State of the Science and Decision Support for Measuring Suspended Sediment with Acoustic Instrumentation

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Abstract

Acoustic instrumentation can be used to provide time-series and discrete estimates of suspended-sediment concentration, load, and sediment particle sizes in fluvial systems, which are essential for creating informed solutions to many sediment-related environmental, engineering, and land management concerns. Historically, scientists have developed relations between suspended sediment characteristics and other parameters, most commonly streamflow, to estimate sediment information when physical sediment samples cannot be collected. Approaches using streamflow can have substantial accuracy limitations because of hysteresis effects, giving rise to the use of more direct surrogate approaches such as acoustic methods. Interagency efforts in recent years have advanced the testing, methods development, operational guidelines, and training on acoustic methods for measuring suspended sediment. Scientists interested in using these methods are faced with many decisions on the type of application and deployment: horizontal profiling, vertical profiling, or point acoustic instruments; single or multifrequency instruments; continuous or discrete sediment measurements; and fixed or mobile instrument deployments. To promote cost-effective, accurate, and high-resolution fluvial sediment data for the Nation, the interagency Sediment Acoustic Leadership Team (SALT) develops technical guidance and training for using acoustic instruments to measure aquatic sediment. Even though acoustic instrumentation has been used successfully to measure suspended-sediment characteristics throughout the world, some deployments have been unsuccessful because of limited technical guidance and selection of an inappropriate method. To guide decisions on method selection, the SALT has compiled the state of the science for the main types of acoustics-based suspended-sediment measurement methods in development, testing, and use, and has created a flowchart to guide method selection.

Introduction

Sediment monitoring in fluvial systems is essential to informed solutions to sediment- and water resource management-related issues. However, sediment monitoring by U.S. agencies, including the U.S. Geological Survey (USGS), has decreased considerably over the past quarter century. Sediment sampling often requires substantial resources and funding to purchase specialized equipment, train field personnel, collect representative samples, analyze the samples for sediment concentrations in a laboratory, and ensure safe working conditions. Techniques involving more easily measured parameters that can be related to sediment (called surrogates) have shown great potential for accurately and cost-effectively estimating suspended-sediment concentrations (SSCs). These techniques allow for increased spatial and/or temporal resolution in sediment data and, once relations are developed, allow for rapid estimates of sediment concentration or load when samples are not feasible or cost effective.

The use of acoustic instrumentation for monitoring suspended sediment characteristics has shown great potential because it is often used extensively for other monitoring needs, such as streamflow; it is not as susceptible to biofouling as other in-situ monitoring technologies; and it can potentially provide information on sediment size if multiple acoustic frequencies are used. Applications of acoustic instrumentation in monitoring suspended sediment are at varying stages of research and development, but some general guidelines and recommendations have emerged based on researchers' experience. These guidelines are summarized in this paper with consideration of monitoring program goals, data needs, and environmental settings.

Major Considerations

The proper selection and use of acoustic methods to estimate suspended sediment (hereafter referred to as "sediment-acoustic methods") are dictated by needs of the monitoring program, end user requirements, environmental settings, and characteristics of the sediment and other sediment-like material in suspension in the river. An understanding of these major considerations is needed in advance of initiating an acoustic monitoring program to mitigate challenges with developing relations and to avoid having to change approach after expending significant resources.

Often, program goals require short-term studies that intensively monitor a management decision. An example of this is monitoring sediment dynamics during and after dam removal. In these cases, it is often conducive to have some type of continuous measurement of sediment transport like acoustic instrumentation can provide. Similarly, when determining sediment loads and trends in rivers, the calculated values' uncertainty can be reduced by using continuous data and surrogate relations rather than using only discrete samples and models (Hodson et al., 2021). Continuous monitoring allows reporting of data at a higher temporal resolution which can better capture the dynamic sediment response to storm events than discrete sampling alone. Alternatively, sediment-acoustic methods can be used to provide a discrete estimate of SSC in the river's cross section at a single point in time, after relations between acoustic data and SSC samples are developed. Such estimates can add to the overall discrete sediment dataset at a site of interest and can be used to assess the distribution of sediment in a river cross section or to calibrate sediment transport models.

Environmental Considerations

The selection and proper use of sediment-acoustic methods must be informed by river characteristics in the desired area of monitoring. Users should perform a thorough reconnaissance of river depths, widths, sinuosity, and distribution of suspended sediment, ideally over a range of hydraulic and sediment transport conditions, to determine which sediment-acoustic method(s) would be most appropriate. Users should be cautious of potential sites downstream of riffles or rapids due to the likely presence of bubbles in the water column which can negatively affect sediment-acoustic ratings. The ability to monitor using horizontal profiling (hereafter referred to as "sidelooking") acoustic meters is limited by river depth and width because of concerns about the acoustic beams and beam sidelobes hitting the riverbed, water surface, or other obstructions (Levesque and Oberg, 2012). Users should determine the feasibility of installing and deploying acoustic instrument(s) to measure acoustic data in a portion of the river with relatively higher sediment transport within the cross section which varies proportionally with the overall mean SSC or load in the cross section. Site selection criteria and assumptions behind many sediment-acoustic methods in use are more easily met in rivers where either sediment is well mixed throughout the cross section or is at least homogenous with offsetting variations within the ensonified volume of the acoustic instrumentation (Landers et al., 2016).

