essential Ancillary Data Requirements for the Validation of Surrogate Measurements of Bedload: Non-Invasive Bed material Grain Size and Definitive Measurements of Bedload Flux (http://pubs.usgs.gov/sir/2010/5091/papers/)
Rempel, Jason, Hassan, Marwan A., and Enkin, Randy	Laboratory Calibration of a Magnetic Bed Load Movement Detector (http://pubs.usgs.gov/sir/2010/5091/papers/)
Rickenmann, Dieter, and Fritschi, Bruno	Bedload Transport Measurements Using Piezoelectric Impact Sensors and Geophones (http://pubs.usgs.gov/sir/2010/5091/papers/)
Shrestha, S.M., Shibata, K., Hirano, K., Takahara, T., and Matsumura, K.	River Bedload Monitoring Using a Radar System (http://pubs.usgs.gov/sir/2010/5091/papers/)

Bedload-Surrogate Technologies

Varied technological approaches are being brought to bear to solve the bedload-measurement problem. This section provides an overview of technologies and the extent to which they are promising, with summary information on the principles of operation, status of development, and application information for field deployment. Most of the technologies addressed in this section were presented at the International Bedload Surrogate Monitoring Workshop in April 2007 (hereafter, “2007 Bedload Workshop”). Links are identified between the technologies and the papers from that workshop listed in table 2, in which further details on the technologies can be found.

One approach to categorizing the various bedload-surrogate technologies is by sensor type. In general, surrogate-technology sensors may be described as operating on passive or active principles. Sensors operating on active principles—active sensors—emit signals and record selected properties of the reflected signal. Pinging sonar or laser devices are examples of active sensors. Technologies operating on passive principles—passive sensors—record naturally generated signals. Examples of passive sensors include hydrophones, which

are deployed in water, and geophones, which are mounted on or near a streambed.

The next two sections provide information on active- and passive-sensor technologies. As is true with conventional bedload samplers, controlled ground-truth testing over a range of bedload-transport conditions is a prerequisite for evaluating the performance of any measurement technique. In addition to the development and verification of advanced bedload technologies, efforts are ongoing to further develop field- and laboratory-based ground-truth facilities and capabilities. Table 3 lists selected characteristics of the various surrogate technologies addressed herein.

Active Sensors

Active sensor-surrogate technologies include devices that sense, either by light or sound, characteristics of the riverbed to produce estimates of sediment motion. A number of active sensor devices are in development for use as bedload-surrogate technologies. These include acoustic Doppler current profilers, active sonar, radar, and “smart” tracers.

Table 3. Selected characteristics of bedload-surrogate monitoring technologies addressed in this report.—Continued

[mm, millimeter; cm, centimeter; >, greater than; <, less than]

Technology	Technology description	Continuous operation (yes/no)	Mode of operation	Sediment types	Stage of development	Ease of use*	Durability*	Portability*	Reliability*	Spatial coverage*	Cost*
ACTIVE SENSORS (all require field calibration)											
Acoustic Doppler current profiler (ADCP)	Commercially available device that uses sonar and principles of Doppler to determine vertical velocity profile. Device also provides information on bedload movement (velocity).	Yes	Stationary ADCP device - sonar.	Sand and gravel	Moderately well developed. In preliminary usage.	2	4	2	1	Point/cross-section reach	High
Sonar: Backscatter	High-frequency sonar transceiver to measure spatial and temporal fluctuations in sand-sediment concentrations over bedforms.	Yes	Stationary sonar.	Sand	Needs further work to quantify spatial and temporal characteristics of suspended sediment transport. Small-scale applications. Early stage of development.	4	4	2	3	Point/cross-section	Low
Sonar: Bed differencing	Techniques for computationally differencing temporally distinct bathymetric surveys of a stream/river reach to determine total bedload flux.	No	Boat-mounted multi-frequency sonar and post processing.	Sand	Moderately well developed. Used in large rivers.	4	5	5	1	Reach	High
Radar	Short-pulse electromagnetic waves are transmitted into open-channel flow. The waves are scattered by particles in transport and recorded by receiving antennae.	No	Electromagnetic-wave return produced by presence of grains.	Gravel	Tested in laboratory but not in field. Early stage of development.	4	4	3	4	Reach	Moderate

Table 3. Selected characteristics of bedload-surrogate monitoring technologies addressed in this report.—Continued

[mm, millimeter; cm, centimeter; >, greater than; <, less than]

Technology	Technology description	Continuous operation (yes/no)	Mode of operation	Sediment types	Stage of development	Ease of use*	Durability*	Portability*	Reliability*	Spatial coverage*	Cost*
Smart tracers	Micro-radio transmitters, radio frequency identification, and other advanced tracers used to track particles through channel or watershed.	Yes	Place tracer in system and monitor location through various techniques.	Gravel	Laboratory and field testing completed. Useful for specific applications. Systems are affordable but can be delicate to operate.	4	3	2	3	Reach	Moderate
PASSIVE SENSORS (all require field calibration)											
Impact pipes	Air-filled pipe installed within riverbed with passive sensor (geophone or hydrophone) recording impacts of grains on pipe.	Yes	Signal produced by impact of grain on pipe.	Gravel > 4 mm	Moderately well developed. Testing in both laboratory and field. Requires local calibration.	2	2	4	2	Cross-section	Low
Impact plates	Steel plate installed within riverbed with passive sensor (geophone or hydrophone) recording impacts of grains on plates.	Yes	Signal produced by contact of grain on with plate.	> 10 mm	Moderately well developed. Testing in laboratory and field. Requires local calibration.	2	2	4	2	Cross-section	Low
Impact columns	Gravel transport sensor (GTS) - piezoelectric vibration sensor or momentum sensor.	Yes	Signal produced by impact of grain on column.	10 to 128 mm	Early development with only laboratory testing to date. Requires local calibration.	3	3	2	2	Cross-section	Moderate
Magnetic tracers: Coil log	Tracer technique that uses naturally magnetic or imbedded magnets in natural particles to track flux and trajectory of bedload particles. Parallel "inductors" are placed in the bed of the channel to measure passage of magnetic particles.	Yes	Signal produced by passage of grain over inductor.	Magnetic gravels	Early-to-moderate development. Technology is for specific application and specific sites where magnetic particles are found.	3	3	4	4	Cross-section	Low

