Published online in 2010 as part of U.S. Geological Survey Scientific Investigations Report 2010-5091.

Calibration of a Passive Acoustic Bedload Monitoring System in Japanese Mountain Rivers

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ABSTRACT

A pipe geophone has been deployed and calibrated at several sabo dams on gravel bed rivers located throughout the Japanese Alps. The principle of this surrogate bedload monitoring technique is based on the sound wave generated as a bedload particle collides on the pipe. The acoustic response, registered by a microphone located within the open space of the pipe, is amplified and recorded whenever a threshold is surpassed. The number of collisions is thence related to the bedload discharge recorded by a nearby automatic, Reid-type slot sampler.

Results from two geophone-slot sampler systems on the gravel-bedded Nishi-takiga-tani and the Ashi-arai-tani mountain rivers show that calibration may readily be obtained for 5-min averaged data when bedload discharge is intermediate (0.01-0.1 kg/sm), but for low bedload discharges (<0.01 kg/sm) the averaging time needs to be increased. At high bedload discharges (>0.1 kg/sm) the acoustic system becomes saturated. By utilizing a geophone recording system with 6 channels, each fourfold less sensitive than its predecessor, sensitivities in the range 1-1024 are obtained, such that the less sensitive channels do not become saturated even at very high bedload discharges. The relationship between the responses of channels of varying sensitivity allows calibration also during high floods on the Joganzi River, when bedload discharge is very elevated.

INTRODUCTION

The determination of bedload discharge involves technological difficulties with particular reference to coarse-grained sedimentary particles. The stumbling blocks result from energetic flow conditions involving considerable turbulence, high turbidity and a rough character of the bed. The intricacies are supplemented by the influence that samplers may have on bedload discharge, sampler hydraulic and sampling efficiency, as well as ability to sample for long durations. Samplers are still widely used for research as well as for routine monitoring of bedload discharge and texture, but the relevant complexity have brought forwards the realization that the development of surrogate bedload monitoring techniques is required.

Acoustic detection of bedload has been studied during half a century (e.g., Ivicsics, 1956; Johnston and Muir, 1969; Tywoniuck and Warnock, 1973; Anderson, 1976; Jonys, 1976; Richards and Milne, 1979; Downing, 1981; Froehlich, 1982; Thorne, 1986a; Bänziger and Burch, 1990; Sawai, 1990). Noteworthy are the large number of field studies undertaken by the Swiss on piezoelectric and passive acoustic detection of bedload transport since the end of the 80's (see Rickenmann and Fritschi, 2007) and ongoing (e.g., Rickenmann and McArdell, 2007).

A series of publications on the use of acoustic signals to monitor bedload movement in the marine environment are also notable, among others because the motion of bedload was not only monitored acoustically, but it was observed by videography contemporaneous with the monitoring of turbulent fluctuations of near-bed flow velocity (Thorne et al., 1984; Thorne, 1985; 1986a; 1986b; Williams et al., 1989). Indeed, the marine environment is particularly interesting for the study of phenomena by modern acoustic techniques (Caiti et al., 2006) that may in part be transferable to the study and monitoring of sediment transport in rivers.

Although some success has been gained in monitoring bedload discharge by the use of passive acoustics (Jagger and Hardisty, 1991; Rouse, 1994; Rickenmann, 1997; Mizuyama et al., 1998, Rickenmann, 1998; Taniguchi et al., 1992; Mizuyama et al., 2002; Bogen and Møen, 2003; Mizuyama et al., 2003; Hoshino et al., 2004; Oda et al., 2004, 2005) and more recently by using active acoustics (Rennie and Millar, 2004) as well as other methods (Tunnicliffe et al., 2000; Downing et al., 2003; Gottesfeld & Tunnicliffe, 2003), several technical problems appear to have remained unsolved. Among the most crucial aspects requiring further investigation relevant to the use of passive acoustics are (1) the characteristics of a geophone that determine the detection limit of small bedload particles and, relevantly, (2) the detection of small bedload discharges, (3) the extent to which the acoustic signals determined by particle mass (essentially size, but may also include density) and shape can be separated from the effects of bedload discharge, (4) acoustic monitoring of very high bedload discharges and (5) flow conditions (hydraulics, mode of particle movement) as important elements which may influence calibration of a passive surrogate bedload monitoring device. Most relevant to this study, hitherto no attempt has been undertaken to calibrate passively-generated acoustic signals (or Self-Generated Noise, SGN a-la Thorne, 1986a) generated by the transport of coarse-grained (> 2 mm) sediment under field conditions involving (1) automatic, (2) short-term and (3) long duration of monitoring. This is the objective of the study reported herein.

The objective of this study is to determine the extent to which the Japanese pipe geophone system may be calibrated against continuously monitored, direct bedload discharge measurements obtained from automatic slot samplers deployed in Japanese gravel-bed mountain rivers. This is obtained by simultaneous acoustic monitoring of gravel impacts and proximal direct measurements of low, intermediate or high bedload discharges. The effect of geophone characteristics, sediment discharge and sediment size on geophone response is in a companion paper (Mizuyama et al., 2010).

SEDIMENT PROBLEMS AND SURROGATE BEDLOAD MONITORING IN JAPANESE MOUNTAIN RIVERS

Japanese mountain rivers generally have low concentrations of suspended sediment and low bedload yields. However, both are elevated in areas of volcanic activity and after heavy rainfall, especially because hillslopes are steep as are river gradients. The very considerable role of Sabo[1] works (http://www.sabo-int.org/) in the construction and maintenance of geophone deployment for bedload monitoring in Japan cannot be overstressed. Bedload discharge monitoring is undertaken to evaluate bed activity and sediment wedge advance after major typhoons, landsliding and debris flows have occurred, generating hazards to human occupancy of riparian lands. Unlike suspended sediment, bedload discharge is difficult to measure in mountain rivers: floods are short-lived on all but the largest rivers, flow is often supercritical, bed topography is very rough and irregular and bedload may include large clasts. These conditions require the construction of gigantic Reid (formerly termed Birkbeck-type[2]) automatic bedload slot samplers, and although these are accurate and very well-suited for particular studies of bedload, they are expensive and rather difficult to deploy as a government-operated, standard national technology.

Indirect bedload monitoring methods such as acoustic geophones are required not only to determine bedload discharge, but also for the prediction of river bed elevation change downstream, based upon which warning may be issued to trigger the operation of downstream Sabo dam gates. The development and deployment of surrogate bedload monitoring in Japanese mountain rivers is expected to allow inter-comparison among bedload formulae, and to determine conditions of initiation of bedload and which best fits such rough conditions for the use of Sabo works. Additional to the study of bedload and the passage of bedload waves, a variety of fluvial phenomena dependent on bedload discharge may be studied with a technology such as the Japanese pipe geophone system, the field calibration of which is presented herewith.

THE JAPANESE ACOUSTIC BEDLOAD MONITORING SYSTEM

The following describes basics of the acoustic response due to particle collision onto a pipe, components of the passive acoustic Japanese pipe system, data processing, system deployment and river locations.

Acoustic principles

When bedload particles collide onto a half-buried pipe that is closed at both ends and deployed across a river bed, oscillations of air are generated inside the pipe. These propagate to the circumference, radial and axial directions in the closed pipe. The frequencies of the 1st mode of the peripheral (f_p), radial (f_r) and axial (f_a) directions are represented by:

$$f_p = 0.30\ c/r \tag{1}$$

[1] Sabo erosion and sediment control activities are meant to reduce sediment discharge in order to decrease the risks of flooding due to river bed aggradation by excess sediment discharge from mountainous areas. Sabo is a Japanese word: *Sa* literally means sand or sediment and *Bo* is control. The intensive erosion and sediment control works with high check dams (Sabo dams) in Japan are a world-unique phenomenon.

[2] The infamous Birkbeck slot sampler was developed by Ian Reid (Reid et al, 1980), who at the time was working at Birkbeck College. In sympathy with the naming of the Helley- Smith Arnhem-type bedload sampler, it is hereby suggested to name this slot sampler the Reid sampler.

$$f_r = 0.61\ c/r \tag{2}$$
$$f_a = c/(2\ l) \tag{3}$$

where c is the sound velocity in air, r is radius, and l is the length of the confined space in the pipe. The peripheral frequency f_p is the most dominant when the pipe ends are stabilized for free vibration and when vibrations from the base are decreased (Sawai, 1990). Identifying the impact of individual particles allows determination of the total number of particles and for those of constant size, it permits evaluating the total mass of moving particles; i.e. bedload discharge.

The energy density of the echo, ε, in a room depends on the initial energy density of the sound, ε_o:

$$\varepsilon = \varepsilon_o \exp(-13.6\ t/T) \tag{4}$$

where t is elapsed time and T is the characteristic time of the echo. Factors such as the velocity, mass, position and angle of collision of particles affect ε_o. This explains the complexity of determining grain-size of moving bedload particles from collision impact (e.g., Sawai, 1990), although some studies indicate that analysis of frequency spectra may allow the separate determination of grain-size (Thorne, 1986a; Møen et al. 2007; Krein, et al., 2007).

