Scooping-Induced Bias of Physical Bedload Measurements and A Recommended Solution for Pressure-Difference Bedload Samplers

David Pizzi, PE, Sr. Hydraulic Engineer, Tetra Tech, Fort Collins, CO, David.Pizzi@tetratech.com
Michael Pierce, PE, Sr. Hydraulic Engineer, Tetra Tech, Fort Collins, CO, Michael.Pierce@tetratech.com

Abstract

The ability of rivers to transport sediment is often a key consideration for ensuring that improvements to both riverine habitat and infrastructure are resilient and sustainable. Pressure-difference bedload samplers are the most widely-used devices for directly measuring physical bedload transport in U.S. streams and rivers. Because of hydraulic forces exerted on such samplers when lowered to, and raised from, the channel bed, these samplers are susceptible to scooping bed material. Scooping can introduce substantial error to the collected sample, leading to inaccurate measurements of both bedload transport and the maximum size of sediment in transport. Current practice relies on the equipment operators to evaluate scooping-induced bias, which is challenging even under ideal conditions with experienced operators.

Bedload measurements frequently establish the prototype against which numerical models of bedload transport and incipient motion are compared, so substantial error in the prototype can confound the calibration and application of a model, compromise the reliability of interpretations of modeled results, and prevent appropriate consideration of risk in decisions based on modeled results.

Available data can be used to demonstrate situations where scooping bias was likely introduced into the bedload measurements. For example, a dataset collected in Alaska in the mid-1980s shows that the coarsest gravels were collected at the lowest discharges, yet these discharges were unlikely capable of mobilizing and transporting these gravels. Another example dataset collected on the San Joaquin River in the mid-2010s includes cobbles when underwater video does not confirm appreciable mobilization of the cobble-dominated bed surface. In both datasets, scooping of the bed surface into the bedload measurement is suspected.

Currently-available and actively-implemented tools to avoid or mitigate the effects of scooping on measurements collected with pressure-difference bedload samplers are not commonly used in the industry. Tetra Tech has formulated a potential solution based on observations made while collecting boat-based bedload measurements during challenging flood conditions. Tetra Tech's proposed solution would prevent the inadvertent collection of dislodged or scooped sediment, and it would be particularly valuable when operating under a limited ability to see or feel the sampler contacting the bed. The proposed solution is an attachment on the nozzle of the bedload sampler that would allow the operator to remotely open a door on the attachment such that water and bedload can enter the sampler nozzle only when the operator is ready; the operator then closes the door to exclude water and sediment from entering the sampler nozzle before raising it from the bed.

A potential drawback to such an attachment is that it could induce differences in the hydraulic and sediment collection efficiency of the sampler, either of which could complicate comparisons to previous samples measured without the attachment. Tetra Tech is pursuing grant funding to further develop and test this attachment, in hopes of improving the industry standard while maintaining consistency in the intended sampler performance. This paper will (1) provide an overview of the potential sources of error associated with bedload sampling, (2) summarize Tetra Tech's proposed solution to this problem, and (3) summarize recommended next steps in further development of the idea.

Introduction

One of the principal concerns in studies of sediment transport is the determination of the total sediment discharge of coarse sediments; because suspended sediment can easily be measured, the main problem is the determination of bedload (the sediment that slides, rolls, or skips along in almost-continuous contact with the stream bed) (Hubbell 1967). The collection of accurate bedload samples has always been a challenge; however, sampling programs using manually-operated portable samplers continue to be the method of choice (Diplas et al. 2008). The U.S. Federal Interagency Sedimentation Project (FISP) requires all bedload sampling be performed with pressure-difference type samplers (Davis 2005), a type of manually-operated portable samplers. In part, because of the FISP's endorsement, pressure-difference bedload samplers are the most widely-used devices for directly measuring physical bedload transport in U.S. streams and rivers.

Background for Scooping-Induced Bias of Physical Bedload Measurements

Despite the FISP's endorsement of pressure-difference bedload samplers, replicate bedload samples collected with such equipment can be highly variable. This variability is influenced by both the inconsistent (in space and over time) nature of bedload transport (Hubbell 1967, Emmett 1980, Carey 1985, Kuhnle et al. 1989, Childers 1999, Dhont and Ancey 2018), and, as noted by Hubbell (1967), the inadvertent collection of bed material. Regarding this second source of variability, which is an error in the sampling as opposed to natural variability in transport, Van Rijn and Gaweesh (1992) identify the *initial effect* (disturbance of the bed when the sampler initially contacts the bed) and the *scooping effect* (when drag on the sampler causes it to act as a grab sampler). Van Rijn and Gaweesh (1992) note that both of these inadvertent collections lead to oversampling, thus biasing the bedload sample high. Childers (1999) redefined these effects as (1) potential for *scooping errors* if the sampler nozzle contacts the bed before other sampler points touch, and (2) *dredging errors* if the sampler is dragged along the streambed. Thus, researchers and practitioners are aware of the potential for scooping-induced bias in bedload samples collected with pressure-difference samplers, yet there are no known solutions to avoid or at least mitigate the biasing effects of scooping.

