toward the root also when using 16 mm sediment (Fig 5d), varying only slightly for channel 1. This lack of variation may be related to microphone sensitivity and the characteristics of the pipe, such as its natural period.

In summary, it appears that for coarse-grained (> 8 mm) bedload the number of pulses may be about twice larger for the root in comparison with the tip. Thus, calibration of a pipe-geophone also requires specification of the location (on a pipe) of the collision segment, which in a river would often be located centrally.

VARIATION OF NUMBER OF PULSES WITH MICROPHONE SENSITIVITY

Experimental conditions

In this experiment, we observed changes in the number of pulses by varying the sensitivity of the microphone, using an uncovered microphone at one end of a U-type pipe and a microphone covered by a filter installed at the other end of the U-type pipe. The length of the centrally-located pipe segment on which particles collided was 10 cm (Photograph 2). The flume width was 10 cm and slope ranged between 1/50 to 1/13 (2.0–7.5%). Both 4 and 8-mm particles were used in these runs, the volume of sediment was 6.0 ℓ and amplifier magnification was 3 (Table 4).

Table 4. Experimental conditions: microphone sensitivity.
'High' – no cover over microphone; 'Low' – microphone with cover.

run	sensitivity	slope	grain size mm	unit bedload discharge g/s m
43	High	1/20	4	1030
44	High	1/20	4	867
45	Low	1/20	8	964
46	High	1/50	8	40.3
47	High	1/50	8	51.5
48	Low	1/33	8	70.2
49	Low	1/33	8	295
50	Low	1/33	8	235
51	High	1/33	4	376
52	High	1/33	4	380
53	High	1/13	4	2330
54	High	1/13	4	2330

Experimental results

The variation of number of pulses was almost identical for channels 3 and 4 (for a 4 mm grain-size): the maximum number of pulses was recorded on channel 2 without a filter and on channel 3 with filter (Fig 6a). The number of pulses in the high-sensitivity channel was higher in the microphone with filter due to decrease of its sensitivity. For high bedload discharge (runs 43, 44), the number of pulses could be identified only by deploying a filter. However, use of the filter to decrease microphone sensitivity was insufficient for detection of pulses when bedload discharge was highest (runs 53, 54).