Table 3. Selected characteristics of bedload-surrogate monitoring technologies addressed in this report.—Continued

[mm, millimeter; cm, centimeter; >, greater than; <, less than]

Technology	Technology description	Continuous operation (yes/no)	Mode of operation	Sediment types	Stage of development	Ease of use*	Durability*	Portability*	Reliability*	Spatial coverage*	Cost*
Magnetic tracers: Bedload movement detector	Tracer technique that uses naturally magnetic or imbedded magnets in natural particles to track flux and trajectory of bedload particles. The Bedload Movement Detector has an approximately 1-cm "inductor" that detects movement of magnetic particles.	Yes	Counts/time.	8- to 90-mm artificial stones	Early development conducted in the laboratory. Technology is for specific application where magnetic particles are found.	2	2	2	3	Point/cross-section	Low
Passive hydroacoustics	Recording natural sound generated by rock-rock collisions during bedload transport in channels using a hydrophone and data acquisition system.	Yes	Signal produced by impact of grains with one another.	Gravel and larger	Needs additional work to be an operational monitoring technique.	2	3	1	3	Reach	Low

*Ease of use 1 easy; 5 difficult

*Durability 1 durable; 5 fragile

*Portability 1 portable; 5 not portable

*Reliability 1 low maintenance needs; 5 high maintenance needs

*Spatial coverage Point - single point measurement; Cross-section - cross sectional measurement; Reach - measurement of an entire reach

*Cost Low, relatively inexpensive; High, relatively expensive

Acoustic Doppler Current Profiler (ADCP)

Over the last two decades, the ADCP has become a standard technology for measuring water flow in marine, estuarine, and freshwater environments (fig. 10). They are commercially available from a number of manufacturers, with the primary purpose of measuring velocity distributions and depths across a channel for use in automatic computations of river discharge. ADCPs have a built-in bottom-tracking feature that was originally intended for use in computationally correcting for movement of the watercraft-deployed ADCP, but can now also be exploited to yield estimates of apparent bed velocities and ultimately to infer bedload-transport rates.

The ADCP is typically mounted on a watercraft and oriented nearly vertical so as to emit short sound pulses from its sonar transducers toward the bed. Water-velocity measurements are based on the Doppler shift of echoes reflected from particles moving within the water column. The water-velocity measurements are corrected for the velocity of the boat by measuring the boat velocity using the Doppler shift of echoes from the streambed. When the velocity of the ADCP is referenced to the bed, a systematic negative bias in discharge measurements attributable to the movement of bedload and near-bed suspended sediment may occur and is referred to as a moving-bed error (Mueller and Wagner, 2006).

Data from a stationary ADCP will erroneously infer from the bottom tracking feature that the ADCP is moving in the upstream direction at a rate equal to the ambient bottom-track value, referred to as the apparent bed velocity. Physical measurements of bedload transport can be correlated to the apparent bed velocity determined in the ADCP-sonified region of the bed, thus providing an empirically based measure of the bedload-transport rate.

Status of development.—The application of the ADCP technology for inferring bedload-transport rates is progressing rapidly, and the technology holds considerable promise for producing bedload data using a manually deployed ADCP.



Figure 10. An acoustic Doppler current profiler (ADCP) deployed from a boat (photograph courtesy of Paul R. Baker, USGS), with inset showing a submerged ADCP (photograph courtesy of Timothy J. Reed, USGS).

Research suggests that ADCPs are more successful in sand-bed systems than in gravel-bed systems; however, the less successful results for gravel-bed studies may be due to the scale limitation of the laboratory experiments in which the studies were conducted, and (or) to the precision of the comparative bedload-sampler data. Flume and field studies have been conducted in recent years with foci on developing methods for improving correlation techniques between bottom track and apparent bedload velocity.

Three papers were presented on this technology at the 2007 Bedload Workshop and are listed in table 2:

- Gaeuman, David, and Pittman, Smokey, Relative Contributions of Sand and Gravel Bedload Transport to Acoustic Doppler Bed-Velocity Magnitudes in the Trinity River, California.
- Holmes, Robert R., Jr., Measurement of Bedload Transport in Sand-Bed Rivers: A Look at Two Indirect Sampling Methods.
- Ramoos, Rauf, and Rennie, Colin D., Laboratory Measurement of Bedload with an ADCP.

Sonar

Sound has long been used as a measurement tool in water bodies for locating objects in water columns and for measuring bathymetry and stratigraphy. The principle of sonar measurement is based on the two-way travel time of a short burst of sound. The distance to the reflecting object can be calculated based on the velocity of sound under the ambient water conditions. Sonar has long been used to collect bathymetric data in lentic and lotic water bodies. Recent advances in sonar technologies and post-processing capabilities have led to new bedload-monitoring techniques. Using sonar for sediment-transport monitoring is a promising area of research. Two types of sonar were presented at the 2007 Bedload Workshop. Both are based on the same fundamental principles of sonar; however, they differ in the spatial scale of measurement.

Temporal and Spatial Characteristics of Bedload and Suspended-Load Transport Rates Using High-Frequency Sonar

The first application uses an array of small, high-frequency transceivers (capable of emitting and measuring the reflected sound waves) to examine the backscatter properties associated with bedload and suspended load. The focus has been on using sonar to examine the temporal fluctuation in bedload transport associated with migrating bedforms. A transducer frequency that responds optimally (or at least adequately) to the size and types of sediments in suspension but has sufficient strength to avoid being completely attenuated within the water column should be selected. The laboratory-based results using a well-sorted sand mix show that backscatter has great potential for identifying spatial and temporal fluctuations in sand-sediment concentrations over bedforms.

