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Necessity and Difficulties of Field Calibrating Signals from Surrogate Techniques in Gravel-Bed Streams: Possibilities for Bedload Trap Samplers

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Abstract

Field calibration for bedload signals recorded with surrogate devices is necessary but difficult. The necessity arises because lab conditions likely produce a smaller range of transport rates, particle sizes, and transport patterns than typically experienced in a stream. Field conditions likely produce more electronic noise in the surrogate device which may require lowering signal amplification. Too many signals are recorded in the first case and too few in the latter. To calibrate signals recorded from surrogate devices against physical bedload samples and to arrive at mathematical calibration functions requires reliable field measurements of bedload mass and particle sizes.

The difficulties of field calibration include temporal and lateral fluctuations of transport rates, scatter in the calibration data sets, interference between two devices sampling simultaneously, and lack of a suitable sampler. When transport is temporally and laterally fluctuating, the calibration sampler should average over these fluctuations because otherwise the calibration and surrogate device might sample different transport rates. The calibration sampler must match the temporal and spatial scale of the surrogate device as much as possible. Fluctuating transport rates also cause data obtained from calibration efforts to be scattered. This requires collection of many samples to improve the statistical confidence of the analyses, to permit post-sampling averaging, and to identify patterns in the data set indicating disturbances. The problem of interference between calibration and surrogate device may be minimized by increasing their temporal or lateral spacing, but doing so can decrease calibration accuracy.

A major difficulty in field calibration is finding a suitable bedload sampler that provides accurate measurements of transport rates and particle sizes against which to calibrate outputs from the surrogate technology. The sampler should facilitate averaging over temporally and laterally fluctuating transport rates and match the measuring scale of a surrogate device. Stationary devices such as vortex and conveyor belt samplers, weighable pit traps and debris basins can provide accurate measurements of bedload transport but require that the calibration effort be conducted at the site of the stationary sampler. Portable samplers offer the logistical advantage of conducting the field calibration at the stream of interest. Of the portable devices, Helley-Smith-type samplers are readily available in different sizes and shapes and easy to operate. However, they seem to provide accurate samples only when used on stable

gravel beds, during high transport rates, or when deployed from a sill or ground plates. They also require collection of numerous samples to achieve temporal and lateral integration.

Bedload traps may provide a useful alternative to the HS sampler for field calibration in coarse-bedded mountain gravel-bed streams. The 0.3 m wide sampler with its long net is portable and fastened onto ground plates installed flush with the bed surface. Intensive field testing suggests that traps provide accurate samples of transport rates and particle sizes when deployed on stable, coarse gravel beds. Bedload traps permit hour-long sampling times during low transport rates, and several traps can be installed side-by side, facilitating temporal and lateral averaging over many scales. Bedload traps are unsuitable for collecting particles finer than 4 mm, for unwadeable flows, and on highly erodible beds.

Introduction

Surrogate techniques used for recording bedload transport in gravel- and cobble bed streams typically measure signals that are created by the motion of sediment particles. Signals may be caused by particles hitting an underwater microphone or each other (e.g., Rouse 1994; Bogen and Møen 2003; Richardson et al. 2003; Barton and Slingerland 2005, Barton et al. 2006) or by the impact of particles hitting a deformable membrane (piezoelectric elements) (e.g., Bänzinger and Burch 1990; Rickenmann, 1994, 1997; Dowing and Hausmann 2000). Signals may also be created by naturally or artificially magnetic bedload particles passing over coils implanted into the streambed (e.g., Ergenzinger and Custer 1983; Spieker and Ergenzinger 1990; Ergenzinger et al. 1994; De Jong 1995; Bunte 1996; Tunnicliff et al. 2000; Gottesfeld and Tunnicliff 2003). Bedload signals are electronically modified, amplified, and stored in a computer. The output is typically a time series of signal rates or a distribution of signal properties (e.g., amplitudes, durations, frequency) recorded over a specified time period. Other techniques of indirectly measuring bedload transport include repeated topographic surveys of the channel bed (e.g., Bransington et al. 2000, 2002) and measurements of the bedload transport velocity (Frey et al. 2002; Rennie and Millar 2002 a and b; Rennie et al. 2002). Field calibration is necessary for all surrogate technologies. This study deals with field calibration of signals generated by a relatively small number of gravel particles passing a stream cross-section or a part of it per time increment. The objective of this paper is to show the necessity and difficulties of field calibration of such signal outputs, to discus the suitability of various samplers, and to offer bedload traps as a sampling device that might be suited for this task in coarse gravel-bed streams.

Field calibration of surrogate signals

Necessity

Field calibration of a surrogate bedload measurement device is a step in instrument development that must not be neglected. Because lab or flume studies will almost certainly play a major part in surrogate instrument development, it may be tempting to rely on them for calibration as well. However, the lab presents a sheltered environment in which measurement variables (bedload particle sizes, transport rates, flow depth, etc.) are controlled. Factors that produce electronic noise can be eliminated or kept to a minimum in the lab as well. A stream, by contrast, often produces a wider range of transport rates and particle sizes, as well as different temporal and spatial transport patterns than those that may have been mimicked in the lab during test trials. Consequently, signals, i.e., their rates, amplitudes, durations, frequency and patterns are likely different in the field, and field calibration needs to ensure that the surrogate device can accurately record bedload transport rates and particle sizes. Another reason to do field calibration is that signals recorded from a surrogate technique in the field likely contain "noise". Signal noise can be generated from numerous sources. Equipment that is placed into a stream may be subjected to acoustic noise and physical impacts from water bubbles, quickly moving pieces of organic debris of various sizes, and vibration due to turbulence of flow. Lightning storms, radio waves, car ignitions, people walking about, and long cables between the measuring device and recording unit can generate electrical noise. Noise signals can mask or override true signals as well as create false ones, thus creating a record that contains signals from sources other than bedload. Conversely, lowering signal amplification in an attempt to reduce signal noise can suppress true particle signals. Without field calibration, one cannot be sure how signal rates and other signal properties translate into bedload transport rates and particle sizes.

What should field calibration accomplish?

The ideal calibration setup is one in which the two devices (one a surrogate technique, the other a device collecting bedload samples) measure the same bedload transport over the same time period. One can then compare results from the two measurements to determine whether transport rates and particle sizes computed from the signal output of the surrogate device match with those collected by the sampler, whether there is a general bias, or whether the surrogate device over- or under-records certain transport rates and particle sizes. Ultimately, the calibration should produce a quantifiable, mathematical function (a regression relationship for example) with which the surrogate's signals can be transformed into an estimate of bedload transport rates and, if possible, its particle-size distribution. Having calibrated the surrogate device, one should be able to make surrogate measurements alone and have a method to transform the surrogate's signals into a reasonable estimate of the true bedload rate and its particle sizes.

