2 Surrogate technologies for monitoring bed-load transport in rivers

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Surrogate technologies for bed-load transport monitoring are being evaluated toward eventually supplanting traditional data-collection methods that require routine collection of physical samples and subsequent field or laboratory analyses. Commercially available and prototype technologies based on active- and passive-hydroacoustic principles are the foci of much of the current research on bed-load surrogate techniques, and are the subjects of this chapter. Field and laboratory tests of bed-load surrogate-monitoring techniques using active hydroacoustics (acoustic Doppler current profilers (ADCPs)) in sand- and gravel-bed rivers or passive hydroacoustics (various sensors) in gravel-bed rivers have been shown to provide useful data in a limited number of flume and field tests, and some are the subject of continuing research. Research on other technologies including tracer-tracking (visual, radioactive, magnetic, and radio); sonar, load-cell, videography, particle-tracking, ground-penetrating radar, and magnetic techniques is ongoing in several countries.

Similar to choices for monitoring suspended-sediment transport, selection of an appropriate technology for bed-load transport monitoring usually entails an analysis of the advantages and limitations associated with each technique, the monitoring objective, and the physical and dynamic sedimentary characteristics at each deployment site. Some factors that may limit or enhance the efficacy of a surrogate technology used to monitor bed-load transport include cost (purchase, installation, operation, calibration, and data analysis), reliability, robustness, accuracy, size and location of the instantaneous and time-integrated measurement realm, and range in size of bed-load particles. Most if not all surrogate technologies for monitoring bed load, including passive and active hydroacoustics, require periodic site-specific calibrations to infer transport rates occurring over the entire channel cross section.

Should bed-load surrogate technologies prove successful in a wide range of applications, the monitoring capability could be unprecedented, providing the prospect of obtaining continuous records of bed-load discharge potentially qualified by estimates of uncertainty. As with suspended-sediment surrogate technologies, the potential benefits could be enormous, providing for more frequent and consistent, less expensive, and arguably more accurate bed-load data obtained with reduced personal risk for use in managing the world's sedimentary resources.

2.1 Introduction

Bed load is the part of total-sediment load that is transported by rolling, skipping, or sliding on the riverbed (ASTM International 1998) (Fig. 2.1). Historically, bed-load data for US rivers have been produced by gradation and gravimetric analyses performed on samples obtained with manually deployed samplers (Edwards & Glysson 1999; Kuhnle 2008). As with suspended sediment, traditional bed-load data-collection methods tend to be expensive, labor intensive, time-consuming, difficult, and under some conditions, hazardous. Specialized instruments and considerable training in their proper deployment are prerequisites for obtaining reliable bed-load samples.

Sedimentology of Aqueous Systems, 1st edition.
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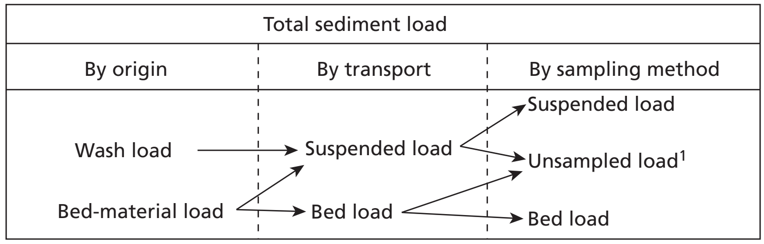

[1]That part of the sediment load that is not collected by the depth-integrating suspended-sediment and pressure-difference bed-load samplers used, depending on the type and size of the sampler(s). Unsampled-zone sediment can occur in one or more of the following categories: (a) sediment that passes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

Fig. 2.1 Components of total-sediment load considered by origin, by transport, and by sampling method.
From Diplas *et al.* (2008).

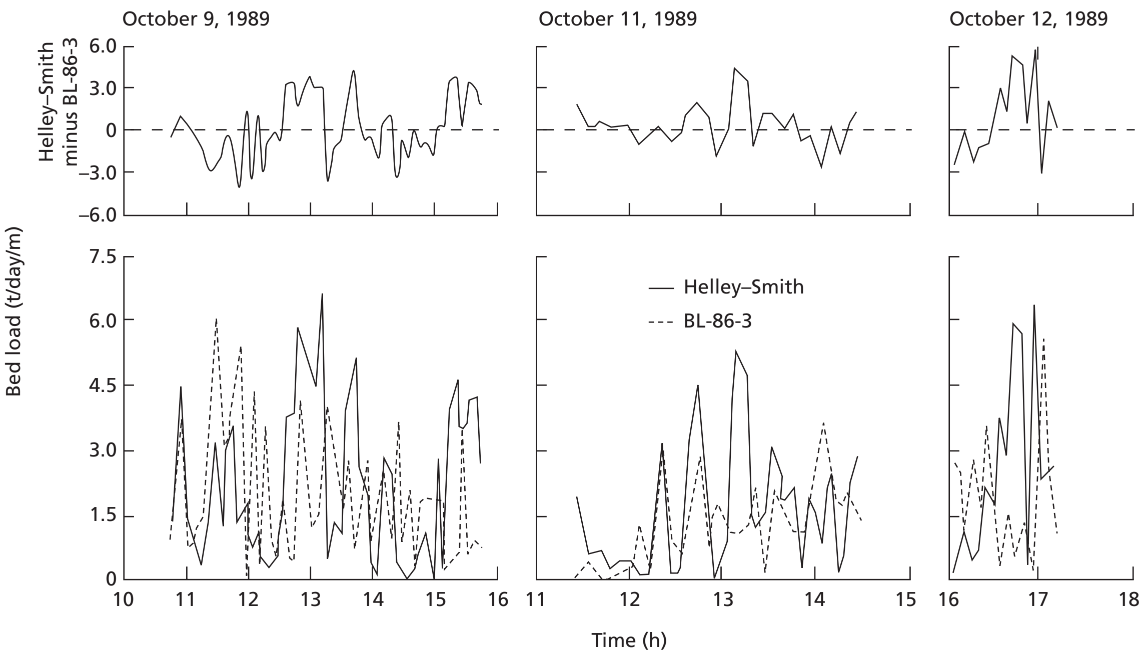

Fig. 2.2 Variability in sand bed-load transport rates measured 2 meters apart by a Helley–Smith bed-load sampler and a BL-86-3 bed-load sampler (the latter identical to the US BL-84 bed-load sampler), at the U.S. Geological Survey (USGS) streamgage on the Colorado River above National Canyon near Supai, Arizona, USA, October 1989.
From Gray *et al*. (1991).

The spatiotemporal distribution of bed material transport is a complicated, non-linear function of sediment supply, bed state, and fluid forcing (Gomez 1991). Figure 2.2 shows variations in bed-load transport rates measured by two types of pressure-difference sampler deployed at fixed locations 2 meters apart during steady flows near the middle of the sand-bedded Colorado River above National Canyon near Supai, Arizona, USA (Gray *et al*. 1991). Such variability is more or less typical for at-a-point bed-load measurements. However, after collection of 390 discrete bed-load transport samples using two types

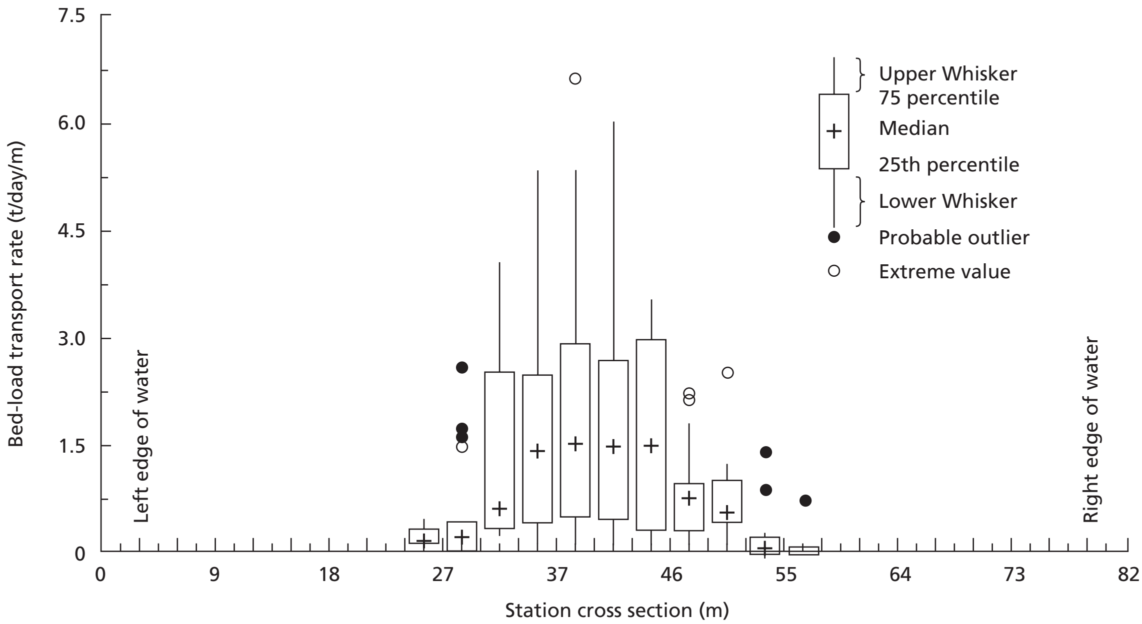

Fig. 2.3 Spatially averaged transport rates computed from 390 bed-load samples collected by a Helley–Smith bedload sampler and a BL-86-3 bedload sampler (the latter identical to the US BL-84 bed-load sampler), at the USGS streamgage on the Colorado River above National Canyon near Supai, Arizona, USA, October 1989.
From Gray *et al.* (1991).

of pressure-difference sampler from points across the channel, a pattern in bed-load transport became evident with most bed load occurring in the center third of the river (Fig. 2.3). These data are illustrative of the fact that bed-load data collected by traditional manual techniques as part of periodic or runoff-initiated site visits are rarely sufficient to reliably characterize the spatiotemporal variability in bed-load transport rates over periods exceeding a fraction of a day.

Lacking a reliable means for developing a bed-load transport time series, practitioners often revert to estimations based on stochastic techniques, such as a bed-load transport equation or an empirically derived bed-load transport curve with instantaneous water discharge as the independent variable (Glysson 1987; Gray and Simões 2008). However, the uncertainty associated with bed-load-discharge estimates is rarely quantified or quantifiable, and is more often the subject of speculation rather than reliable calculation. Thus, considerable interest and effort has been directed toward surrogate measurements that may potentially provide a bed-load time series that is representative of the cross section or reach of interest.