Further research is needed using poorly sorted sediment and mixtures of sediment.

Status of development.—Further research is needed before this technique can be considered for operational bedload monitoring. It has specific relevance to bedload-transport measurements with an ADCP, as it could provide critical information on the thickness of the active-transport layer. One paper was presented on this technology at the 2007 Bedload Workshop and is listed in table 2:

- McLelland, Stuart J., Observing Bedload/Suspended Load Using Multi-Frequency Acoustic Backscatter.

Estimation of Bedload-Transport Rates from Bathymetric Differencing

Sonar is a commonly used technology to generate bathymetric data. Bathymetric surveys in rivers are typically performed by moving the sonar upstream and downstream in the channel. Estimating bedload-transport rates from sequential bed-elevation profiles or stationary bed-elevation data is not a new concept; however, hardware and software advances in recent years have made the technology more tractable and appealing.

Status of development.—Advances in data-collection technologies such as multi-beam swath bathymetry and water-penetrating lidar have resulted in a resurgence of interest in their measuring capabilities. These methods are being used to estimate bedload-transport rates in rivers where dense data are available. If their performance can be shown to be sufficiently accurate and reliable, the methods should be applicable to both sand- and gravel-bed systems. However, sand-bed systems have been the focus of most progress with this technology for two reasons: (1) most large, deep rivers are sand bedded, and (2) the analytical method involves resolving sequential differences in bedform features, which are most common and prominent in sand-bedded systems. Two papers were presented at the 2007 Bedload Workshop that focused on bathymetric differencing and are listed in table 2:

- Holmes, Robert R., Jr., Measurement of Bedload Transport in Sand-Bed Rivers: A Look at Two Indirect Sampling Methods.
- Habersack, Helmut, Seitz, Hugo, Liedermann, Marcel, Integrated Automatic Bedload Transport Monitoring.

Radar

Preliminary research is underway on using ground-penetrating radar (GPR) as a means for measurement of sand-bedload transport. This research has heretofore been restricted to laboratory flume studies. Similar to correlating empirically derived bedload-transport values to backscatter generated from active sonar applications, short-pulse electromagnetic waves are transmitted into open-channel flow. The waves are scattered by transported particles and are recorded by receiving antennae. Post processing of the return acoustic signal

involves correlating the signal intensity with sand-bedload transport.

Status of development.—Research on GPR as a bedload-surrogate monitoring technology is at a very early stage of development, involving only laboratory testing. Further laboratory testing is needed but early results show that GPR returns can be correlated with the size and flux of bedload. The technology has only been tested for sand-bedded systems. One paper was presented on this technology at the 2007 Bedload Workshop and is listed in table 2:

- Shrestha, S.M., Shibata, K., Hirano, K., Takahara, T., and Matsumura, K., River Bedload Monitoring Using a Radar System.

Smart Tracers

Advances in electronics and microprocessors have resulted in the development of microsensors amenable for use in river systems for particle tracking. These “smart tracers” allow research into a host of fundamental and applied topics relating to the characteristics of particle transport, such spatial and temporal movement of particles through watersheds or reach-scale transport and storage of grains. Radio Frequency Identification tags (RFIDs) and micro-radio transmitters are examples of these smart tracers. RFIDs are cylinder-shaped sensors, approximately 2 mm in diameter and 25 mm in length, that can be inserted into a hole drilled into a clast, or cast into manufactured (concrete) rock. Passive RFIDs, which do not require a power supply, are used in conjunction with detection antennae. When an RFID passes through the electromagnetic field generated by the antennae, the RFID activates and emits a signal with a unique identification number, which is sensed by a receiving antennae array and recorded on a data logger. A micro-radio transmitter works in a similar manner but has a built-in power supply.

Particle location is determined by triangulating particle position through a geo-referenced receiving-antennae array. Both of these technologies are ideal for acquiring data on large spatial scales for understanding particle movement through rivers, as well as statistical information on in-channel storage and release of sediment.

Status of development.—Both the RFID and micro-radio transmitter technologies continue to improve. While sediment-transport monitoring is not the primary market for these technologies, river research will benefit from the continued pursuit of such small and comparatively energy-efficient devices. One paper was presented on this technology at the 2007 Bedload Workshop is listed in table 2:

- Habersack, Helmut, Seitz, Hugo, and Liedermann, Marcel, Integrated Automatic Bedload Transport Monitoring.

A paper on RFIDs was not included in the April 2007 workshop but Nichols (2004) and Lamarre and others (2005) provide descriptions of RFID use for characterizing bedload movement.

Passive Sensors

Passive sensor surrogate technologies rely on natural signals to produce estimates of sediment motion. The advantage of passive sensors is that the monitoring system makes use of the active nature of bedload transport to report the unknown variables in a way that can easily be recorded. Therefore most passive systems record impacts of sediment (either impacts of sediment with the recording device or impacts between sedimentary particles). The following passive sensors are described in this section: geophones (inclusive of impact pipes, impact plates, and impact columns with the following respective sensors: microphones, accelerometers, piezoelectric sensors), hydrophones, and magnetic detectors. These sensors are used either in stand-alone mode, such as a hydrophone recording the acoustic energy of rock collisions or in combination with an impact device, such as an air-filled pipe or plate on the riverbed.

Impact Pipes

When acoustic sensors are attached to a durable body placed in the streambed, the frequency and acoustic magnitudes of impacts of the stream sediments with that body can be recorded and processed, and with appropriate ground-truth bedload-transport calibration, used to infer bedload fluxes and possibly grain sizes. Pipe geophones detect acoustic waves generated from clast strikes transferred through the pipes and translate the number of strikes, or strike frequencies, into bedload-transport rates.

Testing of the impact pipes has shown that the movement of coarse particles can be tracked continuously without significant disturbance to the flow. Froelich and Mizuyama and others (listed in table 2) found that sound intensity increases with transport rate, and the frequency of an impact is inversely proportional to the diameter of the moving particle using single-size grain mixtures. These characteristics have been provisionally exploited to infer bedload-transport rates from impact data.