Difficulties of field calibration

Field calibration faces a number of difficulties that include temporal and spatial variability of transport rates, the analyses of poorly matching calibration results, and interference of the sampling devices with natural transport rates. A major problem is the lack of a suitable bedload sampler to provide accurate transport rates against which to calibrate the surrogate signal output.

Effect of temporal and spatial variability of transport rates on field calibration

Ideally, when comparing signal outputs measured with a surrogate technique to transport rates collected in a bedload sampler, transport rates should be constant over time and space. In this case, transport rates computed from the surrogate device at a time 1 and location 1 ($Q_{B\ surr}$) can be directly compared to those measured with the calibration device at a nearby time 2 and location 2 ($Q_{B\ cal}$) **(Fig. 1a)**. However, in gravel-bed streams transport rates are rarely constant over time and space. Instead, they fluctuate widely over time (e.g., Hayward and Sutherland 1974, Carey 1985, Reid et al. 1985; Custer et al. 1987; Tacconi and Billy 1987; Pitlick 1988, Whiting et al. 1988; Dinehart 1989; Lisle 1989; Gomez et al. 1989; Gomez and Emmett 1990; De Jong 1995; Bunte 1996, Garcia et al. 2000, Tunnicliffe et al. 2000; Habersack et al. 2001; Gottesfeld and Tunnicliffe 2003; Cudden and Hoey 2003) as well as space (Pitlick 1988; Powell et al. 1998, Bunte 1996, Ergenzinger et al. 1994; De Jong 1995; Gottesfeld and Tunnicliffe 2003). Temporal variability occurs over various time scales (seconds, minutes, hours, days, event, seasons, and years), and effects from different time scales can overlap. Similarly, lateral variability occurs over different spatial scales, ranging from a few cm to the entire stream width.

Temporal and spatial variability of natural transport rates and particle sizes can pose significant difficulties when attempting to compare signal rates measured with a surrogate technique to transport rates collected in a sampler, because a transport rate that occurred at time 1 at location 1 can be measured neither at time 2 and location 1 nor at time 1 and location 2. Thus, temporal and spatial averaging is required for measurements with both devices. The larger and more irregular the variability is, the longer the integration time needs to be and the wider the spatial extent of averaging (**Fig. 1b - d**).

The degree of temporal and spatial averaging one is able to accomplish with the deployment of a single bedload sampler is limited by the sampler width in relation to the bedload particles, the sampler capacity, and the number of samplers deployed concomitantly. Sampler dimension might not pose a limitation at low transport rates, but when transport is high, the sampler opening needs to be large enough to allow coarse gravel and cobbles to enter, while the sampler volume needs to be large to facilitate long sampling times. A small sampler volume permits only short sampling times, thus, numerous samples may need to be collected to facilitate temporal averaging. Similarly, deployment of the sampler at a single location per time requires the collection of numerous samples for lateral averaging.

If a calibration device is not available when a surrogate device is deployed, one might attempt, as a stopgap measure, to take calibration samples at some later point in time and compare results from both devices using a rating curve approach (Bunte and Abt (2009). However, a calibration after the fact is only valid if the relationships of transport rates and particle sizes with flow remained the same as when the surrogate device was deployed. This might be the case in some streams and over some years, but variability of bedload transport rating and flow competence curves within and between years seems to be the more common case (e.g., Vericat et al. 2006b; Bunte 1996, Bunte et al. 2008). If transport rates have changed between $Q_{B\,surr}$ and $Q_{B\,cal}$, an *a posteriori* calibration can no longer take place (**Fig. 1e**) (Bunte 1996).

