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Relative Contributions of Sand and Gravel Bedload Transport to Acoustic Doppler Bed-Velocity Magnitudes in the Trinity River, California

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Abstract

A field investigation in the gravel-bedded Trinity River of Northern California indicate that acoustic bed velocities recorded with an acoustic Doppler current profiler (ADCP) reflect the intensity of bedload sand transport, but are relatively insensitive to the gravel and cobble fractions of the bedload. Bed velocity measurements exploit the bottom-tracking feature used by acoustic Doppler instruments to detect instrument motion with respect to the stream bed. When actual instrument motion is eliminated or subtracted from the apparent instrument velocity, any residual instrument velocity is assumed to represent the motion of sediment particles near the bed. More than 100 paired acoustic bed velocity and physical bedload samples were collected from 11 verticals on a stream cross section located near the US Geological Survey streamflow gage at Douglas City. Physical bedload samples obtained with a TR-2 sampler show that the bedload particle size distribution is bimodal with peaks in the sand and coarse gravel ranges. The bulk of the sand transport occurred at two of the 11 verticals, whereas the transport of coarser size fractions was distributed more evenly across the channel. This cross-stream spatial distribution of transport is captured in the bed velocity data, which show high values at the two verticals where most sand transport was observed and low values elsewhere. Underwater video observations confirm that sand transport rates at the bed were high on streamlines where high bed velocities were recorded, and sand transport rates at the bed were low on streamlines where bed velocities were small. Underwater video also indicates that bed velocities register the motion of sand moving as bedload, but not as suspended load. Low bed velocities were measured where the video shows that fast-moving sand particles were present in the near-bed water column but bedload sand transport was minimal. The presence of gravel fractions in transport appears to have little or no effect on the measured bed velocity. Correlations between bed velocities and fractional transport rates determined by physical sampling are substantially stronger for sand and very fine gravel fractions than for coarser fractions, and the total transport rates of samples composed primarily of sand show a stronger correlation with bed velocity than do samples composed primarily of coarser fractions. Bed velocities obtained with this instrument therefore represent a potentially useful supplement to bedload sampling in sand-bed streams or in mixed-bed streams in cases where information regarding the fractional transport of the sand-sized load

is desired. However, this instrument appears to be ineffective for monitoring coarse sediment transport or total bedload transport in gravel-bedded streams.

Introduction

The use of acoustic Doppler current profilers (ADCPs) to detect and measure bedload sediment transport was first proposed and described by Rennie et al. (2002). The technique exploits the bottom-tracking feature used by ADCPs and similar instruments to detect instrument motion with respect to the stream bed. In the context of measuring streamflow, the bottom-track velocity is taken as the velocity of the instrument over an immobile bed, and is used to correct water velocity measurements. However, if bedload particles are in motion near the stream bed, the bottom-track velocity may also contain a velocity component corresponding to the particle movement. When corrected for any actual instrument motion, the residual bottom-track velocity reflects particle movement only and is referred to as the acoustic bed velocity (ν).

The interpretation of ν and its application to various geomorphic problems has received significant attention in recent years. In addition to empirical comparisons between ν and bedload transport rates determined by physical sampling (Rennie et al. 2002; Rennie and Villard 2004; Gaeuman and Jacobson 2006) or by dune migration (Gaeuman and Jacobson, 2007a), bed velocity has been used to investigate bedform dynamics (Kostaschuk and Best 2005), the spatial distribution of relative bedload transport intensity (Rennie and Millar 2004), and benthic habitat conditions (Gaeuman and Jacobson, 2007b). Still, little progress has been made in applying the technique to the practical problem of quantitative sediment transport monitoring. Present understanding of the information encoded in the acoustic signal is sufficient to interpret ν in qualitative terms only.

For the application discussed here, it is useful to distinguish between acoustic reflection and acoustic scattering. Reflection occurs when sound waves encounter a surface, and implies that a coherent image of the original wave is propagated back toward the sound source (Medwin and Clay 1998). Scattering occurs when sound waves encounter small (similar in scale to the acoustic wavelength) objects or irregularities, such that the acoustic energy is dispersed in many directions. Backscatter is the portion of the scattered energy that propagates back toward the sound source. In the case of acoustic Doppler instruments, scattering is caused by particles carried in the water or moving across the streambed. Information regarding the velocities of those particles is encoded in frequency and/or phase changes in the backscattered energy (Simpson 2001; Kostaschuk et al. 2005), and the strength of the backscatter is linked to particle size and concentration (Thorne et al. 1991; Thorne and Hanes 2002).