The Japanese impact pipe geophone has been laboratory tested extensively to determine the effects of geophone characteristics on the acoustic response of bedload (see Mizuyama, T., Laronne, J.B., and others, listed in table 2). Characteristics evaluated included pipe length, microphone sensitivity, and the location of the sensitive section of the pipe. Separately, the acoustic response was related to bedload discharge and to bedload texture. It is apparent that sensor characteristics affect response, such that the technical specifications of a sensor, be it passive or active, must be known prior to calibration and use.

The impact pipe requires deployment on a stable bed such as a weir. About half a dozen such geophones have been deployed in the Japanese Alps, each in conjunction with a calibrating Reid-type continuously recording bedload slot sampler (fig. 11). The lower limit of grain-size detection by the Japanese pipe geophone is 4 to 8 mm. As the horizontal pipe protrudes about 5 cm from the bed, it is less likely to be buried

by oncoming gravel sheets in comparison with the Swiss plate geophone described hereafter. According to Dieter Rickenmann (Swiss Federal Research Institute, written commun., 2009), this effect will likely depend also on the thickness of the gravel sheet. Given the deposits in the vicinity of the pipe (upstream) in figure 11A, the probability of pipe burial depends on the ratio of the mean particle size to pipe diameter. To avoid sediment deposition, an ideal location for the impact pipe or the plate geophone is at the crest of a check dam or a sill.

Status of development.—The impact pipe device is in use at a dozen or more Sabo dams in Japan and at a gaging station on the Bacza stream, Poland. The latter includes a long-term dataset based on information from periodic excavations of sediment basins downstream from the devices. The device, like all sensors, requires in situ calibration. Indeed, this is the only surrogate bedload-monitoring device that has been calibrated under field conditions with short-term (30 second) slot-type bedload-discharge data. For bedload-discharge rates that are not too high to cause saturation or too low to detect collisions, this type of sensor may be well calibrated even against short-term sediment-flux data. To enable calibration under a low bedload-transport regime, the acoustic signal needs to be monitored for longer durations to accumulate a sufficient number of strikes. To monitor very high bedload fluxes, it is necessary to use multi-sensitivity channels—less sensitive ones for higher fluxes and lower sensitivity ones for lower fluxes.

Three papers were presented on this technology at the 2007 Bedload Workshop and are listed in table 2:

- Froelich, Wojciech, Monitoring of Bed Load Transport Within a Small Drainage Basin in the Polish Flysch Carpathians.
- Mizuyama, Takahisa, Laronne, J.B., and others, Calibration of a Passive Acoustic Bedload Monitoring System in Japanese Mountain Rivers.
- Mizuyama, Takahisa, Oda, Akira, Laronne, Jonathan B., Nonaka, Michinobu, and Matsuoka, Miwa, Laboratory Tests of a Japanese Pipe Geophone for Continuous Acoustic Monitoring of Coarse Bedload.

Impact Plates

Impact plates function in a manner similar to the impact pipes described previously, but the acoustic devices are instead attached to the bottom of a steel plate that is mounted flush with the streambed. The sound produced by gravel impacts on each plate is measured and processed to give an indication of the flux and grain size of the sediments moving as bedload. Figures 12 and 13 show an example of an impact plate installation at the Erlenbach stream, Switzerland. The installation recently has been enhanced with a movable bedload-collection basket located immediately downstream from the plates (fig. 13).



A



B

Figure 11. View of a (A) pipe geophone located on a stable bed surface of a slotted debris dam on the Joganzi River, Japan. Flow is from right to left. (B) An automatic, continuously recording Reid-type bedload slot sampler located upstream of the slotted debris dam used to calibrate the pipe geophone. Flow is from lower right to upper center. This is the largest sampler of its kind, with a total volume of 9.25 cubic meters and a slot width of 1 meter. The slot sampler is full of captured bedload following a flood.



Figure 12. Impact plate array for measuring bedload transport in the Erlenbach stream, Switzerland (downstream view, with plates visible in the foreground). Geophone sensors are mounted underneath the steel plates at the crest of the large check dam. Photograph courtesy of Dieter Rickenmann.



Figure 13. Impact plate array for measuring bedload transport in the Erlenbach stream, Switzerland (lateral view of the tailwater section, with plates visible in the upper right and water falling into an automatically driven basket-type bedload sampler). Sensors are mounted underneath the steel plates at the crest of the large check dam. The moveable bedload-collection basket provides calibration data. Photograph courtesy of Dieter Rickenmann.

The impact plates are best situated at a weir crest or other location where flow is sufficiently swift to preclude accumulation of bed material (burial of the plates would render them useless for monitoring bedload transport). Depending on the hydraulic conditions, thickness of the steel plate, and on integrated acoustic properties of the experimental impact-plate infrastructure, a minimum size of sediment (about 1 to 2 cm

for the Swiss impact plate geophone) is required to produce a measurable acoustic signal.

The components of the impact plate systems are relatively inexpensive compared to many other available options. The bulk of the cost of these systems is associated with site construction and installation and the expertise for assembling the data-collection equipment and analysis programs. By capturing the entire acoustic signal it may be possible to resolve bedload particle sizes.

Status of development.—Impact plates have been tested and calibrated in the laboratory experiments by Møen and others, as accelerometers, and by Rickenmann and Fritschi using piezoelectric sensing (see table 2). They have been field-deployed among others in the Erlenbach and Pitzbach streams in Austria. Plates have recently been installed in the Elwha River, Washington, United States (fig. 14) and will be ready for data collection when demolition of the upstream Glines Canyon and Elwha dams, Elwha River, Washington, United States, begins as early as 2011. Currently, no off-the-shelf options are available; all systems require expertise to assemble the components and analyze the results and to calibrate the system. At the Elwha River, the acoustic responses of the plates will be calibrated with data collected by pressure-difference-type bedload samplers.

