Advances in Estimating Suspended-Sediment Concentration From Multiple-Frequency, Downlooking Acoustic Doppler Current Profilers: Missouri River Focus

Wood M.S., Boldt J.A., Landers M.N. and Oberg K. A.
Office of Surface Water
U.S. Geological Survey
USA
mswood@usgs.gov

Szupiany R.N., Lopez Weibel C.
Faculty of Engineering and Water Sciences
Littoral National University - CONICET
Santa Fe, Argentina
rszupian@fich.unl.edu.ar

***Abstract* — The use of sidelooking acoustic Doppler velocity meters (ADVMs) to estimate fluvial suspended-sediment concentrations (SSC) by the U.S. Geological Survey has become more operational in recent years; however, direct transfer of these techniques to downlooking acoustic Doppler current profilers (ADCPs) currently is not feasible. The use of ADCPs to estimate SSC has been investigated by other researchers, but the requirements and limitations of an operational method that could be successfully applied at many locations are not well defined. In order to evaluate the efficacy of using ADCPs of multiple frequencies to estimate SSC, a dataset was collected on the Missouri River at St. Charles, Missouri, in July 2016. The Missouri River dataset is being compared to similar datasets to determine: 1) what factors influence successful use of downlooking ADCPs to estimate SSC, 2) what are the minimum datasets required to develop SSC calibrations, and 3) what modifications are needed to existing methods, instruments, and software tools.**

Keywords* — *ADCP, multiple-frecuency, suspended sediment, Missouri River

I. Introduction

In river applications, acoustic Doppler meters typically are used to measure water velocities and discharge and are deployed in "sidelooking" and "downlooking" orientations. The acoustic pulse emitted by the meters reflects off of particulate matter in the water and is measured as acoustic backscatter, which can then be related to the amount of suspended sediment in the water [1]. The use of sidelooking acoustic Doppler meters to estimate total fluvial suspended-sediment concentration (SSC) has become operational in recent years, within and outside of the U.S. Geological Survey (USGS), following general principles that are well founded in theory and described in the literature [2, 3]. However, direct transfer of these published techniques to downlooking acoustic Doppler current profilers (ADCPs) currently is not feasible. A key assumption for the sidelooking meter method is sediment homogeneity within the acoustic measurement volume. This assumption is almost never valid in sand-bedded rivers because SSC and particle size commonly vary with depth and location in the river cross section. The use of downlooking ADCPs to estimate SSC has been investigated by other researchers [4] [5] [6] [7] [8] [9] [10] to answer specific science questions or to perform qualitative assessments. Despite these efforts, the requirements and limitations of a quantitative, operational method that could be successfully applied at many locations over changes in sediment characteristics are not well defined.

II. Acoustic Calibration Concept

Acoustic pulses passing through a water-sediment mixture will scatter and attenuate as a function of fluid, sediment, and acoustic instrument characteristics [11]. Acoustic backscatter data must be adjusted when used as a sediment surrogate for several factors to isolate the attenuation (rate of absorption of the signal with distance from the instrument) and backscatter characteristics of sediment [10]. The effects of background acoustic "noise" from the surrounding environment and acoustic instruments also must be considered. After correction, the acoustic backscatter data from downlooking ADCPs can be related to concurrent measurements of SSC at several points throughout the water column to develop a calibration equation (1), adapted from [12] that may be applied to a cross-sectional, moving-boat ADCP measurement to calculate cross-sectional average SSC:

$$10\,log_{10}(SSC) = k_c E - C_r + 2(\alpha_w + \alpha_s)R + 10\,log_{10}\left(\frac{T_t R^2 \psi^2}{L P_T}\right) + C - 10\,log_{10}(K_s) \qquad (1)$$

where kc is a known conversion factor between instrument-specific internal ADCP units (counts) and decibels (dB), E is echo intensity (counts), Cr accounts for the noise or undesired portions of the received signal as well as uncertainties in other terms (unknown), α_w is the absorption coefficient due to water viscosity, α_s is the attenuation coefficient due to sediment scattering out of the acoustic beams and the viscous stresses between water and sediments, R is the range, T_t is the temperature, ψ is a coefficient to correct the signal in the near field zone, P_T is the acoustic transmit power, L is the acoustic transmit length, C is a factor representing the geometry and efficiency of the acoustic transducer, and K_s is a coefficient depending on the particle characteristics and the form factor (f) [13].