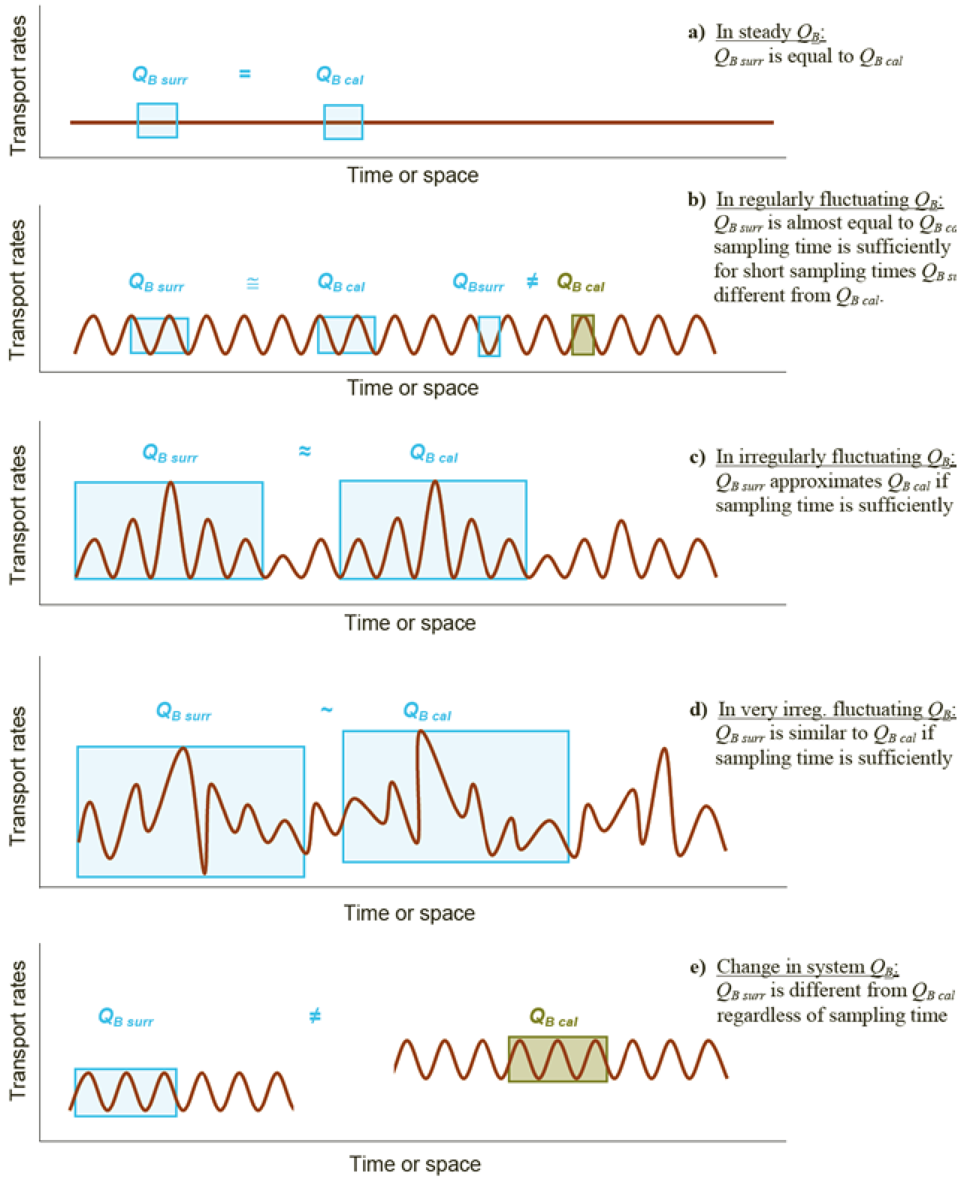

Figure 1. Transport variability and conditions under which transport sampled with the surrogate device 1 at time and/or location 1 ($Q_{B\ surr}$) is equal, approximate, or similar to transport sampled with the calibration device 2 at time and/or location 2 ($Q_{B\ cal}$). Olive-colored fields indicate misfit.

The spatial extent of field calibration needs to match the spatial extent of the surrogate's technology, thus the surrogate's lateral measuring range must be known. If, for example, signals are created at one or several discrete points in the stream (e.g., from an impact sensor), a calibration sampler needs to collect samples at these points as well, unless the surrogate device alters the particle trajectory. If the surrogate device integrates over the entire stream width (e.g., a hydrophone), or large portions of it (magnetic tracer technique), the calibration samples need to cover the same width.

Lateral variability, both natural as well as caused by the deployment of a measuring device, can cause significant problems for calibration of a surrogate device. Two examples are given below. The bedload impact sensors developed by Downing and Hausmann (2000) are 76 and 100 mm wide, and their impact planes are positioned diagonally to stream flow. Particles hitting and bouncing off the sensor are deflected in their downstream path. Due to particle deflection and the sensor's effects on nearby flow hydraulics, a calibration sampler had to be spaced at least 0.2 m apart from the sensor, thus the two devices measured along different "lanes" of gravel transport. Consequently, sample mass computed from the impact sensor was different from transport rates collected in nearby samplers (Downing and Ryan 2001; Downing et al. 2003). However, when the lateral scale was extended and both the sensor and a bedload sampler were placed at several verticals across the stream, cross-sectional transport rates from both devices matched within 83% (Downing and Ryan 2001). Similarly, lateral averaging also improved the match of transport rates from two sampling devices in a study by Bunte and Swingle (2007). Of 35 individual samples from bedload traps, only 16 were within 50-200% of the transport rates measured at weigh pans installed about 1 m behind the traps just before the bedload trap samples were collected. When transport rates for both devices were averaged over the entire 2.7 m flume width, 12 of 18 samples matched within 50-200%.

Problems in the analysis of scattered data

Due to temporally and spatially varying transport rates, transport rates that are computed from two devices and plotted against each other may scatter over a wide range. Comparing such data and evaluating their fit is problematic. Studies by Hubbell et al. (1985, 1987) used the probability matching approach that does not compare measured data pairs, but data pairs obtained when each data set is sorted from smallest to largest. Thomas and Lewis (1993) showed that probability matching is not suitable for this purpose because it creates a statistical relationship even when applied to uncorrelated data. To overcome this problem, we suggest collecting as large a number of samples as practical in order to have room for statistical maneuvering and a detailed data analysis. A large sample size provides several advantages: (a) it improves the statistical confidence of the degree with which transport rates from the two devices match or mismatch; (b) it permits post-sampling temporal and lateral averaging of the data; (c) it can provide the opportunity to observe and analyze patterns in the data and to determine exactly the time and conditions under which the over- or under-predictions occurred (e.g., did a lightning storm cause electrical noise, were cables unconnected, did the accuracy of recorded signals rates decrease for some reason, or was the sampler disturbed and did not collect accurate transport rates?).

Interference between two devices

A calibration attempt can become problematic when the presence of the surrogate device affects transport rates measured with the calibration sampler and vice versa. One also needs to consider that not only the presence of the two devices themselves, but also the operators' activities when servicing the two devices may cause interference. For example, interference between two samplers occurred when attempting to calibrate bedload traps against weigh pans at the St. Anthony Falls Laboratory (SAFL) flumes (Bunte and Swingle 2007). Two processes disturbed natural transport rates and supplied large amounts of sediment close to the weigh pans: 1) stepping onto the flume bed scoured the highly mobile bed and 2) shaking sediment out of the sampler bag where it had accumulated before the start of a sampling interval. Sediment from both sources was immediately mobilized and measured within seconds at the weigh pans about a meter downstream from the end of the bedload trap nets (**Fig. 2**). Both samplers were obviously too close to each other. Walkways and stepping stones might help to decrease bed scour, as they did in this example, and should be installed if necessary in order to decrease interference between the calibration and the surrogate devices. Accurately recording the timing and extent of man-made or natural streambed disturbances at the site during the calibration trials is also important for pinpointing reasons that cause mismatches in the compared transport data. It is further helpful for the calibration success to analyze signal outputs and calibration samples without delay, such that the outcome of the analysis can be applied to solve adjustment problems before continuing with long set of calibration runs.