Sediment-surrogate technologies are defined as instruments coupled with operational and analytical methodologies that enable acquisition of temporally and (or) spatially dense fluvial-sediment data sets without the need for routine collection and analysis of physical samples other than for periodic calibration purposes. Bed-load surrogate technologies have been addressed as part of at least three workshops held since 2002, namely:

- 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 *et al.* 2003).
- Federal Interagency Sediment Monitoring Instrument and Analysis Research Workshop, September 9-11 2003, Flagstaff, Arizona, USA, sponsored by the Advisory Committee on Water Information's Subcommittee on Sedimentation (Gray 2005).
- International Bedload Surrogate Monitoring Workshop, April 11-14 2007, Minneapolis, Minnesota, USA, sponsored by the Advisory Committee on Water Information's Subcommittee

on Sedimentation (Gray *et al.* 2007; Laronne *et al.* 2007).

The 2002 workshop in Oslo, Norway, included 13 papers under the category, "bed-load monitoring and transport processes." The workshop paper by Ergenzinger and DeJong (2003) listed and briefly described each of, "… the well known measuring techniques of sediment trapping and sampling, tracing, and surveying using both conventional techniques and remotely sensed images." Those techniques that qualify as "bed-load surrogate technologies" include passive hydroacoustics; visual, radioactive, magnetic, and radiotracers; magnetic detectors; underwater video cameras; load-cell traps; and analyses of scanned or photographic images.

Breakout session II from the 2003 workshop in Flagstaff, Arizona, USA, was entitled, "Bedload-Transport Measurements: Data Needs, Uncertainty, and New Technologies" (Ryan *et al.* 2005). Among other information, the table in that report section (reproduced herein as Table 2.1 without annotation) lists eight bed-load surrogate technologies: active and passive hydroacoustic sensors; gravel impact sensors; magnetic tracers, and sensors; topographic differencing with sonar; sonar-measured debris basin; and underwater video cameras. The breakout group identified characteristics associated with the ideal bed-load sampling device or technology, as paraphrased below.

Surrogate technologies should:

- provide accurate measurements and precise data on the amounts and sizes of bed-load material over a wide range of flow conditions;
- be reliable, safe to operate, and used without wading in streams at high flow;
- be foolproof, easy to calibrate, and not disrupt the local transport field to the extent that it affects measurements,
- be rugged, durable, and able to withstand occasional collisions with large grains;
- have minimal and tractable power requirements for use in remote environments;
- automatically provide continuous record;
- be scalable; and
- be affordable.

The 2003 workshop summary (Gray, 2005) included a matrix that compared and contrasted selected characteristics of bed-load surrogate technologies to other types of sediment-surrogate technologies, and to related data-management and flux-computation issues. This matrix is reproduced herein as Table 2.2. About 50 participants from nine countries attended the 2007 workshop in Minneapolis, Minnesota, USA; others participated by video link. The 25 papers submitted to the workshop identified passive- and active-hydroacoustic, magnetic-tracer and magnetic-sensor, load-cell trap, topographic differencing with sonar, particle-tracking, gravel-impact sensors, and ground-penetrating radar technologies to infer bed-load transport.

This chapter presents descriptions, progress in, and examples of applications of active and passive hydroacoustics considered by the editors to be among the most promising of the aforementioned bed-load surrogate technologies. This observation is in part based on the fact that no fewer than a combined 14 papers presented at the three workshops listed above described passive- and active-hydroacoustics research results. In comparison, the next most prevalent topic among these workshops was magnetic- and radiotracer studies, described in four of the papers. It was also noted that in many cases hydroacoustic technologies are affordable, portable, and relatively robust. Additionally, results from some techniques that are not based on, or calibrated with integrated cross-section bed-load measurements, such as some of the tracer technologies and some impact sensors, can be relatively difficult to interpret quantitatively. However, it is important to note that selected technologies other than the hydroacoustics techniques presented below have a potential monitoring niche, and should not be ignored. Those interested in non-hydroacoustic bed-load surrogate technologies are encouraged to peruse the relevant papers from these workshops and from other publications on this subject.

The *in situ* technologies presented in this chapter require periodic site-specific calibrations to infer the bed-load transport characteristics representative of the entire channel cross section or reach segment. This requirement is expected to be substantial for new river-monitoring applications, but may diminish as comparative data accumulate.

None of the technologies represents a panacea for bed-load monitoring in all rivers under all flow and sediment-transport conditions. To make the transition from research to operational monitoring applications, these new technologies must be rigorously tested with respect to accuracy and reliability in different physiographic and (or) laboratory

Table 2.1 Comparison of characteristics of different bed-load sampling technologies (Ryan et al. 2005). See the original table for all annotations.

Bed-load 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 (2003)	Potential use as calibration standard
1. Instream Installations											
Birkbeck sampler (weighable pit trap)	Narrow gravel bed channel	No	No, automatically weighs mass in stream	Typically not; depends on slot width	Depends on slot width	Continuous	Yes	Easy	May change with fill level	Additional testing and modifications	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, unweighable	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	Possibly	Yes	Yes	Yes	Yes	Depends on experimental setup	Can be difficult	Depends on experimental setup	Completed	Possible
Sediment detention basins/weir ponds	Sand-gravel bed channels	No	Periodically	Yes	Yes	Yes	Yes	Relatively easy	No	Completed	High
2. Portable/physical devices											
Pressure-difference samplers (small openings)	Sand-gravel bed channel	Yes	Yes	No	No	No	No	Depends on flow conditions	Slightly	Additional verification	Additional verification needed

Pressure-difference samplers (large openings)	Gravel bed channel	Yes	Yes	No	Yes	No	No	Depends on flow conditions	Highly	Additional verification	Additional verification needed
Baskets (suspended or instream)	Gravel bed channel	Yes	Yes	Depends on design	Depends on design	Yes	No	Depends on flow conditions	Depends on experimental setup	Completed	Moderate
Bedload traps	Gravel bed channel	Yes	Yes	Depends on number of traps deployed	Yes	Yes	Minor	Depends on flow conditions	Slightly	Completed; testing of modifications	Moderate with additional verification
Tracer particles (painted, magnetic, signal emitting rocks)	Gravel bed channel	Possibly	No	Depends on tracer placement	N/A	Yes	No	Easy	No	Additional verification	Low
Scour chains; scour monitor; scour core	Sand-gravel bed channel	Possibly	No	No	N/A	Yes	Yes	Easy	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	N/A	Continuous	No	Logistics and data reduction are complex	No	Moderate (sand systems) early (gravel systems)	Additional verification for gravel bed systems

Table 2.1 *Continued*

Bed-load 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 (2003)	Potential use as calibration standard
Hydrophones (active and passive acoustic sensor)	Gravel bed channel	No	No	Depends on deployment	N/A	Continuous	Possibly	Easy	No	Early	Additional development needed
Gravel impact sensor	Gravel bed channel	Yes, for hand-held model	No	Not as currently designed	N/A	Continuous	Yes for instream model	Easy under many conditions	In fast flow	Early	Additional development needed
Magnetic tracers	Gravel bed with naturally magnetic particles	No	No	Yes	N/A	Continuous	Yes	Relatively easy	Depends on experimental setup	Additional testing	Possible at appropriate locations
Magnetic sensors	Gravel bed channel	No	No	Yes	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	Episodically or continuous	No	Easy	No	Early?	Additional verification for gravel bed systems
Sonar-measured debris basin	Gravel bed channel	No	No	Yes	N/A	Continuous	With debris basin installation	Easy under many conditions	N/A	Early	High
Underwater video cameras	Relatively clear flow	Used from bridges or boats	No	No	N/A	Continuous	No	Easy under right lighting conditions	Slightly	Early	Additional verification needed

N/a, Not applicable.

Table 2.2 Matrix of selected information gleaned from the four breakout sessions as compiled in the second plenary session of the Federal Interagency Sediment Monitoring Instrument and Analysis Research Workshop, September 9–11, 2003, Flagstaff, Arizona, USA. Empty boxes indicate that the topic was not addressed in the breakout or second plenary sessions, or was not applicable to the category.

	Breakout session I: suspended sediment	Breakout session II: bedload	Breakout session III		Breakout session IV	
			Bed material	Bed topography	Data management	Flux computations
Data						
Continuous time-series/ greater data amount, density	Needed	Needed	Needed	Needed	Need to store original data	Critically needed
Ancillary information	Needed	Needed	Needed	Needed	Considerable need	Considerable need
Physical calibration samples	Needed	Needed	Needed	Needed	Needed	Critically needed
Accuracy criteria	Have some	Needed	Needed	Needed	Needed (to accept/reject data)	Needed
Uncertainty estimates	Needed; available in some cases	Needed		Needed	Needed; also need storage capabilities	Needed in some cases
Protocols for data collection, computation & storage	Available for traditional technologies	Available for traditional technologies	Available for traditional technologies	Needed	Databases generally insufficient	Needed for computations
Clearinghouse, data standards		Establish clearinghouse, data standards			Establish clearinghouse, data standards	
Scale limitations	Yes	Yes	Yes	Yes		Yes
Traditional techniques						
Extant	Yes	Not for all conditions	Not for unwade-able gravel bed	For most conditions	Yes	Yes
Accuracy	Relatively accurate	Accuracy uncertain	Mostly acceptable	Mostly acceptable	None available	(Standards for computations)

Table 2.2 *Continued*

	Breakout session I: suspended sediment	Breakout session II: bedload	Breakout session III		Breakout session IV	
			Bed material	Bed topography	Data management	Flux computations
Surrogate techniques						
Availability of instruments	Many, commercially available	Few, mostly research, in early development	Some, but not for unwadeable gravel bed	Several, Government or commercially available	Create data gaps/ problems; need qualifying data	Need protocols for computations
Quantify accuracy	Some need	Major need	Needed	Some need	Major need	Major need
Applicable environments	Fluvial, coastal zone, estuaries	Fluvial, marine and coastal zones	Freshwater, marine and coastal zones	Freshwater, marine and coastal zones		
Models						
Uses and needs		Accurate data needed for better models		Uses and needs		Uses and needs
Research and oversight						
Basic research sought	Yes	Yes, considerable	Yes	Yes	Yes	Yes
White paper sought		Past, present, future technologies				
Extant focus of current research venues or entities	Many field sites	Need national calibration standard sites	Online interest groups		Need sediment database management task group	
SMIAR Program needed	Yes	Yes	Yes	Yes	Yes	Yes
Organizational oversight of a SMIAR Program	FISP, or FISP-type organization	FISP, or FISP-type organization	FISP, or FISP-type organization	FISP, or FISP-type organization	FISP, or FISP-type organization	FISP, or FISP-type organization

SMIAR, Sediment Instrument and Analysis Research; FISP, the Federal Interagency Sedimentation Project.

settings as appropriate. Their performances must be compared with laboratory-control data and (or) field measurements by traditional techniques. In most cases, performance comparisons should include collection of concurrent data by traditional and new techniques for a sufficient period – probably years – to identify potential bias and minimize differences in precision between the old and new technologies. However, with careful matching of surrogate-monitoring technologies to selected river reaches and objectives, it may be possible in the future to remotely, continuously, and accurately monitor bed-load discharges, possibly by particle-size class. Qualifying the derived transport data with reliable uncertainty assessments may also be possible.