The bed-velocity signal received and processed by an ADCP presumably contains both the backscatter from moving particles and reflections from immobile portions of the bed surface (Rennie and Villard 2004). The reflections carry Doppler information indicating zero velocity, potentially resulting in measured values of ν smaller than the actual velocity of the particle moving in the bedload layer. Gaeuman and Jacobson (2006) hypothesize that ν is less than the mean bedload particle velocity by a factor w_b, given by:

$$w_b = \left(\frac{b_p}{b_p + b_b F} \right) \tag{1}$$

where b_p is the fraction of the bed area occupied by moving particles, b_b is the fraction of the bed area that is immobile (by definition equal to $1 - b_p$), and F is the strength of the acoustic reflections per unit area of immobile bed compared to the strength of backscatter per unit area of moving particles. An analysis of data collected in the sand-bedded Missouri River suggests that the value of *F* may be approximately 10 for the type of ADCP used in this study (Gaeuman and Jacobson 2006).

In addition to backscatter and reflections from the bed, the bed-velocity signal can incorporate backscatter from faster-moving suspended particles higher in the water column that can bias ν toward larger values (Simpson 2001; Rennie et al. 2002; Kostaschuk and Best 2005). This phenomenon, which is usually referred to as 'water bias,' is especially problematic when suspended sediment concentrations are high. Field experiments suggest that backscatter from suspended sediments in the water column have relatively small effects on ν measured under favorable operating conditions (Rennie and Millar 2004; Gaeuman and Jacobson 2006).

In streams with mixed sediment sizes, the size of particles entrained as bedload tends to increase with flow strength as bedload transport conditions grade through degrees of partial transport toward full mobility (Wilcock and McArdell 1997). This is especially true of gravel-bed streams, where particles sizes on the bed surface typically spans several orders of magnitude. Under these conditions, some size fractions may influence backscatter characteristics more than others. For example, if it is assumed that the surfaces of large gravel particles produce strong acoustic reflections, one might expect ν to increase markedly as larger particles begin to mobilize. Gaeuman and Rennie (2006) demonstrate that relatively minor differences in bed material grain sizes in two sand-bedded rivers can account for relatively large differences in ν observed under otherwise similar sediment transport conditions. However, the effect of changing grain size distributions with changing transport intensity within a single reach has not been evaluated.

This paper reports findings from perhaps the first use of ν in an applied sediment monitoring program. Sediment transport data reported here were collected under the auspices of the Trinity River Restoration Program (TRRP) as part of an intensive sediment monitoring effort to assess the effects of the 2006 Trinity River flow release. A 1200-kHz ADCP was deployed for a subset of bedload samples collected during the release to evaluate whether ν can be used to aid interpolation between less-frequent physical samples, much as continuous turbidity data can be used to interpolate between suspended sediment samples (Christensen et al. 2000). The Trinity data are uniquely suited to evaluate the effect of mixed-size transport on acoustic bed-velocity response because 1) significant bedload transport rates were observed for grain sizes ranging from sand to 128 mm, 2) bedload samples were sieved to yield fractional transport rates, and 3) the sampling transect contained distinct gravel and sand transport paths with highly variable proportions of transport for different size fractions.

Study Area

The Trinity River drains the south side of the Klamath Mountains of Northern California, joins the Klamath River at Weitchpec, and discharges into the Pacific Ocean near Klamath (Figure 1). The river downstream from Trinity and Lewiston Dams has been regulated since 1960. The pre-dam 2-yr recurrence peak flow, based on annual maximum flows for water years 1912 through 1959 at Lewiston (USGS 11525500, Trinity River at Lewiston, CA), was about 450 m^3/s. With the exception of a few isolated storm events, flows downstream from the dams from 1960 through the early 1990s were generally less than about 4 m^3/s year-round. Decline of the anadromous salmonid fishery in the river led to the implementation of mandated annual flow releases from Lewiston Dam and the establishment of a number of other rehabilitation and management activities in the early 1990s. The 2-yr recurrence peak flow at the Lewiston gage for water years 1992 through 2006 was about 145 m^3/s.