Two papers were presented on this technology at the 2007 Bedload Workshop and are listed in table 2:

- Møen, Kurt M., Bogen, Jim, Zuta, John F., Ade, Premus K., and Esbensen, Kim, Bedload Measurement in Rivers Using Passive Acoustic Sensors.
- Rickenmann, Dieter, and Fritschi, Bruno, Bedload Transport Measurements Using Piezoelectric Impact Sensors and Geophones.

Impact Columns

The gravel-transport sensor (GTS) is an impact column that is mounted vertically from the streambed into the water column (fig. 15). It consists of a steel pressure plate covered with polyvinylidene fluoride film. When gravel strikes the column, an electric charge is generated, the magnitude of which is indicative of the force of impact and the momentum of the particle. The number of impacts divided by the size-fraction-weighted-grain velocities is an indication of mass transport of bedload.

The magnitude of grain impacts is a function of particle momentum—the product of particle mass and impact velocity. Hence, inferences of particle mass and bedload flux are predicated on a static and known bedload particle-size distribution. Additionally, the fast moving particles tend to register more accurately with the GTS, so they may be preferentially sampled. In laboratory studies, the larger particles are also preferentially sampled because the smaller particles tend to flow around the cylinder. For more information on processing the signals, see the paper by Downing (listed in table 2).



A



B

Figure 14. Plate geophones deployed across the Elwha River, Washington, United States; flow is from left to right. (A) Grouted riprap is present upstream and downstream of the weir before removal of the wood retainer to emplace the geophone impact sensors. (B) the operational geophone installation (photograph (B) by Timothy J. Randle, Bureau of Reclamation)

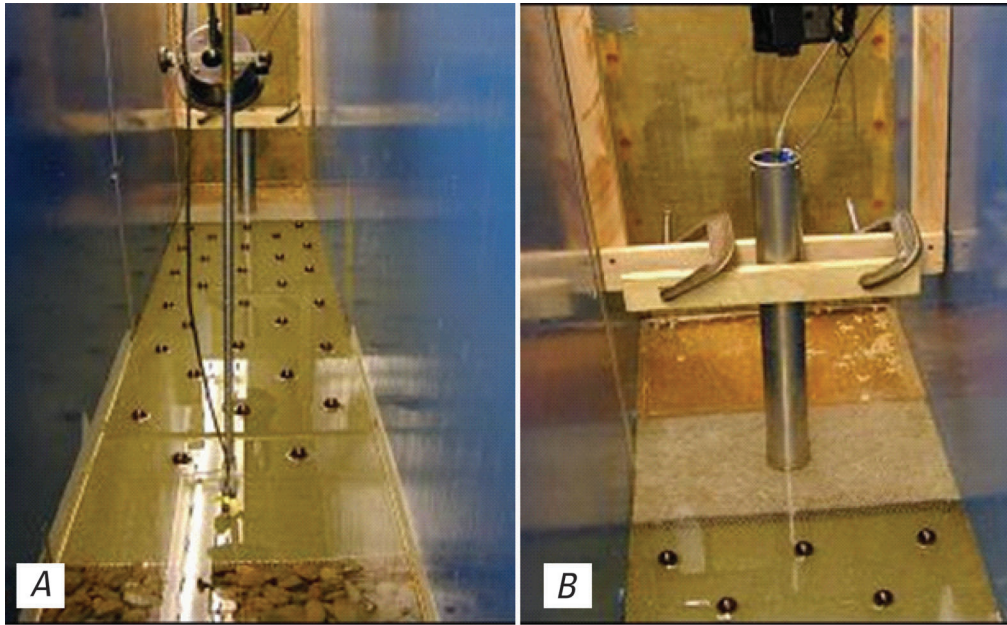


Figure 15. An experimental gravel-transport sensor (GTS). (A) Swoffer 2100 current meter in front of the GTS cylinder. (B) A close-up view of the GTS cylinder. The flow direction is from the current meter toward the GTS cylinder. From Papanicolaou and Knapp, listed in table 2.

Status of development.—The GTS was laboratory tested by Papanicolaou and Knapp (table 2), and some modifications were recommended. The design presented by Downing (table 2) seems to be revised in this manner and may be ready for renewed testing.

Development needs to include relatively minor engineering refinements of packaging, circuit-board layout, and operator controls (see Downing in table 2). However, critical review of this system shows that it is far from being usable in its present form for reliable determination of bedload-transport rates.

One paper was presented on this technology at the 2007 Bedload Workshop, and a second was submitted after the workshop; both are listed in table 2:

- Downing, John, Acoustic Gravel-Momentum Sensor.
- Papanicolaou, Athanasios (Thanos) N., and Knapp, Doug, A Particle Tracking Technique for Bedload Motion.

Magnetic Tracer Detection

Magnetic tracer techniques for bedload monitoring include the use of naturally magnetic clasts and natural clasts with imbedded magnets to study the flux and the trajectory of bedload particles. A magnetic particle passing over an inductor induces a voltage peak that can be measured and used to count the magnetic particles. This system is generally referred to as a bedload movement detector (fig. 16). Various setups can be used to acquire information. One comprises several individual units implanted in the streambed; another is a detector log with two parallel inductors that span the stream width and are separated by a known length that can detect the duration of the particles' movement through the system.

A well-designed system has the potential to provide long time-series data on relative bedload-transport rates for a given site with naturally magnetic particles. When the gravels must be tagged and seeded in the system, the resolution of the accrued data is diminished, as they pertain only to the fraction of the magnetic particles in transport. This system is ideally coupled with information on bedload-transport rates and grain-size distributions of the bedload to make the count most useful. Older systems required frequent manual adjustments to reduce electronic noise and interference. Similar to other surrogate technologies that employ large pieces of equipment, the magnetic tracer technique requires vehicle access as well as an external power supply. Field calibration with large bedload samples from the netframe sampler showed that the system tends to underestimate bedload at high fluxes. Depending on the shape of the detector, information can be skewed based on the distance of the tracer or magnetic grain from the detector.

