CROSS-SECTIONAL PROGRESSION OF APPARENTBEDLOAD VELOCITIES

Terry A. Kenney, Hydrologist, U.S. Geological Survey, Salt Lake City, Utah, tkenney@usgs.gov

Abstract: An acoustic Doppler current profiler was used to measure apparent bedload velocities as river discharge increased from 5,400 to 19,400 cubic feet per second at a cross section of the Green River near Green River, Utah. Apparent bedload velocities were obtained through the exploitation of the bottom-track bias of acoustic Doppler current profilers. A divergence in the progression of apparent bedload velocities along the cross section was identified. As discharges steadily increased, apparent bedload velocities on one side of the river channel increased while velocities on the other side initially increased and then approached zero. Average cross-sectional apparent bedload velocities were compared with river discharge and suspended-sediment conditions measured during the event.

INTRODUCTION

The dynamic processes associated with the transport of material along a channel bed are complicated. Bedload transport describes the movement of particles by flow through rolling, saltating, and (or) sliding along the channel boundary. Accurately determining the amount and rate of bedload transport in natural channels has proven to be an extremely daunting task. Rennie and others (2002) introduced a technique that utilizes an acoustic Dopper current profiler (ADCP) to measure apparent bedload velocities. Bedload-transport rates within a single cross section have been shown to vary with time and space under steady flow conditions, and rates of bedload transport are known to be greatest during large discharge events. Accurate collection and computation of bedload data under these conditions is necessary for the quantification of total bedload discharge. Further investigation into the variability of bedload processes within a single cross section under changing discharges is needed. In an effort to add some insight into these processes, this study, conducted by the U.S. Geological Survey (USGS), deployed an ADCP to measure apparent bedload velocities at nine stations across a single-channel cross section during a period of rising discharge and fluctuating suspended-sediment conditions.

BACKGROUND

Rennie and others (2002) identified four factors contributing to the difficulty in measuring bedload: (1) spatial and temporal variability is great in natural channels; (2) physical samplers are difficult and dangerous to deploy during channel-forming processes; (3) physical samplers disrupt the natural flow, thus biasing the transport; and (4) bedload sampling and processing is labor intensive. Conventionally, bedload has been collected by two methods: portable samplers or material traps. Material traps, such as slot or pit samplers, are semi-permanent installations that are designed to collect all material being transported along the bed during a set time period. Presently, the portable Helley-Smith bedload sampler is the most widely used. Portable physical samplers typically are lowered down to the streambed from cable-reel systems to collect material for a specified time interval. A series of point samples are collected within a cross section and integrated to compute total bedload discharge. The efficiency of material traps is close to 100 percent (Edwards and Glysson, 1999), and laboratory studies have determined the Helley-Smith efficiencies to be 150 percent (Helley and Smith, 1971; Hubbell and others, 1985; Edwards and Glysson, 1999). The practicality of material traps limits their usage—they are notably difficult to install, retrieve, and maintain in large rivers, and the efficiency of the portable samplers is undesirably high. Fortunately, the nearly exclusive usage of the Helley-Smith samplers during the past 30 years allows for fair comparison of most of the bedload data that has been collected. These factors emphasize a need for new techniques for the measurement of bedload transport in natural channels. An ideal technique would possess a sampling efficiency close to 100 percent without disrupting the natural flow path of sediment particles. It would account for spatial and temporal variability of transport, and be safe to deploy during large discharge events. Recently, Rennie and others (2002) introduced a new technique to measure what they termed the apparent velocity of bedload with an ADCP. The study presented by Rennie and others (2002) shows strong agreement between the apparent bedload velocities and bedload transport rates obtained with conventional samplers in the Fraser River in British Columbia, Canada. To further advance this new technique, which appears to address many of the conventional bedload sampling shortcomings, more field and laboratory investigations will need to be conducted.