Sediment is transported in rivers as bedload and/or suspended in the water column. The suspended material consists of sands, silt/clay (smaller than 62.5 microns [µm] in diameter [D]), and organic matter. The river's flow dynamics and sediment characteristics govern how sediment is transported (Rouse, 1937), but several processes can cause sediment to be out of sync with streamflow, otherwise known as hysteresis. These processes include changes in the supply of sediment, bed scour and fill, and/or lags in the adjustment of bedforms shape and size (Colby, 1964; Topping et al., 2021; Malutta et al., 2020; Dean et al., 2022). Also, certain streamflow conditions can cause the shear stress to be higher on the rising limb than on the falling limb of the hydrograph (Julien, 2002). At a given flow depth, this results in a larger sediment transport capacity and different sediment sizes in transport on the rising limb than on the falling limb. This can result in hysteresis depending on the sediment supply available.

Because sand is larger in size and more heterogenous in suspension than silt/clay, it can be difficult to measure with commonly used water quality parameters such as turbidity (or optical backscatter) and total suspended solids ([TSS] Merten et al., 2014; ASTM, 2000). For turbidity, the signal decreases with increasing particle size because there is less surface area on the particles and less probability for a particle to be hit by the turbidity light source (Downing, 2006; Merten et al., 2014). The TSS laboratory analysis often fails to capture the sand-size particles because the particles settle before a representative sub-sample can be collected (Gray et al., 2010; Groten and Johnson, 2019) while the SSC laboratory analysis measures all particles in the sample (Guy, 1969). Acoustic instrumentation can be more responsive to sand-sized particles and a better choice in environments with sand.

Flocculation is the process in which primary particles— in this case silts/clays and organics— aggregate to a larger particle termed a 'floc' (D > 50 µm). The process of flocculation is driven by three mechanisms: Brownian motions, differential settling, and turbulent interaction (Witerwerp and van Kesteren, 2004). The cohesive nature of clays, along with the positive ionic charge of the water and particles, allows for aggregation. In estuarine and coastal environments, turbulent interaction is the main mechanism (Witerwerp and van Kesteren, 2004) where the interaction of primary particles creates a process where flocs aggregate and break continuously, up to a turbulent maximum where flocs no longer hold together. Krone (1986) described two different aggregates states: flocs and flocculi; where flocculi are on the order D < 20 µm, and do not disperse back into primary particles at the maximum turbulent energy of the system. Therefore, in a tidal environment where turbulence increases as slack tide turns to either flood or ebb stages, we expect flocculation to occur predominantly around slack tide. As flocs develop and disaggregate, the acoustic intensity of sediment-acoustic instrumentation would respond not only to the size but potentially to the shape and density of the flocs or primary particles. While past work has utilized semi-empirical models to represent the backscattering form function, scattering attenuation coefficient, and viscous attenuation coefficient for primary particles of various shapes, density, minerology, and particle-size distribution width (Thorne and Hurther, 2014, and references therein), only recently have investigations examined the acoustic response to flocculated sediment (MacDonald et al., 2013; Thorne et al., 2014; Vincent and MacDonald, 2015; Sahin et al., 2017; Bux et al., 2019; Pedocchi and Mosquera, 2022).

The presence of organic matter in a monitored environment can introduce variability in sediment-acoustic relations. Particulate organic matter in transport, particularly within the measurement volume of the acoustic instrument, can scatter and reflect sound emitted from an acoustic instrument and thus can be interpreted as "sediment". However, some of this organic matter can be burned off during sample analysis at the laboratory and not reported in the concentration result. Additionally, organic matter and related biological processes can promote adhesion and flocculation of particles (Deng et al., 2022) which can be interpreted as larger aggregates than the individual sediment grains. Changing amounts of particulate organic matter over environmental conditions can result in errors or variability in sediment-acoustic relations (Voichick and Topping, 2014). Sediment-acoustic monitoring programs at sites with known or suspected organic matter in transport would benefit from the inclusion of laboratory analysis of organic matter content in samples.

Acoustic Methods

The following sections provide the state of the science for the primary acoustics-based suspended-sediment measurement methods in development, testing, and use. The primary focus of this paper is on fluvial applications, but the paper does provide a section applicable to estuarine and marine environments with adaptations and unique considerations. The following figures and table were created to provide a visual of the primary methods (Figure 1), a flowchart to guide method selection (Figure 2), and a table providing important resources and technical assistance contacts for each method (Table 1).