These are revolutionary concepts in sedimentology when considered from an operational perspective. The benefits of such applied capability could be enormous, providing for safer, more frequent and consistent, arguably more accurate, and ultimately less expensive fluvial-data collection for use in managing the world's sedimentary resources.

This chapter begins with an overview of traditional instruments and techniques used for measuring bed load, against which the surrogate technologies using hydroacoustics are evaluated. Descriptions of the theory, applications, some advantages, limitations, and costs of each surrogate technology are presented and compared. A subjective evaluation of the efficacy of each technology concludes this chapter. Use of firm, brand, or trade names are for identification purposes only and do not constitute endorsement by the US Government.

2.1.1 Background: traditional bed-load sediment-sampling techniques

Published records of bed-load sampler use dates back to at least the late 1800s, and published attempts at bed-load sampler calibration date to at least the early 1930s (Carey 2005). As with the development of isokinetic suspended-sediment samplers, the Federal Interagency Sedimentation Project (FISP) endeavored to address problems and needs related to bed-load data collection starting in the later 1930s (Federal Interagency Sedimentation Project 1940). However, development and calibration of reliable portable bed-load samplers capable of sampling a wide range of particle sizes and transport rates remains a work in progress (Marr *et al.* in press). No single apparatus or procedure has been universally accepted as completely adequate for the determination of bed-load discharges over the wide range of sediment and hydraulic conditions found in nature (ISO 1992).

Bed-load samplers fall under one or a combination of the following four categories: Box or basket samplers; pan, tray, or slot samplers; pressure-difference samplers; and trough or pit samplers (Hubbell 1964). Box or basket samplers retain sediment deposited in the sampler owing to a reduction in the flow velocity and (or) capture by the sampler screen (Hubbell 1964). Pan, tray, or slot samplers retain the sediment that drops into one or more slots after the material has rolled, slid, or skipped up an entrance ramp (Hubbell 1964). Pressure-difference samplers are designed so that the sampler's entrance velocity is about equal to or somewhat larger than the ambient stream velocity. They collect material that is small enough to enter the nozzle but too large to pass through the mesh collection bag. Figure 2.4 shows selected pressure-difference bed-load samplers. Trough or pit samplers are rectangular holes constructed in the streambed, into which bed-load particles drop. Troughs are usually continuous across the channel, whereas pits cover only a part of the streambed (Hubbell 1964). Troughs and pits tend to provide the most reliable bed-load data (Federal Interagency Sedimentation Project 1940; Hubbell 1964; Emmett 1980; Carey 2005).

There can be substantial differences in calibration and deployment between the trough and other types of sampler. The trough-type samplers are the most difficult to construct and operate but the least challenging to calibrate. In contrast, no universally agreed-upon method has been developed for calibrating portable bed-load samplers, but they are the easiest to deploy (Carey 2005).

The efficiency of a bed-load sampler is the ratio of the sampled bed-load mass divided by the mass that would have been transported in the same section and time in the absence of the bed-load sampler. Unlike FISP isokinetic suspended-sediment samplers which are designed for isokinetic efficiencies within about 10% of unity (Federal Interagency Sedimentation Project 1940, 2008; Gray *et al.* 2008), known or potential bias in efficiencies of bed-load samplers can cast doubt upon the reliability of their derivative

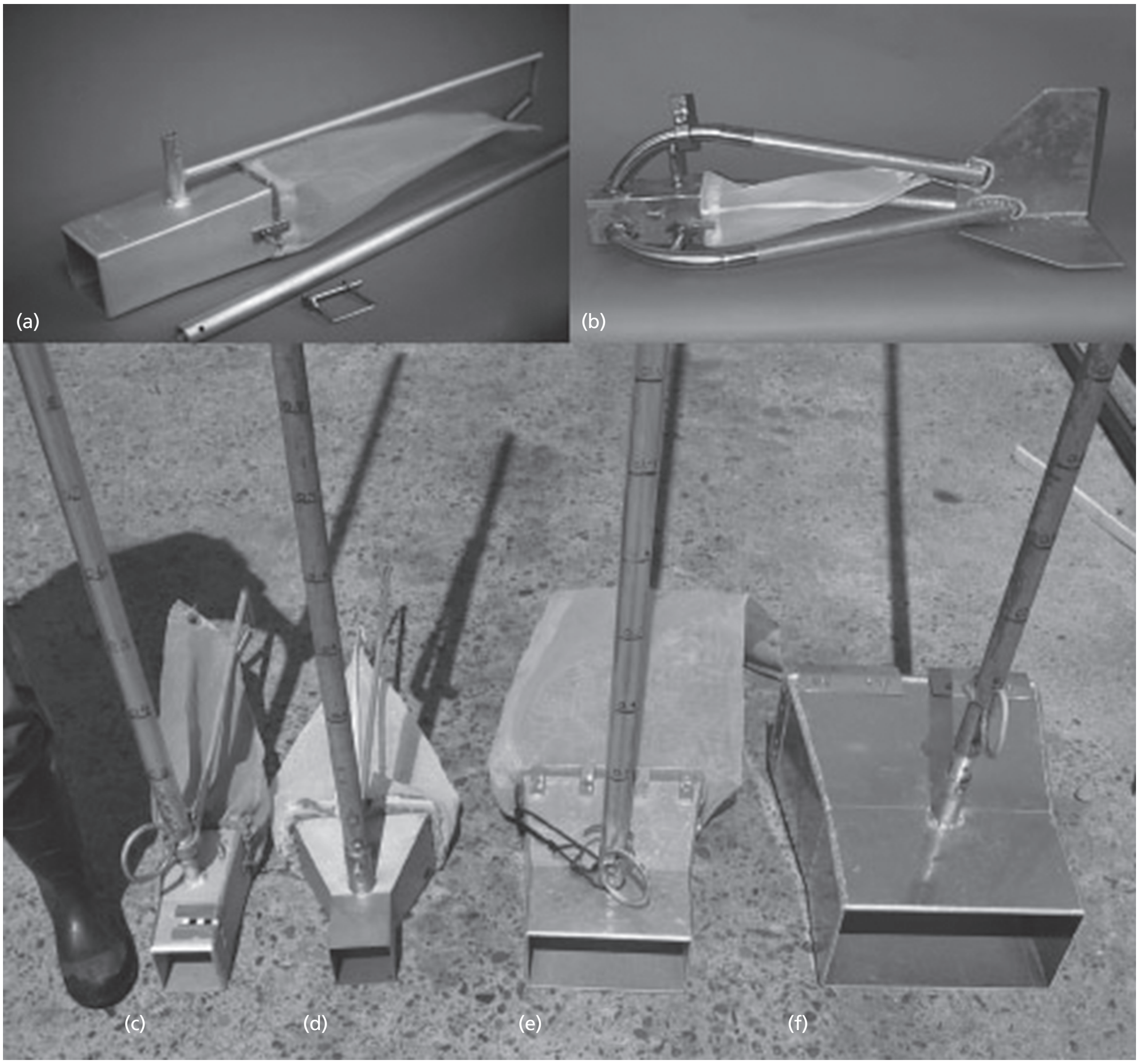

Fig. 2.4 Pressure-difference bed-load samplers. (a) and (c) Hand-held US BLH-84; (b) Cable-suspended US BL-84; (d) hand-deployed Helley–Smith; (e) hand-deployed Elwha; (f) hand-deployed Toutle River-2 (TR-2) without bag (although only one cable-suspended sampler is shown, all of these bed-load samplers are also available in cable-suspension configurations). Lower photograph courtesy of Kristin Bunte, Colorado State University, USA.

data. Bed-load sampler calibrations are complicated by a fundamental dichotomy, to wit: an innate inability to quantify the bed-load transport rate that would have occurred in a stream section in the absence of a deployed bed-load sampler, unless the bed-load sampler's efficiency is known *a priori*.

Most calibration studies have been performed in laboratory flumes where bulk bed-load transport rates can be controlled. Although flume bed-load transport-rate measurements – often referred to as "ground truth" measurements – can be quite accurate, they do not represent natural river conditions well. Leopold & 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. The variety of conditions controlled in a laboratory experiment cannot be established in a natural river.

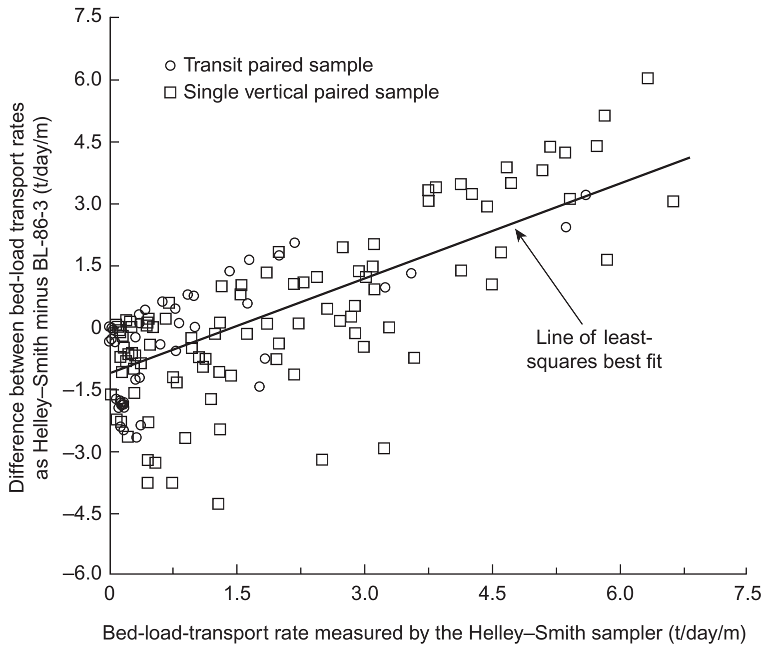

Fig. 2.5 Relation between sand bed-load transport rates measured 2 meters apart by a Helley–Smith bed-load sampler and a BL-86-3 bed-load sampler (the latter identical to the US-BL-84 bedload sampler), at the USGS streamgage on the Colorado River above National Canyon near Supai, Arizona, USA, October 1989. From Gray *et al.* (1991).