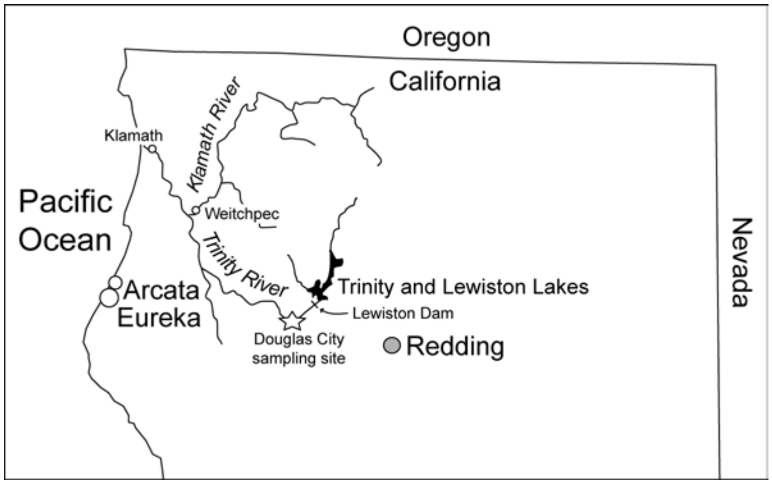

Figure 1. Map of Northern California showing the location of the Trinity River and the Douglas City sampling location.

Sediment transport is currently monitored at four locations in the Trinity River. All sediment samples and associated ADCP data reported here were collected at the Douglas City sediment monitoring site about 30 km downstream from Lewiston Dam (Figure 1). The Douglas City site consists of a single transect located near the downstream end of a straight reach more than 300 m (10 channel widths) long (Figure 2). The channel cross section is approximately rectangular (Figure 3), and the longitudinal profile is relatively straight with a water surface slope of about 0.0016. Surface bed material at the sampling transect is gravel and cobble (D_{50} = 0.065 m, D_{90} = 0.170 mm) with 5-10% sand.

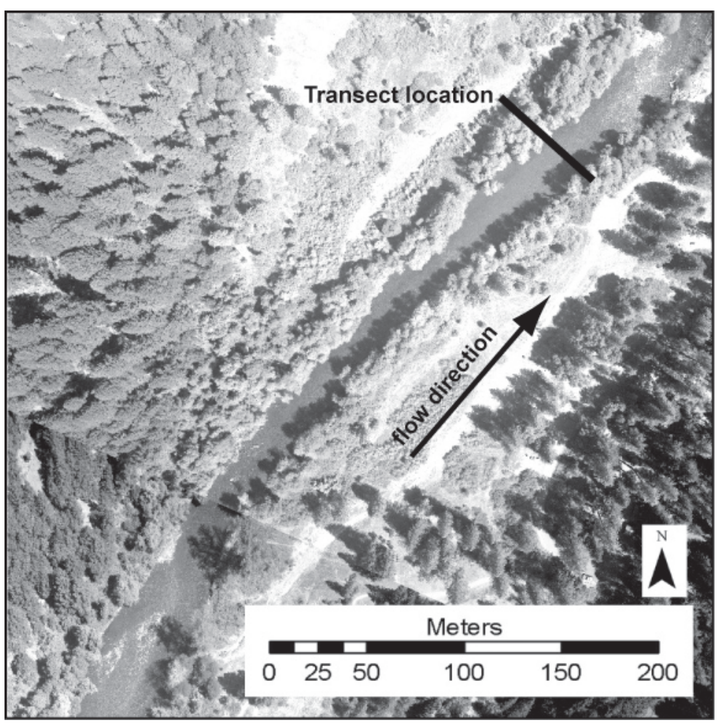

Figure 2. Aerial view of the Douglas City sampling location.