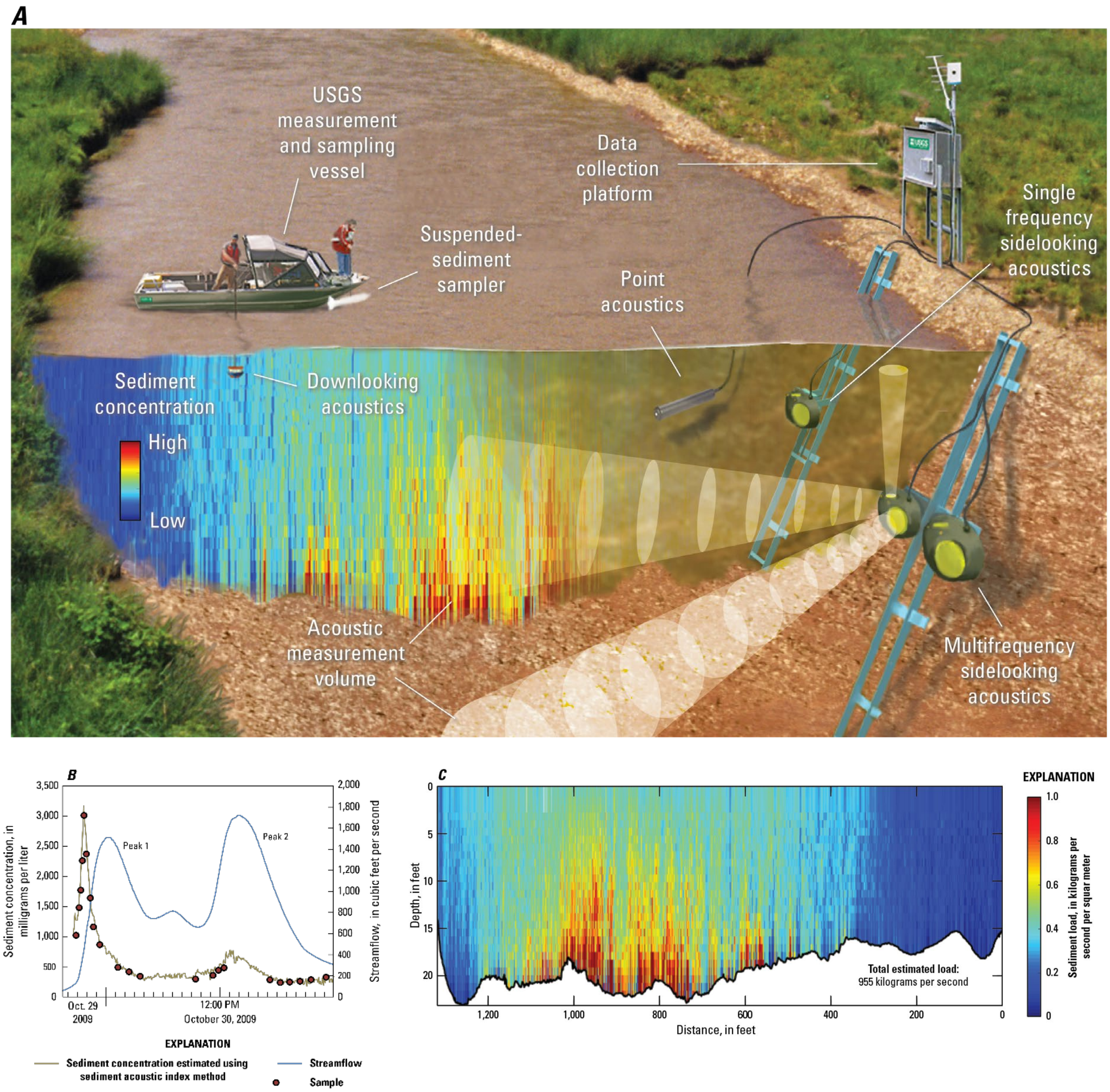

Figure 1. A) Visualization of four acoustic methods for measuring suspended sediment in a fluvial system: downlooking acoustics, point acoustics, single frequency sidelooking acoustics, and multifrequency sidelooking acoustics (not to scale; modified from Landers et al., 2016). Examples of data resulting from sediment-acoustic methods and ratings: B) time series, continuous SSC using the single frequency acoustic method (from Landers et al., 2016) and C) discrete, cross-sectional sediment load using the downlooking acoustic method.

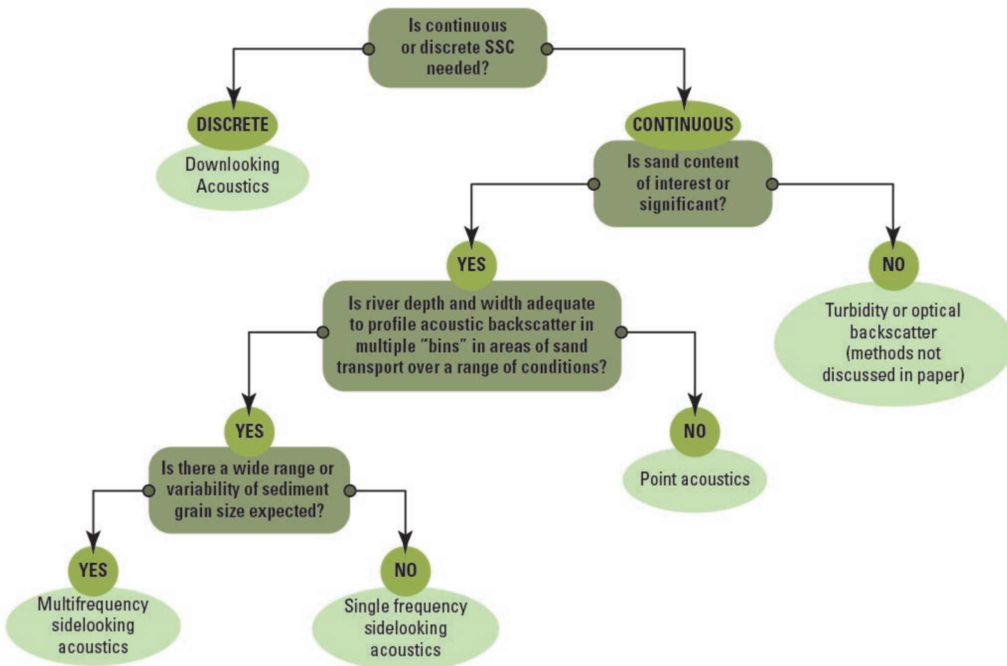

Figure 2. Decision support flowchart to guide selection of sediment-acoustic methods

Table 1. Summary of selected methods for measuring suspended sediment using acoustic and other instrumentation