Status of development.—Magnetic tracer systems have been laboratory tested (Rempel and others (see table 2)) and field deployed at several sites including Montana, United States, and British Columbia, Canada (Gottesfeld and Tunnicliffe, 2003), and Poland (Froehlich and others, listed in table 2). Technological advances in signal output may increase the usefulness of the magnetic tracer data (Bunte, listed in table 2). In their present forms the systems are suitable for showing temporal and spatial variation of relative transport intensities. However, without field calibration the systems are impractical for the determination of bedload flux. Three papers were presented on this technology at the 2007 Bedload Workshop and are listed in table 2:

- Bunte, Kristin, Measurements of Gravel Transport Using the Magnetic Tracer Technique: Temporal Variability Over a Highflow Season and Field-Calibration.

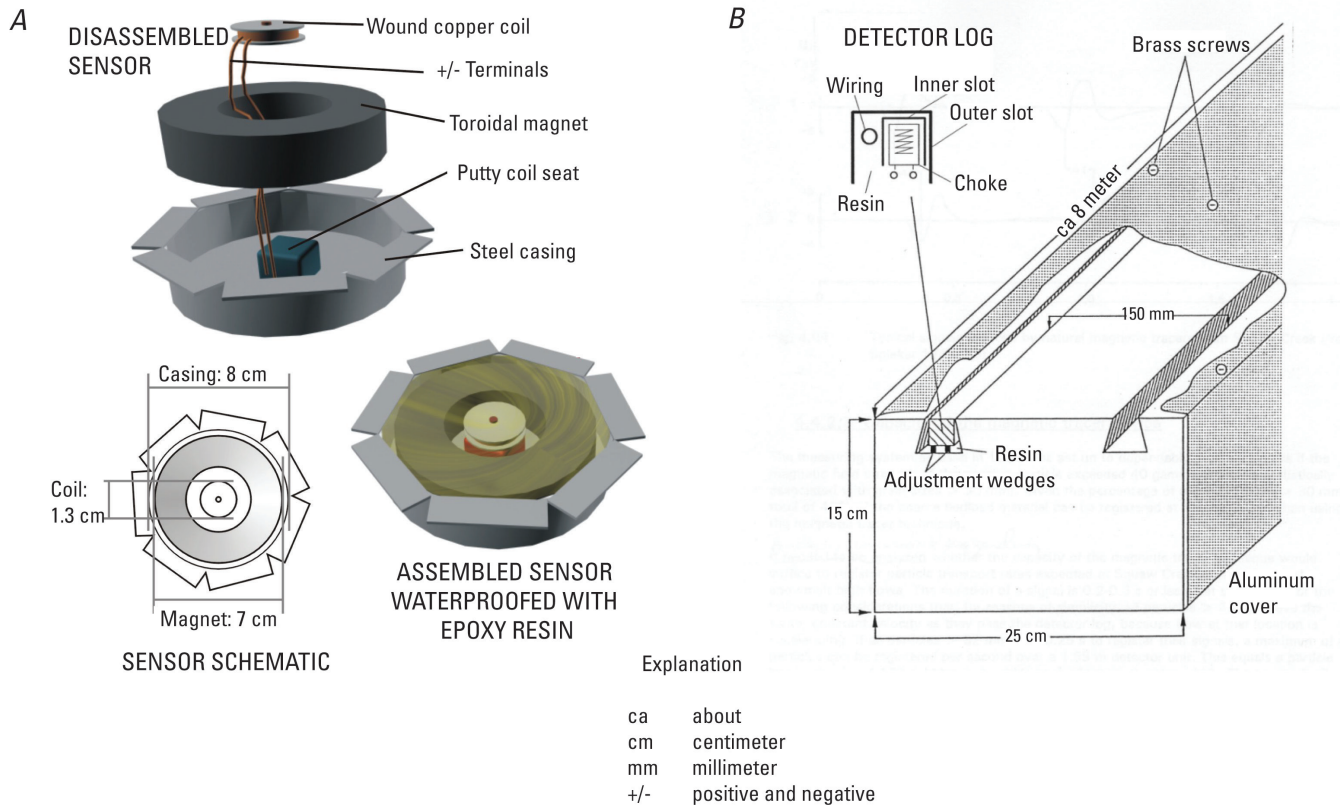


Figure 16. Diagrams of the bedload movement detector magnetic system used by Rempel and others (listed in table 2). (A) A schematic view of an individual sensor, showing the three principal components: the coil, the magnet, and the steel casing. (B) A detector log with two parallel coil units (cross section) used by Bunte (listed in table 2).

- Froehlich, Wojciech, Monitoring of Bed Load Transport Within a Small Drainage Basin in the Polish Flysch Carpathians.
- Rempel, Jason, Hassan, Marwan A., and Enkin, Randy, Laboratory Calibration of a Magnetic Bed Load Movement Detector.

Hydrophones

Passive acoustic devices are similar to those used in conjunction with impact pipes or plates, but instead of recording the sound of sediment colliding with a rigid body, the device senses and records the acoustic energy of moving sediment particles colliding with other particles—moving or stationary—on the streambed. Hydrophones are also sensitive to other acoustic signals, predominantly those associated with flow turbulence. The devices may be mounted from a tripod or arm, or can be deployed in a container such as a PVC pipe capsule (Barton and others, listed in table 2; Belleudy and others, table 2 and fig. 17).