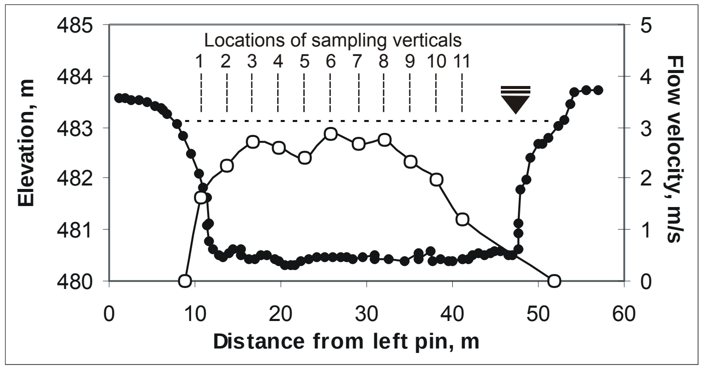

Figure 3. Graph of the sampling cross section with solid symbols indicating bed elevations, open symbols indicate depth-averaged flow velocity, and the dotted line indicates the water surface elevation (discharge = 233 m^3/s). Sampling verticals are numbered sequentially from left to right.

Methods

Sediment transport was monitored over a range of flows on numerous days spanning the 2006 spring release from Lewiston Dam. The 2006 release ramped up through April and May, in part due to unusually wet weather and concerns over dam safety, and reached a peak of 286 m^3/s on May 24. After three days near the peak discharge, flows were decreased and held between 230-240 m^3/s until June 2. Flows were gradually ramped down through June and July, reaching the summer baseflow level of 12.7 m^3/s on July 22. Bedload samples were obtained with a cable-suspended TR-2 bedload sampler with an intake nozzle measuring 0.152 by 0.305 m and a 0.5-mm mesh bag. The sampler was deployed from a cataraft attached via rollers to a temporary cableway secured to trees on either side of the channel. Individual samples were collected at verticals spaced 3.04 m (10 ft) apart across the width of the active channel following standard USGS equal-width increment procedures (Edwards and Glysson 1999). Once the cataraft was positioned at a vertical, the sampler was lowered to the bed from a boom extending from the downstream end of the boat. Sampler down times were typically 30 or 60 seconds, depending on transport rates. The cataraft was moved from one vertical to the next by hauling on the cableway. In most cases, 2 complete passes were made across the channel. Samples collected in conjunction with ADCP data were kept separate by vertical for subsequent sieve analysis.

Bed velocities were collected in conjunction with a subset of the bedload samples collected on 6 different days during the release period (Table 1) using a 1200-kHz Workhorse Rio Grande ADCP. A total of 115 paired bedload-ν samples were gathered on 11 verticals spanning the active portion of the channel. The ADCP was mounted near the upstream end of the cataraft, and configured to collect bottom-track data with no velocity reference (boat speed set to 0). ADCP data logging was started once the cataraft was in position at a vertical and stopped when the sampling crew was ready to move to the next vertical. The duration of individual ADCP samples ranged from 2.5 to more than 30 minutes, with a typical sample duration of about 6 minutes. Minor boat motions while at a vertical were assumed to average out to no net displacement (Gaeuman and Jacobson 2007b). It is reasonable to assume that the difference in the actual boat positions at the beginning and end of an individual ADCP sample was 1 m or less, in which case the maximum net error in ν due to the net change in boat position for a typical sample is about 0.003 m/s or less. Because the TR-2 was lowered from the downstream end of the boat and was swept even farther downstream by the current, the area ensonified by the ADCP was approximately 6 m upstream from the point where bedload samples were obtained. There can be no doubt that this difference in sampling locations, as well as differences in the areal extent of the bed sampled by the two methods, complicates comparisons of the measurement results. We attempted to minimize this problem by positioning the ADCP as close as possible to the TR-2 on the same streamline, and by maximizing the number of physical samples collected so as to incorporate as much small-scale spatial and temporal variability as possible.

Because the ADCP data was logged from a quasi-stationary platform, the bottom-track velocities output by the standard ADCP system software are approximately equivalent to ν. The north-south and east-west bottom-track components were averaged over all pings for each sample, then combined via the Pythagorean theorem to yield an average bed-velocity vector.

Table 1. Dates and characteristics of paired bedload-ADCP samples.