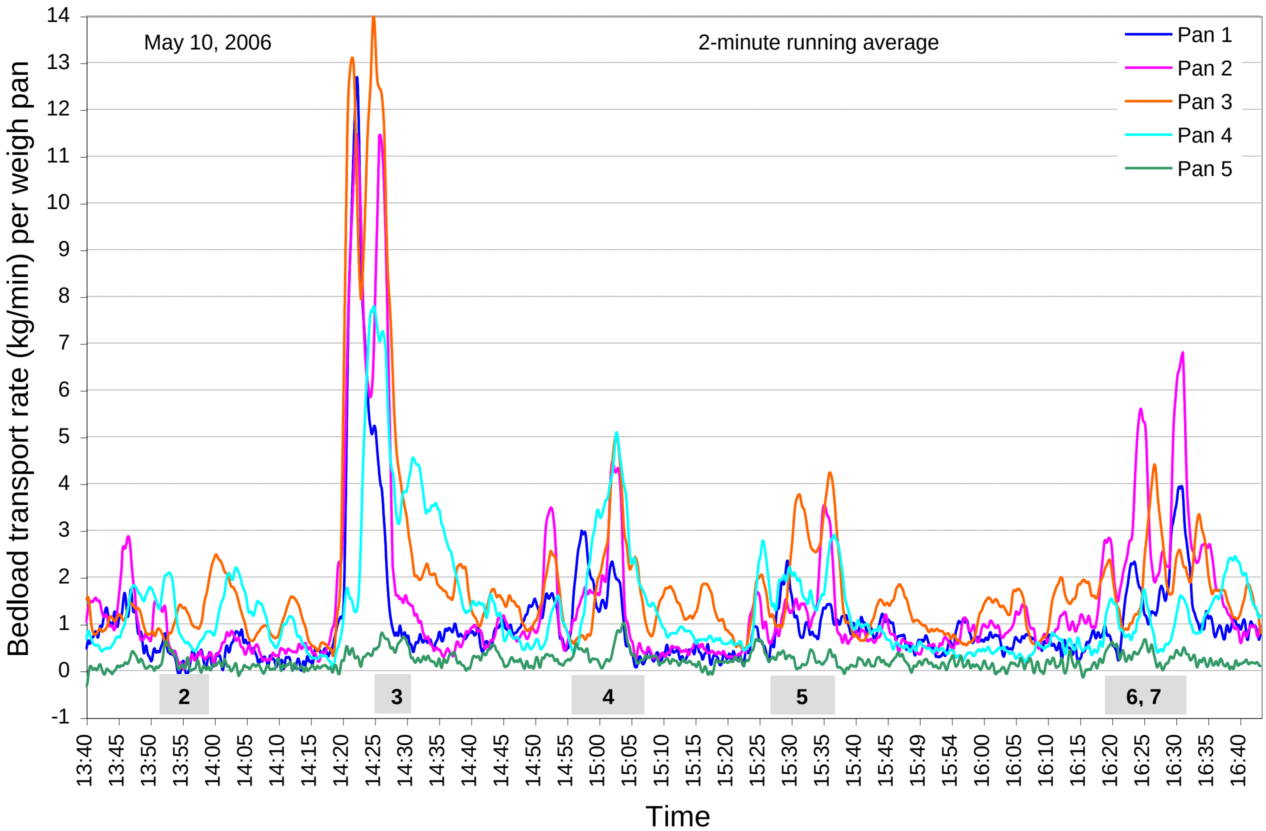

Figure 2. Two-minute running average of transport rates measured at the weigh pans at the SAFL flume. Note the interference between the two samplers and extreme increases in transport rates caused by stepping onto the bed and servicing bedload traps. Numbered gray boxes above the x-axis indicate sample number and duration over which bedload traps were deployed (from Bunte and Swingle 2007).

Interference between two samplers can be compensated to some degree. Under steady or regularly fluctuating transport conditions, placement of the two devices further apart—temporally or spatially—might remedy the problem. Instead of comparing transport rates $Q_{B\,surr}$ computed from the surrogate device at time 1 and location 1 with transport rates $Q_{B\,cal}$ measured by the calibration device at a nearby time and/or location 2, one can compare $Q_{B\,surr}$ to a $Q_{B\,cal}$ measured at a more distant time 2 and/or location 2 (**Fig. 3a**), provided that both devices facilitate temporal and/or spatial averaging. However, if the distance between the two devices causes an increase in the difference in transport between time 1 and/or location 1 and that at time 2 and/or location 2, distancing the two devices exacerbates problems that are caused by temporal and spatial variability in the stream system (see above). Similarly, if transport rates fluctuate irregularly, or are affected by underlying long-term variability, spacing the calibration device $Q_{B\,cal}$ to avoid interference may not result in a completely satisfactory solution unless it is accompanied by an increase in the integration time or the number of samples (**Fig. 3b**).

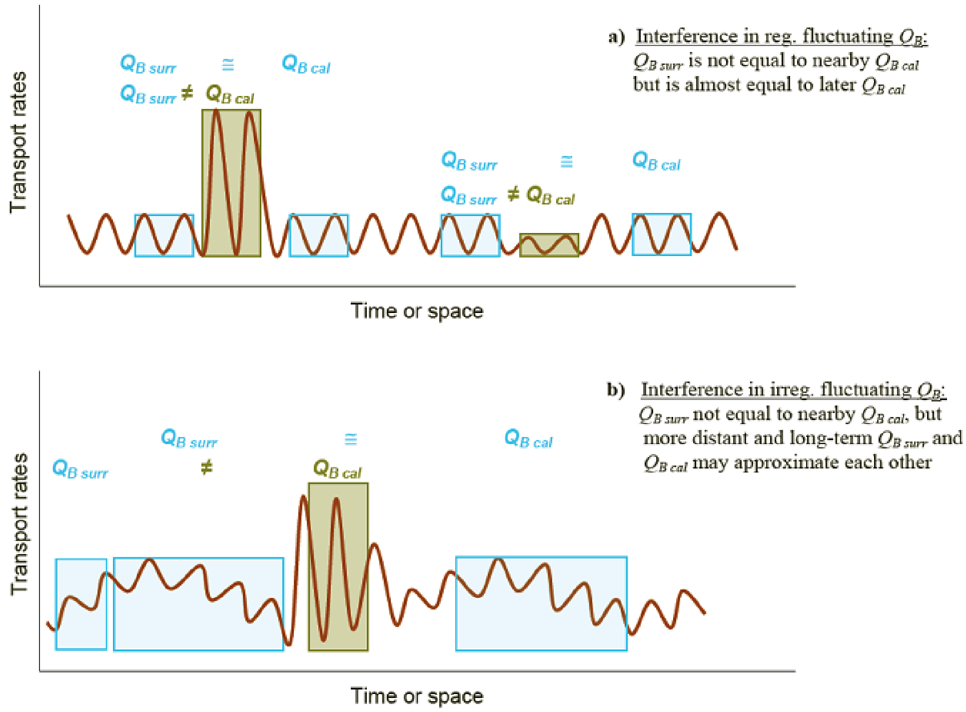

Figure 3. Transport variability and conditions under which transport sampled with the surrogate device 1 at time and/or location 1 ($Q_{B\ surr}$) is unequal to transport sampled with the calibration device 2 at time and/or location 2 ($Q_{B\ cal}$). Olive-colored fields indicate misfit.

Lack of a suitable sampler

A suitable sampler for calibration of surrogate devices is one that provides relatively accurate bedload transport rates and particle sizes due to features such as large opening size, no involuntary particle dislodgement and entrainment from the bed, long sampling duration, and acceptable sampling efficiency for a specified set of stream and flow conditions. The sampler also needs to be able to average over different temporal and lateral scales in order to integrate over fluctuating transport and to facilitate measurements in a scale over which the surrogate device measures. Unless the calibration effort can be moved to an existing stationary sampler, the calibration sampler should be easy to install and operate at any stream location with respect to the surrogate device without significant stream disturbance. A selection of stationary and portable samplers that are commonly used for bedload sampling will be examined with respect to these tasks.