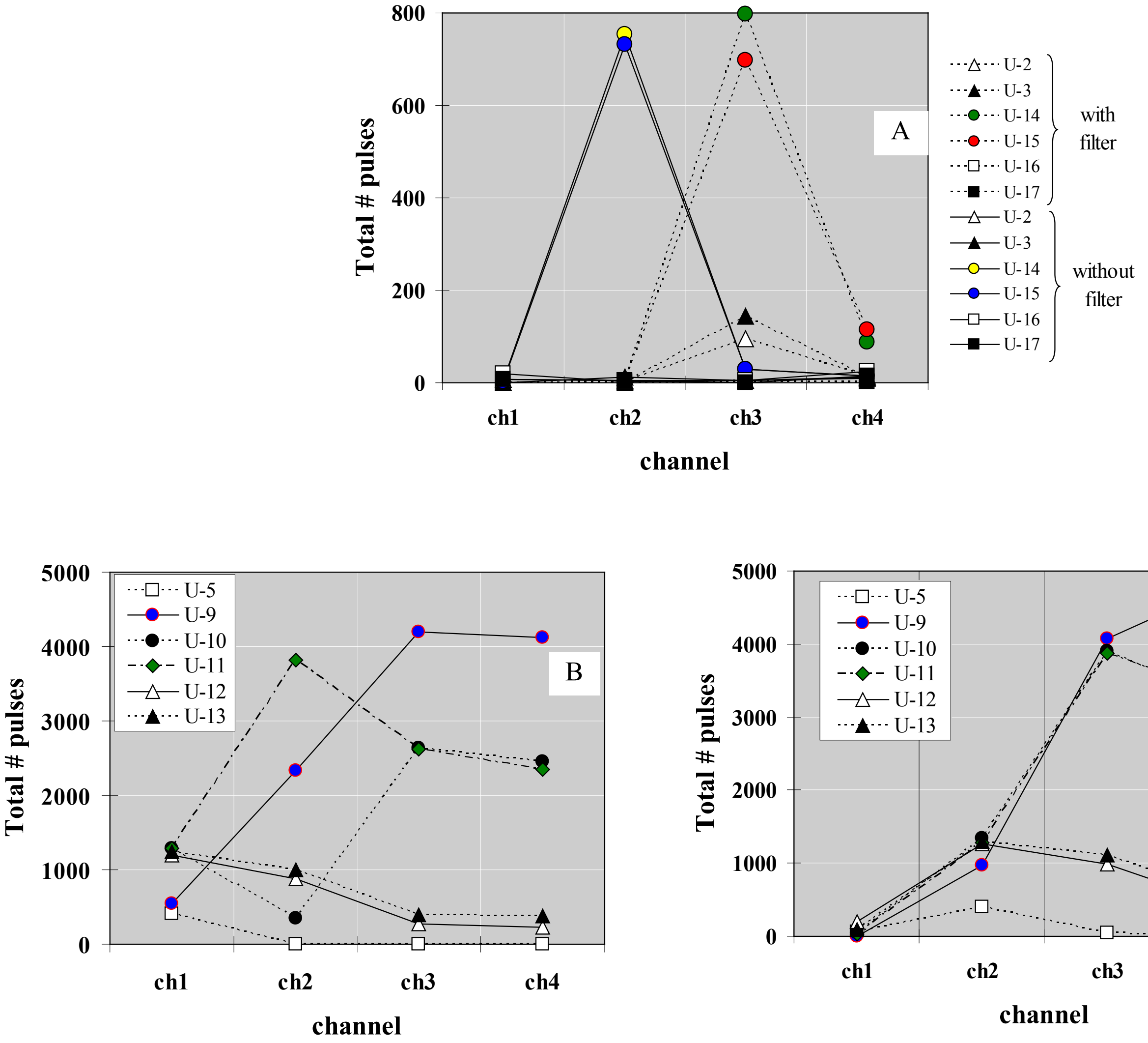

Figure 6. Variation of total number of pulses with microphone sensitivity for varying grain-size: 4 mm (A), 8 mm without filter (B) and 8 mm with filter (C).

For a grain-size of 8 mm, the filter increased the number of identified pulses in runs 45, 49 and 50 (Figs. 6b, 6c). The response for 8 mm grain-size with filter was more straightforward than for the uncovered microphone: number of pulses increased with channel sensitivity (except for channel 4, the most sensitive), but it was also governed by bedload discharge (Fig 6c). Installation of the filter increased the number of pulses in high sensitivity channels. In runs 46, 47, and 48, which had the lowest bedload discharges, the number of pulses at each channel did not depend on microphone sensitivity. These results indicate that reducing microphone sensitivity allows identification of pulses also when bedload discharge is high. However, because sensitivity must be reduced as discharge increases, other means in addition to the decrease of microphone sensitivity are required to monitor very high bedload discharges.

VARIATION OF NUMBER OF PULSES WITH BEDLOAD DISCHARGE

Experimental conditions

In this experiment we observed changes in the number of pulses by varying bedload discharge. The flume widths were either 10 cm or 30 cm with constant slope using both L-type as well as U-type pipes. The segment where particle collisions took place was centrally located and its length remained 0.1 m in all the runs. Flume inclination was 1/16.6 (6.0%), amplifier magnification index was 3 and grain size was 8 mm (Table 5).