Date	Passes	Discharge (m^3/s)	Verticals Sampled	Samples per Vertical per Pass
5/25/2006	2	280	1-11	1
5/26/2006	1	277	1-11	1
6/1/2006	1	234	1-11	1
6/2/2006	1	238	1-11	1
6/7/2006	1	181	1-2, 3-11	1,3*
	Partial	181	8-10	1
6/12/2006	1	149	1-2, 3-11	1, 3*

* Multiple bedload samples collected sequentially at the same vertical without moving the boat.

Results and Discussion

The size distribution of the bedload captured in the TR-2 was bimodal, with peaks in the sand and coarse gravel ranges (Table 2). The intensity of total bedload transport and the relative proportions of transport of different size fractions were distributed unevenly across the sampling transect (Figure 4). The bulk of the sand transport consistently occurred at verticals 9 and 10 near the right bank, whereas the transport of coarser size fractions (16 to 128+ mm) was distributed more evenly across the central and center-right portions of the channel. Transport of fine gravel sizes (2-16 mm) was heavily concentrated at vertical 9. Although this cross-stream distribution of sediment transport was consistently observed on all 6 days when paired TR-2 and ADCP samples were obtained, reasons for the observed pattern were not obvious. As noted above, the channel cross section is rectangular and the planform is straight. Surface and depth-averaged water flow was swift in the downstream direction across the central portion of the transect (Figure 3).

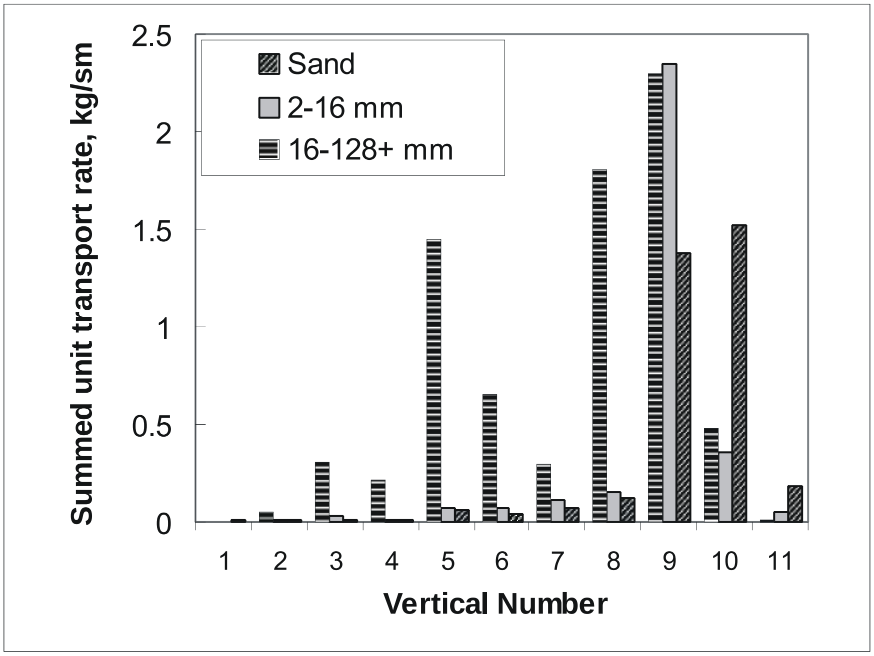

Figure 4. Percent of total transport by grain-size range and sampling vertical. Total transport is defined as the sum of all TR-2 transport rates observed on the 6 days when ADCP samples were obtained, and is equivalent to the total mass of sediment captured in the TR-2 divided by the total TR-2 sampling time.

The correlation between ν and unit bedload transport rates for total load is poor, with a coefficient of determination for a log-log regression of 0.30 (Table 2). However, regressions with the fractional transport rates clearly show that the strength of the correlation between ν and unit bedload transport rate is substantially stronger for sand and very fine gravel. Given the variability typical of bedload transport measurements and the fact that the acoustic samples were obtained several meters upstream from the point of physical sampling, the correlation between ν and sand transport is reasonably strong (Figure 5). The correlations weaken dramatically with increasing particle-size, and essentially vanish for fractions larger than about 8 mm (Table 2).