Method	Monitoring Location: Fixed, Variable, or Mobile	Data Generated	Readiness Level*	Key Publication (s)	Federal Agency Points of Contact
Downlooking Acoustics	Mobile	Discrete cross-sectional SSC	6	Wood et al. (2019); Szupiany et al. (2018)	Justin Boldt, jboldt@usgs.gov Molly Wood, mswood@usgs.gov Tim Straub, tdstraub@usgs.gov
Turbidity and Optical Backscatter	Fixed or Variable	Continuous SSC	9	Anderson (2005); Rasmussen et al. (2009)	Kim Shaffer, kshaffer@usgs.gov Patrick Rasmussen, pras@usgs.gov Chauncey Anderson, chauncey@usgs.gov
Point Acoustics	Fixed or Variable	Continuous SSC	6	Manaster et al. (2020); Straub et al. (2019); Snazelle (2017)	Tim Straub, tdstraub@usgs.gov Jeb Brown, jebbrown@usgs.gov Jason Alexander, jalexand@usgs.gov Steven Suttles, ssuttles@usgs.gov Patrick Dickhudt, patrick.j.dickhudt@erdc.dren.mil
Multifrequency Sidelooking Acoustics	Fixed	Continuous SSC, grain size	8	Topping and Wright (2016); Haught et al. (2020); Vergne et al. (2021)	Ron Griffiths, rgriffiths@usgs.gov David Topping, dtopping@usgs.gov Dan Whealdon-Haught, dwhealdo@usgs.gov
Single Frequency Sidelooking Acoustics	Fixed	Continuous SSC	9	Landers et al. (2016)	Molly Wood, mswood@usgs.gov Tim Straub, tdstraub@usgs.gov Joel Groten, jgroten@usgs.gov Zuli Lucena, zlucena@usgs.gov

* Readiness Level is used to characterize the status of research and development relative to its operational readiness (NOAA, 2016).

Single Frequency - Point Acoustics

One sediment-acoustic method for obtaining continuous estimates of SSC is the use of point acoustic instruments. If sand content is of interest or significant, but there is not adequate river depth and width to profile backscatter in multiple bins, meaning the measurement of acoustic energy is divided into successive segments, then a higher frequency acoustic instrument (for example, 8-megahertz [MHz]) that profiles within centimeters of the instrument may be an option. Like other acoustic instruments, the sensor emits an acoustic pulse and measures the acoustic energy scattered by sediment back toward the signal source (called backscatter). For a point acoustic instrument, the relative strength of the backscatter is used only at one bin instead of multiple bins along an acoustic beam like the other methods and instruments discussed in this paper. Sequoia Scientific's LISST-ABS is a single frequency 8 MHz acoustic sensor that measures acoustic backscatter at a fixed point 5.5-centimeter (cm) away from the transducer (Sequoia, 2016a). The LISST-ABS frequency and short path length minimize the effects of sound attenuation, and the water and sediment attenuation are measured and internally used for correction (Sequoia Scientific, 2016a; Snazelle, 2017). The relative strength of the backscatter is measured and converted to a concentration reading in milligrams per liter (mg/L) as calibrated by the manufacturer (Sequoia Scientific) in a laboratory using particles 75–90 µm in diameter (Sequoia Scientific, 2016a, 2016b). If the sediment in a fluvial environment differs from 75-90 µm, a regression can be completed between instrument readings and discrete samples analyzed for suspended-sediment concentration and collected following methods described by Edwards and Glysson (1999). The USGS tested the LISST-ABS in the laboratory (Snazelle, 2017) and compiled and analyzed field data (Manaster et al., 2020). USGS researchers are currently writing methods to check the calibration of the instrument in the field or laboratory (Alexander et al., 2023). Some instrument readings have drifted (instrument gives a different value for the same concentration and sediment conditions) over time, and the only way to recalibrate the instrument is to send it back to the manufacturer. This calibration check method will help determine when an instrument should be sent back to the manufacturer for calibration. Additionally, USGS research is ongoing to test the concept of pairing ABS readings with optical turbidity readings to obtain better estimates of SSC over a broader range of particle sizes (Agrawal et al., 2019).

Single Frequency - Sidelooking Acoustics

Another sediment-acoustic method for obtaining continuous estimates of SSC involves the use of single frequency acoustic instruments, such as acoustic Doppler velocity meters (ADVMs). The research and application of single frequency sediment acoustics has been thoroughly documented, and more recently, it has been made operational by the USGS (Landers et al., 2016). The operational procedures have helped to standardize data collection and data processing leading to improved data quality and operational efficiencies. An ADVM deployed in a fixed location, usually as part of a streamgage, horizontally profiles acoustic backscatter data within a known volume of water (ensonified volume). These backscatter data are processed and corrected for variables affecting the backscatter signal such as water absorption and sediment attenuation. Data from discrete, isokinetic, depth-integrated suspended-sediment samples are then related to the corrected backscatter signal to develop a sediment-acoustic rating.

The use of a single frequency instrument is only appropriate at locations where SSCs and grain-size properties are predominantly homogeneous in the measurement volume or have variations that offset and do not affect average backscatter values. Typical frequencies used to successfully apply this method range from 0.5 to 3 MHz, but selection of the most appropriate frequency is driven by site conditions and sediment characteristics. It is important to collect reconnaissance data prior to application to decide if this is the appropriate method, to help determine what frequency should be used for the site, inform where the acoustic instrument should be installed, and how it should be configured (Landers et al., 2016).

The single frequency sidelooking acoustic method for computing SSC requires the collection of multi-bin backscatter data from the ADVM. A minimum of 10 bins is recommended, but more bins may improve the resolution of acoustic attenuation measurements. The instrument should be configured to minimize signal attenuation over a range of sediment conditions and avoid obstructions and interference from boundaries. The lower frequencies have a longer profiling range than the higher frequencies; however, with any frequency used it may not be advantageous to maximize distance profiled due to the risk of attenuation during high sediment transport events or inadequate reflection of the acoustic signal during low sediment transport periods. The ADVM should also be configured with appropriate averaging periods and measurement intervals based on rate of SSC fluctuations at the site. The Surrogate Analysis and Index Developer (SAID) software was developed to process and correct backscatter data to develop a sediment-acoustic rating (Domanski et al., 2015). Databases, such as the AQUARIUS-Time Series (Aquarius Informatics, 2022) platform used by the USGS, can also be set up to process and correct the backscatter data in real-time.