This acoustic device presents a weighted spatial average of transport because of the dependence on the proximity of the sensor to the grain impacts. The measurement method requires periodic calibration and may be better used to take

measurements in hard-to-reach areas and fill in gaps rather than as a stand-alone method (see Barton, listed in table 2). Background noise, if present, such as from turbulence, cavitation, banks, or from aerial sources must be factored out of the flux computation. The technology is limited to gravel and larger grain sizes (Belleudy and others, listed in table 2). Hydrophones can be effectively deployed in quiescent backwater or eddy regions of streams—including wide gravel-bed rivers where deployment of plate geophones may be impractical—where the potential for direct collisions with the hydrophone is minimal. The single most important advantage of hydrophones compared to geophones is that hydrophones are not affixed to the streambed but are suspended in the water column and are, therefore, particularly relevant for the surrogate monitoring of gravel transport in large, gravel-bedded streams and rivers. The cost of installation of hydrophones tends to be substantially smaller than that for plate geophones.

Status of development.—This passive-acoustic technology has been tested in the Isère River, France, and the Trinity River, California, United States. Further developments are needed in technology and data processing before bedload fluxes can be determined from a spectral analysis of the sound. Belleudy and others (listed in table 2) expressed a desire to test the technology further in a controlled laboratory setting,

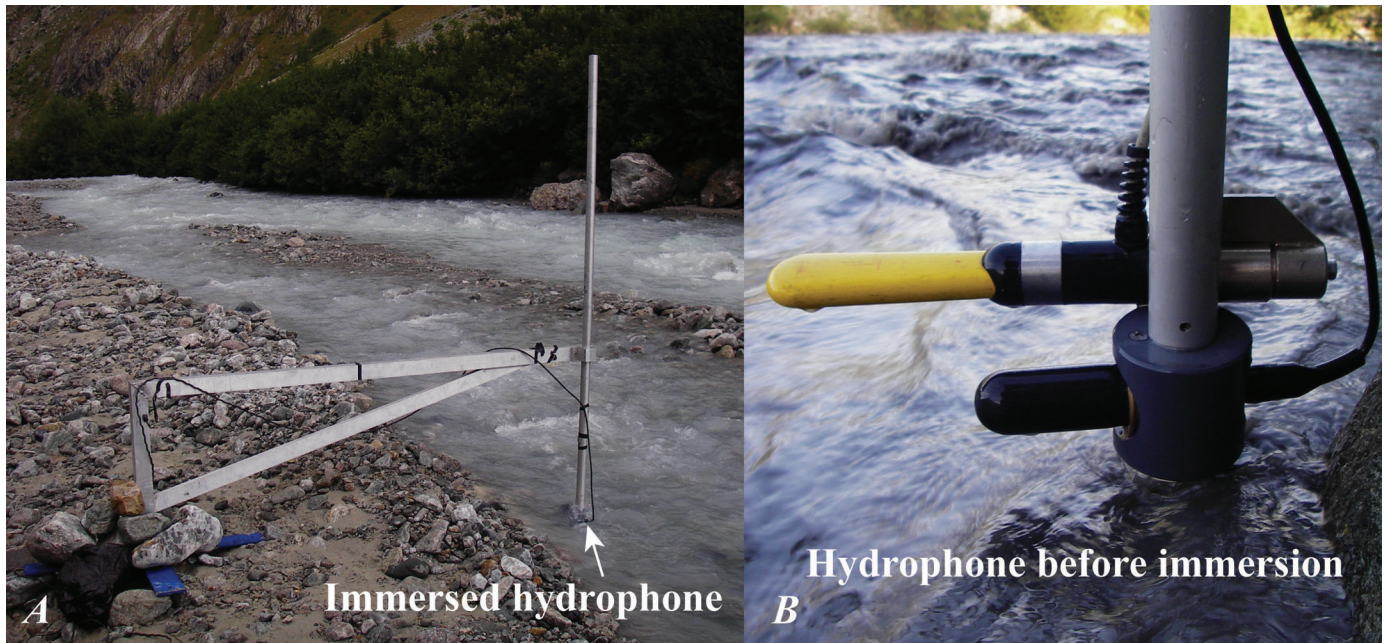


Figure 17. A hydrophone (A) held by a fixed frame on the Torrent de Saint-Pierre, France, and (B) on the frame before immersion. Photographs from Belleudy and others (listed in table 2).

as well as the need to find more efficient ways to filter noises and quantify signal energy. The technology is promising, but requires an expanded verification dataset before it can be accepted for operational deployment.

Two papers were presented on this technology at the 2007 Bedload Workshop and are listed in table 2:

- Barton, Jonathan S., Slingerland, Rudy L., Pittman, Smokey, and Gabrielson, Thomas B., Monitoring Coarse Bedload Transport with Passive Acoustic Instrumentation: A Field Study.
- Belleudy, Philippe, Valette, Alexandre, and Graff, Benjamin, Passive Hydrophone Monitoring of Bedload in River Beds: First Trials of Signal Spectral Analyses.

Selected Relevant Bedload-Surrogate Research and Publications Since April 2007

Since the April 2007 workshop—and in part as a result of the April 2007 workshop—bedload-surrogate research has continued; several publications germane to the field have been released; and selected research and publications brought to the attention of the authors are described below.

Selected Additional Research

The following is a synopsis of post-2007 bedload-surrogate research projects; the list is neither exhaustive nor comprehensive.

- The Sabo (erosion and sediment control) Department of the Japan Ministry of Land, Infrastructure, Transport and Tourism will be installing sediment observation units at 120 mountain torrent sites for monitoring by 2010. Each unit contains a sediment and a water-level observation system connected to a data logger. The observation system includes two pipe geophones differing in length, thus having variable sensitivities; a turbidity sensor; a pressure type water level recorder; and a time-integrated sampler. The pulse data obtained from the geophones will be analyzed for conversion to bedload discharge. Most of the systems are installed at the crests of 10- to 15-m high Sabo concrete sediment check dams. For further information contact Prof. Takahisa Mizuyama (mizuyama@kais.kyoto-u.ac.jp).
- The SANDS project (<http://www.hydralab.eu/>)—scaling and analysis and new instrumentation for dynamic bed tests—is a research project financed by the European Commission within the 13-project HYDRALAB III initiative. It investigates the performance of Mobile Bed Tests, looking at the flume and paddle characteristics but also at the sedimentary body behavior and the corresponding instruments deployed in the flumes or basins. Hitherto, about 20 papers, some in international journals, have been published on the SANDS project.