Signal processing

The Japanese acoustic bedload monitoring system consists of a pipe deployed across a riverbed (Fig. 1a). Vibrations of air generated by collision of a sediment particle onto the pipe are detected by a microphone (Fig. 1b). These are amplified by a preamplifier (Fig 1c) and transmitted to a converter (Fig 1d). Microphone and preamplifier are installed inside the pipe. The output of the preamplifier is a waveform (Fig 2a) which has a given frequency response (Fig 2b), for which no Fourier transformation is undertaken, but for which a converter undertakes corrugated processing, ultimately involving the transformation of an output (Fig 2c) to a square wave (Fig. 2d). The transformation of the signal from a sinusoidal to a square wave form is undertaken to ensure that the collision of a single particle is recorded when the output from a channel surpasses a given threshold.

The peak output of the preamplifier (magnified by a factor of 10 relative to the peak output of the microphone) is sent to the converter. The converter generates a voltage (200 mV) which is processed through a 6-channel band-path filter, each channel having a gain of 4 relative to the previous, lesser voltage-output channel. The band-path filters have lower (2.5 V) and upper (5 V) thresholds: a pulse is generated when the output of a channel surpasses 2.5 V. For example (denoting channel by ch), a peak microphone output of 0.5 mV is magnified 10 times by the preamplifier, sending 5 mV to the converter. Generating 200 mV, the 6-channel voltage exiting the converter's amplifier is as follows: ch6 (x1) = 0.05 V, ch5 (x4) = 0.2 V, ch4 (x16) = 0.8 V, ch3 (x64) = 3.2 V, ch2 (x256) = 5.0 V, ch1 (x1016) = 5.0 V. In this instance only channels 1-3 will generate a pulse as they surpassed the threshold of 2.5 V.

Figure 1. The Japanese acoustic bedload monitoring system consists of a half-buried pipe installed across the river-bed (a) exemplified by the Sumiyoshi River downstream of its tributary, the Nishi-takiga-tani; the waterproof pipe contains a microphone (b) and a preamplifier (c), from which acoustic signals are transmitted by cable to a converter (d).

Components and deployment of the geophone system

The deployment of the system involves setting the pipe into a stable cross section. This is attained on a Sabo dam (Fig. 1a), on a sill of a slit Sabo dam (Fig. 3a) or in a flume (Fig. 3b). For calibration of the acoustic bedload monitoring pipe system, it is positioned immediately upstream of an automatic and continuously monitoring Reid-type bedload slot sampler (Fig. 4). This sampler has been used worldwide to continuously and automatically monitor bedload discharge in a variety of gravel-bed streams (Laronne et al., 2003). The acoustic system is positioned in the Abe River where a sampler collects all the water and sediment and on the Yotagiri River the pipe is positioned near a slot leading to a continuously operating trommel (cylindrical revolving drum) sampler. Calibration of geophone systems is undertaken in 6 among 10 locations where pipe geophones monitor bedload discharge in steep, gravel-bedded mountainous rivers in the central island of Honshu (Table 1). The locations include sandy-gravel reaches such as the Nishi-takiga-tani to bouldery reaches such as the upper Tsuchitaru on the Uonogawa (Fig 5; Table 2).

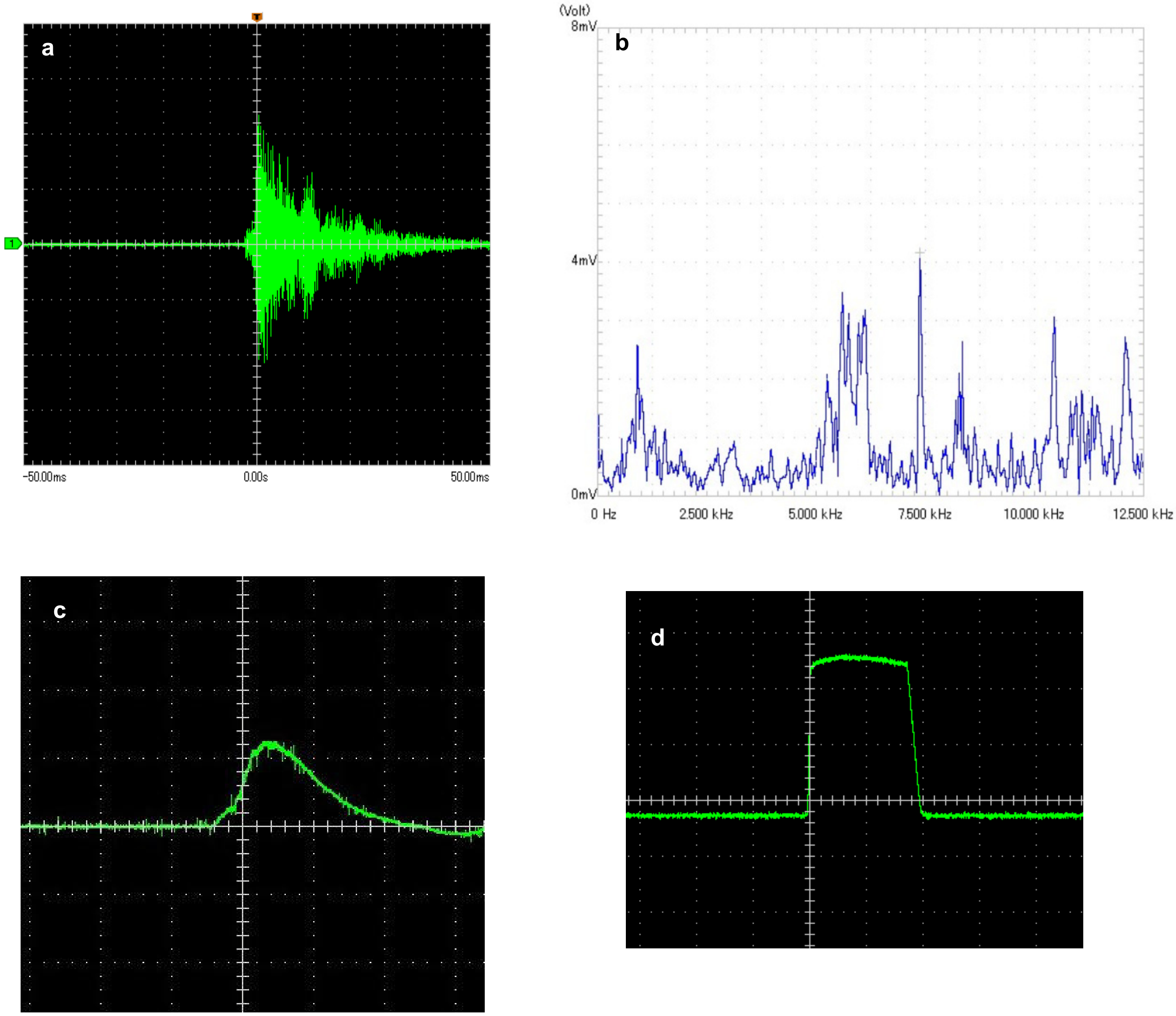

Figure 2. The output of the preamplifier is a waveform (a; herein shown for a duration of 500 ms) with a given frequency response (b), for which a converter undertakes corrugated processing, ultimately involving the transformation of an output (c) to a square wave (d).

Data for calibration of the geophone system are obtained by independent and contemporaneous monitoring of (1) pulses indicative of sediment collisions, (2) rate of slot-sampler filling by bedload and (3) water depth, the last two required to determine bedload discharge (e.g., Laronne et al., 1992). At most locations the entire database is acquired by telemetry. Other relevant parameters, such as turbidity and temperature, are also determined at several sites (Fig. 6).

The geophone systems deployed throughout Japan vary in terms of the location of the preamplifier (inside or outside the pipe), length of acoustically-sensitive pipe segment , total pipe length, whether the pipe is half buried in a sill, covered by cement or neither, date of deployment and method of data transmission (Table 3). The diameter of the stainless steel pipe as used in all the rivers is 4.8 cm with a 2 mm or 3 mm wall thickness.