In addition to acoustic backscatter data, collecting representative SSC samples following methods described by Edwards and Glysson (1999) is essential to the successful development of a sediment-acoustic index rating. Samples should reasonably represent seasonal variability and the range of flow and sediment conditions observed at the site, with particular focus on medium- and high-flow conditions. After a rating is developed from a calibration dataset, validation SSC samples should be collected to assess the long-term stability of the rating.

The USGS operational procedure for development of a sediment-acoustic index rating is by using ordinary least squares linear regression (Helsel et al., 2020). A sediment-acoustic index rating can be a simple linear regression or multiple linear regression. Sediment corrected backscatter (SCB) is often used as the explanatory variable for SSC, but the sediment attenuation coefficient (SAC) can also be used. The SAC is not typically correlated to SCB because it measures different suspended sediment characteristics (Landers et al., 2016).

Concurrent measurements of acoustic parameters (SCB and/or SAC) and SSC are combined into a calibration dataset used to develop a linear regression model. The calibration dataset should be representative of all seasons and most streamflow and sediment conditions. Having more SSC samples is always helpful when developing a sediment-acoustic rating, but it is important to consider that oversampling the same storm event can lead to autocorrelation (Helsel et al., 2020). Development of the calibration dataset and sediment-acoustic rating or linear regression model can be completed using the SAID software.

Multifrequency - Sidelooking Acoustics

Since single frequency methods may not be adequate in systems with highly variable grain sizes within the ensonified volume, a method using multiple frequencies of acoustic methods must be explored. Similar to the point acoustic and single frequency acoustic methods, the multifrequency acoustic method can produce continuous estimates of SSC if a sediment-acoustic rating is successfully developed. While the use of single frequency acoustics to invert scattering material dates back more than a half century (Hay, 1983 and references therein), one of the pioneering papers on the multifrequency techniques is that of Hay (1991). More recently, there have been studies that provide assessments of multifrequency methods in rivers (Topping and Wright, 2016; Haught et al., 2020; Vergne et al., 2021), where Vergne et al. (2021) assess multiple variations of some contemporary and varying inversion methods.

When multiple frequencies are available to invert acoustic signals, and the ensonified volumes ideally overlap in space and are close in time, the uniqueness of each acoustic response for each frequency can be used to invert N-1 unknown parameters, where N is the number of frequencies used. This is based on the assumption that each acoustic frequency is ‘seeing’ the same volume of water and sediment, and the only difference should be the response between frequencies. While there are many different variations to the multifrequency method (Thorne and Hanes, 2012; Thorne and Hurther, 2014; Vergne et. al. 2022), many approaches iterate through a possible range of mean particle size until sediment attenuation converges to a minimum variation amongst frequencies, solving for particle size, and providing a solution for concentration. Specifically, the method developed by Topping and Wright (2016) uses two frequencies and solves for SSC for each frequency separately, and the two frequencies are used to solve for median sand size and D50 corrected sand concentration.

The first step in the multifrequency method is to calibrate each frequency. The main two methods available are:

1) calibrate with a standard target of known density and diameter, or

2) calibrate with sediment of known size, concentration, and distribution.

At higher frequencies where wavelengths are small, using a known target becomes difficult if not impractical as the target size approaches that of sediment, thus method 2— described by Betteridge et al. (2008)— is recommended. The Betteridge et al. (2008) method calibrates each frequency by collecting sediment samples within the ensonified range (i.e., while it is recording) where SSC and the grain size distribution (GSD) are analyzed. Concentration and mean particle size, along with the semi-empirical models of attenuation and scattering, are used to account for all the parameters in the sonar equation except for the system calibration parameter (often notated K_t), which is then solved.

Single Frequency – Downlooking Acoustics

The downlooking method is similar in concept to the sidelooking method in that the acoustic backscatter data recorded by a downlooking acoustic Doppler current profiler (ADCP) are related to discrete samples of SSC. Point samples rather than depth-integrated, isokinetic samples are collected in the downlooking method to understand sediment grain size variations with depth. Another primary difference in the downlooking method compared to other sediment-acoustic methods is that ADCPs are typically deployed from a floating platform or boat as it moves across a river. The appeal of the downlooking acoustics method in relation to continuous SSC monitoring is that it measures much more of a river cross section and the variability therein and results in a discrete estimate of SSC in the cross section at a given point in time. The high spatial resolution visualizations of suspended sediment from the downlooking acoustics method are unmatched by any other physical or acoustic method (Figure 1C).

Like the sidelooking method, SSC samples are collected concurrently with acoustic backscatter data, but instead of varied over time, they are varied spatially within the cross section. There is not a universal strategy for collecting samples, but generally, the point sediment samples are collected within multiple verticals in the cross section and at various depths within each vertical. Selecting sampling locations within the cross section to include the range of expected backscatter conditions (low to high) is ideal. Early usage of the downlooking acoustics method used ADCPs with a constant bin size, but modern ADCPs tend to be auto-adaptive (changing bin sizes and modes) according to the hydraulic conditions. In general, any ADCP can be used in the downlooking acoustics method if the raw, uncorrected backscatter are available along with specific instrument properties including transducer diameter, received signal strength indicator (RSSI) scale factors, and transmit parameters.

A challenge of the downlooking acoustics method is that the particle characteristics (SSC and GSD) in the water are not homogeneous in the vertical direction. Although calibrations have been relatively successful at several testing sites with a range of hydraulic and sediment conditions (Wood et al., 2019), it is still unknown how robust a calibration is over time (during higher and lower flows and during different seasons). Calibrations are typically made from acoustic and sediment data collected on a single day (generally within a 4–6-hour window) and at a relatively stable streamflow.