Table 2. Percent of total sampled transport by size fraction, and the coefficient of determination for log-log regressions of fractional transport rates as a function of ν.

Size fraction (mm)	% total transport	r^2
< 2	25	0.63
2-4	8	0.52
4-8	7	0.37
8-16	9	0.22
16-32	13	0.12
32-64	20	< 0.1
64-128	17	< 0.1
>128	1	< 0.1
Total load	100	0.30

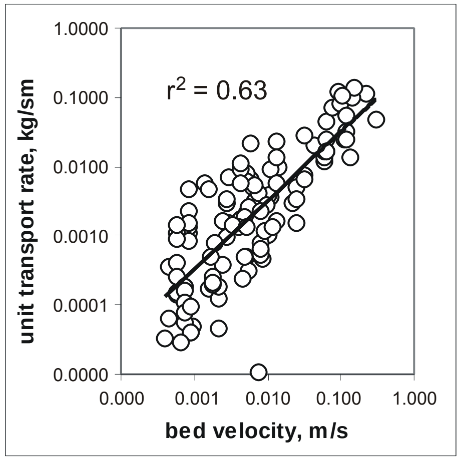

Figure 5. Unit sand transport rate versus bed velocity.

Bed velocities were consistently large at verticals 9 and 10, whereas ν at most other verticals was small and in some cases directed upstream (Figure 6). Although the occurrence of upstream bedload transport is counter-intuitive given the strong downstream depth-averaged flow through the sampling transect, underwater video appears to support the ADCP measurements (a video camera was mounted on the TR-2 sampler during the rising limb of the release before it was damaged at high flows). Video shot from a height of approximately 0.5 m above the bed at verticals near the channel center and center left shows frequent lateral or upstream movement of sand and fine gravel particles at the bed in apparent response to turbulent events (discharge about 151 m^3/s). Downstream transport of the fine fractions is observed primarily when the particles are swept into suspension above the tops of the larger clasts, where their motion apparently does not contribute substantially to ν. Gravel particles move primarily downstream, but are entrained relatively infrequently. By contrast, the video shows that near-bed motion is predominantly downstream for all particle sizes at verticals 9, 10 and 11.

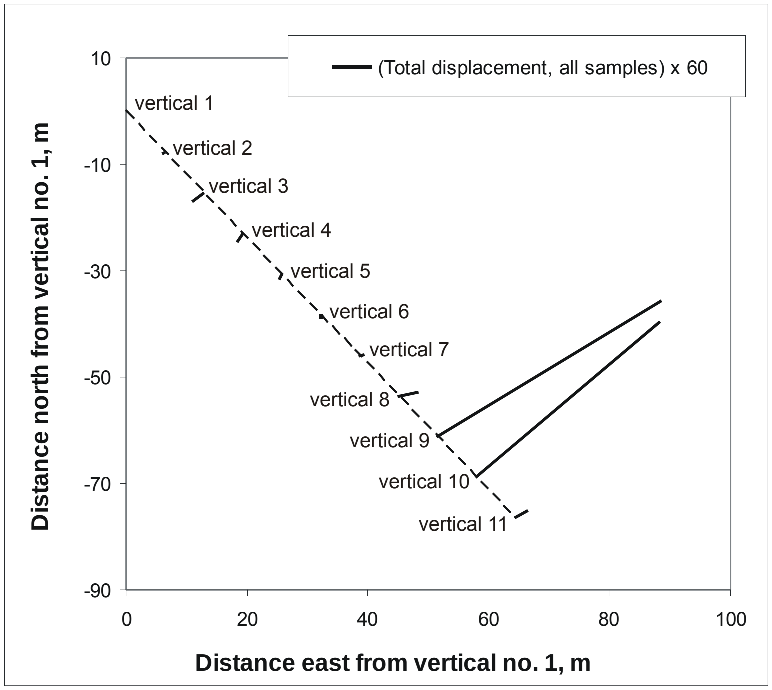

Figure 6. Sum of average bed velocity vectors for all samples per all vertical. Vector sums are scaled by a factor of 60 for display purposes. Dashed line is the sampling transect with verticals labeled. Downstream is toward the upper right.