Table 5. Experimental conditions: bedload discharge.

run	water discharge ℓ/s	channel width m	unit bedload discharge g/s m
16	2	0.1	909
17	2	0.1	795
18	2	0.1	830
19	2	0.1	994
20	2	0.1	1080
21	2	0.1	1070
22	2	0.1	1110
23	4	0.3	1140
24	4	0.3	1150
25	4	0.3	1310
26	4	0.3	1240

Experimental results

The total number of pulses *decreases* with increase in bedload discharge using an L-type pipe, as is shown for the least sensitive channel 1 (Fig 7a). The number of recorded pulses was very low in the more sensitive channels at this range of bedload discharge. It is likely that the level of sound collision was above the set threshold, resulting in an inability to count pulses in the more sensitive channels also at the lowest bedload discharge used in this run. The same effects were documented in the run using the U-type pipe without a filter (Fig 7b).

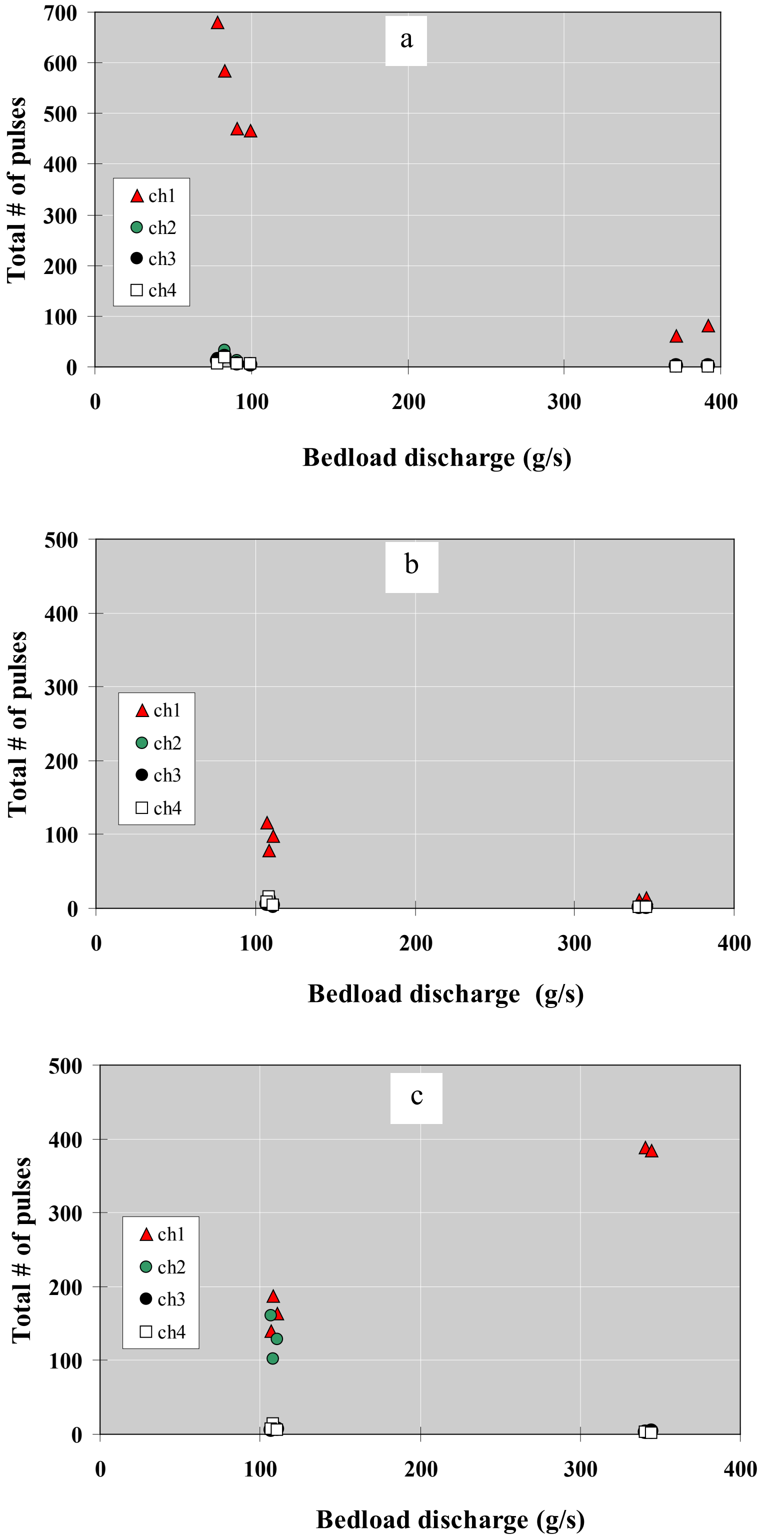

Figure 7. Variation of total number of pulses with bedload discharge using an L-type pipe (a); U-type pipe without filter (b) and U-type pipe with filter (c).