Stationary samplers include vortex samplers, weighable pit traps, conveyor belt samplers, and sediment retention basins. Those samplers are typically installed as part of a permanent research facility. Vortex (e.g., Milhous 1973; Hayward and Sutherland 1974; Atkinson 1994) and conveyor belt samplers (Klingeman and Emmett 1982, Leopold and Emmett, 1997) permit long sampling times and can yield adequate samples of instantaneous transport rates and particle sizes against which a surrogate's signal output could be compared. However, installing these devices requires substantial streambed construction, and the resulting lack of mobility of these collectors requires that the surrogate technology be tested at an existing site. Debris or sediment-retention basins exist on several streams or can be temporarily built if the stream is small. Signal rates and properties recorded over a transport event can then be compared to the mass and particle-size distribution of sediment accumulated in the debris basin during the same event (e.g., Troendle et al. 1996; Bunte and Swingle 2003). A problem with the event- or season-long integration time is that one cannot determine whether the surrogate device correctly estimated all transport rates and particle sizes, or whether it overestimated some while underestimating others. Weighable pit traps (such as the Reid slot sampler previously termed the Birkbeck sampler, as well as load cells, e.g., Reid et al. 1985; Laronne et al. 1992; Garcia et al. 2000; Laronne et al. 2003; Sear 2003) are the most commonly used semi-permanent samplers which nevertheless require considerable construction effort. They continuously and automatically weigh the sediment mass accumulating in an underground weighable chamber. While they can provide accurate accounts of bedload transport rates, they do not provide continuous information on the instantaneous bedload particle-size distribution. Net frame samplers (Bunte 1996; Whitaker 1997; Whitaker and Potts 1996) and unweighable pit traps (e.g., Powell and Ashworth 1995; Hassan and Church 2001; Sterling and Church 2002) require less stream installation and provide physical samples, but are difficult to operate at high flow and may require several persons to operate.

Among bedload samplers that are portable are Helley-Smith type (pressure difference) samplers (e.g., Helley and Smith 1971, Emmett 1980; Ryan 2005), basket samplers (e.g., Nanson 1974, Engel and Lau 1981; Nankervis 1994; Wilcock 2000), and bedload traps (e.g., Bunte et al. 2004, 2007a, 2008). Due to their availability and relative ease of use, Helley-Smith type (HS) samplers are often used for field measurements of bedload transport in gravel-bed streams (King et al. 2004, Ryan et al. 2005). However, HS samplers are not always ideal for calibration of surrogate devices in gravel bed streams. The original HS sampler with a 7.6 by 7.6 cm opening (3-inch Helley-Smith) was designed for collection of bedload ranging in size from sand to medium gravel. It has a strongly flared opening to compensate for the retardation of flow velocity through the fine sampler net, but this shape results in a hydraulic efficiency larger than 1. Helley-Smith type samplers with larger opening sizes exist to allow larger particles to enter the sampler (e.g., the 15.2 by 15.2 cm or 6-inch Helley-Smith, the 10.2 by 20.3 cm opening Elwha sampler, the 30.4 by 15.2 cm opening Toutle River II sampler, and the 30.4 by 30.4 cm opening BTMA-2 sampler (Duizenstra 2001 a and b)). Some versions of HS samplers (e.g., US BL 84, Elwha, and Toutle) have reduced the high hydraulic efficiency. However, when compared in similar settings, the differently sized and shaped HS samplers collect different transport rates and particle sizes (e.g., Gray et al. 1991; Childers 1991, 1999; Ryan and Porth 1999; Ryan and Troendle 1997, Ryan 2005; Vericat et al. 2006a), a factor that makes them not well suited for field calibration of surrogate devices. The variations in sampler opening size and shape also do not solve the core problem of HS-type samplers that arises from direct placement of the sampler onto a gravel bed. On gravel beds rich in small gravel particles, the direct placement of the sampler onto the bed occasionally dislodges some bed particles that can then be entrained into the sampler due to its hydraulic efficiency larger than 1. Involuntary particle captures can add up when the sampler is placed onto a mobile gravel bed up to 20 or 40 times for one cross-sectional sample and may cause oversampling (Bunte et al. 2005, 2007 b). When placed onto a coarse gravel or cobble bed, the sampler can become perched on top of large rocks, and smaller particles can pass under the sampler, causing undersampling. Consequently, transport rates collected with Helley-Smith type samplers seem to be afflicted by over- or undersampling of gravel transport when compared to other devices (e.g., Hubbell et al. 1985, 1987; Sterling and Church 2002), particularly when transport is below 10 g/m·s (Bunte et al. 2004; 2005, 2007 b and 2008). At high transport rates when a large number of particles are streaming into the sampler on an otherwise stable coarse gravel bed, effects from perching or involuntary particle entrainment become negligible. Another problem of HS-type samplers is the short sampling times of typically 0.5 - 2 minutes (ranging from about 10 seconds to 5 minutes). Not being able to integrate over short-term fluctuations of bedload transport requires that a large number of consecutive samples are collected and combined. Short sampling times also compromise the sampling accuracy, leading to oversampling of fluctuating transport rates when transport is low and undersampling when transport is high (Bunte and Abt 2005 a). Based on these sampling characteristics, HS-type samplers seem to provide their best sampling results when used on a stable coarse gravel bed during high transport rates > 10 g/m·s, when placed onto a sill or ground plates, and for the collection of sand to gravel particles that fit easily into the opening size. When tested on a sill, Emmett (1980, 1984) found that most sampling results from the original HS sampler were within 50 to 200 % of those collected in a conveyor belt sampler.

Basket samplers can take a variety of different shapes, sizes, mesh widths (Hubbell 1964; Engel and Lau 1981), and deployment modes (e.g., by crane, Nanson 1974; hanging from an overfall, Wilcock 2000; staked to the streambed, Nankervis 1994). Their sampling times can range from minutes to days. Because their performance varies depending on sampler shape, size, mesh width, bed contact, sampling time, transport rates (Engel and Lau 1981), their suitability for calibration of surrogate devices needs be established for each case.

Bedload traps are a relatively new device developed for sampling gravel bedload in wadeable mountain gravel-bed streams in 1998. Bedload traps have been tested in numerous field studies (Bunte et al. 2004, 2005, 2007a and 2008). Their construction and performance is discussed below.

Bedload traps likely suitable for field calibration of signal outputs

Bedload traps were introduced by Bunte and Abt (2003) and Bunte et al. (2004, 2007a and 2008) and designed to overcome some of the problems of HS-type samplers. Bedload traps have a large opening size, a large sampler volume, permit long sampling times, and avoid direct bed contact and thus involuntary particle capture. Due to these properties, bedload traps have relatively accurate sampling results, particularly for relatively low transport rates of gravel particles, and they were approved as appropriate samplers for coarse channels by the Federal Sedimentation Interagency Project (FISP 2009). Bedload traps permit the temporal and spatial averaging that is often required for calibration of surrogate devices. Combined with portability and ease of installation, bedload traps may be suited for calibration of surrogate technologies in conditions typical of flows up to bankfull (approx. 1.5 to 2-year recurrence interval flow) in wadeable mountain gravel-bed streams.