To date, research efforts described in this paper for the Missouri River have focused on developing calibrations to estimate the suspended sand or coarse concentration (SSC_C). In doing so, the backscatter and attenuation contributed by sand (coarse material > 0.063 mm) and silt and clay (fine material <0.063 mm) have been separately evaluated. In theory, (1) can be rewritten in simplified form as:

$$log_{10}(SSC_c * K_s) = 0.1(S_T) + K_T \qquad (2)$$

where S_T is the corrected backscatter signal, and the parameter K_T represents other factors previously described (Cr, L, P_T, and C).

III. Data Collection Methods

A dataset was collected on the Missouri River at St. Charles, Missouri (USGS station no. 06935965), on July 20, 2016, to evaluate the efficacy of using downlooking ADCPs to estimate suspended-sediment concentration. Instrumentation included a US P-6 point sediment sampler and 600 kHz and 1200 kHz Teledyne RD Instruments Rio Grande ADCPs (any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government). Moving-boat discharge measurements were first made at the site using both ADCPs. The measured discharge, channel width, channel depth, and velocity averaged 2,800 m^3/s, 400 m, and 5.6 m, respectively. Scientists then positioned the boat at the location of five Equal Discharge Increment (EDI) [14] stations to collect concurrent acoustic backscatter data and point suspended-sediment samples. Three replicate sets of five point suspended-sediment samples were collected at 0.2-, 0.4-, 0.6-, 0.8-, and 0.9 times total depth (D) at each EDI station, resulting in 75 total samples. Bottles for two of the three sample sets were individually analyzed; the third set was composited by station. Concentrations of fine (SSC_f) and coarse (SSCc) material were separately computed. Acoustic data were collected using the ADCPs by remaining stationary over each EDI station while the sediment samples were collected, for durations ranging from 17 to 31 minutes.

IV. Sediment Characteristics

Total SSC in the point samples ranged from 240 to 742 mg/L among all points sampled (Table I). At stations 1 and 5, near the river's edges, suspended sediment was fairly well-mixed through the water column and was comprised of mainly fine material. Across all stations and points sampled, SSC_f was fairly homogeneous (average value 233 mg/L, standard deviation 20.3 mg/L), but SSCc varied widely (average value 92.1 mg/L, standard deviation 103 mg/L). SSCc was highest at stations 2, 3, and 4, where water velocities were highest. Median diameter (D50) of the sand material generally increased with depth at all stations (Fig. 1). Most of the measured suspended sand was classified as "fine sand" according to the Wentworth [15] scale. A substantial portion (31.4 to 52.9 percent) of the measured fine material was smaller than clay-sized material (<0.002 mm).

TABLE I. Summary of suspended-sediment characteristics in three sets of point samples collected July 20, 2016, Missouri River at St. Charles, Missouri (USGS station no. 06935965).

	Station number				
	1	**2**	**3**	**4**	**5**
Average total SSC (mg/L)	257	345	423	320	275
Total SSC range (mg/L)	240–289	247–545	289–742	248–453	258–308
Average % finer than 0.063 mm, all depths	90.1	67.8	56.8	73.7	95.2
Average % finer than 0.063 mm, 0.2D	93.6	86.6	72.9	88.9	94.4
Average % finer than 0.063 mm, 0.9D	83.3	45.0	34.5	50.5	92.9