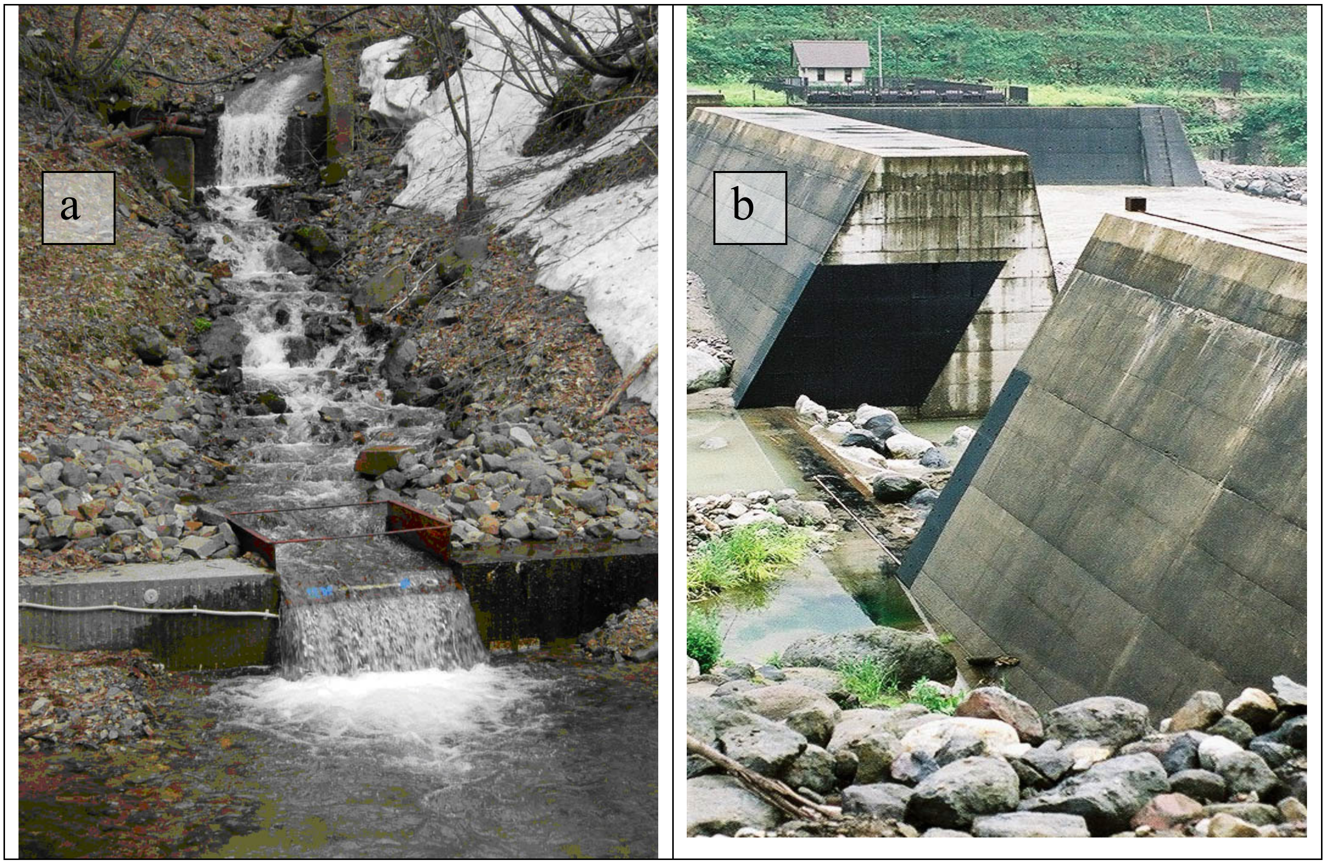

Figure 3. Deployment of a pipe geophone across a flume on the Hirudani River (a) and across a slit Sabo dam on the Joganzi River (b).

Table 1. General characteristics of perennial mountain rivers in Japan where acoustic monitoring of bedload takes place.

river	drainage area	basin relief	annual rainfall	lithology	river pattern	mean annual flow	bankfull flow
	km^2	m	mm			m^3/s	m^3/s
calibrated against sampler-discharge							
Ashi-arai-tani	6.5	1,355	2,500	andesite,granite-porphyry,slate, serpentine	single-thread	0.3	8.5
Nishi-takiga-tani	1.48	526	1,700	granite	single- thread	-	-
Uono-gawa	97.6	1,590	3,020	granite	braided	-	
Abe	8.8	898	3,000	sedimentary rocks	single-thread	-	170
Osawa	12.5	3,290	2,150	volcanics	single-thread	-	250
Yotagiri	35.7	2,095	2,530	granite	braided	2.87	-
seasonal calibration (pond)							
Hirudani	0.85	800	2,500	andesite,granite-porphyry,slate	single-thread	0.037	0.35
uncalibrated							
Joganzi	132	480	3,000	volcanics, granite, metamorphics	braided	5.4	1016 (slit)
Sumiyoshi	10.9	836	1,700	granite	braided	-	-
Tedori	187	2,400	2,150	volcanics	braided	-	2200

Figure 4. For calibration of bedload discharge the pipe geophone is positioned immediately in front of the slot opening of a Reid slot sampler. Upstream view on the Uonogawa (Tsuchitaru tributary).

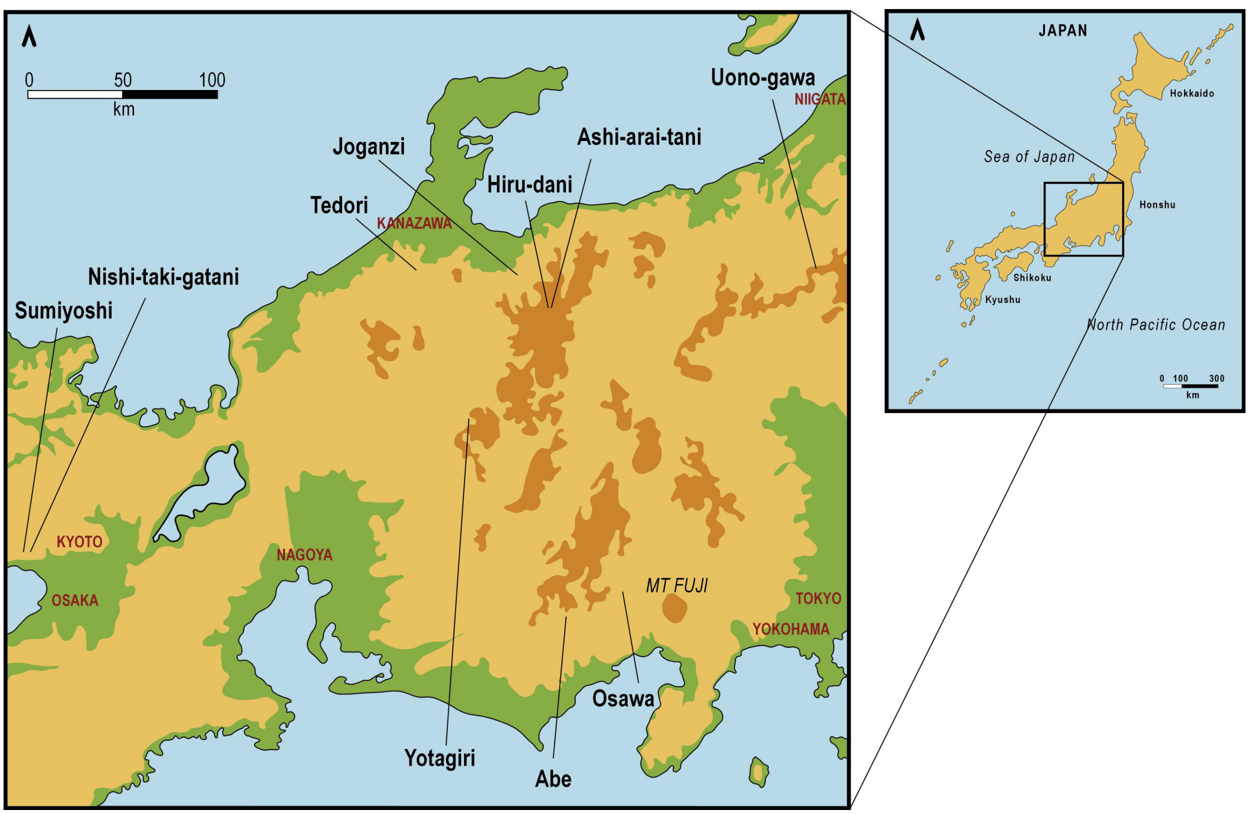

Figure 5. Map (part of Honshu Island) showing river locations where geophone systems have been deployed, many of which are calibrated.

Table 2. River reach characteristics at sites where acoustic monitoring of bedload is undertaken in Japanese rivers. A 9.25 m^3 Reid-type slot bedload sampler was installed in 2008 on the Joganzi River for geophone calibration inclusive of boulder (< 1000 mm) transport.

river	bed width	local bed slope	bank-full depth	surface grain-size character		
				D_{50}	D_{95}	sand content
	m		m	mm	mm	%
calibrated against sampler-discharge						
Ashi-arai-tani	5	1/20	1	100	600	10
Nishi-takiga-tani	8	1/10	0.4	3.5	3.5	38
Uono-gawa	50	1/41	3.2	40	40	15
Abe	36	1/15	-	12	150	20
Osawa	26	1/55, 1/45	3	-	-	-
Yotagiri	50	1/25	-	38	38	21.3
Tedori (seto)	5	1/20	-	-	-	-
seasonal calibration						
Hirudani	1.2	1/5	0.5	80	500	15
uncalibrated						
Joganzi	200[2]	1/28	7	-	-	-
Sumiyoshi	26	1/12	-	-	-	-
[3]Tedori Hosotani1	50	1/323	4	-	-	-
[3]Tedori Hosotani10			-	-	-	-

river	# acoustic sensors	# bedload samplers	sampler capacity	typical bedload discharge	highest bedload discharge
			m^3	kg/sm	kg/sm
calibrated against sampler-discharge					
Ashi-arai-tani	1	1	1.33	0.5	3.5
Nishi-takiga-tani	1	1	0.58	0.01	0.053
Uono-gawa	3	3	6.00	-	-
Abe	2	1	45.50	1.8	35.6
Osawa	1	1	2.03	-	-
Yotagiri	1	1	-	-	2.13
Tedori (seto)	1	1	1.33	-	-
seasonal calibration					
Hirudani	1	pond	139[1]	0.03	0.1
uncalibrated					
Joganzi	1	0	n/a	n/a	n/a
Sumiyoshi	2	0	n/a	n/a	n/a
[3]Tedori Hosotani1	1	0	n/a	n/a	n/a
[3]Tedori Hosotani10	1	0	n/a	n/a	n/a

Notes: 1: pond volume; 2: water flow width 30 m and slit width 8 m. 3: The Tedori Hosotani1 & Hosotani10 are 600 m apart in the same valley.