Bedload trap description and installation

Bedload traps consist of an aluminum frame 0.3 by 0.2 m (**Fig. 4 a and b**) that is non-flared and large enough to accommodate coarse gravel and small cobble particles. A large and sturdy nylon net 0.9 – 1.6 m long is attached to the frame to receive the bedload. A 3.5 mm mesh opening allows water to flow through the net with little retardation of flow and collects particles larger than 4 mm while smaller particles pass through the net. The sampler frame can be welded in a metal shop. The net is hand sewn using netting available from aqua culture supplies. With volumes of 25 and 45 liters for 0.9 and 1.6 m long net, the bedload trap capacity (40% of the sampler volume) is approximately 10 and 18 liters or 16 and 29 kg of gravel, respectively (assuming a bulk density of 1.6 g/cm^3 for gravel > 4 mm). This capacity permits the collection of large samples which is necessary because streams often carry large amounts of coarse organic debris, particularly on the first rising limb of a highflow event. Gravel transport rates in relatively undisturbed coarse-bedded mountain streams were found to range from 1E-3 to 1E-6 at the lowest transporting flows and yielded 0.03 to 100 g/s at bankfull flow (Table 1) (Bunte et al. 2008). Localized unit transport rates ranged from 1E-6 to 10 g/m·s but exceeded 100 g/m·s when sediment supply was very high. Local transport rates of 10 g/m·s fill a 0.9 m long bedload trap net with about 11 kg of gravel within one hour. If local transport rates reach 100 g/m·s, those traps may fill within a few minutes, whereas the 1.6 m long nets take a few minutes more to fill.

Bedload traps are mounted onto ground plates 0.28 by 0.41 m in size that are placed at the average height of the bed (non-protruding) and are anchored to the stream bottom with two metal stakes pounded into the bed. Placement of bedload traps onto ground plates avoids involuntary particle pick-up when deploying, emptying, and retrieving the traps. Should the bed scour or aggrade at high flows, ground plates may no longer sit at the average height of the bed and need to be lowered or elevated to be at the average height of the bed. This can be tricky at high (but still wadeable) flow and may not achieve as good a fit as when done at low flows, and biased transport rates are possible. Bed scour due to operators wading close to the traps can be limited by installing iron stepping stones (e.g., 25 lb gym weights) at the average height of the bed (non-protruding). Attachment of the bedload traps to the stakes with webbing straps permits long sampling times (typically one hour) during which operator attendance is not required. Several bedload traps can be installed across a stream spaced 1-2 m apart, and they sample simultaneously. Traps do not need to be spaced evenly, but can cover stream sections of presumed high transport more densely than sections where transport is presumed to be low. Detailed information on how to construct and operate bedload traps is provided in a guideline document (Bunte et al. 2007a).

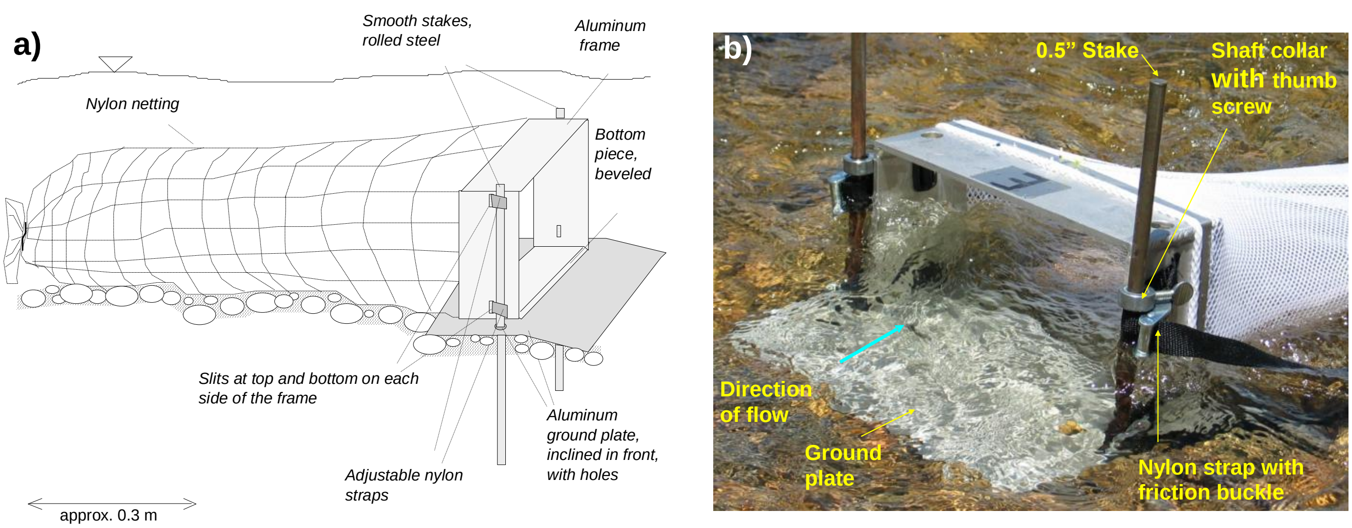

Figure 4. Drawing of bedload trap (a). Bedload trap installed on a ground plate at low flow (b) (from Bunte et al. 2007a).

Typical operation

Because local transport rates in Rocky Mountain gravel-bed streams are typically below 10 g/m·s during much or all of a snowmelt highflow season, a sampling time of 1 hour per sample can be maintained for the majority of the samples. Long sampling times are desirable to integrate over fluctuating transport rates and to avoid oversampling at low and undersampling at high transport (Bunte and Abt 2005a). If local transport rates exceed 10 or 100 g/m·s, sampling time needs to be reduced to 30 or even 5 minutes in order not to overfill the sampler net. When local transport rates exceed about 300 g/m·s, bedload moves in gravel sheets several cm thick. In these conditions, bedload traps fill to capacity within minutes and have reached the limit of deployment.