Flume bed-load sampler calibrations are subject to at least two serious problems: First, even with a stable mean bed-load transport rate, the instantaneous rate normally varies widely about the mean value (Hamamori 1962; Carey 2005; Gray & Simões 2008). Second, transport conditions in the section of the flume in which the bed-load sampler is deployed may differ from those at the flume ground-truth measuring point, such as a slot sampler.

Emmett's (1980) solution to these problems was to construct a conveyor-belt bed-load trap in a concrete trough across the bed of the East Fork River, Wyoming, USA. The trap caught all of the bed load that dropped into the trough, conveyed it to the stream bank for weighing and sampling, and returned it to the river downstream from the trough. This apparatus was used to collect bed-load data for seven years and to field-calibrate the Helley–Smith bed-load sampler (Helley & Smith 1971), the precursor to the US BLH-84 and US BL-84 bed-load samplers. This work is as notable for its considerable success in quantifying the bed-load characteristics of the East Fork River and calibrating the Helley–Smith bed-load sampler as it is in highlighting difficulties and the considerable expense of obtaining reliable bed-load data.

Field-based comparisons between sequentially or side-by-side deployed bed-load samplers cannot be used to identify the absolute sampling efficiency of any bed-load sampler without ground-truth data. However, such comparisons are useful to infer the relative efficiency of two or more bed-load samplers. Childers (1999) compared the relative sampling characteristics of six pressure-difference bed-load samplers in high-energy flows of the Toutle River at Coal Bank Bridge near Silver Lake, Washington, USA. The sampling ratio of each pair of samplers tested was computed by dividing the mean bed-load transport rate determined for one sampler by the mean rate for a second sampler. Ratios of bed-load transport rates between measured bed-load sample pairs ranged from 0.40 to 5.73, or more than an order of magnitude over the relative range of bed-load sampling efficiencies. Gray *et al*. (1991) demonstrated that two pressure-difference bed-load samplers exhibited divergent sampling efficiencies when deployed simultaneously 2 meters apart in the thalweg of the 76-m-wide sand-bedded Colorado River above National Canyon, near Supai, in Grand Canyon, Arizona, USA, under steady low-flow conditions (Fig. 2.5).

The accuracy quantified for any bed-load surrogate technology can only be as reliable as the accuracy of its calibration data. Because bed-load surrogate technologies require empirical calibrations with data collected by physical bed-load samplers, it should come as no surprise that careful calibration with the most appropriate bed-load sampler is a prerequisite for reliable bed-load transport-surrogate monitoring in rivers.

2.1.2 Information germane to surrogate technology costs

After surrogate-technology efficacy is resolved, cost considerations are often of penultimate interest. The cost of producing reliable, quality-assured bed-load data can be separated into four categories:
- the purchase price of the instrument;
- other capital costs associated with installation, and initial operation of the instrument;
- operational costs to maintain and calibrate the instrument;
- analytical costs to evaluate, reduce, compute, review, store, and publish the derivative data.

Of these four categories, only the current purchase price is relatively straightforward to quantify. The others are dependent on several factors, including site location and physical characteristics, hydrological and sedimentological regime, availability of electrical power, limitations associated with accessibility, safety considerations, and the time and complexity associated with data analysis. Additionally, any such information inevitably becomes obsolete due, in part, to technological advances, marketing competition, and changes in currency valuation. Costs referred to in the ensuing sections might be placed in perspective considering that the cost to compute, store, and provide daily suspended-sediment-discharge data at a United States Geological Survey (USGS) streamgaging station in 2001 (adjusted for inflation in 2008 dollars) ranged from US$24,000 to US$78,000 (Gray 2003). No comparable cost statistics were available for acquisition of time-series bed-load data.

2.2 Technological advances in bed-load surrogate monitoring

Unlike daily suspended-sediment records, which have been collected and computed for the better part of a century in the USA, bed-load transport is rarely measured on a continuous basis. Hence, any technology capable of providing a time-series of bed-load transport, even with a relatively large coefficient of variation, would represent a major technological advance. The following sections describe theoretical principles, selected examples of field or laboratory applications, and advantages and limitations of two bed-load surrogate technologies considered to be the most promising by the USGS.

2.2.1 Active hydroacoustics with a acoustic doppler current profiler

Janet Gaskin & Colin D. Rennie

2.2.1.1 Background and theory

Active hydroacoustics refers herein to the use of an acoustic emission and reception system to infer and quantify the mobility of the riverbed. In this case, an ADCP is used to perform a fast, non-intrusive measurement of an apparent bed velocity, which yields a spatial distribution of relative bed-load transport when the ADCP is deployed from a boat. Apparent bed velocity is defined as the difference between the boat velocity measured by the bottom track pulse, biased by near-bed sediment movement, and the absolute boat velocity measured by a global positioning system (GPS). The bottom track boat velocity is determined from the Doppler shift of the returning acoustic echoes of the bottom track pulse. The measurement realm comprises the locations of the conical beams' "footprints" on the riverbed (Rennie *et al.* 2002).

The technology generally requires manual deployment. The cost of a commercially available, manually deployable ADCP is about US$20,000 in 2008. Because quantification of bed-load transport is typically difficult and problematic even in sand-bed rivers, any surrogate means for providing quantifiably reliable sand bed-load data is desirable. Because the technology is heretofore manually deployed, there is no routine field-maintenance cost.

An ADCP transmits sound pulses into the water from either three or four transducers and measures the Doppler shift of the echoes that reflect off particles in the flow. The particles that scatter the acoustic signal are assumed to be traveling at the speed of the filament of flow in which they are suspended. The Doppler shift is thereby related to the velocity of the water relative to the instrument. The Doppler shift is defined as:

$$F_{\mathrm{d}} = 2F_{\mathrm{s}}\left(\frac{V}{c}\right) \tag{1}$$

where: F_d is the Doppler shift frequency; F_s is the frequency of the ADCP; c is the speed of sound (~1500 m/s); and V is the relative velocity of the scatterers.

Velocities measured along each slanted beam are coordinate-transformed to estimate a three-dimensional velocity for separate segments of the water column, namely bins in the vertical profile. The algorithm used to determine the velocity components assumes homogeneous conditions over the area encircling those ensonified by the transducer beams. This assumption becomes more tenuous as the distance from the ADCP increases.

Bottom track is a Doppler sonar measurement designed to measure the relative velocity between the instrument, or the boat to which it is attached, and an immobile bed. In the case of a mobile bed, the bottom-track velocity is biased by the movement of the sediment along the bed; a differential global positioning system (DGPS) system is required to measure the velocity of the boat relative to the Earth. The difference between the biased bottom track velocity and the DGPS velocity is known as the apparent bed velocity. The apparent bed velocity is considered a measure of the bed-load transport rate.

$$v_b = v_{DGPS} - v_{bt} \quad (2)$$

where: v_b is the apparent bed velocity; v_{DGPS} is the velocity of the ADCP relative to the Earth; and v_{bt} is the bottom track velocity of the ADCP relative to the bed.

It is essential that the ADCP internal compass is properly calibrated, such that both v_{DGPS} and v_{bt} are measured in the same coordinate system. The beam homogeneity assumption is especially significant for the apparent bed velocity because flow depths can be large, bed topography can be irregular, and bed-load particle transport can be locally variable.

The bottom-track pulse measures the echoes from a volume, not an area. The echoes from the bed consist of echoes from particles moving in the bed layer as well as echoes from immobile sections of the bed. Backscatter, from particles moving just above the bed, contributes positively to the signal and is known as water bias. The distance above the bed to which particle movement influences the signal depends on the pulse length selected (Rennie & Millar 2004).

The average surface velocity (v_{pa}) of the bed-load layer depends on the various sizes and velocities (v_p) of bed-load particles. Apparent bed velocity (v_b) should be representative of the average surface velocity within the ensonified volume, except that v_b is weighted by the relative backscatter strength of all individual mobile and immobile particles in the sample volume. The relative backscatter strength of mobile particles depends in part on the frequency of the instrument and the characteristic size of the particles. Acoustic backscatter strength, relative to particle size, is greater for particles with a diameter equal to or greater than 2/π times the wavelength of the instrument's sound wave (Thorne *et al*. 1995). Thus, for a 1200-kHz ADCP, backscatter from particles with diameters equal to or greater than 0.8 mm is emphasized, and the weighting of these particles in the apparent bed velocity should be greater. The relative contribution of mobile particles versus the stationary bed is discussed further below.

For a sand bed where the depth and porosity of the active layer can be assumed constant, the bed-load transport rate can be calculated as (Rennie *et al*. 2002):

$$g_b = \overline{v_p} d_a (1 - \lambda_a) \rho_s \quad (3)$$

where: g_b is the bed-load transport rate; $\overline{v_p}$ is the average particle velocity; d_a is the depth of active bed layer; λ_a is the porosity of active bed layer; and ρ_s is the density of sediment.

2.2.1.2 Example field applications

The active-hydroacoustic technology has been applied to both stationary and moving-boat studies. Stationary measurement of apparent bed velocity has been conducted in sand- and gravel-bed reaches of Canada's Fraser River, and in a sand-bed reach in the lower Missouri River, USA. Apparent bed velocity was correlated to bed-load transport measured by physical bed-load samplers in the Fraser River. A kinematically calculated bed-load transport rate has also been correlated to that measured with physical samplers. Apparent bed velocity was also correlated to bed-load transport measured by dune tracking in the lower Missouri River, USA. Coherent patterns existed between spatial distributions of apparent bed velocity and the flow's near-bed velocity, depth-averaged velocity, and shear velocity in two reaches of the Fraser River, Canada. Use of a statistical deconvolution technique has allowed successful modeling of the distribution of actual bed velocity and of instrument noise for measured data from two gravel bed sites. The use of ADCP-measured apparent bed velocity as a surrogate for bed-load transport is a technique that shows considerable potential for characterizing bed-load transport, although calibration is required for each site, and instrument noise is substantial.

2.2.1.2.1 Stationary boat studies. Initial studies of apparent bed velocity correlated the bed velocity with bed-load transport rates measured by a physical sampler and by dune tracking. The first study was conducted in 2000 (Rennie *et al*. 2002). Apparent bed velocities were correlated with bed-load transport rates, measured by concurrent physical bed-load sampling, in the Agassiz gravel bed reach in the Fraser River, British Columbia, Canada. This was the first indication that apparent bed velocity could serve as a useful measure of bed-load transport.