Physical Bedload Measurements as Prototypes

Bedload measurements are frequently used to establish the prototype for comparing to numerical models of bedload transport or incipient motion. Substantial error in the prototype can confound the calibration and application of a model, compromise the reliability of interpretations of modeled results, and prevent appropriate consideration of risk in decisions based on modeled results.

Prototype Bedload Transport

Development of a bedload transport function: Barry et al. (2004) proposed a new bedload transport equation developed using 2,104 bedload transport observations in 24 gravel-bed rivers in Idaho. The observations were obtained using a 3-inch Helley-Smith (1971) pressure-difference sampler, and multiple lines of evidence indicated that during the largest flows almost all sizes of bed material were mobilized, including sizes larger than the orifice of the sampler. The observations were typically collected following methods presented in Edwards and Glysson (1999) at 20 equally-spaced positions across the wetted width. Barry et al. reviewed each observation for quality, and they removed 284 out of 2,388 observations; only 41 of these removals were because of concern that significant amounts of measured transport at extremely low discharges indicated scooping.

While the choice of Barry et al. (2004) to exclude potentially biased observations from the prototype dataset upon which they developed their bedload transport function is not ideal, no other options are available to reliably calculate potential scooping bias and remove it. Excluding such measurements not only has a direct financial cost associated with the collection of the measurement but also an indirect cost associated with the lost opportunity (perhaps during relatively infrequent hydrologic conditions) to have collected a robust measurement.

Calibration of a numerical model: Using the U.S. Army Corps of Engineers' HEC-RAS software, Tetra Tech developed a one-dimensional bed evolution model (BEM) of the Susitna River near Anchorage, AK. The purpose of the BEM was to assess potential effects of a proposed hydroelectric project on the dynamic geomorphology of the river downstream of the proposed project. The BEM was calibrated to observations of sediment transport and geomorphic change. A concern arose because of differences between the simulated grain size distribution of transported loads and the USGS's measurements of bedload transport (Knott and Lipscomb 1983, Knott and Lipscomb 1985, Knott et al. 1986, Knott et al. 1987), particularly transport of sediment coarser than 16 mm (Tetra Tech 2015). The USGS used a 3-inch Helley-Smith (1971) pressure-difference sampler deployed from a boat to collect 30 bedload measurements.

Because the USGS reported hydraulic conditions during the bedload measurements, Tetra Tech (2015) was able to calculate total shear stress and estimate dimensionless shear stress (also referred to as the Shields (1936) parameter) for the median grain size of the bed surface (D50) (which was based on Tetra Tech's sampling). Tetra Tech cited various references for critical dimensionless shear stresses (Vanoni 1967, Neill 1968, Andrews 1983, Buffington and Montgomery 1997) as a basis for determining that the estimated values, all being less than 0.027, indicated none of the flow conditions were likely to have mobilized the D50.

Tetra Tech (2015) noted a concern that all the coarsest bedload was collected during the first three of the USGS's measurements in 1982, at relatively low flows; measurements at the greatest measured flows contained none of the coarsest bedload and even relatively little gravel between 2 and 32 mm. The most-likely reasons Tetra Tech offered for this discrepancy were (1) disturbances as the Helley-Smith sampler contacted the bed surface causing dislodged particles to enter the sampler, and (2) scooping the bed with the Helley-Smith sampler. Tetra Tech recognized the difficulty of collecting these bedload measurements using a sampler deployed from a crane mounted on a boat in high-velocity flows. Tetra Tech estimated the sampled transport rates of the coarsest gravels were probably derived from collecting only a few individual particles, which could reasonably have been collected from disturbance or scooping during the difficult sampling conditions. Thus, dislodgement or scooping of just a few particles can substantially bias the measurement.

After removing the first three of the available 30 measurements and adjusting the gradations of the prototype bedload rating curve, Tetra Tech found that the simulated bedload gradation closely aligned with the prototype. These three measurements, representing 10-percent of the available measurements, were reluctantly excluded because Tetra Tech stated that if the Helley-Smith sampler disturbed or scooped the bed, finer shielded particles likely also entered the sampler, but the degree of bias in the sample was unknown. Lacking a reliable method to adjust the load and gradation of a bedload sample, excluding the samples from further consideration was the only reasonable option.