Bedload traps can be operated by two people at flows up to the limit of wadeability (Abt et al. 1989) (**Fig. 5a**). A foot bridge is convenient when bedload traps are operated throughout a highflow season. Typically, the trap nets are emptied from the rear with the frame remaining fastened on the ground plate. One operator stands next to the trap entrance (at the upstream side of the bridge), checks the position of the ground plates, and lifts the net out of the water (onto the bridge). The other operator stands near the end of the net (or crouches on the bridge), unties the cord that holds the end of the net together and empties the contents of the net into buckets (**Fig. 5b**). The net is retied and released into the flow for the next sample. The collected bedload is washed in the field to remove the organic debris, bagged, dried, sieved in 0.5 phi increments and weighed. Transport rates are computed individually for each bedload trap (g/m·s), assigned to the fraction of stream width represented by each trap (g·m/m·s = g/s) and summed over all traps in the cross-section to obtain the cross-sectional transport rate (g/s). No special technical expertise is required to derive reliable data from the bedload trap technology. Once an operator is familiar with the details of bedload trap deployment and potential problems to avoid, the most important operator qualification is diligence and perseverance.

Figure 5. Six bedload traps installed in the stream are emptied at 80% of bankfull flow (a). Emptying of bedload trap using a foot bridge (b)

Performance of bedload traps: results from field and flume testing

Over the past nine years, we have used and tested our bedload trap design in nine field studies at eight different sites in coarse gravel- and cobble-bed mountain streams with snowmelt regimes (Bunte et al. 2008) (Table 1). The stream reaches were selected to have relatively wide and wadeable cross-section at bankfull flow, with flow depths of less than 0.5 m and flow velocities of less than 2 m/s. Sampled flows ranged from 10% to 149% of bankfull discharge (Q_{bkf}), where bankfull flow approximates the 1.5 to 2 year recurrence interval flow. In the Rocky Mountain streams studied, bankfull flows occur on average for a few days per year, although there are years when flows will reach only 70% of bankfull flow, while other years have several weeks of flow higher than bankfull. Bedload traps worked well as long as flows remained wadeable, local transport rates did not exceed 20 g/m·s, and the bed near the traps did not experience pronounced scour or aggradation.

Table 1: Main characteristics of the nine Rocky Mountain bedload trap study sites.

PARAMETER / STREAM AND YEAR SAMPLED	BASIN AREA (KM²)	BANK-FULL FLOW (M^3/S)	BANK-FULL WIDTH (M)	MEAS'D RANGE OF FLOW (% Q_{BKF})	WATER SURFACE SLOPE (M/M)	BED SUR-FACE D_{50} (MM)	GRAVEL TRANSPORT RATE Q_B (G/S) AT 20% Q BANK FULL	GRAVEL TRANSPORT RATE Q_B (G/S) AT 100% Q BANK FULL	PREDOMINANT STREAM TYPE (MONTGOMERY AND BUFFINGTON 1997)

St. Louis Cr., ‘98	34	3.99	6.5	26 - 65	0.017	76	9.3E-8	3.30	plane-bed
Little Granite Cr., nr. confluence ‘99	55	5.66	14.3	61 - 131	0.017	59	5.1E-11	10.7	plane-bed
Cherry Cr., ‘99	41	3.09	9.5	49 - 145	0.025	49	7.3E-11	0.034	plane-bed, forced pool-riffle, cascade
E. St. Louis Cr., ‘01	8	0.76	3.7	26 - 71	0.093	108	1.9E-6	1.39*	step-pool
Little Granite Cr., abv. Boulder Cr. ‘02	19	2.83	6.3	37 - 102	0.012	67	5.8E-6	4.56	plane-bed
E. St. Louis Cr., ‘03	8	0.76	3.7	44 - 144	0.093	108	1.3E-7	0.24	step-pool
Halfmoon Cr., ‘04	61	6.23	8.6	17 - 77	0.014	49	1.6E-4	52.5*	plane-bed, with forced pool-riffle
Hayden Cr., ‘05	39	1.92	6.5	28 - 149	0.038	63	1.8E-7	1.43	step-pool, plane-bed, mixed
East Dallas Cr., 07	34	3.40	7.5	10 - 113	0.016	58	2.6E-3	157	Plane-bed, with forced pool-riffle

* Bankfull bedload transport rate extrapolated from fitted power function relationship $Q_B = aQ^b$.

Several observations led us to believe that bedload traps produce relatively accurate samples of gravel transport. One is that bedload transport rating and flow competence curves are well defined at all sites and that the relationships are steep (Bunte et al. 2008). The exponents of fitted power function relations between transport rates and flow ranged between 7 and 16. Similarly high exponents have been reported by other studies in mountain gravel-bed streams that use samplers that likewise had large openings, permitted long sampling times, and did not involuntarily pick up particles from the streambed (e.g., Nanson 1974; Whitaker 1997; Whitaker and Potts 1996; Bunte 1996; 1997; Garcia et al. 2000; Wilcock 2000, 2001; Hassan and Church 2001). Theoretical considerations suggest that the relationship between bedload transport and flow should be steep in coarse-bedded streams when transport rates are low and relatively few particles are involved in transport (see bedload equations by Einstein (1950) and by Parker et al. (1982)).

An incipient motion study gave further evidence that bedload traps produce relatively accurate samples of gravel transport. Wilcock (1988) postulated that incipient motion results obtained from the largest particle approach and the small transport rate approach would not be compatible unless sampling errors were small. Our samples showed that critical flow for all particle sizes was quite similar from both approaches (Bunte et al. 2004).

The sampling efficiency of bedload traps compared favorably with the sediment mass excavated from a debris basin. Transport rates obtained from more than three weeks of intensive bedload trap sampling just upstream from a debris basin over a snowmelt highflow season were summed to computed annual load (Bunte and Swingle 2003; Bunte and Abt 2005b). Transport rates for unmeasured times were interpolated and assigned a low, medium (2 x low) and a high (3 x low) estimate. Depending on the estimate used, bedload traps matched the sediment mass accumulated in the debris basin to within 56 - 117%.

The hydraulic patterns at the bedload trap entrance appear to indicate relatively little disturbances on bedload particles advancing towards bedload traps. Velocity profiles measured on the ground plate and on the bed at various distances in front of the bedload traps (Bunte and Swingle 2004) showed that smooth ground plates accelerated the near-bottom flow velocity by 14 to 48% compared to the bed 0.69 m upstream of the traps, while the flow velocity 0.1 m above ground in the center of the traps was between 5% faster and 15% slower compared to velocity profiles 0.3 to 0.7 m in front of the traps. Higher flow and trap fullness decreased the hydraulic effects caused by the presence of bedload traps. The increase in near-bottom flow velocity on the ground plates as well as its smoothness ensures that particles that have moved up to the ground plate keep moving into the bedload trap. How far the increased near-bottom velocity on the ground plate extends onto the bed in front of the bedload traps could not be determined because near-bottom flow velocities measured on the bed at various distances upstream of the bedload traps were either faster or slower than on the ground plate and showed no trend with distance away from the trap. These variations are attributed to local bed topography and the roughness around individual bed particles. Most likely, the increase in near-bottom velocity on the ground plate does not to extend onto the bed, because the unflared bedload trap frame generally retards the approaching flow (i.e., causes a hydraulic efficiency < 1). The effect of ground plates is thus not likely to be comparable to the increased hydraulic efficiency of the Helley-Smith sampler. Besides, the hydraulic efficiency > 1 of the Helley-Smith sampler appears to act primarily on particles that bedload traps do not capture: sand and pea gravel moving in near-bed suspension as well as particles dislodged and mobilized when the HS sampler is set onto the bed.