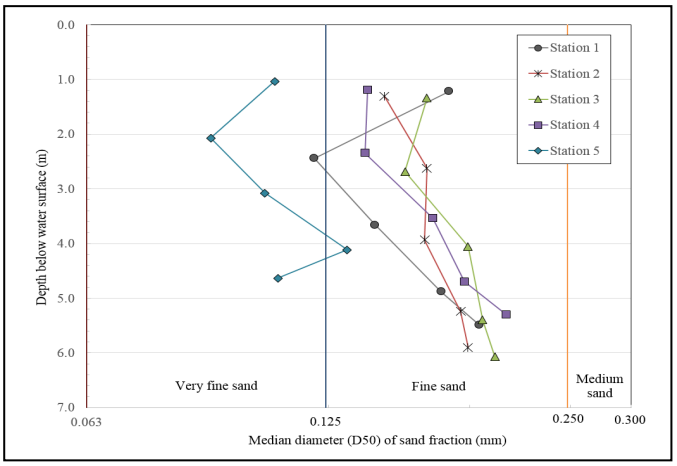


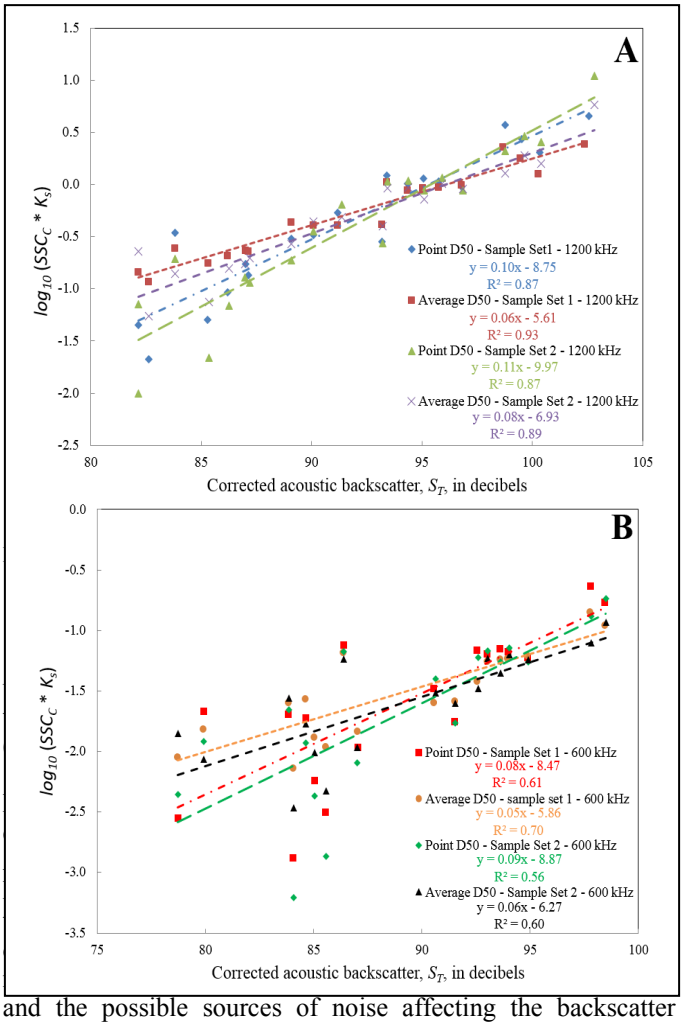
Fig. 1. Variation in median diameter of suspended sand with depth in point samples collected July 20, 2016, Missouri River at St. Charles, Missouri (USGS station no. 06935965).

V. Sediment Characteristics

Preliminary acoustic calibrations were developed for SSCc, using the two sample sets with individual bottle analyses. For comparison, separate acoustic calibrations were developed using a D50 for suspended sand 1) computed from each point sample and 2) averaged from all point samples (Fig. 2). The slopes of the calibrations were similar to the theoretical value of 0.1 (2) for the calibrations developed using the point sample sand D50 values, which may indicate that the use of the point sample sand D50 values resulted in calibrations that better represent the variation in sand characteristics through the water column. Analyzing the sand D50 of each point sample is resource intensive, however, so the significance of the difference in results between using the average and point sand D50 will be evaluated in more detail. Calibration slopes close to the theoretical value of 0.1 also may indicate that there is negligible influence by fine particles on the acoustic backscatter measurement when sand particles are present.

Higher dispersion or scatter was observed in the calibrations at low S_T measured near the water surface, particularly for the 600 kHz ADCP and for calibrations developed using the point sand D50 (Fig. 2). This observation

may have been due to apparent grain size fluctuation near the water surface, seen as an unexpected higher sand D50 at the 0.2D than the 0.4D for four out of five stations (Fig. 1), but more evaluation is needed to confirm. Overall, the 600 kHz ADCP produced poorer calibration curves than the 1200 kHz ADCP.



and the possible sources of noise affecting the backscatter signal.

VI. Future Plans And Needs

The Missouri River dataset will be further analyzed to better understand the effect of grain size fluctuation near the water surface, sensitivity of various frequency ADCPs, sources and effects of noise, and whether calibrations can be developed to estimate SSC_f and ultimately, total SSC. The collection of additional datasets is planned in other U.S. rivers in 2017 to further investigate factors that influence successful use of downlooking ADCPs to estimate SSC over a range of conditions. In the future, the accuracy and efficiency of efforts to estimate SSC using ADCPs would be improved by enhancing instrument capabilities and software tools. In particular, new or enhanced acoustic instruments are needed to measure backscatter with greater precision and accuracy, specifically for sediment applications. Such instruments ideally would include transducers of multiple frequencies, would employ a constant transmit power, and would allow transfer of developed calibrations to another instrument of the same make, model, and frequency.