Because ADCPs also measure velocity at the same high-resolution scale (sub-meter bins within a cross section), the suspended sediment discharge (or load or flux, in units of mass per time) for a river cross section can be computed from this method. Although the total suspended sediment discharge for a cross section is usually of interest, the downlooking acoustics method can also visualize the load at the same high spatial resolution as the SSC.

Another benefit of the downlooking acoustics method is that it can help improve the understanding of short-term variability (seconds to minutes) of suspended sediment in rivers. During the collection of sediment point samples at a vertical, the ADCP typically is recording continuously for approximately 20-30 minutes (Figure 3). Whereas a physical sample might only represent a 10-20 second snapshot of the SSC at a specific depth (Figure 3C), the stationary ADCP data can also be calibrated and plotted (or animated) to show the variability and range of SSC in the water column over a longer time period (for example, 30 minutes; represented by box plots in Figure 3B).

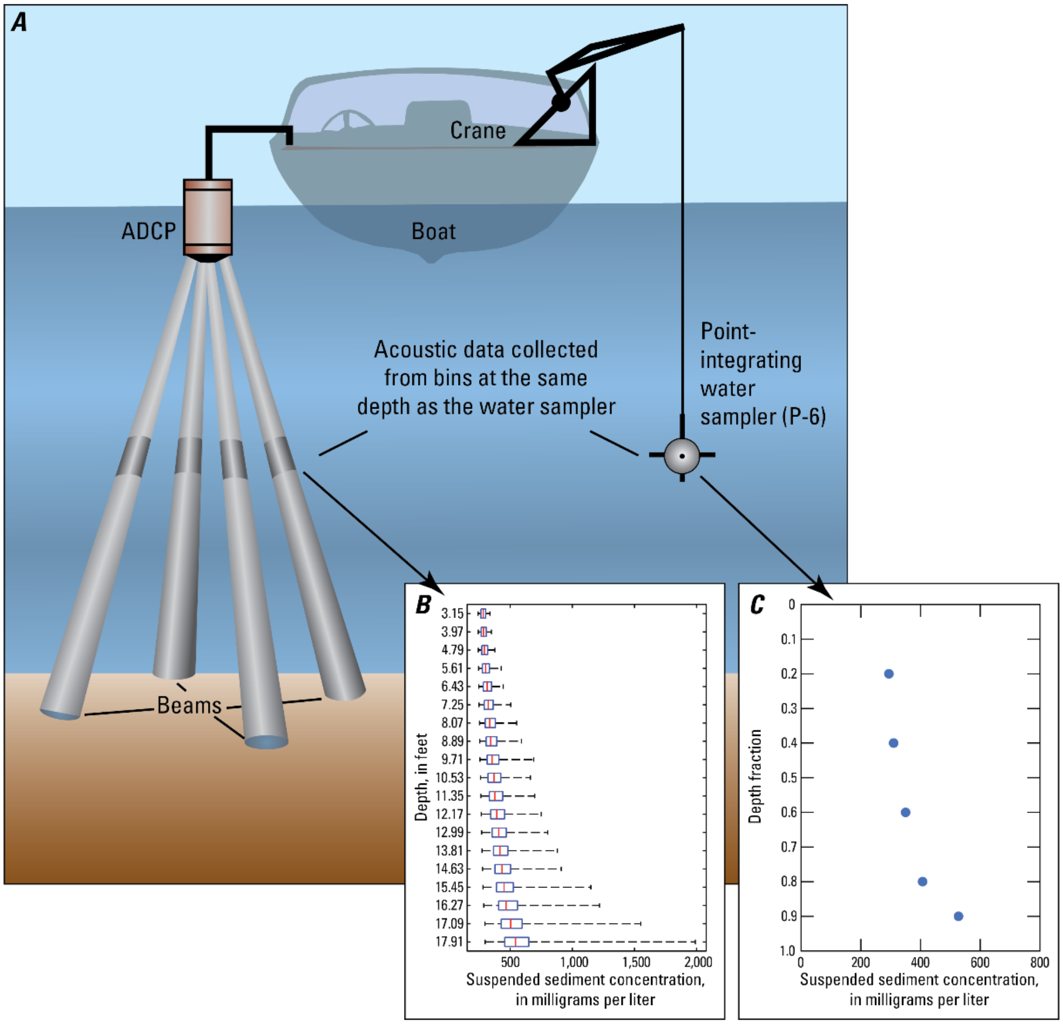

Figure 3. A) Visualization of acoustic Doppler current profiler (ADCP) and water sampler at a single vertical for the downlooking acoustics method (modified from Wall et al., 2006). B) SSC results from the calibrated ADCP data collected over 30 minutes (extent of bars indicates data range). C) SSC results from physical point samples.

