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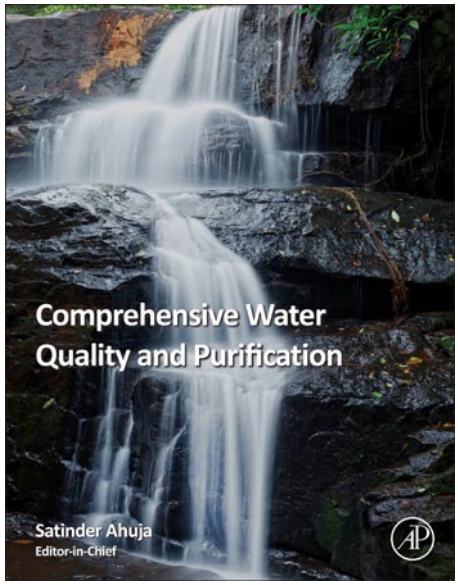

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1.10 Measuring Suspended Sediment

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Glossary

Bedload Material moving on or near the stream bed by rolling, sliding, or skipping.

Bed material The sediment mixture of which the stream bed is composed.

Composite sample A sample formed by combining two or more individual samples or representative portions of the samples.

Concentration of sediment (mass) The ratio of the mass of dry sediment in a water–sediment mixture to the mass of the mixture. Also commonly referred to as "suspended-sediment concentration."

Concentration of sediment (volume) The ratio of the volume of dry sediment to the volume of the water–sediment mixture.

Depth-integrated sediment sampler A device that collects a representative water–sediment mixture at all points along the sampling vertical.

Diameter, sedimentation The diameter of a hypothetical sphere of the same specific gravity and the same settling velocity as the given particle in the same fluid.

Equal-discharge-increment method A procedure for obtaining the discharge weighted suspended-sediment concentration of flow at a cross section whereby depth integration is performed at the centers of three or more equal flow segments of the cross section.

Equal-width-increment method A procedure of obtaining the discharge weighted suspended-sediment concentration of flow at a cross section by performing depth integration at a series of verticals equally spaced across the cross section and using the same vertical transit rate at all sampling verticals.

Fine-material load The part of the total sediment load that is composed of particles of a finer size than the particles present in appreciable quantities in the bed; normally, the fine-material load consists of material finer than 0.062-mm median diameter.

Fluvial sediment Particles derived from rocks, biological materials, or chemical precipitants, that are transport by, suspended in, or deposited by flowing water.

Gaging station A particular site on a stream, canal, lake, or reservoir at which systematic observations of hydrologic data are obtained.

Instantaneous sampler A suspended-sediment sampler that takes a representative specimen of the water–sediment mixture in a stream at a desired depth and a moment of time.

Isokinetic sampling To sample in such a way that the water–sediment mixture moves with no change in velocity as it leaves the ambient flow and enters the sample intake.

Nephelometer An instrument that measures the amount of light scattered in a suspension.

Particle size A linear dimension, usually designated as diameter, used to characterize the size of a particle; the dimension may be determined by any of several different techniques, including sedimentation, sieving, micrometric measurement, or direct measurement.

Point integration A method of sampling at a relatively fixed point whereby the water–sediment mixture is withdrawn isokinetically for a specified period of time.

Point-integrating sampler An instrument capable of collecting a water–sediment mixture isokinetically for a specified period of time by opening and closing under water; an instrument suitable for performing point integration.

Point sample Sample of water–sediment mixture taken at a single point, either with an instantaneous or a point-integrating sampler.

Pumping sampler A device that draws the water–sediment mixture through a pipe or hose, the intake of which is placed at the desired sampling point in a stream.

Sample vertical An approximately vertical path from the water surface to the bottom along which one or more samples are collected to define various properties of the flow, such as sediment concentration.

Sampled zone That part of a channel transect presumed to be wholly represented by sediment samples.

Sediment discharge A mass or volume of sediment passing a steam cross section in a unit time (the term maybe qualified as suspended-sediment discharge, bedload discharge, or total-sediment discharge).

Sediment load A general term that refers to material in suspension or in transport, or both; it is not synonymous with either discharge or concentration.

Sediment particle A fragment of mineral or organic material in either a singular or aggregate state.