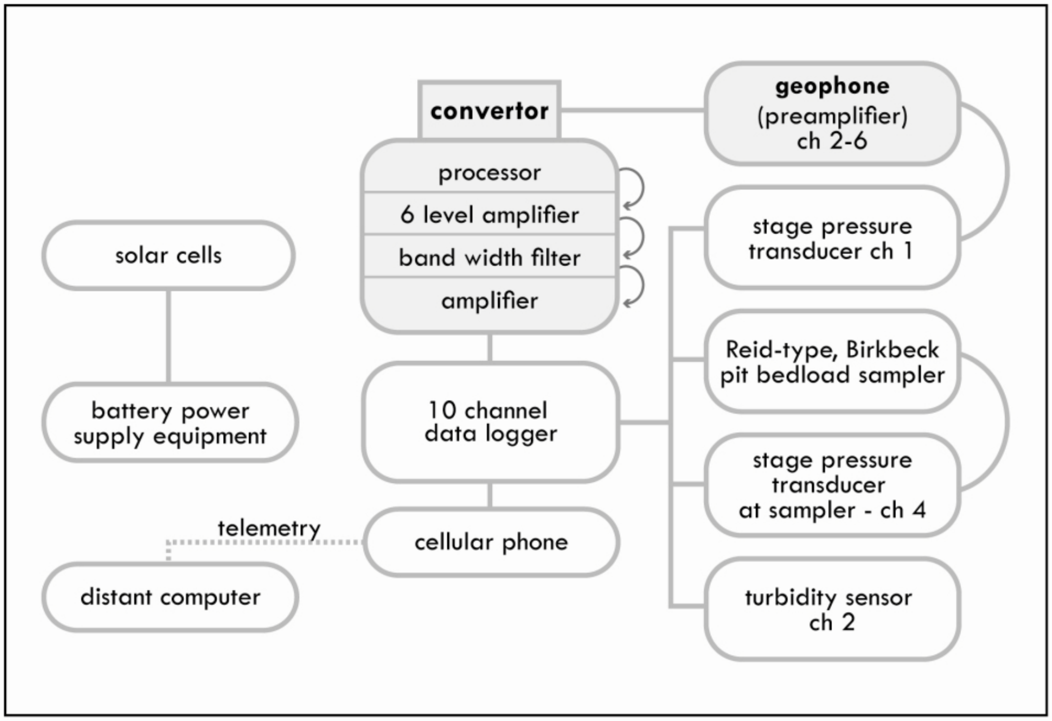

Figure 6. Components of the geophone system and the automatic monitoring Reid-slot bedload sampler juxtaposed for calibration of the acoustic system. Two independent pressure transmitters are required only at the Ashi-arai-tani. See text for details.

FIELD CALIBRATION OF THE JAPANESE ACOUSTIC BEDLOAD MONITORING SYSTEM

Flume experiments have been undertaken to determine the effects of varying parameters on the Japanese geophone system. These include the effects of sensitive pipe-segment length, location of collision on a pipe and microphone sensitivity, as well as the effects of bedload discharge and bedload grain-size on the number of recorded pulses (Mizuyama et al., 2007). Unlike flume conditions, those in Nature involve among others a wide range of grain-size, turbulent flow and high concentrations of suspended sediment. Hence, calibration of a surrogate bedload monitoring technology is more complex than in a flume. This acoustic bedload monitoring system has recently been calibrated in various rivers.

Calibration at an intermediate range of bedload discharge

The Nishi-takiga-tani is a small, steep gravel-bed river, where most of the granitic bedload transported at low shear is sand, but at higher discharges granules and pebbles are also mobilized. The sympathy between the acoustic output and bedload discharge during a relatively small flow event is apparently very good (Fig 7). The good correlation between acoustic response and bedload discharge is evident during the short rises and also during the recessions. Figure 7 shows the acoustic response documented by one channel; data acquisition includes 6 channels of varying sensitivity, the advantage of which will be shown hereafter for high bedload discharges. The data included in the calibration (Fig 8) are only those during the rises in stage when bedload discharge was low to intermediate (0.001-0.02

kg/sm but averaged over 30-60 min intervals) for a period of altogether about two days during one month of monitoring. This refers to the two steep segments of the cumulative bedload mass curve (Fig. 7). Relevant to lower bedload discharges (next section), very low but continuous transport of bedload is noticeable between stage rises; this is also observed in the subdued acoustic response.

Table 3. Character and installation of pipe systems at sites where acoustic monitoring of bedload is undertaken in Japanese rivers.

river	date initially deployed	data trans-mission	location of preamplifier	full pipe length m	length of sensitive pipe section m	pipe installation method
Ashi-arai-tani	.20	T+L	inside pipe	1	0.35	B
Nishi-takiga-tani	03.2003	T+L	outside pipe	6.5; 2[1]	6.5	B
Uono-gawa (Ounohara-bashi)	07.2004	L	inside pipe	2	1	C
Uono (Tsuchitaru)	10.2005	L	inside pipe	2	1	C
Abe	08.2003		outside pipe	3; 3.3[1]	3	C
Osawa	11.2006	T+L	inside pipe	1	0.8	A
Yotagiri	10.2004	T+L	inside pipe	8	8	B
Tedori (seto)	11.2004	T+L	inside pipe	2	1.6	A
Hirudani	10.2004	L	inside pipe	0.5	0.5	A
Joganzi	06.2001	T+L	inside pipe	8	8	B
Sumiyoshi[2]	09.2004	T+L	inside pipe	8	8	B
Tedori (Hosodani1)	11.2004	L	inside pipe	8	8	B

T – telemetry; L - data logger; A: the lower half of the pipe is embedded in cement. B: concrete protection. C: no concrete protection to the vertical pipe segment. A straight-pipe type has been used where the preamplifier is located inside the pipe.

[1] At these sites the 2 numbers denote the length of the horizontal; vertical sections of a bent pipe. At all other locations the pipe is a single straight unit.

[2] previous geophone observations took place in the nearby Tsuga River at Rokkou Hachisu-tani (1993~1996) and in the Rokkou Huka-tani (1999~2003).

Higher, intermediate range, bedload discharges have been recorded on the volcanics-underlain and steep Ashi-arai-tani. Akin to the data averaged for longer durations and low bedload discharges on the Nishi-takiga-tani (Figs. 7-8), there is a very good agreement between acoustic response and bedload discharge averaged over 5-min durations (Fig 9a), leading to a credibly high correlation between them (Fig 9b) under the hydraulic and sedimentary conditions of the Ashi-arai-tani. The main difference between the Nishi-taki-gatani (Figs 7-8) and the Ashi-arai-tani (Fig 9) is in the averaging time for calibration: one order of magnitude longer for the former.