A comparison of transport rates from bedload trap with those measured in the weigh pans in the St. Anthony Falls Laboratory flumes showed the effects of bedload trap deployment in unfavorable conditions (Bunte and Swingle 2007). The 0.6 m flow depth was too deep to properly service the traps, and the bed was very loose. Consisting of gravel 2.8 to 32 mm with very little sand (surface D_{50} size of 10 – 16 mm and subsurface D_{50} size of 9 mm) made the bed easy to mobilize by wading and local scour—very different from conditions encountered in mountain gravel-bed streams (Compare to Table 1). Although bedload traps were not designed for those conditions, 12 of the 17 cross-sectionally averaged samples collected in the flume were within 50-200% of the cross-sectionally averaged transport rates measured over five weigh pans immediately downstream.

Limitations of bedload traps

Similar to other physical samplers, bedload traps have their limitations. They do not collect particles smaller than 4 mm (unless traps can be equipped with a 1.18 mm net at very low flows (Bunte and Swingle 2009)). They are operable in wadeable flows only, and they require a stable coarse gravel or fine cobble bed for optimal sampling results. Scour and aggradation of the bed near the sampler entrance can negatively affect the sampling result (as it does for stationary samplers as well as HS-type samplers), thus operators need to be careful when wading close to the traps, particularly on finer or mobile beds. High transport rates of 100 g/m·s reduce the bedload trap sampling time to a few minutes per sample (similar to HS sampler), and traps loose their advantage of averaging over short-term fluctuating transport rates. Bedload traps are relatively labor intensive to operate: it takes two persons about 1 minute to retrieve a sample from one bedload trap and up to 10 or 20 minutes to field process and/or bag it, depending on the collected mass and the amount of organic material a sample contains. The operation of bedload traps can be physically demanding, particularly when flow approaches the limit of wadeability, when it gets dark, when a large number of samples are collected, when the sample mass becomes large, and when the operators get cold and wet and tired (all good reasons for using a surrogate technology).

Summary and conclusion

This study discussed the necessity and difficulties of field calibration. Field calibration is necessary because lab experiments provide a sheltered environment for the surrogate device in which several sources of electrical noise that may occur in the field are eliminated. Field conditions are also likely to have a larger range of transport rates, particle sizes, and transport patterns than lab trials, and one should ensure that the surrogate device is capable of accurately measuring those.

Field calibrations of surrogate devices require a physical sampler that provides true transport rates and bedload particle sizes. However, a suitable sampler is often not available. Temporal and spatial variability of transport rates also pose difficulties because samples collected one-after-the-other or one-next-to-the-other exhibit different transport rates. Spatial and temporal averaging can mitigate these problems, but to do so, one either needs a sampler that permits long sampling times or one needs to collect a large number of samples. To calibrate a surrogate technology that integrates over the stream width, the sampling device needs to collect bedload simultaneously at different stream locations. Stationary samplers can provide accurate sampling results, but require that the calibration device be brought and tested at the stationary sampler. Of the portable samplers, HS-type samplers seem to provide relative accurate sampling results when deployed on a relative stable, coarse gravel bed, during high transport rates and when placed on a sill or on ground plates, provided that particles to be collected fit easily into the opening size. However, sampling times for HS-type samplers are typically short and—unless uncommonly large bags are attached to the sampler or numerous samples are collected—do not allow temporal averaging. Cross-sectional averaging likewise requires numerous samples.

Based on the authors' experience with bedload traps for many years, bedload traps may be suitable for calibration of surrogate devices due to their sampling characteristics:

- Several findings suggest that bedload traps produce relatively accurate sampling results:
  - The steep increase in relationships of gravel transport rates and flow during low transport rates typical of bedload trap samples is suggested from theoretical considerations of bedload transport;
  - Bedload trap transport relationships are relatively well defined;
  - Critical flow for incipient motion is similar for both the largest particle and the small transport rate approach—an indication of low sampling error (Wilcock 1988; Bunte et al. 2004)).
  - Field and lab calibration of bedload traps showed that they matched true transport rates to within 56 - 117% in field measurements, and to within 50 – 200% for most of the flume samples, even though flume conditions were unfavorable for bedload traps.

- Bedload traps can be relatively easily manufactured and brought to a field site; their installation and operation is easily learned (Bunte et al. 2007a);
- Bedload traps can be installed at any wadeable stream location, preferably on relatively stable and coarse gravel beds and downstream of the surrogate device;

- The long sampling time possible with bedload traps during low and moderate transport rates facilitates temporal averaging over fluctuating transport rates which
  - provides a more meaningful mean transport rate in relation to flow,
  - is necessary to prevent oversampling at low transport and undersampling at high transport (Bunte and Abt 2005a), and
  - is important for a meaningful comparison of transport rates derived from a surrogate device and a measured with a calibration device because otherwise, calibrations and surrogate devices might measure different transport rates (see Figs. 1b – 1d).

- Bedload traps can cover and integrate over different lateral scales:
  - a row of traps can be installed that sample simultaneously and cover the stream width to match the lateral scale of a surrogate device that integrates its measurements over the stream width (e.g., a hydrophone),
  - one or a few individual traps can be installed close to an individual surrogate device to match the spatial scale of a surrogate device that records local transport (e.g., an impact sensor),

- When transport is laterally fluctuating, the calibration and surrogate device might sample different transport rates. Lateral integration averages over the fluctuations and provides a more meaningful comparison of sampled transport rats with signal rates recorded from the surrogate device.

Based on the possibilities that bedload traps offer, bedload traps appear suitable as calibration device when bedload particles larger 4 mm in size are to be collected on a stable, coarse gravel-bed, under partially mobile transport condition (e.g. Wilcock and McArdell 1993, 1997) with transport rates below 10 g/m·s, and when flows are wadeable (Table 2). Bedload traps accurately sample bedload at transport rates up to 100 g/m·s, but they loose their advantage of long sampling times. Bedload traps cannot be used as calibration device for bedload particles smaller than 4 mm. They are not designed for loose and highly mobile gravel beds or those composed of coarse cobbles only, nor when significant bed scour or aggradation occurs, nor for unwadeable flows.

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