Cross-sectional variability of bedload transport can be large, especially under unstable flow conditions. Bedload transport is known to be greatest at large discharges, often experienced for only a small fraction of time throughout a water year. Acquisition of a valid annual bedload discharge requires the ability to quantify transport during these periods of unstable flow conditions, times in which the cross-sectional variability of bedload can be extreme. Moreover, natural channels commonly undergo complex hydraulic and geometric adjustments during these events. Most equations developed to predict bedload were derived under the theoretical assumption of an achieved equilibrium and do not account for the possibility of the channel undergoing aggradation or degradation (Graf, 1984). Applying these equations to periods of unsteady flow and extreme bedload variability can lead to gross errors. Empirical bedload-transport data, such as apparent bedload-velocity measurements, collected under unsteady flow conditions will lead to an improved understanding of certain components of bedload transport.

Use of the ADCP to measure apparent bedload velocities: The concept of exploiting the bias in the bottom tracking-feature of an ADCP to acquire apparent bed velocities was introduced by Rennie and others (2002). ADCPs measure water velocities relative to themselves. In order to determine true water velocities, the velocity of the ADCP is required. By assuming a stationary streambed and utilizing the principle of the Doppler effect, bottom tracking is the most common method of obtaining the velocity of the ADCP. Bottom tracking treats any shift in sound-wave frequency associated with the streambed as velocity of the ADCP. In the presence of a moving bed, a stationary ADCP in bottom-tracking mode will sense that it is moving in the opposite direction of the bed. Apparent bedload velocities (v_a) from stationary measurements are computed by dividing the distance "made good" reported by the ADCP in the bottom-track mode (d_{mg}) by the elapsed time of the measurement (t).

$$v_a = d_{mg} / t \tag{1}$$

The distance "made good" is equal to the straight-line distance from the initial to the final position of the ADCP. In the presence of a moving bed, the bottom-track mode distance "made good" is equal to the straight-line distance from the initial to the final position calculated by the ADCP.

Rennie and others (2002) discussed some potential limitations of deploying an ADCP for bedload measurements. Most of these limitations are related to the geometric characteristics of the acoustic beams of the ADCP and how they sample the channel bed. Beam diameters increase with depth, as does the areal extent that the beams occupy (figure 1). Therefore, the region of the bed insonified by the ADCP varies with depth. Transducer geometry and angular orientation, the number of transducers in an array, and total water depth will have an effect upon how the channel bed is sampled. Greater depths allow for improved spatial averaging, but the geometry of the beams dictates the amount of channel material that is measured. There is also the potential for these instruments to possess an inherent preferential particle-size registration. Data indicate that different acoustic frequencies will register backscatters from different particle sizes in a dissimilar manner. This can lead to an instrument with one frequency identifying a moving bed while one of another frequency indicates no movement. Further study of how these limitations affect the measurement of apparent bedload velocities is needed.