Most of the publications address the measurement of turbulence and the motion of sand in suspension in the swash zone; however, some of these may be pertinent to the reader, such as the use of an acoustic sand transport meter. For further information send an inquiry to Prof. Agustín Sánchez-Arcilla, Director, Maritime Engineering Laboratory, LIM/UPC, Spain (*agustin.arcilla@upc.edu*).

- Funding of a CEMAGREF (Agricultural and Environmental Engineering Research, Grenoble University, France) research proposal has been provided to Fred Liebault, Philippe Frey, Alan Reckin, and Didier Richard by the French Agricultural and Environmental Engineering Research Institutes on geophone use for surrogate bedload monitoring in Alpine Mountain rivers.
- Funding of a Ben Gurion University (Jonathan Laronne with Ian Reid) research proposal has been provided by the Israel Science Foundation to monitor bedload fluxes using geophones during entire runoff periods in upland dryland channels.
- Funding for the development of advanced acoustic methods for measuring bedload transport has been obtained by Nortek Scientific (Eric Seigel) and Dalhousie University (Alex Hay). See <http://www.nortek-as.com/news/nortek-scientific-collaboration-receives-aif-grant>.
- Philippe Belleudy of the University of Grenoble, France, has developed a Web site for research on the use of a hydrophone for bedload monitoring (<http://www.lthe.fr/LTHE/spip.php?article555>).
- Funding of a Swiss Federal Research Institute WSL (Birmensdorf, Switzerland) research proposal has been provided to Dieter Rickenmann by the Swiss National Science Foundation. Research will focus on the further development of the geophone measuring system for surrogate-bedload monitoring in steep streams. See http://www.wsl.ch/forschung/forschungsprojekte/sedimenttransport/index_EN

Selected Publications

The following is a synopsis of post-2007 bedload-surrogate research publications; the list is neither comprehensive nor exhaustive.

- Interpretation of acoustic signals from the Japanese pipe geophones (Mizuyama and others, 2008a, 2008b; Oda and others, 2008; Tsutsumi and others, 2008; Hirasawa and others, 2009).
- Interpretation of acoustic signals from the Swiss plate geophones (Rickenmann and McArde, 2008;

Turowski and others, 2008; Turowski and Rickenmann, 2009). A similar plate geophone was used to study bedload discharge and texture (Krein and others, 2008).

- ADCP-related techniques have been considerably improved and developed for the surrogate monitoring of sand transport (Gaeuman and Jacobson, 2007; Kashyap and others, 2007; Ramooz and Rennie, 2007; Rennie, 2007; Rennie and Church, 2007; Rennie and Millar, 2007; Rennie and others, 2007; Rennie and Rainville, 2008; Gaskin and Rennie, 2010). Interestingly, single-particle transport under waves has also been monitored acoustically (Mason and others, 2007). The motion of sand has been monitored also in the sea (Thorne and Meral, 2008).
- Video-based gravel-transport measurements with a flume-mounted light table and a gravel transport sensor, both presented orally at the workshop, have since been published (Zimmerman and others, 2008; Papanicolaou and others, 2009). A different approach using advanced photographic techniques has been published (Radice and others, 2006; Radice and Ballio, 2008).
- Monitoring the river reach scale by Terrestrial Laser Scanning (TLS), repeat topographic surveys with total stations and particle tracking have also been undertaken (Milan and others, 2007; Liébault and Laronne, 2008; Rumsby and others, 2008) as well as with the inclusion of impact plates to determine timing of bedload motion (Reid and others, 2007; Raven and others, 2009; Raven and others, 2010).

Summary

Advances in technologies for quantifying bedload fluxes and in some cases bedload size distributions in rivers show promise toward supplanting traditional physical samplers and sampling methods predicated on the collection and analysis of physical bedload samples.

Traditional samplers used for some or all of the last eight decades include box or basket samplers, pan or tray samplers, pressure-difference samplers, and trough or pit samplers. Although still useful, the future niche of these devices may be as a means for calibrating bedload-surrogate technologies operating with active- and passive-type sensors, in many cases continuously and automatically at a river site. Direct sensors include acoustic Doppler current profilers (ADCPs), sonar, radar, and smart sensors. Passive sensors include geophones (pipes or plates) in direct contact with the streambed, hydrophones deployed in the water column, impact columns, and magnetic detection. The ADCP and geophones are currently the most developed techniques, several of which have been calibrated under both laboratory and field conditions.

Although none of the bedload-surrogate technologies described herein are yet broadly accepted for use in large-scale monitoring programs, several are under evaluation. The benefits of verifying and operationally deploying selected bedload-surrogate monitoring technologies would be considerable, providing for more frequent and consistent, less expensive, and arguably more accurate bedload data obtained with reduced personal risk for use in managing the world's sedimentary resources.

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Appendix 1. List of Attendees, International Bedload-Surrogate Monitoring Workshop, April 11–14, 2007, Minneapolis, Minnesota, United States

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Appendix 2. Sponsors of the International Bedload-Surrogate Monitoring Workshop, April 11–14, 2007, Minneapolis, Minnesota, United States

In addition to the Subcommittee on Sedimentation (SOS), workshop sponsors were The American Institute of Hydrology (AIH), Ben Gurion University of the Negev, Bureau of Land Management (BLM), International Association of Hydrological Sciences (IAHS), Bedload Research International Cooperative (BRIC), International Sedimentation Initiative, International Research and Training Centre for Erosion and Sedimentation (IRTCES), National Center for Earth-surface Dynamics (NCED), St. Anthony Falls Laboratory (SAFL), U.S. Geological Survey (USGS), and the World Association for Research on Erosion and Sedimentation (WASER). The SOS, NCED, and BLM provided the bulk of funds used to host the workshop at the SAFL. The SAFL and BRIC led the workshop.

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