Prototype Incipient Motion

Evaluation of bed surface mobilization: In 2014 and 2017 Tetra Tech (in preparation) carried out bedload measurements on the San Joaquin River near Fresno, CA to improve the understanding of the relationship between hydrology, hydraulics, and bed surface mobilization. Bedload measurements were collected over riffles following standard USGS methods (Edwards and Glysson 1999) using a Toutle River (TR-2, 6-inch-high by 12-inch-wide nozzle) sampler deployed from a work platform on a 16-foot-long cataraft (Figure 1).

Figure 1. Tetra Tech engineers sampling bedload on the San Joaquin River in January 2017

During the near-bankfull flows in June 2014, Tetra Tech staff could see through the relatively shallow and clear flows to confirm that the bed surface was not mobilized, so cobbles collected in the samples were judged to have been either dislodged or scooped. Because these observations were made in real time, each vertical could be re-sampled if it was judged to be biased. This was critically important because subsequent calculations of incipient motion would be based on the largest sizes in transport (i.e., collected in the samples).

During the major flooding in January 2017, flow depths were much greater than depths in June 2014, and the elevated suspended sediment load precluded observing the sampler move through the water column and contact the bed surface. Further, the greater flow velocities substantially increased the drag on the sampler as it was lowered into the water, so the operators lost nearly all ability to feel when the sampler contacted the bed. Under these conditions, judgment is too subjective to reliably determine whether a bedload measurement was biased by dislodgement or scooping of the sample.

Unlike the applications where bedload measurements are used to develop prototype rating curves, the coarsest fractions can be excluded from a measurement used to inform the largest size in transport. This is because the sizes, and not the sampled masses, are of interest; when developing rating curves, even if coarse scooped particles are excluded, finer particles entrained with the coarser scooped particles cannot be reliably excluded from the sampled mass. However, the determination of which sizes to exclude and which to retain can still be subjective, which may eliminate, or at least limit, the utility of the adjusted sample gradation for informing the largest grain size in transport.

Proposed Solution

As noted in the examples above, scooping-induced bias in bedload samples can preclude the utility of such samples, coming with both direct and indirect costs. To reduce the potential for dislodged or scooped bed material to bias bedload measurements collected with pressure-difference samplers, Tetra Tech is developing an attachment that will mount to the nozzle of existing samplers (Figure 2 and Figure 3). This attachment will operable so that it can be (1) shut as the sampler is lowered through the water column to the bed, (2) opened once the sampler is positioned on the bed, and (3) closed before the sampler is raised from the bed.

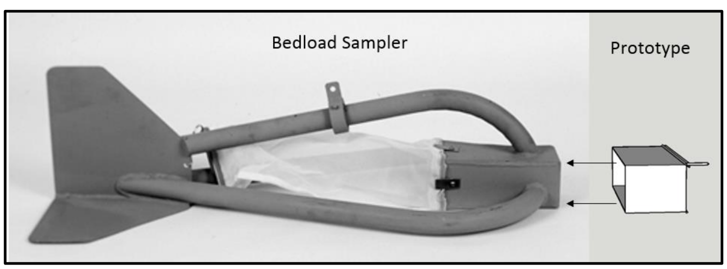

Figure 2. BL-84 bedload sampler and prototype of proposed attachment

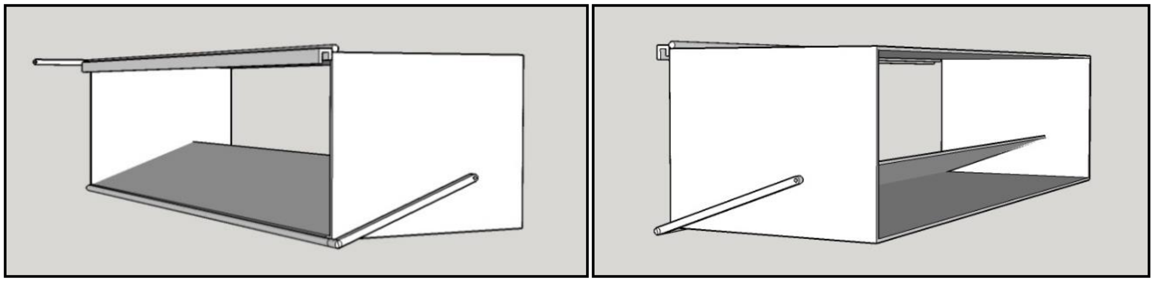

Figure 3. Schematics of proposed attachment – front (left) and back (right)

Tetra Tech has considered alternate configurations of the operable door, such as a bi-fold door hinged along the sides of the attachment to allow water and sediment to be shed through open sides of the attachment. Such a configuration could reduce drag when the sampler is lowered and raised through the water column, but it would be more mechanically complex. Additional considerations include the mechanism to operate the door, including a basic system that opens and closes in response to the sampler contacting the bed (e.g., a spring-loaded plate on the bottom of the attachment and downstream of the nozzle entrance) or an automated mechanism operated by the sampling crew.