The total number of pulses increased with increase in bedload discharge using a U-type pipe with a filter (Fig 7c). The number of pulses increased by a factor of 2.35 (using magnification to arithmetical averages of the number of pulses in each case). The contemporaneous increase in bedload discharge was by a factor of 3.1. In channel 2 the total number of pulses decreased with an increase in bedload discharge; the total number of pulses did not vary in other channels (Fig. 7c). The tendency observed in channel 2 was likely the same as that when no filter was used (Fig 7a).

These results indicate that the number of pulses will decrease when bedload discharge is high unless microphone sensitivity is adjusted (e.g., by using a filter). Furthermore, when microphone sensitivity is indeed adjusted, a high correlation appears between total number of pulses and bedload discharge, suggesting that it is possible to quantitatively monitor bedload discharge by using a geophone.

VARIATION OF NUMBER OF PULSES WITH BEDLOAD GRAIN-SIZE

Experimental conditions

In this experiment we observed changes in the number of pulses by varying bedload grain-size. The flume width was 10 cm, and this flume experiment used an L-type pipe 1.0 m long. The length of the portion of pipe on which particles collided was constant throughout this experiment. Runs were separately undertaken for the tip, center and root sections of the pipe. Flume inclination was 1/50 (2.0%), discharge was 3.0 ℓ/s, total sediment volume was 3.0 ℓ, amplifier magnification index was 5, and the experiment used three bedload grain-sizes: 2, 4, and 8 mm (Table 6).

Table 6. Experimental conditions: bedload grain-size.

run	grain size	collision on	unit bedload discharge
	mm		g/s m
1	2	tip	190
2	4	tip	170
3	4	tip	147
4	8	tip	98.4
5	8	tip	79.8
6	2	center	208
7	4	center	154
8	4	center	152
9	8	center	80.3
10	8	center	86.1
11	2	root	217
12	4	root	155
13	4	root	154
14	8	root	74.0
15	8	root	75.7

Experimental results

For 2.0-mm grain-size the total number of pulses was altogether very low and did not vary substantially with location of microphone in the pipe - including the most sensitive channel 4 (Fig 8). This lack of response likely occurred because (1) channel sensitivities were low in comparison with the sound of collision, and (2) the sound of collisions was weak in comparison with that of the flow.