Considerations for High Suspended-Sediment Concentrations

When considering the upper operating limit (maximum SSC) of acoustic instruments in sediment-acoustic methods, it is important to understand the interplay between signal (backscatter and attenuation) and noise (instrument and environment). Although difficult to determine an absolute upper operating limit for all acoustic instruments, herein we define high SSC as those exceeding 1,000 mg/l with substantial decreases in data quality as SSCs approach ~50,000 mg/l. Data may be effectively impossible to collect at extreme SSCs. Acoustic profiler beam length (the length of the cross-section profiled by the acoustic instrument) is reduced when SSCs become sufficiently high. Dampening of the acoustic backscatter signal due to increasing SSC depends on the frequency of the acoustic instrument, with higher frequency instruments being affected at lower SSCs, and by the size and type of sediment in suspension (Topping and Wright, 2016). As SSCs increase, the acoustic backscatter signal returned from distant measurement bins approaches, and then equals, the noise level of the instrument and surrounding environment (see Haught et al., 2017 for noise floor discussion). Further, increases in SSC thus shorten the beam length over which the acoustic instrument is sampling, eventually “blanking out” the instrument and providing no useable signal. As the acoustic beam length shortens, the number of bins used in processing the acoustic backscatter data are reduced, until the number of acoustic bins approaches the minimum number required (linear regression requiring at least two bins) to calculate sediment attenuation. However, an issue arises when few bins are used in the linear regression of the sediment attenuation from the backscatter intensity and bin distance if the backscatter intensity from the most distant bin with a usable signal is close to the noise floor. Assuming the sediment and water characteristics are uniform along the beam(s), the sediment attenuation correlation is presumed to be linear (Topping et al., 2006; Landers et al., 2016; Haught et al., 2017); however, as the bins along the beam approach the noise floor, the backscatter strength does not decrease in a linear fashion but becomes asymptotic to the noise floor level (for example, figure 7-4 in Topping and Wright, 2016). During periods of high SSC, using backscatter intensity from bins approaching the noise floor will result in lower values of sediment attenuation (and thus calculated silt/clay concentrations) and will also bias high resulting calculations of sand concentrations. For sites with silt/clay transport above several thousand mg/l, bins can be made smaller and closer to the instrument, especially for higher frequencies (Topping and Wright, 2016). Additionally, some manufacturers may list limitations in the instrument specifications. Sequoia, for example, lists upper limits of the LISST-ABS (8 MHz) as 30,000 mg/l for fines (7 µm dust) and 20,000 mg/l for sands (200 µm sands). Best practices for evaluating specific instruments would include the following:

1) check manufacturer specifications,

2) review existing SSC data to understand maximum SSCs at the site,

3) consider using lower frequency instruments for sites with high SSC, and

4) reduce bin size to avoid approaching a limited number of bins as SSC increases to high levels.

Emerging Enhancements

The Federal Interagency Sedimentation Project (FISP) has funded an effort to establish an ADVM beam calibration procedure against a known sound source at the USGS Hydrologic Instrumentation Facility (HIF). The goal of this procedure is to allow users of the sidelooking sediment-acoustic index methods to exchange ADVMs of the same make and model by having a correction method associated with the ADVM that can be applied to the backscatter record. This would make it possible to compare sediment records from different ADVMs and would not require the development of a new rating if one ADVM is destroyed or malfunctions. If an ADVM that has been calibrated needs to be sent in for repair, a backup ADVM can be temporarily installed at the site to prevent missing record.

Most ADVMs are not optimized for sediment acoustics because they are primarily used for velocity measurements, and acoustic backscatter is just a quality assurance parameter for the velocity measurement. Thus, the USGS has worked with manufacturers to explore and develop a sidelooking acoustic instrument optimized for collecting sediment-acoustic data. One recently developed acoustic instrument intended to be optimized for estimation of SSC has three frequencies in one unit (Horizontal Acoustic Sediment and Current Profiler, Rowe Technologies, 2022) and is being tested by USGS in the Colorado River at Cameo, CO (USGS Station ID 09095500). The multifrequency instrument includes 600, 1,200 and 2,400 kilohertz transducers in one housing.

The use of multifrequency acoustic profilers for calculating suspended-sediment loads allows for the median grain size of the suspended sand to be calculated in addition to the sand concentration and silt/clay concentration. While the multifrequency sidelooking method offers the advantage of calculated median grain size and the removal of sand grain-size dependent bias in the calculated sand concentration, implementation of the method has been slowed by the complexities of the method over the single frequency approach. To support use of the multifrequency method developed by Topping and Wright (2016), several MATLAB® scripts have been developed for site-specific calibration of the acoustic instruments to physically collected suspended-sediment samples. Additional scripts have been developed to process calibrated multifrequency acoustic profiler data for suspended silt/clay concentrations, suspended sand concentrations, and suspended sand median grain size. Work improving the MATLAB® scripts is ongoing and will culminate in their publication.

Acoustics in Estuarine and Marine Environments

Though the methods described in this paper primarily focus on fluvial applications, some methods are applicable to estuarine and marine environments with some adaptations and unique considerations that are worth summarizing here. For example, reviews of the multifrequency methods— often used in near-shore marine environments — have been those by Thorne and Hanes (2002) and Thorne and Hurther (2014), where the latter provides a link to useful source code.

In tidal environments, water level can vary throughout the day on the order of meters. Tidal variations at a site can result in changes in the distribution of suspended sediment and in salinity, which should be considered when selecting and siting an acoustic method. If employing the sidelooking acoustic method(s), the acoustic signal may be impacted by changing water levels as the farthest range bins approach the surface. This has the potential to reduce the effective monitoring range. The projection of sound depends on the two-way beam angle and the angle of the center of the transducer relative to the channel orientation (for example, perpendicular to flow in horizontal applications) and the cross-sectional profile. If the acoustic signal interferes with the bed, or surface, the returned signal no longer represents the response of suspended material and needs to be discarded. When averaging the acoustic backscatter as a function of range or using the slope of the acoustic profile to estimate SAC, it is critical to use only valid data. Additionally, salinity can impact the acoustic signal through fluid attenuation. To utilize estimates of sediment attenuation from acoustic profiles, reducing the influence of fluid attenuation driven by salinity gradients is necessary. Fluid attenuation is a direct function of acoustic frequency, and above 1 MHz, the effects of magnesium sulfate and boric acid become negligible and converges to that of pure water (Fisher and Simmons, 1977). Therefore, choosing higher acoustic frequencies may provide a less sensitive signal to salinity but could experience higher overall attenuation levels at the expense of range.