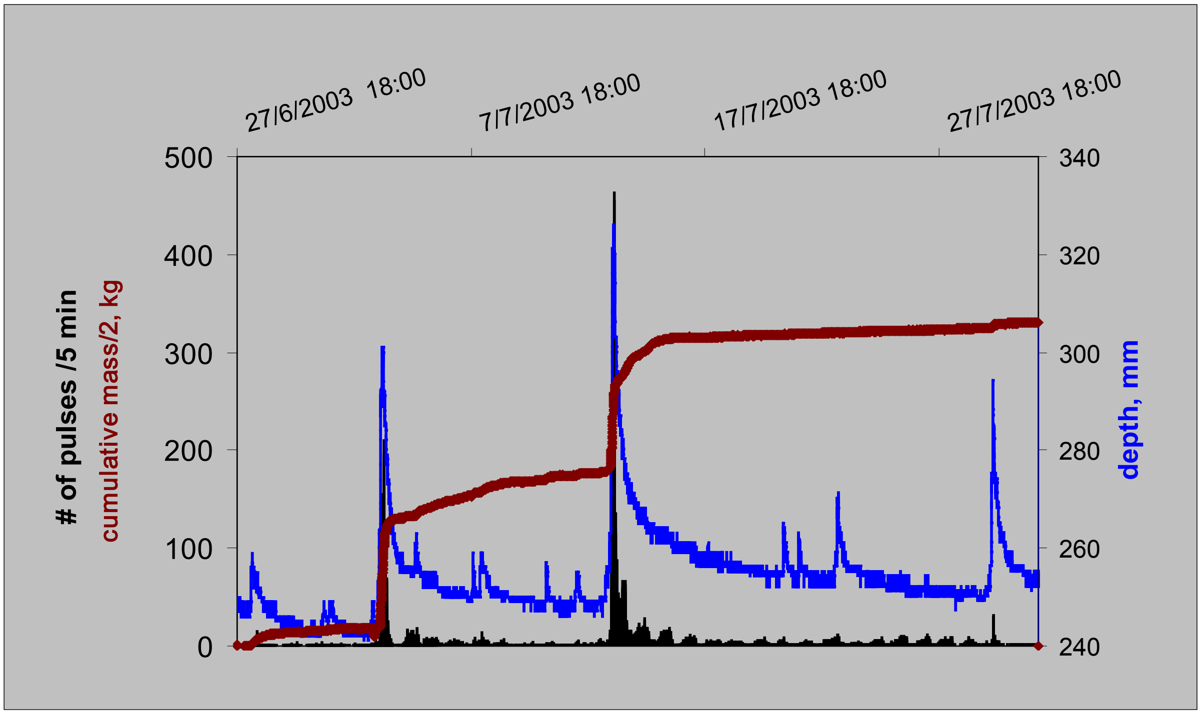

Figure 7. Temporal variation of acoustic response (channel 5) and cumulative bedload on the Nishi-takiga-tani during 1 month of continuous monitoring. Initiation of motion occurs at a flow depth of about 25 cm (measured on the Sabo dam).

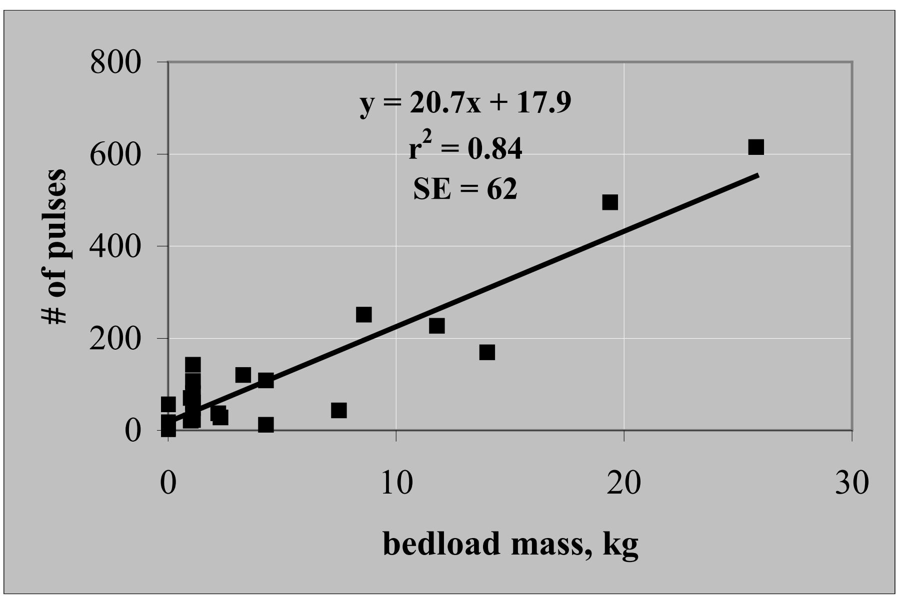

Figure 8. Calibration at intermediate (>0.01 kg/sm) bedload discharge, Nishi-takiga-tani (June-July, 2003). Abscissa denotes bedload mass accumulated during 30-60 min intervals. Data were used only for the flood periods.

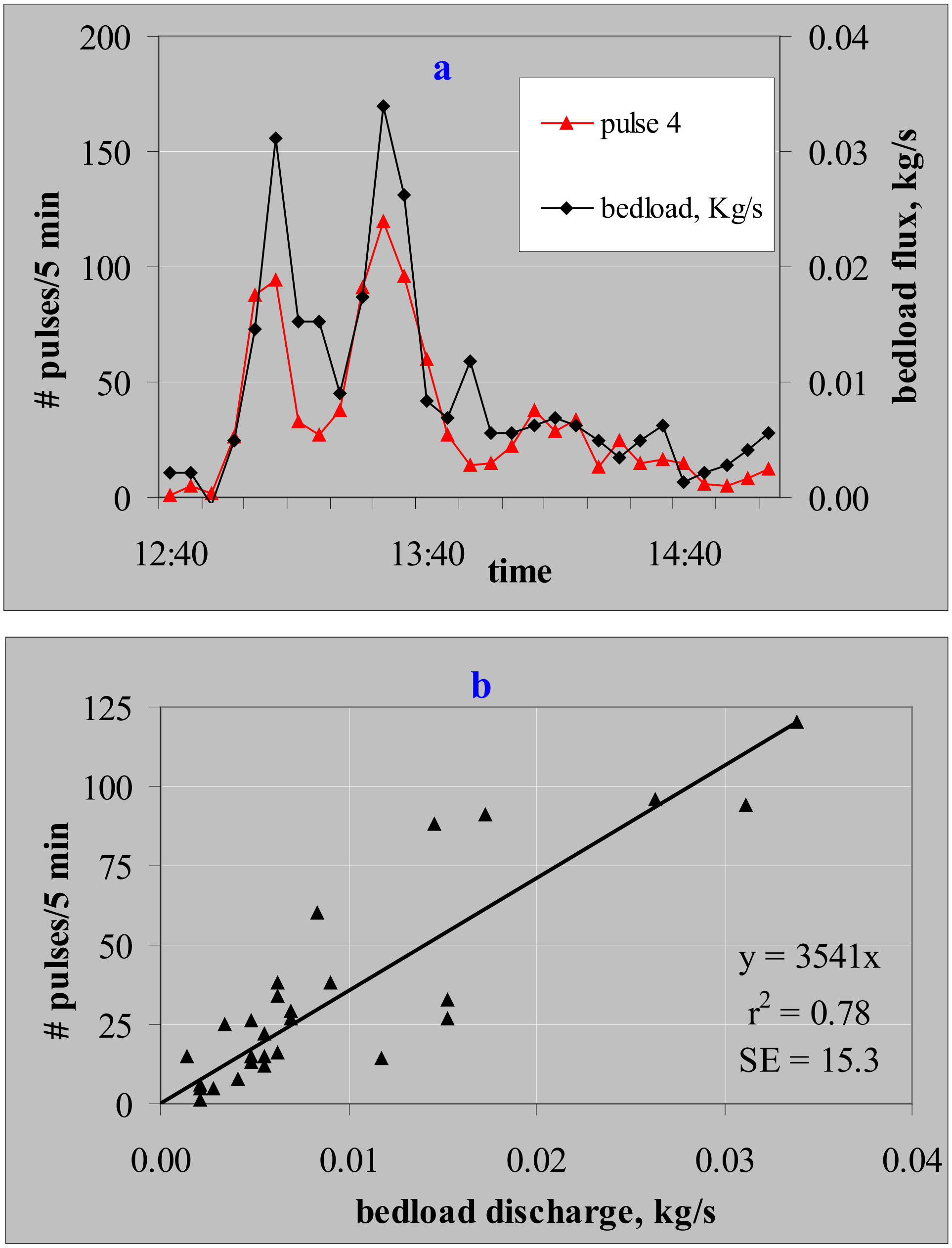

Figure 9. Temporal variation of 5-min acoustic response (x 4 magnification) and bedload discharge (a) and calibration of the acoustic system (b) on the Ashi-arai-tani (16 July, 2004). More than half of the recorded fluxes are > 0.01 kg/sm (i.e., > 0.005 kg/s as slot width was 0.5 m).

Calibration at low bedload discharges

Unlike the good response of the acoustic system to a range of intermediate bedload discharges, at low discharges (0.001-0.01 kg/sm) the response is poor, particularly so for short (5 min) durations; i.e., the dependence of number of pulses on bedload discharge is very low (Fig 10a) and at first impression, calibration appears to be hopeless (Fig 10b). Nonetheless, considering that the nature of bedload transport at very low discharge is very erratic and that the short term accumulation of bedload is lower than slot sampler sensitivity, the acoustic response has been averaged for longer durations; these have been correlated against the mass of bedload accumulated during such longer durations (Fig. 11). Indeed, the acoustic system apparently responds rather well to low bedload discharge (< 0.01 kg/sm) when averaged over several hours. Considering that the Japanese acoustic system with its present characteristics is insufficiently sensitive to bedload particles finer than 4 mm, the response calculated for longer durations is encouraging.