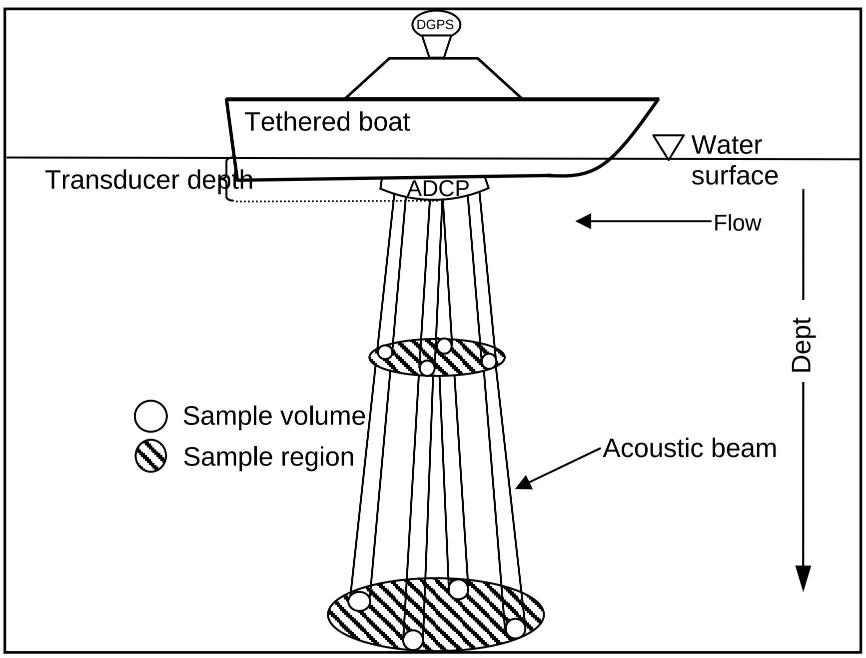

Figure 1 Schematic of ADCP showing increase in apparent bedload-velocity sample volume and sample region with depth.

The ADCP may prove to be a useful tool for acquiring bedload-transport data. There is no disruption of flow near the bed. Samples do not need to be sent away for analysis, decreasing cost and time, which allows for more samples to be acquired. Deployment of the instrument is rapid and safe because the ADCP remains on the water surface and is not submerged within the flow.

The apparent bedload-velocity data presented here should not be interpreted as bedload-transport rates. The data can be used only to identify regions of relatively high or low moving bed velocities. For this investigation, the technique described for measuring apparent bedload velocities was not compared with any conventional bedload sampling data. No attempt was made to calibrate or determine the true relation between actual bedload transport and the apparent bedload velocities obtained during this study. The presence of bed forms can have an effect upon bedload-transport rates. From the methodologies employed during this study, appreciable bed form development was not recognized. This is not to say, however, that bed forms were not present.

SITE DESCRIPTION

The study site was located at the cross section defined by the cableway for USGS streamflow gaging station 09315000, Green River at Green River, Utah. The drainage basin of the Green River at Green River, Utah, is roughly 106,000 km^2. Average river slope of the reach containing the cross section is 0.0004 m/m, and bed materials consist of moderately sized gravels, sand, and silt.

DATA ACQUISITION METHODS

The bias associated with the bottom-tracking feature of an ADCP in the presence of a moving bed allows for a measurement of what Rennie and others (2002) termed apparent bedload velocity. Apparent bedload velocities were acquired at nine channel stations across a single-cross section on the Green River near Green River, Utah, as discharge increased from 5,400 ft^3/s on May 19, 2003, to 19,400 ft^3/s on May 29, 2003. One set of apparent bedload velocities was collected following the receding discharges on June 12, 2003. The ADCP and associated equipment were tethered from the USGS cableway. The ADCP was held in position at the desired channel station for between 60 and 300 seconds. This time span allowed a minimum of 90 subsets, known as ensembles, of data to be collected by the ADCP. The sampling interval of between 60 and 300 seconds was chosen to allow for the acquisition of a near-instantaneous cross-sectional condition. It is understood that longer sampling times would have resulted in improved time-averaged values at each station. The amount of times the ADCP samples the bottom during one ensemble, known as the bottom-track pinging rate, was increased to 3 from the default configuration of 1, to reduce the potential for bedload-velocity errors. A total of 14 sets of apparent bedload velocities were acquired during the study. The progression of apparent bed velocities based upon measurements at channel stations 17, 25, 33, 41, 47, 55, 63, 71, and 79 m is shown in figure 2.

RESULTS

Apparent bedload velocities in the early stages of the flow event, May 20, 2003, through May 21, 2003, were relatively uniform throughout the cross section. As flows continued to increase beyond 12,000 ft^3/s, velocities at channel stations 33 through 47 began to diverge from the velocities at stations on the right side of the cross section. Velocities at stations along the right side of the channel appear to rapidly drop off to near zero values with increasing discharge. The greatest apparent bedload velocity measured was 0.81 m/s at station 41 on May 29, 2003, at 10:05 hours. As would be expected, this velocity corresponded to the largest discharge observed during the study. However, the lowest measured apparent bedload velocities, not