Apparent bed velocity (v_b) and concurrent bed-load transport rate (g_b) measured by physical samplers were compared for five data sets from three reaches in Canada's Fraser River (Rennie & Villard 2004). Sea Reach and Canoe Pass were sand-bed reaches near the river mouth. The third reach was the gravel bed Agassiz site. A Helley–Smith bed-load sampler (Helley & Smith 1971) was used for sand and a VUV pressure-difference-type sampler (Novak 1957; Hubbell 1964; Cashman 1988) was used for gravel. In the sand-bed reaches, measurements were performed on the stoss sides of dunes to reduce spatial heterogeneity. In the gravel-bed reach, several 5-minute VUV bed-load transport samples were collected and averaged during a single ADCP measurement (see Rennie *et al*. 2002). The ADCP samples lasted between 2 and 112 minutes, (two 2-minute samples were taken when the boat could not be tethered to maintain position). The "long average" samples refer to these measurements (Table 2.3). Furthermore, individual 5-minute ADCP measurements contemporaneous with single VUV samples are referred to as "5-minute averages".

The apparent bed velocity was strongly correlated with measured bed-load transport rate for the long average Agassiz data and the Sea Reach data, and less well for 5-minute averaged Agassiz data and both Canoe Pass data sets (Fig. 2.6; Table 2.2). Larger values of bed-load transport existed for the Agassiz data than for the Sea Reach data for similar values of apparent bed velocity; for particles travelling at the same average velocity, the larger the particle the higher the mass-transport rate. In Canoe Pass, similar bed velocities were measured in 2000 and 2001, despite lower bed-load transport rates measured in 2001. Equivalent apparent bed velocity despite lower bed-load transport in 2001 may have resulted from use of a longer ADCP bottom-track pulse length for ADCP bottom track measurement that increased the influence of suspended scatterers on apparent bed velocity. The variations in the regression equations between sites suggested that the relation between apparent bed velocity and bed-load transport is site-specific, thus apparent bed velocity must be calibrated for each site. Similar to the relations shown in Table 2.2, correlations of measured bed-load transport and that calculated kinematically with measured v_b varied for these data sets. Variations resulted from differences in particle-size distributions, suspended-sediment concentrations, and ADCP operating parameters.

All available data were plotted together using non-dimensionalized bed-load transport rate, g_b^*, correlated with non-dimensionalized apparent bed velocity, v_b/u^*, where u^* is shear velocity calculated

Table 2.3 Linear regression and functional relations for measured g_b versus measured v_b, Fraser River, Canada.

Location	N	r^2	Regression	Functional relation	95% CL[a]
Agassiz long avg.	9	0.89	$g_b = 1.2v–0.037$	$g_b = 1.2v–0.041$	0.91–1.7
Agassiz 5 min.	13	0.52	$g_b = 2.0v–0.059$	$g_b = 2.6v–0.088$	0.60–7.8
Sea Reach	68	0.76	$g_b = 0.057v–0.0007$	$g_b = 0.062v+0.0005$	0.062–0.062
Canoe Pass 2000	49	0.38	$g_b = 0.23v+0.001$	$g_b = 0.36v–0.00008$	0.34–0.38
Canoe Pass 2001	15	0.42	$g_b = 0.090v–0.0003$	$g_b = 0.14v–0.0004$	0.0043–0.18
Non-dimensional	127	0.42	$g_b^* = 0.043(v/u)^{0.85}$	$g_b^* = 0.045(v/u)^{0.90}$	0.74–2.6

[a] 95% confidence limits for functional relation slope.
From Rennie & Villard (2004).

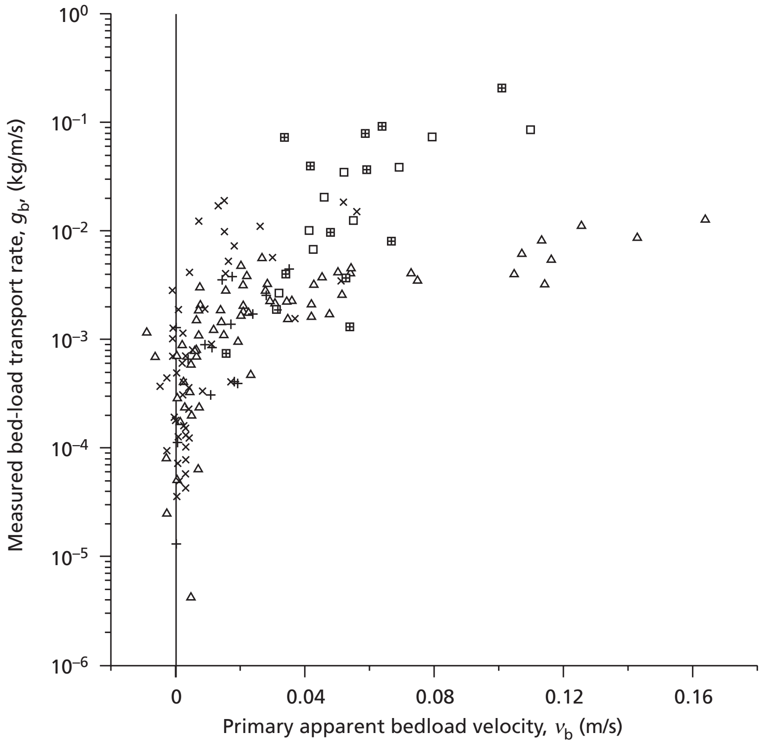

Fig. 2.6 Site-specific measured bed-load transport rate versus measured bed-load velocity. Symbols: □ Agassiz (gravel bed) long averages; ⊞ Agassiz (gravel bed) 5-minute samples; × Canoe Pass 2000 (sand bed); * Canoe Pass 2001 (sand bed); △ Sea Reach (sand bed).
From Rennie & Villard (2004).

from the log-law Keulegan equation (see below). Bed-load transport rate was non-dimensionalized using Einstein's formula (Einstein 1950):

$$g_b^* = \frac{g_b}{\rho_s\sqrt{(S_s-1)gd_{50}^3}} \tag{4}$$

where: S_s is the sediment specific gravity; g is the gravitational acceleration; and d_{50} is the bed-load median grain size. It was found that 42% of the variance in g_b^* was explained by variance in v_b/u^*.

Apparent bed velocity was correlated to bed-load transport rate from physical sampling and dune tracking in the lower Missouri River (Gaeuman & Jacobson 2007). Measurements were taken in the thalweg, which consisted of a sand bed with dunes. Physical bed-load sampling used a Helley–Smith sampler in 2004 and a US BL-84 sampler (Kuhnle 2008) in 2005. Apparent bed velocity was correlated with g_b measured from dune tracking for values lower than 0.9 kg/(m-s), whereas large variability above that value resulted from localized values of g_b being measured over large dunes. No correlation existed between v_b and g_b measured from physical sampling. It was suggested that physical sampling was an unsatisfactory method for characterizing g_b at the higher transport rates found in the lower Missouri River, USA.

Gaeuman & Jacobson (2006) also modeled the relation between the average particle velocity, v_p, and the apparent bed velocity measured by the ADCP. The average particle velocity was calculated using the van Rijn (1984) formula, a shear stress approach. The spatially averaged surface particle velocity (v_{pa}) can be assumed to vary from a value much lower than the calculated v_p near entrainment (because much of the bed surface is immobile) to a value approaching the calculated v_p at higher transporting conditions (Gaeuman & Jacobson 2006).

$$v_b = v_p w_b w_f \tag{5}$$

where: v_p is the particle velocity calculated from van Rijn (1984); w_b is the weighting factor for percentage of bed mobile; w_f = weighting factor for position over bedform.

The weighting function, w_b, evaluates the proportion of the bed particles that are moving and accounts for the relative strength of the backscatter from the immobile bed particles versus mobile particles. Gaeuman & Jacobson (2006) considered particles moving in different layers of the active bed, with the immobile bed consisting of those bed particles that are not acoustically blocked by moving particles in any layer above them.

$$w_b = \left(\frac{b_p}{b_p + b_b F} \right) \tag{6}$$

where: b_p is the fraction of bed area with moving bed particles; b_b is the fraction of immobile bed "visible" to transducer beam; F is the relative strength of echoes reflected from immobile bed.

The bed fractions depend on the particle concentration in the bed-load layer and the height of the top of the bed load layer, both calculated according to van Rijn (1984). The value of F was assumed to be roughly 10. An additional scaling factor, w_f, was proposed, but not defined, to account for spatial differences due to the influence of bedform morphology. As expected, the ratio of v_b/v_p increased with the transport stage, T^*, (the ratio of non-dimensional shear stress to critical non-dimensional shear stress) and the modeled v_b was found to be close to the measured v_b.

Ramooz & Rennie (in press) performed calibration tests on bed velocity versus bed-load transport rates at St. Anthony's Falls Laboratory at the University of Minnesota, USA, in 2006. Apparent bed velocity was reasonably correlated with bed-load transport rate from physical sampling using a continuous-weighing slot sampler and from dune tracking for the sand bed runs. This was the only study to evaluate the sensitivity of v_b correlation with g_b to the ADCP transmit frequency (600 kHz versus 1200 kHz) and bottom track pulse length. Of the operating parameters tested, the most reliable results were obtained with the 1200 kHz ADCP with bottom track pulse length set to the default value of 20% of range to the bottom. This configuration yielded the highest correlation with measured transport rates in the sand-bed runs, and was least sensitive to positive bias at low transport rates in the gravel-bed runs. The results confirmed that longer pulse lengths are more subject to water bias.

Instrument error constitutes most of the measurement error for apparent bed velocity (Rennie *et al.* 2002). The probability density function (PDF) of particle velocities measured in the ensonified beam areas of gravel beds at Agassiz and Norrish Creek was modeled by deconvolving the PDF of the instrument error from that of the measured data (Rennie & Millar 2007). In gravel-bed reaches, bed-load transport occurs as discrete events. A large percentage of the bed is immobile at any given time, with the bed velocity assumed to be an average of moving and stationary particles. Two velocity distributions were used to model the actual bed velocities, a compound Poisson-gamma distribution and an empirically fit gamma distribution. There was good fit between the modeled and measured distributions. However, each of many possible particle velocity distributions yielded a reasonable fit, owing to the strong influence of instrument noise on the measured signal. The compound Poisson-gamma distribution was found to fit better with optimized parameters. The particle- and bed-velocity distributions were positively skewed, which would result from a few high values among mostly low values, as expected for partial transport of gravel. The instrument noise was found to be 0.21 m/s for the Agassiz (adjusted to single ping) and 0.31 m/s for the single ping Norrish Creek data. This error was similar to that for water velocity measurement, estimated to be 0.23 m/s for a 1-second average (nine pings) with 0.20 m pulse length (bin size) for the narrowband ADCP utilized.