If an operational method could be developed, the use of ADCPs would revolutionize sediment science globally by allowing rapid and accurate measurements of sediment flux and distribution at spatial and temporal scales that are far beyond the capabilities of traditional physical samplers. In the U.S. alone, measurements of discharge are made with ADCPs every day at many streamgages. If calibrations could be developed at even a fraction of these locations, the amount of sediment information available to water managers, environmental regulators, the public, and science communities would be greatly expanded.

References

[1] M.S. Wood, "Estimating Suspended Sediment in Rivers Using Acoustic Doppler Meters." U.S. Geological Survey Fact Sheet 2014, 3038, p. 4.

[2] M.N. Landers, T.D. Straub, M.S. Wood, and M.N. Domanski, "Sediment acoustic index method for computing continuous suspended-sediment concentrations." U.S. Geological Survey Techniques and Methods, book 3, chap. C5, 2016, p. 63, http://dx.doi.org/10.3133/tm3C5.

[3] D.J. Topping and S.A. Wright, "Long-term continuous acoustical suspended-sediment measurements in rivers - Theory, application, bias, and error." U.S. Geological Survey Professional Paper 1823, 2016, p. 98.

[4] J.W. Gartner, "Estimating suspended solids concentrations from backscatter intensity measured by acoustic Doppler current profiler in San Francisco Bay, California." Marine Geology, Elsevier, v. 211, 2004, pp. 169–187.

[5] G.R. Wall, E.A. Nystrom, and S. Litten, "Use of an ADCP to compute suspended-sediment discharge in the Tidal Hudson River, New York." U.S. Geological Survey Scientific Investigations Report, 2006, 5055.

[6] J.A. Boldt, J.A. Czuba, T.D. Straub, C.A. Curran, R.N. Szupiany, and K.A. Oberg, "Estimation of suspended-sediment concentration from downlooking acoustic Doppler current profilers using an acoustic backscatter calibration procedure and MATLAB-based tool." Proceedings of the Hydraulic Measurements and Experimental Methods Conference, August 2012, pp 12-15.

[7] M. Guerrero, R.N. Szupiany, and F. Latosinski, "Multifrequency acoustics for suspended sediment studies: an application in the Parana River." Journal of Hydraulic Research, 51 (6), 2013, pp 696-707.

[8] F.G. Latosinski, R.N. Szupiany, C.M. García, M. Guerrero, and M.L. Amsler, "Estimation of concentration and load of suspended bed sediment in a large river by means of acoustic Doppler technology." Journal of Hydraulic Engineering, 140(7), 2014.

[9] A.D. Manaster, M.M. Domanski, T.D. Straub, and J.A. Boldt, "Estimating suspended sediment using acoustics in a fine-grained riverine system on Kickapoo Creek at Bloomington, Illinois." U.S. Geological Survey Open-File Report 2016–1117, 2016, p. 42.

[10] R.N. Szupiany, C. Lopez Weibel, F. Latosinki, L. Dominguez Ruben, M. Amsler, and M. Guerrero, "Sediment concentration measurements using ADCPs in a large river: evaluation of acoustic frequency and grain size", Proceedings of the International Conference on Fluvial Hydraulics, July 12-15, 2016: St. Louis, MO.

[11] P.D. Thorne, C.E. Vincent, P.J. Hardcastle, S. Rehman, and N. Pearson, "Measuring suspended sediment concentrations using acoustic backscatter devices." Marine Geology, Elsevier, 98 (1), 1991, pp. 7−16.

[12] L. Gostiaux, and H. van Haren, "Extracting meaningful information from uncalibrated backscattered echo intensity data." J. Atmos. Oceanic Technol., 27 (5), pp. 943–949, 2010.

[13] P.D. Thorne and R. Meral, "Formulations for the scattering properties of suspended sandy sediments for use in the application of acoustics to

sediment transport processes", Cont. Shelf Res., 28(2), 2008, pp. 309–317.

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

[15] C.K. Wentworth, "A scale of grade and class terms for clastic sediments." Journal of Geology, 30, 1922, pp. 377-392.