As fluvial flows move seaward— and channel slope and energy gradient decline, gravity driven flows diminish, and tidal forces or wind driven circulation dominate within estuaries. Sediment grain-size can be highly variable within these systems with predominately fine sediments in channels and turbidity maxima zones whereas sandy sediments tend to dominate shoals and the seaward extents. Storm events and seasonal changes in sediment delivery or stratification can cause dramatic shifts in both concentration and grain size. Additionally, diminished velocities and the presence of salt can lead to flocculation processes where suspended grain size becomes a function of shear, water quality, and concentration. Because of the dynamic nature of sediment type and state (i.e., floc, primary particle, sand, fine, etc.) in these systems, robust sediment-acoustic calibrations can be a challenge. In regions dominated by fine sediment, small concentrations of sand can have a dramatic effect on the strength of acoustic returns (Agrawal and Hanes, 2015; Thorne et al., 2021; Vergne et al., 2021). Additionally, flocculation processes can contribute to an acoustic response that deviates from that of primary particles (Thorne et al., 2014; Sahin et al., 2017). The use of sediment acoustics in estuaries tends to have been more prevalent in research applications than monitoring. Optical approaches, often associated with water quality sensor packages, are more common for long-term measurements of sediment concentration in estuaries. For either optics or acoustics, site-specific calibrations are critical. As the primary forcing is tidal currents and fortnightly cycles are easily predicted, calibration samples of sufficient concentration range can be effectively collected from a vessel during periods of predicted strong tides.

Along the coast and continental shelf, in water depths of a few to tens of meters, sand tends to dominate the sediment supply. While sandy suspensions can be efficiently measured with acoustic techniques, these regions offer their own set of challenges. Closest to the coast, where waves break, there is interest in the transport of sandy sediment as this material is often associated with storm impacts and shoreline erosion. Collection of calibration samples are rare due to safety concerns during periods of even moderate storms when higher concentrations are expected. Additionally, entrained air bubbles from breaking waves act as scatterers similar to sediment grains convoluting acoustic backscatter signals. In this region, acoustics offer great promise for sediment transport applications but in general this challenging environment has led to insufficient development of acoustic techniques.

On the continental shelf, at depths of tens of meters, entrained air bubbles do not reach the seafloor where sediment transport takes place, simplifying acoustic measurements of concentration or grain-size. However, the collection of high sediment concentration calibration samples — predominantly driven by storm processes—during anything but calm conditions is generally not feasible. As a result, acoustic sensors for continental shelf applications are often calibrated in the laboratory with seabed samples. The use of bed samples for calibration requires the spurious assumption that the grain-size distribution of suspended material matches that of the seabed. For example, even a relatively small silt/clay fraction (5%)

in the seabed can lead to large errors in predicted concentration at 1 meter above the seabed when a bimodal grain-sized distribution devolves from the predetermined narrow, unimodal distribution (Thorne et al., 2021).

Because of these challenges, contemporary methods utilizing acoustics in estuarine and marine environments tend to be novel and predominantly research-based, where a larger range of 'tools' are needed to illuminate sediment processes. To overcome some of these challenges, methods that utilize high frequencies (i.e., less sensitive to salinity), short acoustic path lengths (<1 m), or combined acoustic and optical turbidity sensors are commonly applied. Additionally, in near-shore environments, multifrequency approaches are common where narrow grain-size distributions are expected (Thorne and Hurther, 2014 and references therein). In environments where fine sediment dominates the suspended load, methods similar to that of Moore et al. (2013) could be used. More recently, very high-resolution echo-sounder acoustics have been added to acoustic Doppler velocimeters (ADVs) that have bin-sizes less than 5 mm. These ADVs incorporate a single frequency acoustic response at the same order of the coarsest transport material, potentially leading to direct calibration of the target strength response to the constituent of interest (i.e., phytoplankton, organic, sediment, bubbles, flocs). Additionally, acoustic instruments are often collocated with point sensors that aid in distinguishing constituents (for example, Total Algae Phycocyanin sensor).

Summary

The selection and proper use of acoustic methods for estimating fluvial SSC depends on many factors, including goals of a monitoring program, data needs, and environmental conditions. Identifying these factors in advance and collecting reconnaissance data will increase the likelihood of success in implementing the selected method and developing relations to estimate SSC and loads. One of the first decisions to be made when selecting an acoustic method is whether continuous, time-series data of high temporal resolution or discrete data of high spatial resolution are needed. Most importantly, all these methods rely on the collection of physical sediment samples to create a calibration or relation with acoustic data to ensure data quality. The downlooking acoustic method is a mobile deployment that can provide a high spatial resolution estimate of SSC and load within a cross section at a single point in time, but it can also provide high temporal resolution of SSC variability with river depth where acoustic data are collected during a sampling event. If continuous time-series data are needed, acoustic methods involving a fixed or variable instrumentation deployment should be used. The selection of a fixed deployment is made based on sand content and level of interest in quantifying sand, the river width and depth, and variability in sediment grain sizes in transport. Relatively small rivers with sand content can typically be measured using point acoustic instruments, while larger, more hydraulically complex rivers can typically be measured with sidelooking, profiling acoustic instruments. The use of multiple frequency sidelooking acoustic instruments may be needed in rivers with a wide range and variability in sediment grain sizes in transport or where grain size information is needed. Many of the methods described in this paper can be used in estuarine, marine, and high SSC environments with some adaptations and unique considerations. The use of acoustic methods to estimate SSC in fluvial environments is expected to grow with demands for cost-effective sediment data. Many enhancements to acoustic instruments, methods, and software are in development, which, when finalized, will make the use of acoustic methods for estimating SSC more reliable and accessible for use in operational sediment monitoring programs.

Disclaimer

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