A primary objective behind the design of the attachment is to improve bedload measurements without impairing meaningful comparisons to samples collected without the attachment. For example, in fiscal year 2016 the FISP funded testing of the influence of sampler bag mesh size and type on the hydraulic efficiency of pressure-difference bedload samplers (Bunte et al. 2017). The attachment could change the hydraulic efficiency of the samplers, so avoiding such a change, or at least minimizing the change, is desirable. However, Bunte et al. (2017) identified that scooping a few gravel particles into a sampler may well introduce more error than bag mesh size and type. This finding indicates that eliminating scooping-induced bias in a sample could more than offset a small change in hydraulic efficiency. And the attachment may be designed to change the sampling efficiency if eliminating scooping-induced bias brings this efficiency closer to unity.

Future Steps for Developing the Proposed Solution

In early 2017, Tetra Tech contacted the USGS's Hydrological Instrumentation Facility (HIF) to ask whether equipment was available to prevent scooped sediment from biasing a bedload measurement; HIF staff reported that no such equipment was available. By the end of 2017, Tetra Tech completed a patentability search for a bedload sampler attachment, which indicated that such an attachment may be novel and eligible for a patent. Tetra Tech is unaware of alternate embodiments of such an attachment. However, financial considerations prevented Tetra Tech from internally pursuing development and testing of such an attachment. In 2018 Tetra Tech had informal conversations with engineers at Reclamation's Technical Service Center, the Corps of Engineers' Hydrologic Engineering Center, and the USGS's New Mexico Water Science Center that confirmed support for developing and testing an attachment to pressure-difference bedload samples that would improve the quality of bedload measurements. In late 2018, Tetra Tech submitted a proposal to the FISP requesting funding to develop and test this attachment, but no decision has yet been shared with Tetra Tech.

If FISP funding is not forthcoming, Tetra Tech is interested in a partnership to advance the proposed solution to scooping-induced bias of physical bedload measurements collected with pressure-difference samplers. Tetra Tech has invested sweat-equity in refining this solution from its origin as a sketch on a napkin and hopes that such a solution will benefit all sampling and monitoring programs that rely on bedload transport measured with pressure-difference samplers.

References

Andrews, E.D. 1984. "Bed-material entrainment and hydraulic geometry of gravel-bed rivers in Colorado," Geological Society of America Bulletin, Vol. 94: 1225-1231.

Barry, J.J., Buffington, J.M., and King, J.G. 2004. "A general power equation for predicting bed load transport rates in gravel bed rivers," Water Resources Research, 40(10): W10401, doi:10.1029/2004WR003190.

Buffington, J.M. and Montgomery, D.R. 1997. "A Systematic Analysis of Eight Decades of Incipient Motion Studies, with Special Reference to Gravel-bedded Rivers," Water Resources Research, 33(8): 1993-2029.

Bunte, K., Klema, M., Hogan, T., and Thornton, C. 2017. "Testing the Hydraulic Efficiency of Pressure Difference Samplers While Varying Mesh Size and Type," Submitted to the Technical Committee of the Federal Interagency Sedimentation Project, Colorado State University, Engineering Research Center, Fort Collins, CO, pp 75, plus appendix.

Carey, W.P. 1985. "Variability in measured bedload-transport rates," Journal of the American Water Resources Association, 21(1): 39-48.

Childers, D. 1999. "Field Comparisons of Six Pressure-Difference Bedload Samplers in High-Energy Flow," U.S. Department of the Interior, Geological Survey, Water Resources Investigations Report 92-4068, Vancouver, WA, pp 35, plus appendices.

Davis, B.E. 2005. "A Guide to the Proper Selection and Use of Federally Approved Sediment and Water-Quality Samplers," U.S. Department of the Interior, Geological Survey, Open-File Report 2005-1087, Vicksburg, MS, pp 20.

Dhont, B., and Ancey, C. 2018. "Are Bedload Transport Pulses in Gravel Bed Rivers Created by Bar Migration or Sediment Waves?" Geophysical Research Letters, 45: 5501-5508.