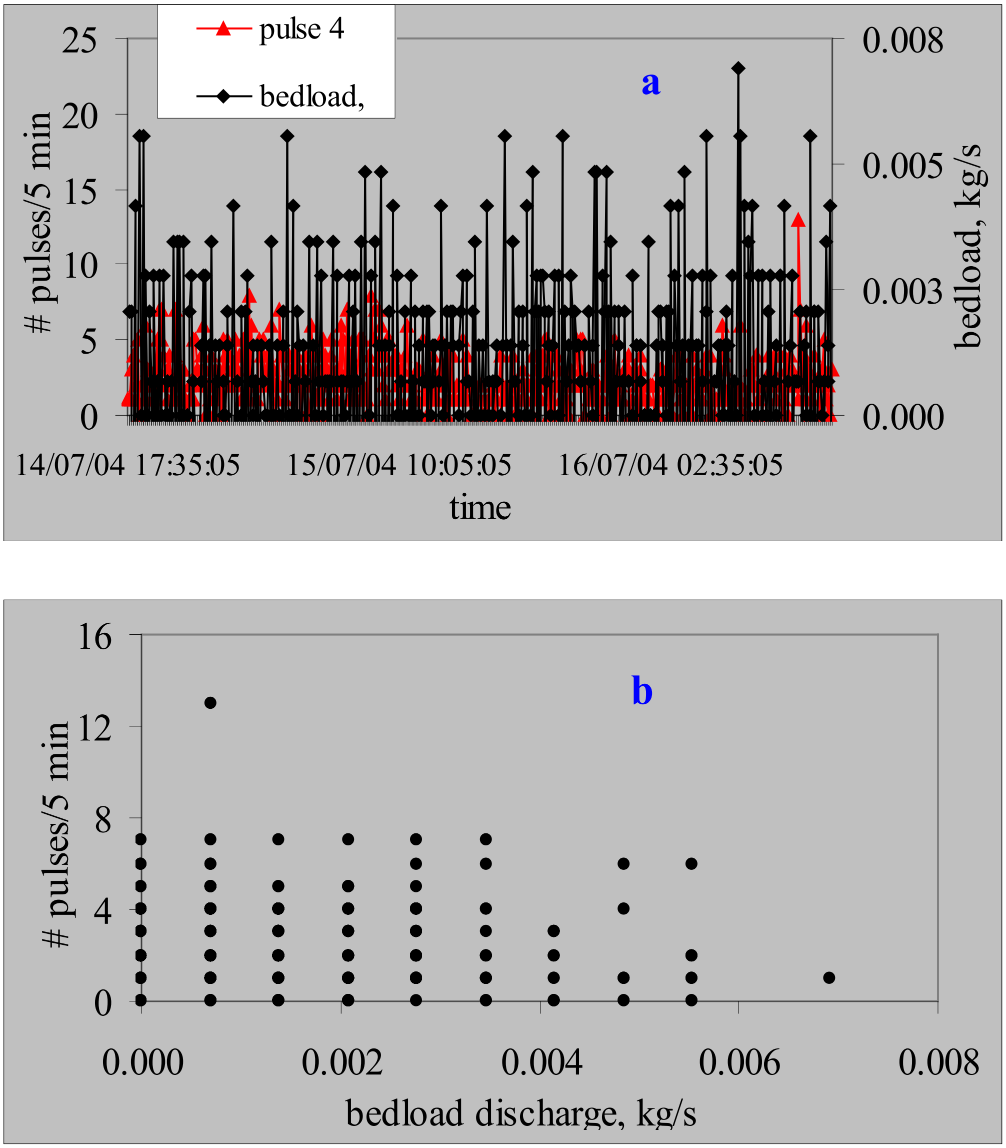

Figure 10. Temporal variation of acoustic 5-min response when bedload discharge averaged over 5 minutes was very low (a) and unsuccessful calibration of the acoustic system at the low discharges (b) on the Ashi-arai-tani (14-16 July, 2004, prior to the rises shown in Fig. 9).

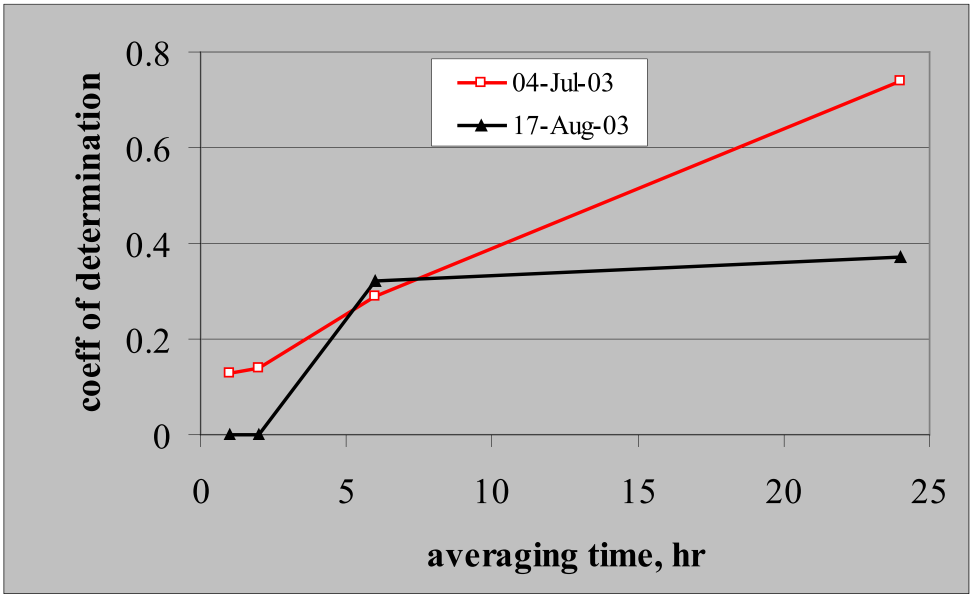

Figure 11. Effect of averaging time on correlation of acoustic response with bedload discharge for two flow events on the Nishi-takiga-tani.

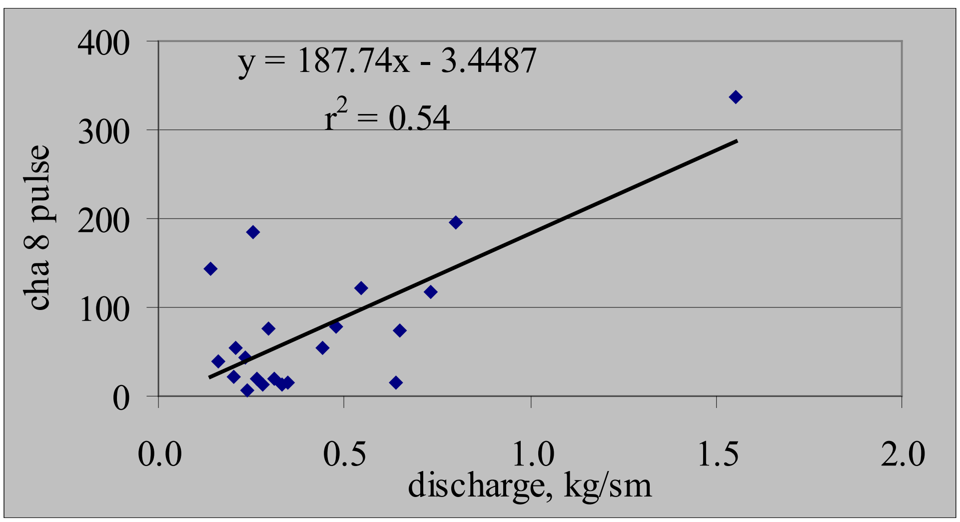

Figure 12. Callibration of 5-min geophone response (channel 8) to 5-min high bedload discharge (> 0.1 kg/sm) on the Ashi-arai-tani, May 20, 2006.

Calibration at elevated bedload discharges

The Japanese acoustic system has also been operational when bedload discharges were high by most standards. The slot samplers in several of the rivers are exceptionally large (those utilized in semiarid and arid washes have a volume as large as 0.4 m^3, in the Alpine Drau 0.75 m^3 whereas in the Japanese rivers sampler volumes attain 6 m^3 (Table 2), allowing elevated (0.1-1.5 kg/sm) bedload discharge to be sampled for relatively long durations (Fig. 12). Fig. 6 incorporates one high datum that considerably affects the calibration, hence clearly more data need to be collected in the high-end range of bedload discharge to study the acoustic response of this system.

At still higher bedload discharges the acoustic response is dampened by excessive vibration and reverberation (e.g., Fig. 1 in the companion paper by Mizuyama et al, 2007). Such dampening and a decrease in response is illustrated by the acoustic response at one of the uncalibrated rivers, the Joganzi, during a large flood (Fig 13a). The most sensitive channel 5, as well as other sensitive channels 6-8, was dampened above 1.5 m flow depth. Nevertheless, the less sensitive channels 9 and even the least sensitive channel 10 responded in sympathy to the high flow depths. It is particularly noteworthy that at lower flow depths (and accordingly lower bedload discharges) the acoustic response of all the channels was good, with the exception of the least sensitive channel 10, which was expectedly insensitive to the lowest discharges. Therefore, for the range of flow depths below 1.5 m the response of each of the sensitive channels (5, 6, 7 and 8) was regressed against the response of channel 9, the coefficients of determination (r^2) of which were very high (0.84. 0.93, 0.96 and 0.99, respectively; e.g., see Fig 13b). This allows reconstruction of the response of sensitive channels at elevated discharges. For instance, the linear regression of channel 7 *vs.* channel 9 response was used to construct a channel 7 acoustic response to the high bedload discharge on the Joganzi (Fig. 13c).