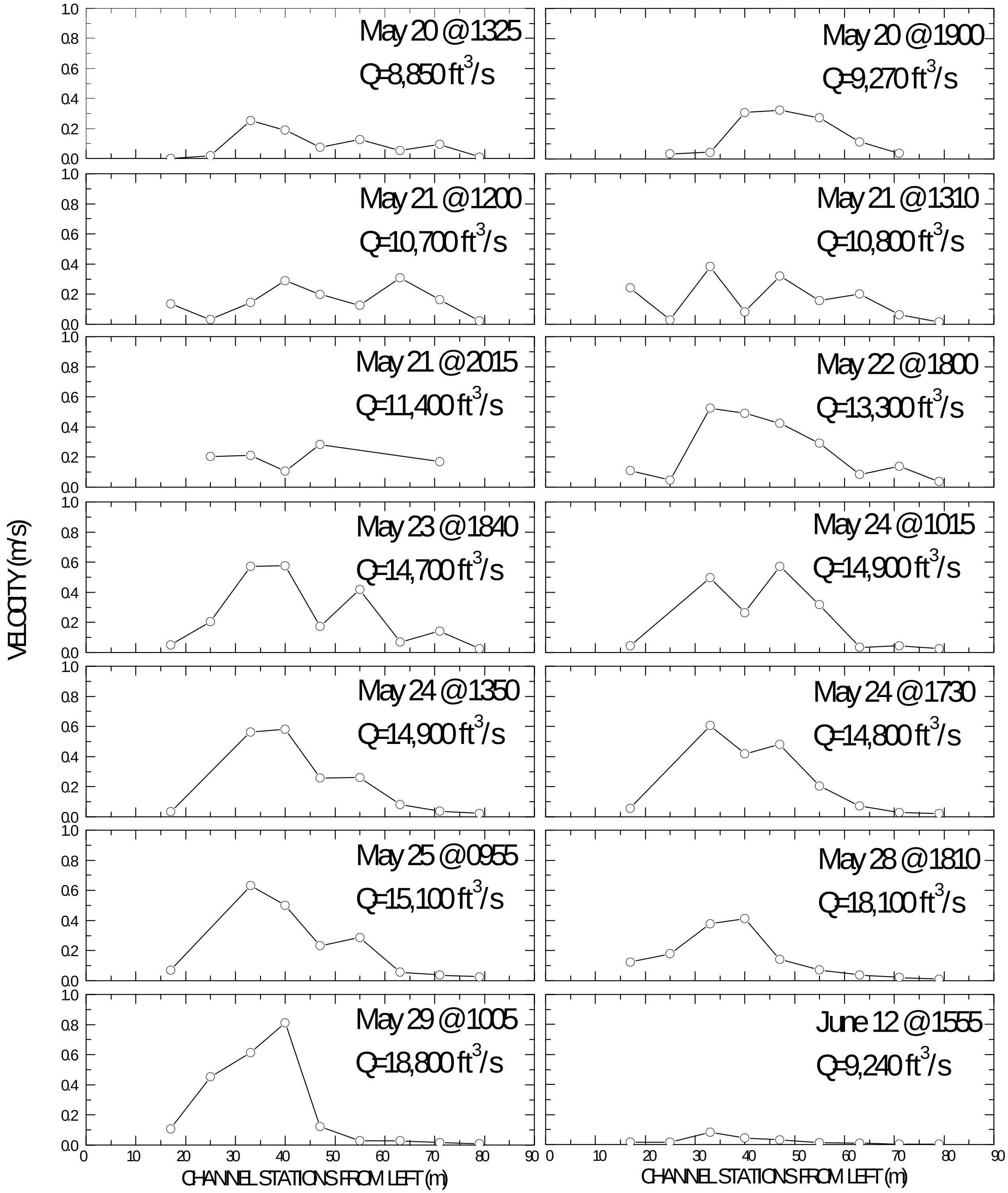

Figure 2 Apparent bedload velocities and corresponding discharge collected at specified channel stations from May 20 to June 12, 2003, at a cross section of the Green River near Green River, Utah.