This spatial distribution of higher and lower ν mirrors the distribution of sand transport across the channel, suggesting that the ADCP tracks the motion of sand at the bed but is unresponsive to the motion of larger particles (Figure 7). Consideration of the percentage of the individual bedload samples consisting of sand versus larger fractions provides further evidence that gravel and cobble transport have little effect on ν. Total transport rates show a relatively strong correlation with ν for samples composed primarily of sand (> 60% sand), whereas total transport rate for samples composed of more than 40% gravel and cobble are poorly correlated with ν (Figure 8). This could be attributed to greater temporal and spatial variability in the transport of coarser particles, or to an increase in the sampling errors associated with coarser particles. However, increased variability can not account for the trends in the mean values of the aggregated data. The mean values of ν for samples with >60% sand and with < 60% sand are the same (0.024 versus 0.025 m/s), whereas the mean unit transport rate for the coarser samples is more than 4 times that of the finer samples (0.227 versus 0.049 kg/sm). It appears that the presence of larger fractions in a sample results in an increase in sample mass, but has little or no effect on the corresponding bed velocities.

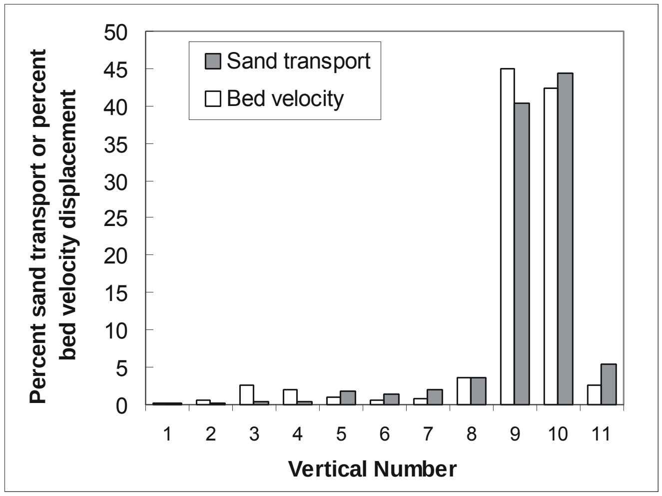

Figure 7. Comparison of percent total sand transport and percent of summed bed velocity magnitudes by vertical. Bed velocity magnitudes shown for verticals 45 through 85 correspond with net upstream displacement as shown in Figure 6.

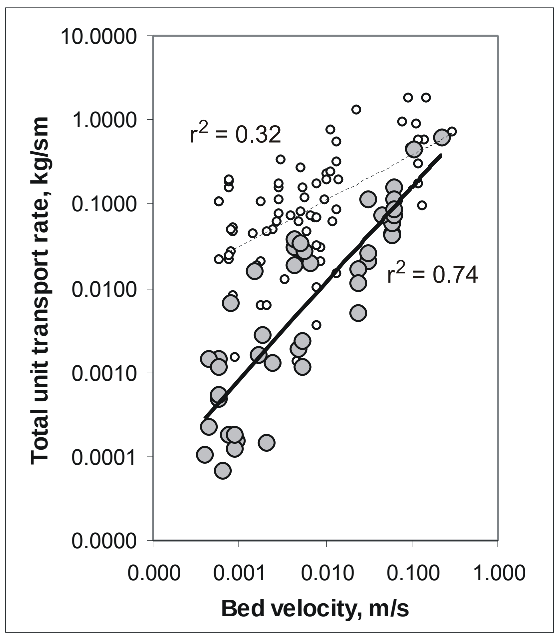

Figure 8. Total unit bedload transport rate versus bed velocity for samples consisting of > 60% sand (large shaded symbols) and samples consisting of < 60% sand (small open symbols). Combined r^2 for is 0.30.

The correct explanation for the lack of a relationship between ν and the transport of gravel and cobble size fractions is uncertain. It is possible that the transport of larger size fractions is captured in the acoustic signal, but their movement is too erratic to produce a coherent velocity signal. In this case, the acoustic response to the larger grains might be considered noise that only interferes with interpretation of the acoustic data. However, it appears likely that the motion of the larger grains is either acoustically invisible or is overwhelmed by the signal from the sand fraction, and so has virtually no effect on ν. The presence of any correlation at all between the gravel sizes and ν could be entirely due to the fact that gravel transport co-varies with sand transport.