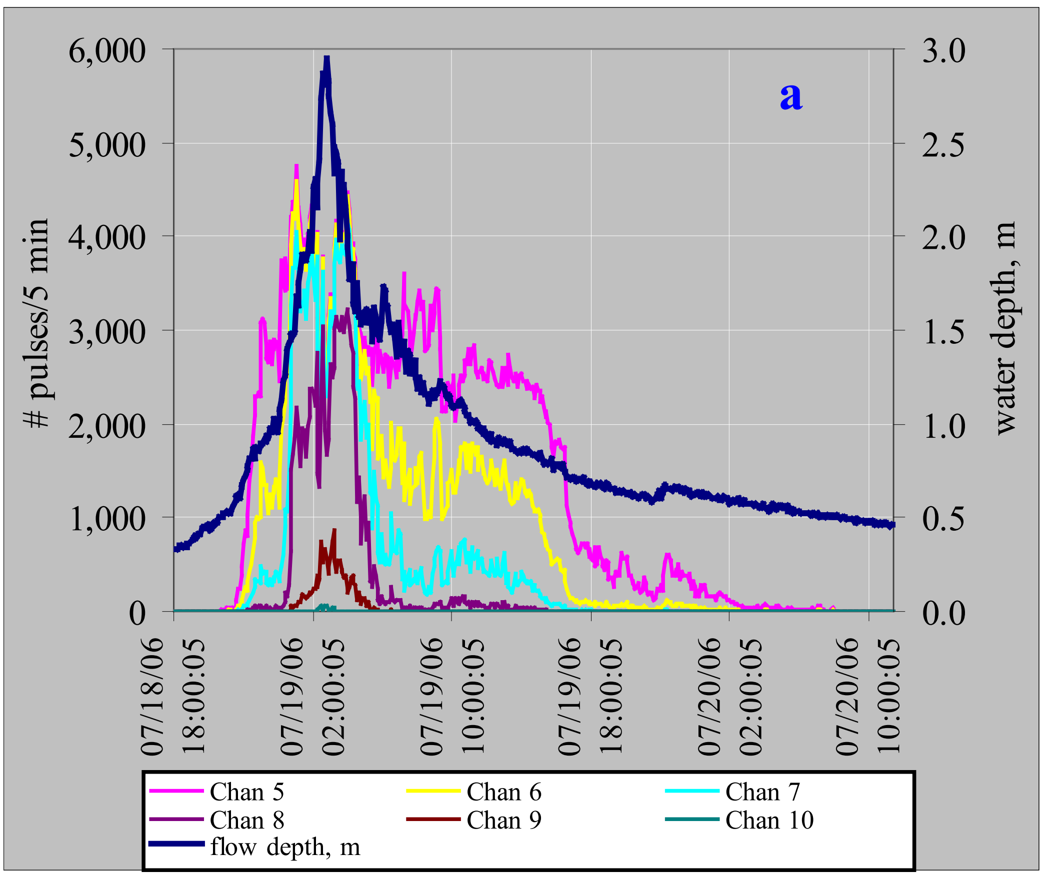

Figure 13a. Multi-channel acoustic response on the braided Joganzi (18 July, 2006). The maximum depth (3 m) was recently surpassed (5 m). The most sensitive channels 5-8 were dampened at peak stage; the least sensitive channels 9-10 were not dampened

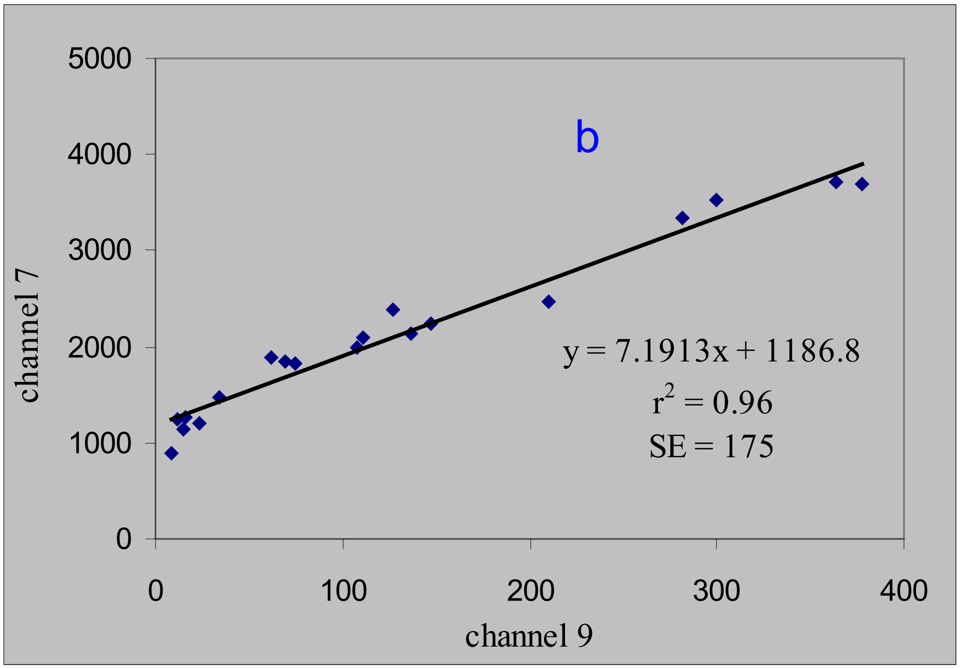

Figure 13b. Multi-channel acoustic response on the braided Joganzi (18 July, 2006). Regression of pulse data: channel 7 vs. channel 9 (b).

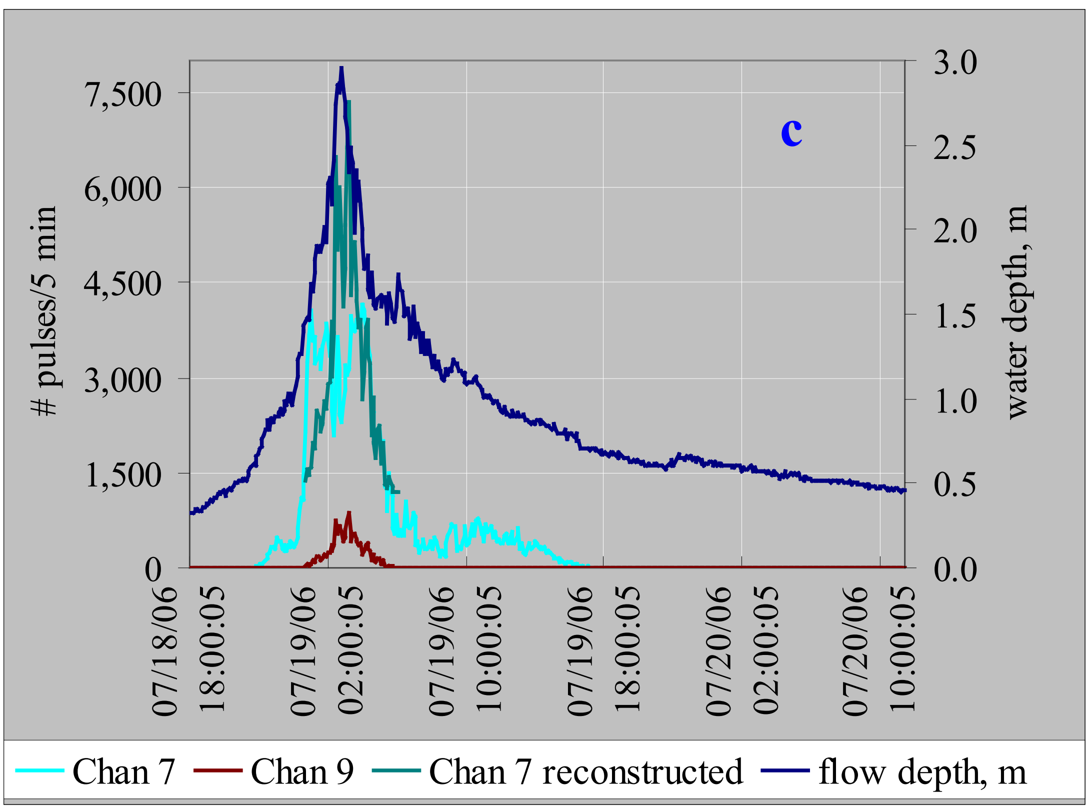

Figure 13c. Multi-channel acoustic response on the braided Joganzi (18 July, 2006). Reconstructed response of channel 7 (c - see text for details).

DISCUSSION

The Japanese pipe-type passive acoustic bedload monitoring system apparently is capable of being calibrated not only under laboratory conditions but also in Nature. The extent to which the system reliably mimics bedload discharge is manifested by the acoustic response to bedload discharge on the Nishi-takiga-tani, even under conditions when bedload discharge varies hysteretically with depth (Fig 14a-b).