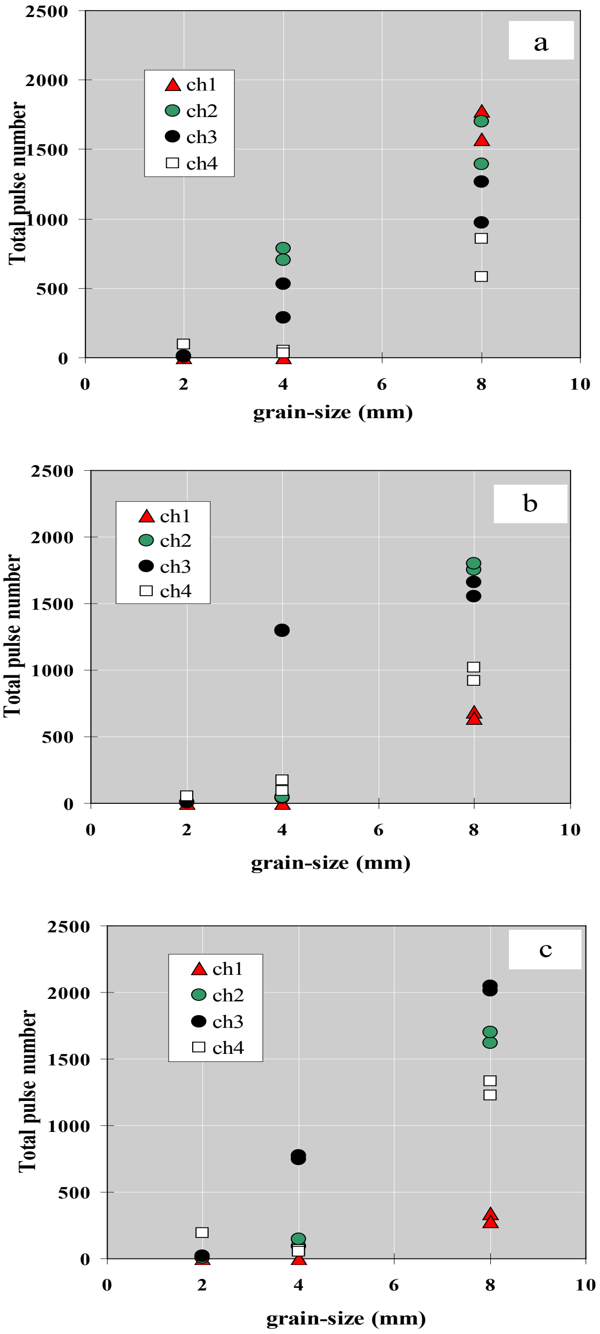

Figure 8. Variation of total number of pulses with bedload grain-size for the tip (a), center (b) and root (d).

For particle size 4.0 mm, channel 3 produced a reasonable response, recording a larger number of pulses in the center relative to the tip, though the number decreased instead of increasing for the root (Fig 8). Bedload discharge was too high to record pulses in the highest sensitivity channel 4, likely caused by reverberant sound or vibration of the metallic tube. In fact, pulse identification is possible when the sound collisions are lower than the threshold value, such that under conditions of high sensitivity these sounds remain detectable. Therefore, it is likely that under this condition, the collision sound level was above the set threshold, resulting in the inability to count pulses. It was also almost impossible to detect pulse at the lowest sensitivity in channel 1 (Figs 8 a-c)

For a grain size of 8.0 mm, the number of pulses increased with increase in channel sensitivity for each of the locations of the microphone (Fig 8a-c). This was the largest particle size with a lower bedload discharge in comparison with the other three runs.

The results of this experiment demonstrate that the pipe hydrophone system has a lower threshold of detecting bedload grain-size. For the pipe used in these experiments this lower threshold in 8 mm.

CONCLUSIONS

The objective of this study was to determine which geophone characteristics affect the extent to which bedload flux and ultimately bedload texture can be determined by surrogate bedload monitoring using a Japanese pipe geophone. The experiments have shown the following effects:

1. The length of the segment of pipe where collisions are recorded affects the number of pulses more than the length of the pipe.
2. Location (tip, center or root) where collisions are recorded affects the number of recorded collisions, increasing towards the root.
3. Lowering microphone sensitivity allows recording at higher bedload discharges.
4. Monitoring of high bedload discharge requires the use of lower channel sensitivity.
5. Bedload discharge of varying grain-size can be monitored by the Japanese pipe-geoophone. However, this acoustic system has a lower truncation grain-size threshold of detection; with the pipe characteristics used in these flume runs, the lower threshold is 8 mm.

Based on the geophone characteristic discussed above, it is likely that bedload monitoring may be improved by using (1) lower (than hitherto used) sensitivity channels in conjunction with still higher sensitivity channels; (2) shortening the length of the pipe portion on which particles collide; and (3) decreasing microphone sensitivity.

Further planned research is scheduled to include constructing a geophone monitoring system that may deal with higher bedload discharges: this will include changes to the construction of the pipe and microphone as well as, a variety of electronic amplification and signal filtering. Indeed, advanced signal processing may turn out to considerably embetter such a system as ours for the continuous and automatic surrogate monitoring of bedload.

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