Greater acoustic sensitivity to sand transport can be partially explained by the fact that the effective cross section presented by sediment particles depends on the size of the particles relative to the wavelength of the acoustic signal. The strength of the acoustic signal backscattered from sediment particles similar in size to the acoustic wavelength is a function of the acoustic frequency and particle size. This scaling function is known as the normalized backscattering cross section (k_s), and is given as (Thorne and Hanes 2002):

$$k_s = \frac{f}{\sqrt{0.5D\rho_s}} \tag{2a}$$

$$f = C_0\left(\frac{1.1(0.5Dk)^2}{1+1.1(0.5Dk)^2}\right) \tag{2b}$$

$$C_0 = 1.1\left\{1-0.25\exp\left[-((0.5Dk-1.4)/0.5)^2\right]\right\}\times\left\{1+0.37\exp\left[-((0.5Dk-2.8)/2.2)^2\right]\right\} \tag{2c}$$

In (2), D is sediment particle diameter, ρ_s is particle density, and $k = 2\pi f_i/c$, where f_i is the frequency of the instrument and c is the speed of sound in water. For the 1200-kHz instrument used in this study, backscatter is strongest from particles about 1 mm in diameter and declines markedly for particles larger than sand (Figure 9). However, objects considerably larger than the wavelength of the acoustic signal, such as gravel particles, reflect acoustic energy rather than scatter it, and the relation shown in Figure 9 does not apply. As explained in the introduction section of this paper, acoustic reflections may be several times stronger than backscatter (Gaeuman and Jacobson 2006). If so, it is unclear why reflections from larger particles entrained on the bed appear to have little influence on ν.

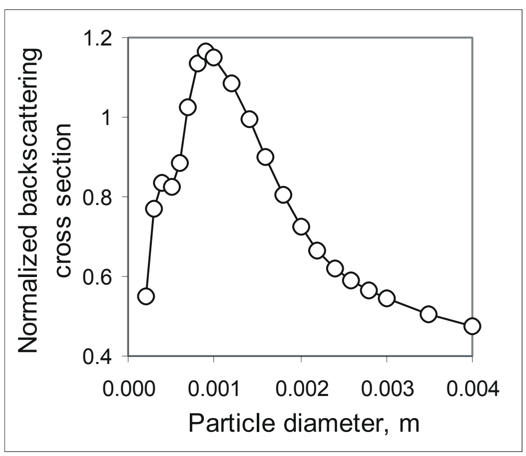

Figure 9. Normalized backscattering cross section versus particle size for a 1200-kHz instrument.

One possible explanation may be that a given mass of gravel or cobble presents a much smaller surface area than an equivalent mass of sand because grain volume scales as the cube of grain radius, whereas grain cross sectional area scales as the square of radius. Thus, the particle cross sectional area presented to an overhead observer by a given mass of spherical grains spread in a horizontal plane decreases by half with each doubling of particle diameter, so that 1 kg of 50-mm gravel presents just 2% of the surface area as a similar mass of 1-mm sand.

Conclusions

Paired bedload and acoustic bed velocity samples collected in the Trinity River indicate that the 1200-kHz ADCP used in this study is sensitive primarily to the motion of sand-sized particles at the bed, but comparatively insensitive to the motion of gravel- and cobble-sized particles. Bed velocities obtained with this instrument therefore represent a potentially useful supplement to bedload sampling in sand-bed streams or in mixed-bed streams in cases where information regarding the fractional transport of the sand-sized load is desired. However, this instrument appears to be ineffective for monitoring coarse sediment transport or total bedload transport in gravel-bedded streams.

Underwater video indicates that bed velocities measured by this instrument reflect the motion of sand moving as bedload, but not as suspended load. High bed velocities were measured at times and in locations where sand transport at the bed was continuous and visually obvious. Low bed velocities were measured where both the video and bedload samples indicated that little or no bedload was being transported, irrespective of the persistence of fast-moving sand particles in the near-bed water column. To the extent that suspended or saltating particles influence the bottom-track signal, they are near enough to the bed to be captured in the TR-2.

Acknowledgements

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