2.2.1.2.2 Studies from moving boats. Three studies of the spatial distribution of apparent bed velocity in a reach have been conducted: Rennie & Millar (2004), Gaeuman and Jacobson (2006), and Rennie & Church (2007). In the studies led by Rennie, kriging was used to smooth the raw data to produce coherent distributions from moving-boat apparent bed-velocity measurements. Assessment of these distributions was achieved by comparison to those of shear velocity, depth, near-bed water velocity, and depth-averaged water velocity.

The near-bed velocity was measured in the bin located between 25–50 cm above the bed. The bed shear velocity was calculated by Rennie *et al.* (2002), Rennie & Millar (2004), and Rennie & Church (2007) by fitting the vertical profile of local streamwise water velocity measured with the ADCP to the log law:

$$u = \frac{u_*}{\kappa} \ln\left(\frac{30h}{k_s}\right) \quad (7)$$

where u is the velocity at h; h is the elevation above the bed; $u_* = \sqrt{\tau/\rho}$ is the shear velocity; τ is the bed shear stress; ρ is the fluid density; κ is the von Karman constant (0.41); and k_s is the bed roughness.

Significant variations existed in the shear velocity distributions mapped in Sea Reach, a sand-bed estuarine distributary of the Fraser River, Canada. (Rennie & Millar 2004). Both the near-bed water velocities and the depth-averaged water velocities were correlated with the apparent bed velocities for spatial lags up to about 10 m. Similarly, areas with high shear velocity matched those with high apparent bed velocities. High shear velocities were found to stretch from the upper left side to the lower right side of the reach.

Velocity distributions were produced for a 5.5-km-long gravel-bed reach of the Fraser River, Canada, about 150 km upstream from the river mouth (Rennie & Church 2007). Vertical velocity profiles, averaged over a width of 7.7 m, were fitted to the log law to calculate the shear velocity. Apparent bed velocities were interpolated by kriging onto a 25-m grid to yield the spatial distribution. The distributions of flow depth, depth-averaged water velocity, and shear velocity were generated likewise. The distributions for depth, depth-averaged water velocity (Fig. 2.7a), shear velocity, and apparent bed velocity (Fig. 2.7b) were very coherent. Maximum values of shear stress were found in the deep bend pools of the thalweg just downstream from areas of flow convergence. Areas of flow separation and over shallow point bars had lower shear stress. Apparent bed velocity matched bed shear except in a deep pool adjacent to a rapidly eroding bank, where highly turbulent flow existed. This pool was located downstream from the river's confluence with a major side channel. The highest apparent bed velocities were measured here with the erosion due to high 3-dimensional turbulence in a region of flow separation. The shear velocity, which is calculated from mean velocity profiles, was not estimated to be high at this location.

2.2.1.3 Summary: active hydroacoustics as bed-load surrogate technology

Stationary measurements of apparent bed velocity in sand and gravel reaches have been correlated to bed-load transport rates measured concurrently from physical sampling, dune tracking (for sand-bed rivers), and bed shear. Apparent bed velocity distributions measured from a moving boat have been correlated to concurrent distributions of near-bed water velocity, depth averaged water velocity, shear velocity, and channel depth.

Error is a significant limitation of computation of apparent bed velocity. Instrument error constitutes the majority of the error (Rennie *et al.* 2002). Raw bed velocities are computationally very noisy, and must be averaged. The error of the bottom track velocity for a mobile bed is the same order of magnitude as that for water velocity (Rennie & Millar 2007). Measurements taken from moving boats use the inherent averaging of kriging to reduce error (Rennie & Millar 2004; Rennie & Church 2007). Another limitation of apparent bed velocity computation is that the technique needs calibration for each site. The calibration is a function of the bed-load sediment size and the operating parameters of the ADCP, and can be influenced by near-bed suspended transport (water bias). The ADCP requires manual deployment, and can be purchased for about fourfold the price of a turbidimeter.

Bottom track velocity is calculated using proprietary firmware. Improvements to the firmware used to determine apparent bed velocity would be helpful. The spectrum of returned echoes could be used to determine the range of velocities contributing to the signal instead of estimating a spectral peak from the autocovariance function to represent an apparent average velocity.

Apparent bed velocity measurement using an ADCP is a fast and non-intrusive surrogate technique for computing bed-load transport. One major advantage of using an ADCP to characterize bed-load transport rates is the ability to measure the spatial distribution of relative bed-load transport. From a more general perspective, because quantification of bed-load transport is typically difficult and problematic even in sand-bed rivers, any surrogate means for providing quantifiably reliable sand bed-load data is desirable.

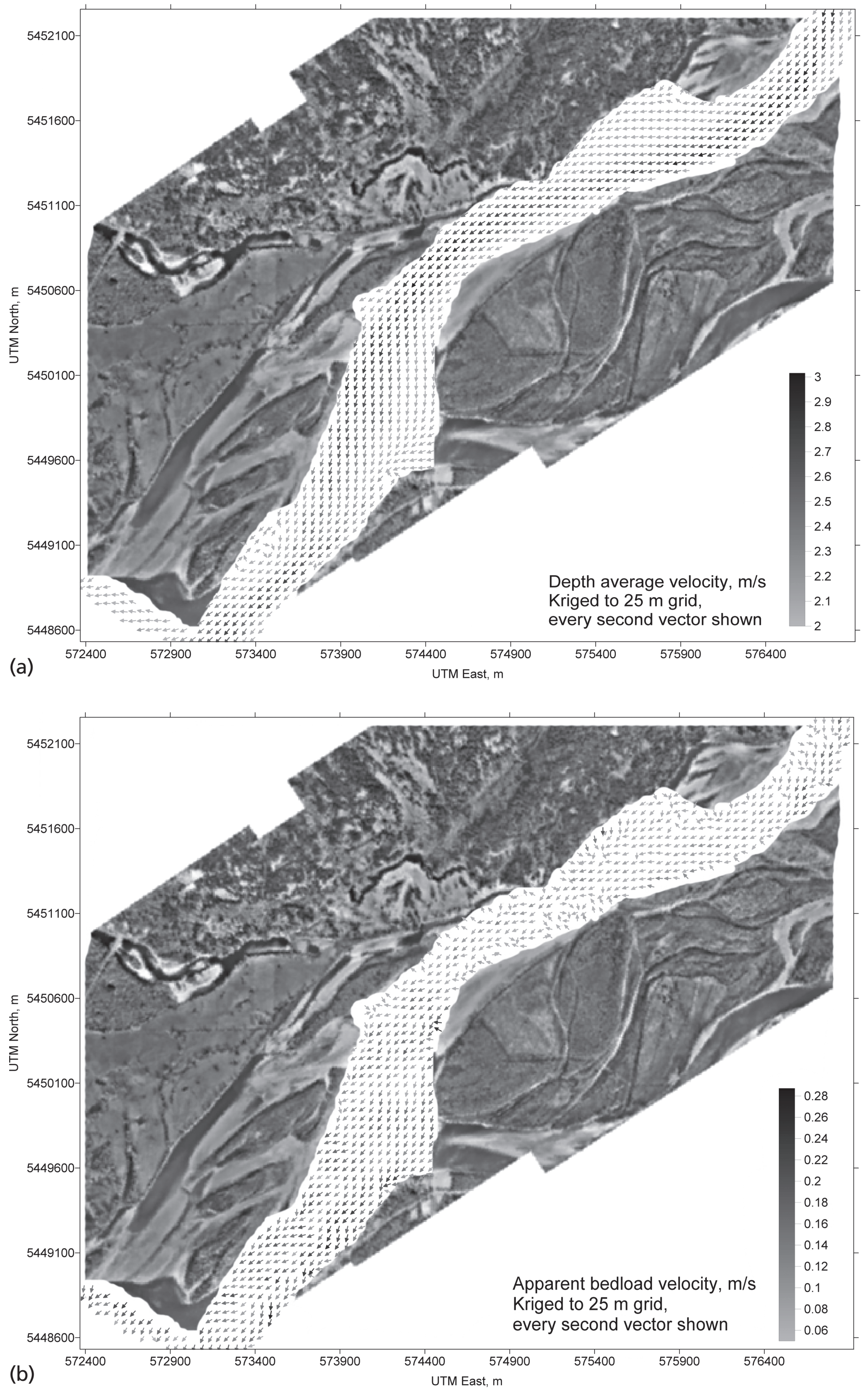

Fig. 2.7 Velocity distributions measured in m/s on the Fraser River, Canada. (a), depth-averaged water velocity, and (b) apparent bed-load velocity.
Modified from Rennie & Church (2007).

2.2.2 Passive-transducer Hydroacoustics

Jonathan S. Barton & Smokey A. Pittman

2.2.2.1 Background and theory

Investigations into the quantification of bed-load transport using acoustic signals have steadily increased in number and in complexity as researchers seek a tractable surrogate for measuring and predicting bed-load discharge. Use of passive hydroacoustic signals is attractive compared with many traditional sampling methods because of:

- relative ease of deployment;
- lower data-collection cost;
- lower hydraulic impact, and perhaps most importantly;
- continuous measurement capability, a characteristic that enables quantification of the considerable variability inherent in the bed-load transport process.

Some technologies also offer the potential for characterizing the bed-load particle size distribution. Passive hydroacoustic technologies can be grouped by the transducer type used in the measurement device. Five acoustic transducer deployments are in current use for the study of bed-load transport: hydrophones (measuring acoustic pressure fluctuations in water), microphones (measuring acoustic pressure fluctuations in air), accelerometers (measuring acceleration of a mass), velocity transducers (measuring velocity of a mass), and pressure plates (measuring impact pressure). The hydrophone is usually deployed in a protective enclosure in quiet water away from the main flow. Microphones are generally deployed within pipes installed on or in the streambed. Accelerometers are usually deployed on the underside of metal plates installed on the bed of the stream. Velocity transducers can be deployed in one of two ways: In the same fashion as accelerometers, or in geophone arrays, as in seismic surveys, along the edge of a river. Pressure plates are typically deployed perpendicular to the streambed (angled to the flow vector), as either an installed system or as a portable device.