Diplas, P., Kuhnle, R., Gray, J., Glysson, D., and Edwards, T. 2008. "Sediment Transport Measurements," In: Garcia, ed. Sedimentation Engineering, Reston, VA: ASCE, pp 307-353.

Edwards, T.K. and Glysson, G.D. 1999. "Field Methods for Measurement of Fluvial Sediment," In: Techniques of Water-Resources Investigations of the U.S. Geological Survey, Book 3, Applications of Hydraulics, Reston, VA: U.S. Government Printing Office, pp 89.

Emmett, W.E. 1980. "A Field Calibration of the Sediment-Trapping Characteristics of the Helley-Smith Bedload Sampler," U.S. Department of the Interior, Geological Survey, Professional Paper 1139, U.S. Government Printing Office, Washing, D.C., pp 44.

Helley, E.J. and Smith, W. 1971. "Development and Calibration of a Pressure-Difference Bedload Sampler," United States Department of the Interior, Geological Survey, Water Resources Division, Open-File Report, Menlo Park, CA, pp 18.

Hubbell, D.W. 1967. "Apparatus and Techniques for Measuring Bedload," United States Department of the Interior, Geological Survey, Water-Supply Paper 1748, U.S. Government Printing Office, Washington, D.C., pp 74.

Knott, J.M. and Lipscomb, S.W. 1983. "Sediment Discharge Data for Selected Sites in the Susitna River Basin, Alaska, 1981-82," United States Department of the Interior, Geological Survey, Open-file Report 83-870, Prepared in cooperation with the Alaska Power Authority, Anchorage, AK.

Knott, J.M. and Lipscomb, S.W. 1985. "Sediment Discharge Data for Selected Sites in the Susitna River Basin, Alaska, October 1982 to February 1984," United States Department of the Interior, Geological Survey, Open-file Report 85-157, Prepared in cooperation with the Alaska Power Authority, Anchorage, AK.

Knott, J.M., Lipscomb, S.W., and Lewis, T.W. 1986. "Sediment Transport Characteristics of Selected Streams in the Susitna River Basin, Alaska, October 1983 to September 1984," United States Department of the Interior, Geological Survey, Open-file Report 86-424W, Prepared in cooperation with the Alaska Power Authority, Anchorage, AK.

Knott, J.M., Lipscomb, S.W., and Lewis, T.W. 1987. "Sediment Transport Characteristics of Selected Streams in the Susitna River Basin, Alaska: Data for Water Year 1985 and Trends in Bedload Discharge, 1981-85," United States Department of the Interior, Geological Survey, Open-file Report 87-229, Prepared in cooperation with the Alaska Power Authority, Anchorage, AK.

Kuhnle, R.A., Willis, J.C., Bowie, A.J. 1989. "Variations in the transport of bed load sediment in a gravel-bed stream, Goodwin Creek, northern Mississippi, U.S.A.," Proceedings of the Fourth International Symposium on River Sedimentation, Science Press, Beijing, China, pp 539-546.

Neill, C.R. 1968. "A Re-Examination of the Beginning of Movement for Coarse Granular Bed Materials," Int. 68, Wallingford, Ministry of Technology, Hydraulic Research Station. England, pp 37, plus figures and tables.

Shields, I.A. 1936. "Application of Similarity Principles and Turbulence Research to Bed-Load Movement," Translated from: Anwendung der Aehnlichkeitsmechanik und der Turbulenzforschung auf die Geschiebebewegung. Mitteilungen der Preussischen Versuchsanstalt fur Wasserbau und Schiffbau, Berlin, Translated by W.P. Ott and J.C. van Uchelen, U.S. Department of Agriculture, Soil Conservation Service, Hydrodynamics Laboratory, California Institute of Technology, Pasadena, CA, pp 36, plus references and figures.

Tetra Tech. 2015. "Fluvial Geomorphology Modeling below Watana Dam, Study Plan Section 6.6, 2014-2015 Study Implementation Report, Attachment 1: Appendix A, 1-D Bed Evolution Model of the Middle and Lower Susitna River: Model Development and Calibration," Prepared for Alaska Energy Authority, Seattle, WA, pp 79.

Van Rijn, L.C. and Gaweesh, M.T.K. 1992. "New Total Sediment-Load Sampler," Journal of Hydraulic Engineering, 118(12): 1686-1691.

Vanoni, V.A. 1967. "Closure of Sediment Transportation Mechanics: Initiation of Motion," Progress Report of the Task Committee on Preparation of Sedimentation Manual, Committee on Sedimentation, Vito A. Vanoni, Committee Chairman, ASCE Journal of the Hydraulics Division, Vol. 93(5): 297-302.