including those of June 12, 2003, occurred at stations 55 through 79 at the same time. Sediment transport, in this case bedload transport, is dependent upon the availability of transportable materials. The timing of this divergence agrees with an increase in suspended-particle size and lower suspended-sediment concentrations. Prior to these changes, apparent bedload velocities were increasing in a somewhat uniform manner throughout the cross section. Another explanation for the divergence is that with the continued increase in discharge, erodible sediments along the right margin of the channel were exhausted, while the bed materials near the left-center were plentiful. It is not known how far up or downstream this phenomenon extended, but a gentle streamwise gradation into an area of nearly zero transport would be expected. The apparent bedload velocities acquired on June 12, 2003, following the peak of the snowmelt runoff, were the lowest measured. Apparent bedload velocities measured on May 20, 2003, and May 21, 2003, at discharges of 8,850 ft^3/s and 9,270 ft^3/s, respectively, were much greater than those of June 12 at a discharge of 9,240 ft^3/s. This is likely due to the removal of easily transportable sediments early on during snowmelt runoff.

Cross-sectional average apparent bedload velocities were computed from each of the 13 composite sets of apparent bedload velocities. In general, average cross-sectional apparent bedload velocities rapidly increased from 0.09 m/s on May 20, 2003, at 13:25 to as much as 0.25 m/s on May 23, 2003, at 18:40. As discharges remained relatively steady, average cross-sectional apparent bedload velocities did so as well. A plot of average cross-sectional apparent bedload velocities and discharge is shown in figure 3. Average apparent bedload velocities appear to increase in relation to suspended-sediment concentrations (Figure 4). The rapid rate of decrease in suspended-sediment concentrations does not seem to be reflected in the average apparent bedload velocities. A plot of average cross-sectional apparent bedload velocities and the percent of suspended material finer than 0.062 mm is shown in figure 5. This plot indicates that an increase in suspended-material size is related to an increase in average cross-sectional apparent bedload velocities. In general, the acquired apparent bedload velocities seem to show a relation to discharge and suspended-sediment conditions. However, it is difficult to evaluate the relations between apparent bedload velocities and these causal mechanisms after May 25 due to the extended temporal spacing of apparent bedload velocity measurements. The reasons for the low average apparent bedload velocity for May 28 are undetermined.

CONCLUSIONS

By exploiting the bottom-track bias common to ADCPs, apparent bedload-velocity data were acquired as river discharges increased from 5,400 ft^3/s to 19,400 ft^3/s at a cross section of the Green River in Utah. Although no calibration of the apparent bedload velocities to actual bedload-transport rates was conducted, the dataset acquired offers an interesting look at bedload behavior during unsteady flow and suspended-sediment conditions. Of particular significance is the cross-stream variability of apparent bedload velocities at the larger observed discharges.

With the shortcomings of physical bedload samplers and conventional techniques, further field and laboratory investigations into the utility of acoustic technology for the acquisition of bedload-transport data are needed.

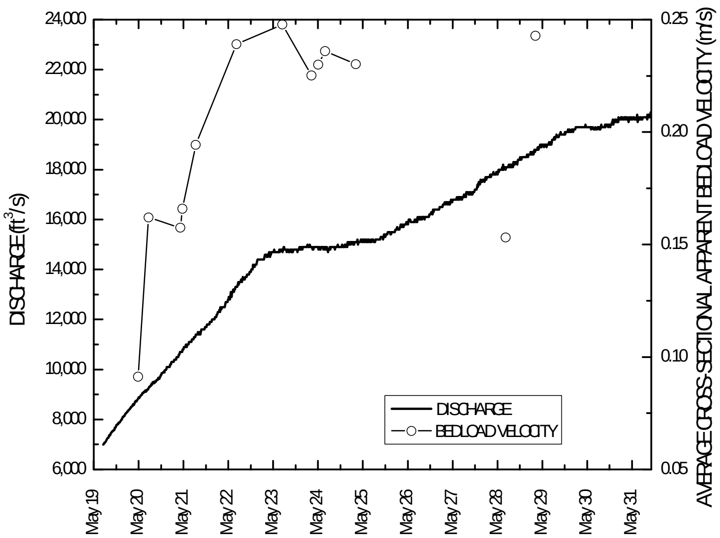

Figure 3 Average cross-sectional apparent bedload velocities in relation to discharge, at a cross section of the Green River near Green River, Utah.