Minimum costs associated with passive surrogate technologies for monitoring bed load are about US$5000. These technologies are relatively robust and, in theory, installations will require minimal field maintenance. The performance of the instruments have been calibrated to bed-load samples manually collected in the cross section or in flume studies (e.g. Barton et al., in press, and Møen et al., in press).

The method of using acoustic energy to derive bed-load transport rates is predicated on theories of impact based on that of Hertz (Goldsmith 2001). Depending on the specific application, the appropriate theory may involve: the collision of two irregular solids (hydrophone, velocity transducer as seismic array); the collision of an irregular solid with a cylinder (microphone); or the collision of an irregular solid with a plate (accelerometer, plate-mounted velocity transducer, pressure plate). In all cases, empirical calibration is necessary to convert to an estimate of bed-load transport rate; in most cases, this calibration must be done *in situ*, though the accelerometer has been calibrated in a flume.

Acoustic measurement of bed-load transport is not a new idea. The earliest measurements were made by Mühlhofer (1933), on Austria's Inn River using a watertight steel box containing a microphone. Bed-load collisions with the box were counted manually through the use of headphones. The Grenoble Laboratory (Labaye 1948) placed a triangular steel plate on the streambed, with a microphone in a steel box above it, and the noise of sediment striking the plate was transmitted to the microphone through a steel bar connecting the plate to the microphone membrane (no results were reported). This system was modified by Braudeau (1951), who used a brass plate and deployed the microphone in direct contact with the plate. The resulting sound was amplified and transmitted to headphones. Braudeau (1951) was able to determine the critical discharge for incipient motion to within 1 m^3/s, but did not attempt to quantify the transport rate. Bedeus & Ivicsics (1964) used a directional microphone in a boat-mounted steel housing to remotely record sediment-generated noise on the Danube River, Hungary. They compared estimates of lateral variability in transport, and results were compared with sampler data from the same cross sections. Johnson & Muir (1969) reported on flume experiments with a piezoelectric microphone, in which they calibrated an empirical relation between bed-load transport and microphone output based on the Meyer-Peter & Müller (1948) gravel-transport relation, the Hertz law of contact, and a saltation-length formula from Einstein (1950), which they also showed to improve insignificantly on a power-law fit to the data.

Froehlich (2003; in press) installed a set of microphones encased in steel pipes, and recorded the signals generated by gravel collisions with the pipes. He was able to quantify the relation between the number of cumulative gravel-pipe interactions and cumulative bed-load discharge captured in sediment basins. Mizuyama *et al.* (2003; two papers in press) and others installed a similar system, consisting of a single pipe containing a microphone deployed on a Sabo-type dam, designed to retard the propagation of debris flows. Mizuyama *et al.* (2003) found good correlation between counted impacts and bed-load transport rate at intermediate- to high-transport rates, with lower correlations at very low transport rates and at extremely high transport rates.

Hinrich (1970) modified the Grenoble sensor to use a hydrophone instead of the microphone, and a brass plate instead of a steel plate. Hinrich (1970) also installed a hydrophone on an Arnhem sampler (Hubbell 1964) and used it to verify the sampler data. Although Hinrich (1970) could recognize incipient motion, he was unable to calculate transport rates. Anderson (1976) based his microphone system on that of Johnson & Muir (1969), and suggested that moving sand generates noise dominated by frequencies above 38 kHz, based on directionality arguments relating to the microphone that he used. Anderson also observed 15- and 6-minute periodicity in the acoustic record. Richards & Milne (1979) modified Anderson's (1976) system to allow frequency analysis and in two field sites, observed that the Froude number of the flow may impact the sensor volume, and that the scatter in the acoustic amplitude was much higher in sand-bed streams than in gravel-bed streams.

In the marine literature, Thorne and colleagues (see, for example, Thorne *et al.* 1984, 1989; Thorne 1986a,b, 1987, 1993; Thorne & Foden 1988; Voulgaris *et al.* 1995) began with a hydrophone recording the noise generated by glass spheres in a rotating drum, then created a theoretical relation based on the Hertz law of contact, and ultimately created a field platform where the agreement of acoustic signals with video recordings and comparisons with Doppler velocity transducer current measurements led the authors to conclude that second-scale temporal variability of gravel transport is dominated by turbulent bursting events.

Barton (2006) and Barton *et al.* (2005, 2006, in press) have expanded upon this work, examining the effectiveness of a hydrophone for fluvial bed-load monitoring. Their hydrophone was mounted in near-bank slack waters of the Trinity River, California, USA, providing protection from impacts with sediment and debris, and separation from turbulent noise. Continuous data were collected concomitant with manual bed-load measurements using pressure-difference samplers (Fig. 2.4). Barton *et al.* (2006) found a significant relation between bed-load transport and the noise generated by the process; the acoustic signals were exploited to predict the bed-load discharge between pressure-difference sampling measurements. Smith (Graham Matthews and Associates 2006, 2007, 2008) has continued this work, collecting data at the same location on the Trinity River.

Rickenmann (1997), Rickenmann *et al.* (1997), Rickenmann & Fritschi (in press), and Hegg & Rickenmann (1998, 2000), building on earlier work by Bänziger & Burch (1990), have shown the effectiveness of accelerometer and geophone (velocity transducer) installations (mounted beneath a metal plate installed on the bed) for long-term bed-load monitoring in the Swiss Alps. Bogen & Møen (2003) and Møen *et al.* (in press), using a system similar to that of Rickenmann (1997), but with different frequency sensitivity, have shown that an accelerometer with a narrow frequency band is heavily influenced by sediment grain size, and that with appropriate calibration, a wideband accelerometer may be able to account for changes in the grain size. Richardson *et al.* (2003) also mounted an accelerometer beneath a steel plate, and found that although the relation between sediment impact rate and transport rate was nonlinear (particularly at high transport rates), the relation was consistent with theory based on shear stress.

Govi *et al.* (1993) counted impacts recorded by geophones (velocity transducers) buried in the streambed immediately upstream from a weir, and were able to establish streamflow discharges corresponding to initiation and cessation of bed-load motion, but did not calculate transport rates. Burtin *et al.* (2008) used a high-density seismic array in the Himalayas to monitor the bed-load flux qualitatively in the narrow and deeply incised Trisuli River, Nepal. Although they were unable to separate contributions to the seismic signal completely owing to turbulence in the flow, they were able to record a hysteresis loop in the seismic rating curve, indicating a significant contribution to the seismic signal from sources other than streamflow.

Downing & Ryan (2001), Downing *et al.* (2003) and Downing (in press) describe a manually deployed pressure-plate device that, when impacted by a moving sediment grain, produces a charge that is proportional to the force applied, which through integration yields the momentum flux. They derived a pulse-count record of the bed-load interaction with the plate above a minimum threshold impact value. Application of the device requires *a priori* knowledge of the size distribution in motion. Unlike the other devices discussed here, this device interacts with the flow, and so a calibration involving the hydraulic efficiency is required. Downing (in press) showed, for two floods on the same river, that assuming a constant calibration coefficient would result in an error in the calculated transport rate of only ±20%.

2.2.2.2 Example field application

A single hydrophone (Geospace Technologies MP-18) system was installed 250 m downstream from the USGS streamgage on the Trinity River at Douglas City, California, USA (Barton *et al.* in press). Acoustic data were collected from May 6 to May 19 2005; total acoustic power ranging from 0.01 to 14.8 kHz over 1-minute intervals was calculated from the data. Sample data collected using a Toutle River-2 (TR-2) bed-load sampler, a modified version of the BL-84-type bed-load sampler capable of collecting medium-size gravel (Childers 1999; Pittman 2005) (Fig. 2.4) deployed from a tethered raft system, were compared with the temporal average of acoustic data collected during a sampling interval (Fig. 2.8). The resulting regression was applied to the 1-minute data (Fig. 2.9). Barton *et al.* (in press) indicate that the range of the acoustic data is consistent with the range of most Toutle River-2 bed-load sampler data. Spectral analysis of the 1-minute data shows discrete frequency peaks, the lowest of which falls within the frequency range reported for bed-load sheet movement.

2.2.2.3 Summary: passive hydroacoustics as bed-load surrogate technology

This technology is applicable for continuous bed-load monitoring in gravel-bed systems where the acoustic energy emitted by contacts of bed-load particles larger than a minimum grain-size threshold can be measured. In all cases, this minimum size is not clearly

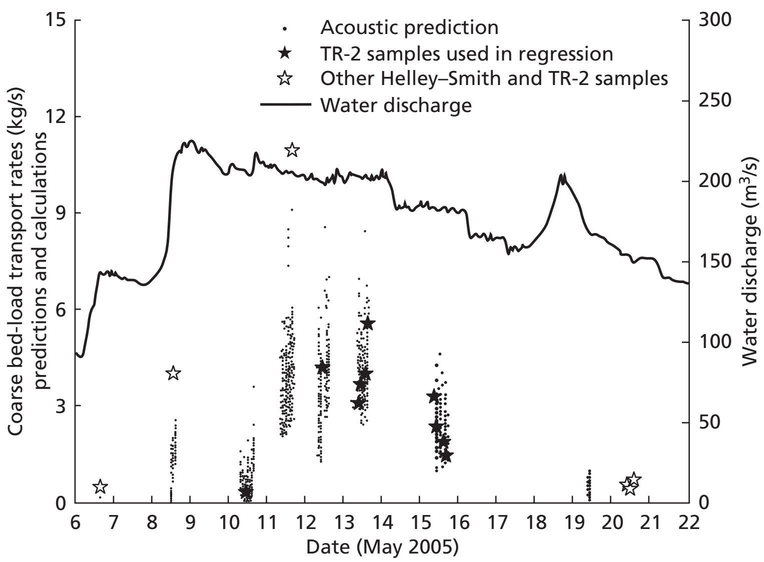

Fig. 2.8 Predictions of coarse (>8 mm) bed-load transport rates from one-minute-averaged acoustic power (small dots) over the study interval plotted with the water discharge (solid line), Trinity River at Douglas City, California, USA, and bed-load transport rates from data collected by Helley–Smith and TR-2 bed-load samplers (solid and hollow stars). The solid stars represent data used in the least-squares regression shown in Fig. 2.9.
From Barton *et al.* (in press).