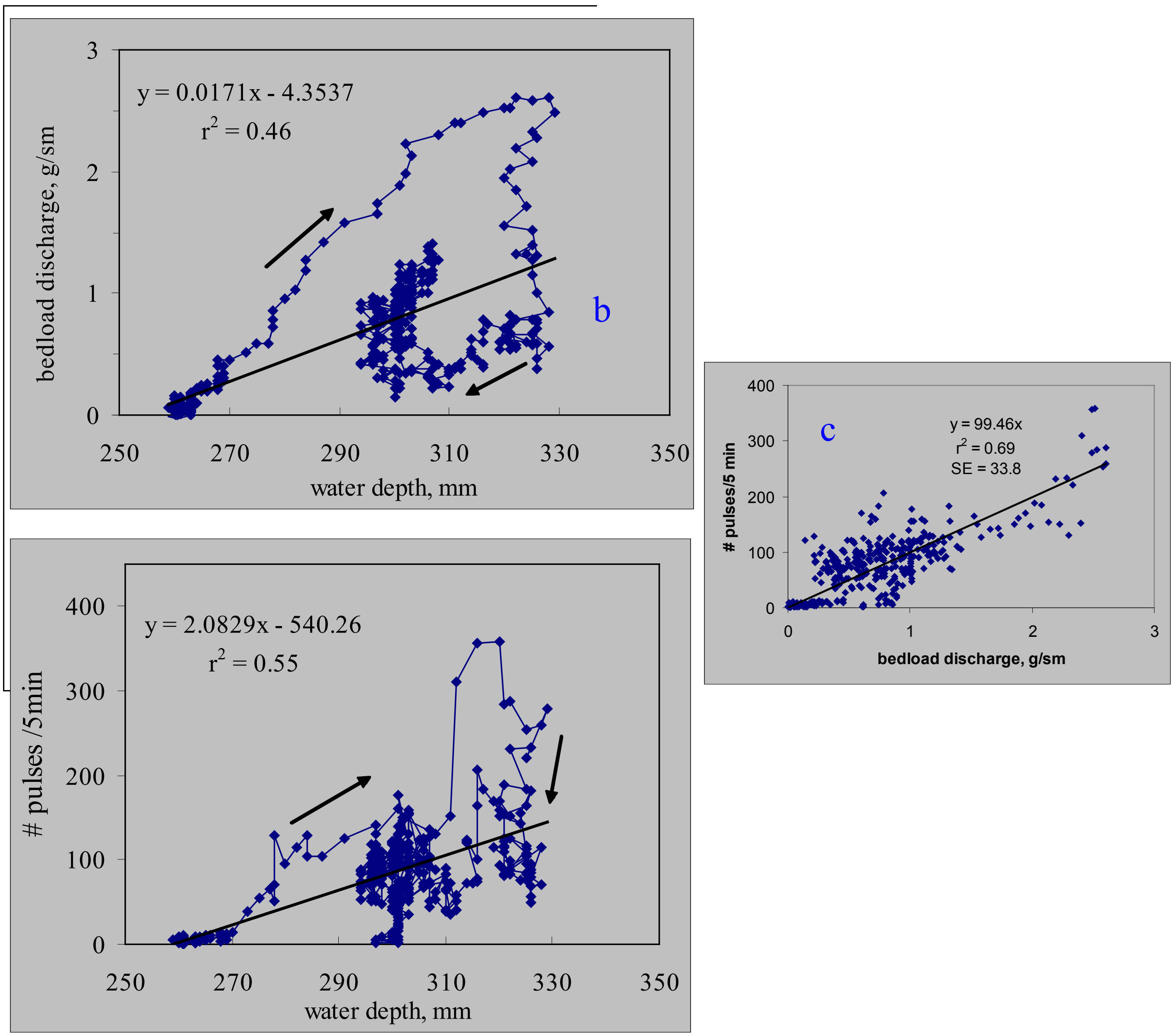

Figure 14. Although a linear (or curvilinear) regression of bedload discharge *vs.* average cross-sectional shear stress (herein denoted by depth of flow) is not high (a), a similar (channel 6) acoustic response to the hysteretic variation of bedload discharge is manifested on the Nishi-takiga-tani (b) with a covariation with bedload discharge (c) on 14 Aug 00:00 -15 Aug. 11:00, 2003..

Initiation of bedload involves finer grain-size (sand and small granules); it may ensue due to a slight increase in flow depth, when bedload discharge is not only very low but also highly unsteady at these conditions. The unsteadiness is result of the patchy nature of bedload sources in the streambed at initiation of motion (Laronne et al., 2001), where the size and grain-size of patches vary spatially, and also due to the slightly variable flow structure in finer-grained patches (Crowder and Diplas, 2002), leading to a succession of within-patch sediment motion prior to extra-patch transport (Garcia et al., 2007). The interconnectedness between patches is required to allow continuous, extra-patch bedload motion, but this interconnectedness varies spatially and is to a large extent dependent on the extent of infill of the coarse layer substrate over which finer bedload must be transported. Hence, a surrogate bedload monitoring technology appropriate for such unsteady conditions also needs to include very high-gain channels sufficiently sensitive to detect collisions of finer-grained bedload particles and also to be deployed for a sufficiently long period of time, often several hours[3].

An additional requirement of such a system is that it needs to be sufficiently sensitive to the impingement of particles of small mass. The collision of such particles may be detected by reducing the thickness of the 2-3 mm stainless steel pipe (Michinobu Nonaka, pers. comm., 2007). Nonetheless, a thin-walled pipe is more susceptible to damage by large bedload clasts. Last but not least, calibration of a surrogate technology for low bedload discharges also requires a high sensitivity of the calibrating device, in this case an automatic, Reid-type slot bedload sampler. Self-evidently, the sensitivity of a slot sampler decreases as its weighing range increases, being low as the volume of the sampler increases. Very large slot samplers which are required in steep mountainous rivers such as the Ashi-arai-tani and the Uonogawa are insensitive to small additions of mass, and are therefore inappropriate as calibrating devices for low discharges. Very small slot samplers such as those employed in some low-energy British rivers (Sear et al., 2000) may be utilized for such calibration, although they cannot be used for calibration at higher discharges.

The pipe geophone may also be deployed to monitor intermediate to high bedload discharges. Because the pipe is deployed on a sill, it may be damaged during large floods by oncoming coarse bedload particles. To partly overcome this problem, we have inserted half of the pipe into the sill; it is thereby less proud and its lower half is protected.

The pipe geophones reported herein vary in dimensions (length of sensitive part) and as shown elsewhere (Mizuyama et al., 2010) this affects the acoustic response. To compare bedload discharge of gravel bed rivers having varied characteristics, a geophone of given technical specifications is to be used. Indeed, the Sabo Department will be installing identical geophone observation units at about 120 torrents during 2010.

CONCLUSIONS

The conclusions from this study may be summarized by referring to relevant questions regarding the use of the Japanese passive acoustic bedload monitoring system.

The cost of the geophone (with preamplifier, cable with connector) is US$1,800 and that of the converter is US$ 2,200. An appropriate multi-channel data logger is also required.

The major benefits of this technology are:

[3] Relevantly, the exceptionally good bedload database derived from Oak Creek (Milhous, 1973) which was utilized to calibrate some of the well-known bedload formulae (e.g., Parker, 1990) is based on bedload discharge averaged over several hours, rather than several minutes as these Japanese rivers or even several seconds at very high bedload discharges.

- ✓ simple to deploy;
- ✓ operates continuously;
- ✓ operates unmanned (automatically);
- ✓ operates for long periods of time (months);
- ✓ may be utilized in conjunction with telemetry to acquire real-time bedload discharge data far from the river;
- ✓ relatively easy to analyze the output; and
- ✓ relatively inexpensive.

A drawback is that at the present state of development it needs to be pre-calibrated for a given river (or set of rivers having similar bedmaterial characteristics). This technology will continue to be calibrated in Japanese mountain rivers with one of several major objectives to determine the extent to which calibration remains stable over several different bedload-transporting flow events.

The performance of this system is acceptable (1) for low bedload discharges as long as outputs are undertaken over sufficiently long periods of time and as long as grain-size > 4 mm (unless thinner pipes are used). The performance is good (2) for intermediate bedload discharges, but (3) for elevated bedload discharges multi-channel outputs need to be compared to ensure no signal-damping occurs. The performance during large floods requires setting the pipe halfway into the sill.

The technology appears to be robust for monitoring fine-grained gravel up to small boulder bedload transport. Because the pipe has a finite downstream size (i.e., its diameter), self-evidently only some saltating particles collide onto the pipe. This means that calibration is absolutely necessary. Long range saltation is also problematic for slot samplers, as they have a finite slot length, even if it is large. This technology may be ready for operational deployment in monitoring programs within few (< 3 years), during which time the stability of its calibration for a given set of river conditions will have been determined.

ACKNOWLEDGEMENTS

The central role played by Sabo Works enabled the deployment and calibration of acoustic bedload monitoring in mountain streams throughout Japan. Roni Livnon assisted with figures and Rachel Zimerman with editorials. JBL acknowledges Kyoto University for allocating funds to undertake research in Japan during 2006 and for hospitality by the Laboratory of Erosion Control (headed by Takahisa Mizuyama) and by Prof. Sawada and the Disaster Prevention Research Center station in the Hodaka Mountains. Comments by Dieter Rickenmann and an unidentified reviewer are gratefully acknowledged.

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