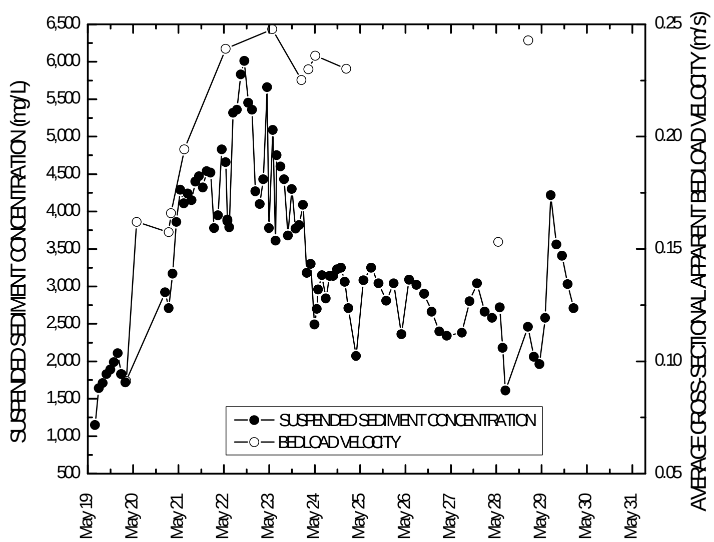

Figure 4 Average cross-sectional apparent bedload velocities in relation to suspended-sediment concentrations, at a cross section of the Green River near Green River, Utah.

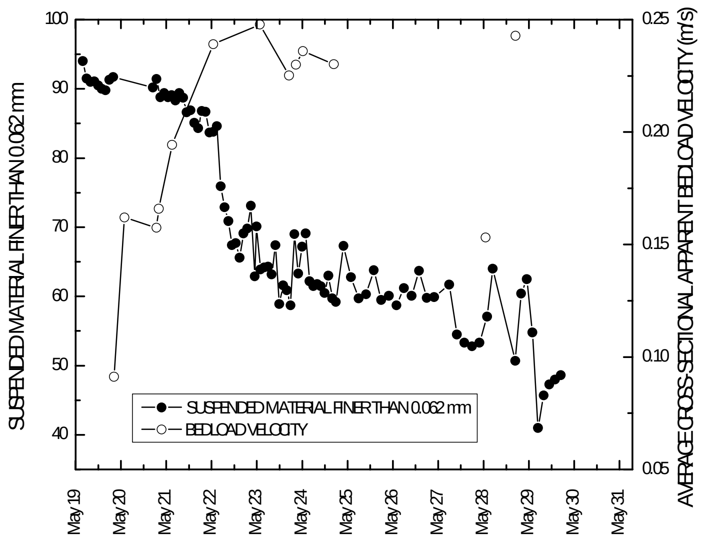

Figure 5 Average cross-sectional apparent bedload velocities in relation to percent of suspended material finer than 0.062 mm, at a cross section of the Green River near Green River, Utah.

REFERENCES

Edwards, T.K., and Glysson, G.D., 1999, Field methods for measurement of fluvial sediment. U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. C2, 89 p.

Graf, W.L. 1984, A probabilistic approach to the spatial assessment of river channel instability. Water Resources Research, v. 20, no. 7, p. 953-962.

Helley, E.J., and Smith, Winchell, 1971, Development and calibration of a pressure-difference bedload sampler. U.S. Geological Survey Open-File Report 73-108, 38 p.

Hubbell, D.W., Stevens, H.H., Skinner, J.V., and Beverage, J.P., 1985, "New approach to calibrating bedload samplers," American Society of Civil Engineers, Journal of Hydraulic Engineering, v. III, no. 4, p. 677-694.

Rennie, C.D., Millar, R.G., and Church, M.A., 2002, "Measurement of bed load velocity using an acoustic Doppler current profiler," Journal of Hydraulic Engineering, 128(5), p. 473-483.