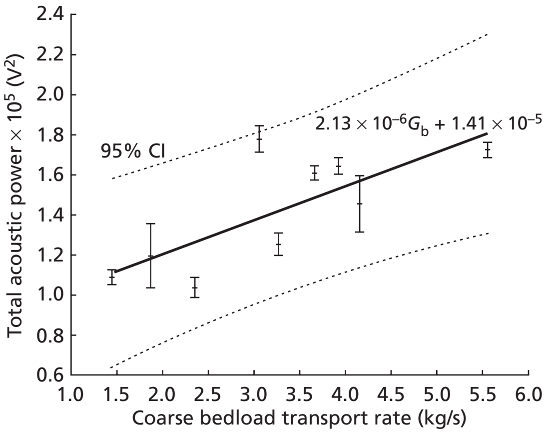

Fig. 2.9 Correlation plot between temporally averaged total acoustic power (totaled over the frequency range of 0.01–14.8 kHz) and bed-load transport rate from the Toutle River 2 sampler. Error bars show ±2 standard errors of the temporal mean. The Pearson's correlation coefficient R is 0.758, with a p-value of 0.0180. Confidence interval for the regression parameters assumes Gaussian error. From Barton *et al*. (in press).

defined; in many cases, size thresholds may depend on the specifics of the surrogate technology installation.

The technique relies entirely on calibrations to cross-section bed-load samples. This technology can be used to infer the incipient motion, and with calibration by reliable bed-load samplers, to infer mass transport. Most parts are available off the shelf at a cost similar to that for a fully equipped *in situ* turbidimeter. Specific advantages and limitations of each type of sensor follow.

2.2.2.3.1 Advantages of passive hydroacoustic technologies

Hydrophone:
• By integrating over a large area of the streambed, the hydrophone allows estimation of average transport rate, compensating for spatial variability in the transport rate.
• Taking advantage of the high acoustic conductivity of water, the hydrophone can be placed in slack water adjacent to the main flow.
• The hydrophone can be installed at minimal cost, requiring no excavation of the bed and can be installed during high flow.

Microphone:
• Isolation of electronics from the water leads to improved reliability and maintainability.
• Sensors can operate unattended for long intervals with minimal maintenance.
• Method is robust for monitoring fine gravel to small boulder transport.

Plate-mounted accelerometer or velocity transducer:
• Sensors can operate unattended for long intervals with minimal maintenance.
• Technique has a 15-year operational history;
• Technique has ability to differentiate grain sizes with sufficiently high-frequency data acquisition and advanced processing techniques.
• Flume calibration may be sufficient.

Velocity transducer as seismic array:
• Sensors are deployed outside the river channel; Burtin *et al.* (2008) showed that sensors as much as 2 km away from the river channel still showed significant sensitivity to river hydraulics.
• Integrated bed-load transport measurements are on the reach-to-basin scale.
• Two-dimensional array deployment may allow watershed-scale transport analysis of regions of high transport using seismic tomography techniques.

Pressure plate:
• Technique can be used as either permanent (installed) system or portable (wading-stick mounted) system.
• Calibration has been shown to be fairly stable (±20% variation) for two floods on the same stream.
• System is effective for grain sizes as small as 4 mm in diameter (the largest size that will not damage the instrument has not been reported).

2.2.2.3.2 Limitations of passive hydroacoustic technologies. All passive hydroacoustic technologies for bed load require site-specific calibrations. Other limitations include the following.

Hydrophone:
• Only single-instrument systems have been tested, and evidence suggests that this arrangement may be sensitive to changes in spatial distribution of bed-load transport. Array deployment may help to reduce this sensitivity.
• Technique is only appropriate for medium-gravel to large-boulder applications. Fine gravel and sand

produce high frequency noise, which may be problematic to separate from flow noise.

Microphone:
- Technique has limited applicability for extremely low or extremely high sediment discharges. Long-term averaging at low discharges can improve signal-to-noise ratio.
- High-flow performance depends upon half-burying the pipe in the bed.

Plate-mounted accelerometer or velocity transducer:
- Selection of placement site is strongly influenced by river geometry, as some sites may be susceptible to deposition at certain flows, which could cover the instrument.
- Installation may be expensive, and possibly require excavation.

Velocity transducer as seismic array:
- An array such as that used by Burtin *et al.* (2008) is expensive to purchase and deploy. Effectiveness of the technology is uncertain if scaled down.
- Studies thus far have focused only on qualitative evaluation of transport. No quantitative information is available yet.
- The minimum particle size to which the system is sensitive has not been determined.

Pressure plate:
- Instrument projects into flow, which changes the local hydraulics, and subsequently the local bed-load transport, leading to scour or deposition.
- Technique requires *a priori* knowledge of size distribution in transport.

2.3 Summary and conclusions

One active (ADCP) and several passive (hydrophone or geophone) acoustic surrogate technologies for monitoring bed-load transport that have been described in this chapter are being tested and evaluated for use in large-scale operational sediment-transport monitoring programs. Active and passive hydroacoustics are but two of more than a dozen bed-load surrogate technologies described in the literature. However, hydroacoustics technologies are considered by the editors to be among the most promising of the bed-load surrogate technologies with which they are familiar.

With the potential exception of some passive bed-load hydroacoustic technologies in selected streams, the *in situ* technologies do not directly measure the constituent of interest over the entire cross section. Hence, the technologies require cross-section calibration with reliable bed-load samplers.

The technique of monitoring bed load using active acoustics has been tested in sand- and gravel-bed systems. Like the passive acoustic technology, site-specific, empirically derived relations using data from an ADCP and a bed-load sampler are required. For active acoustics, the calibration is a function of the sediment size and the operating parameters of the ADCP.

Stationary measurements of apparent bed velocity utilizing manually deployed ADCPs have been correlated with concurrent measurements of bed-load transport and bed shear stress in sand and gravel reaches, and to dune tracking in sand-bed rivers. Distributions of apparent bed velocity measured by ADCP from a moving boat have been correlated to concurrent distributions of near-bed water velocity, depth-averaged water velocity, shear velocity, and channel depth. Instrument measurement variance constitutes the majority of error in the technique. The variance of the bottom track velocity for a mobile bed is the same order of magnitude as that for water velocity.

Apparent bed-velocity measurements made by using active acoustics is a fast and non-intrusive technique for computing bed-load transport. One advantage of using an ADCP to characterize bed-load transport is the ability to measure the spatial distribution of apparent bed velocity. The method also benefits from substantial averaging of measurements. However, lack of spatial homogeneity of apparent bed velocity in the region sampled by the acoustic beams may cause increased variance in bed-load computations. The cost of the technology (ADCP) is about US$20,000, in addition to the costs of a GPS, boat, and other equipment necessary for deployment.

Passive acoustic techniques are limited to applications in gravel-bed systems where bed-load particles are sufficiently large for the acoustic energy emitted by contacts to be measured. In all cases, this particle size is not clearly defined; in many cases, size thresholds may depend on the specifics of the installation.

Many of these techniques, designed to function remotely, can be used to infer incipient bed motion, and with calibration by samples collected manually with reliable bed-load samplers, to infer mass transport. As with the active-acoustic technology, empirical site-specific relations between acoustic signal strength (or other acoustic parameters) and bed-load sampler data must be developed and used with the continuous acoustic signal to compute continuous bed-load transport. The minimum cost of a passive-acoustic instrument is about US$5000.

Five types of passive-acoustic system have been tested: hydrophones, microphones, plate-mounted accelerometers or velocity transducers, pressure plates, and velocity transducers as seismic arrays. Hydrophones, submerged in a relatively quiescent location, integrate the acoustic energy over a large area of the streambed, in effect inferring an average bed-load transport rate. Only single-instrument systems have been tested, and they may respond differentially to changes in the spatial distribution of bed-load transport. The technology is only appropriate for applications where bed-load particle sizes range from medium gravel to large boulders. Fine gravel and sand produce high-frequency noise, which is computationally difficult to separate from ambient noise. When deployed in slack water areas adjacent to the main flow, the system is relatively robust.

Microphones, which measure acoustic pressure fluctuations in air, isolate the instrument's electronics from the water resulting in improved long-term reliability and maintainability. These systems are considered robust for monitoring fine gravel to small boulder transport, but their performance is inferior to other passive acoustic systems at extremely low or extremely high bed-load discharges.

Plate-mounted accelerometers or velocity transducers have proven, over a one- to two-decade operational history, to operate unattended for long intervals with minimal maintenance. The technology can differentiate among grain sizes given sufficiently high-frequency data acquisition and advanced processing techniques. Flume calibration may be sufficient. Instrument placement is strongly influenced by river geometry, as some sites may be susceptible to deposition that could cover the instrument. It is one of the more expensive of the passive-acoustic technologies because installation may require excavation.

Velocity transducers as seismic arrays integrate bed-load transport on the reach-to-basin scale. Sensors are deployed outside the river channel, with sensors installed as much as 2 km from the river channel showing sensitivity to river hydraulics. Two-dimensional array deployment may allow watershed-scale transport analysis of regions of high bed-load transport using seismic tomography techniques. The system can be expensive to purchase and deploy, and the effectiveness of its scaled-down performance is unknown. Only qualitative information is available, and the minimum particle size to which the system is sensitive has not been determined.

Pressure plates can be used as either an installed system or as a manually deployed wading-stick mounted portable device. System calibration has been shown to be somewhat stable (within a range of ±20%) for two floods on the same stream. It is effective for grain sizes as small as 4-mm diameter but the upper size limit is unknown. *A priori* knowledge of size distribution in transport is required. The instrument projects into flow, which changes the local hydraulics, and subsequently the local bed-load transport rate, potentially leading to local scour or deposition.

2.4 Prospects for operational surrogate monitoring of bed-load transport in rivers

This chapter has described an active hydroacoustic and several passive hydroacoustic technologies for monitoring characteristics important to understanding properties of bed-load transport in rivers. Some characteristics common to these technologies include the following:

- All address measurement of bed-load characteristics that are difficult, expensive, and (or) dangerous to directly measure with sufficient frequency to adequately define their spatial and temporal variability.
- At least some are relatively affordable, costing between US$5000 and US$20,000. Some, such as cross-channel impact-plates installations, may cost substantially more.
- Most if not all require site-specific calibrations equating values recorded by the surrogate instrument to the mean cross-section constituent value.
- All require additional testing and evaluation before deployment in operation sediment-transport programs.

None of the technologies is suitable for monitoring bed-load transport under all flow and sediment-transport conditions. Nevertheless, if care is exercised in matching surrogate technologies to appropriate river and sedimentological conditions, it may be eventually possible to remotely and continuously monitor bed-load transport in a variety of rivers over a range of flow and sedimentary conditions within acceptable accuracy limits. This is a revolutionary concept in fluvial sedimentology; benefits of such applied capability could be enormous, providing for safer, more frequent and possibly more accurate, and ultimately less expensive data for use in managing the world's sedimentary resources.

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