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Sediment sample A quantity of water–sediment mixture deposited sediment that is collected to represent one or more properties of the sampled medium.
Silt size Particles with median diameters of 0.004–0.062 mm.
Specific gravity Ratio of the mass of any volume of a substance to the mass of an equal volume of water at 4 °C.
Split sample A single sample separated into two or more individual parts in a manner such that the content of each part is representative of the original sample.
Stream discharge The quantity of flow passing through a cross section in a unit of time.
Suspended sediment Sediment that is carried in suspension by the turbulent components of the fluid or by Brownian movement.
Suspended-sediment load A part of the sediment load which is suspended sediment.
Suspended-sediment sampler A device that collects a representative portion of the water with its suspended-sediment load.
Total-sediment discharge The total quantity of sediment passing a section per unit time.
Total-sediment load All of the sediment in transport; that part moving as suspended load plus that moving as bedload.
Turbidity An expression of the optical properties of a sample which causes light rays to be scattered and absorbed rather than transmitted in straight lines through a sample.
Wash load The portion of the stream sediment load composed of particles, usually finer than 0.062 mm in diameter, which are found only in relatively small quantities in the bed.
Water discharge See 'stream discharge'.

1.10.1 Introduction

This chapter presents techniques for measuring suspended sediment discharges in rivers using traditional samplers and techniques developed by the Federal Interagency Sedimentation Project (FISP; Skinner, 1989; Glysson and Gray, 1997; Federal Interagency Sedimentation Project, 2012) and United States Geological Survey (USGS); and surrogate technologies being used or tested by the FISP, USGS, and others (Wren et al., 2000; Gray and Glysson, 2004; Gray and Gartner, 2009). Sediment and ancillary data are fundamental requirements for the efficient and proper management of river systems, including the design of structures; determining aspects of stream behavior; ascertaining the probable ramifications of removing an existing structure; estimating bulk erosion, transport, and sediment delivery from watersheds and to the oceans; ascertaining the long-term usefulness of reservoirs and other public works; tracking movement of solid-phase contaminants; ecological assessments; restoring degraded or otherwise modified streams; and as ground-truth data for the calibration and validation of numerical models. This chapter on "Measuring Suspended Sediment" has a bearing on several other contributions to this volume, including Chapters 2.13, 2.16, 4.1, 4.2, 4.5, 4.9, 4.15, and 4.18.

The traditional FISP samplers and techniques described herein (Davis, 2005; Edwards and Glysson,1999; Nolan et al., 2005; Gray et al., 2008), which debuted in the mid-twentieth century, are grounded on sound physical and statistical principles and form the basis for production of most fluvial suspended sediment data in the US and in many other countries on every continent other than Antarctica. More information on a broader suite of traditional technologies can be found by perusing the following publications: Manual Sediment Transport Measurements in Rivers, Estuaries, and Coastal Seas (van Rijn, 2007) and Methods for Measurement of Suspended Sediment (ISO, 2002).

Some of the surrogate technologies described herein are being incorporated into operational programs and show considerable promise toward providing the temporally dense, and in some cases spatially robust fluvial sediment data needed to increase and bring more consistency to sediment-discharge measurements worldwide. Even as *in situ* and manually deployed surrogate technologies become operationally ubiquitous, they will continue to require empirical calibrations with traditional technologies.

1.10.1.1 Terminology

Fluvial sediment can be defined by its origin or operationally by its method of collection (**Figure 1**). The total amount of sediment in transport can be described by its origin as being composed of bed material load plus wash load. Bed material load is that part of the total load that is composed of particle sizes present in appreciable quantities in the shifting parts of the streambed. Wash load is that part of the total load composed of particles, usually finer than 0.062 mm in diameter, that originate from the watershed and are found, if at all, only in relatively small quantities in the streambed (ASTM International, 1999).

The operational definition of sediment in transport is in part a function of the instruments and methods used to obtain the data. Suspended sediment and bedload discharges are the quantities of suspended sediment and bedload passing through a stream cross section per unit time, respectively. Suspended sediment discharge can include some of the bed material load component but all of the wash load component. Bedload discharge includes some of the bed material load component. The addition of sediment discharges derived from data collected with physical suspended sediment and bedload samplers may not equal the sum of bed material load plus wash load (**Figure 1**). This is a result of one or more factors associated with the range in size of sediments in transport, and the characteristics and deployment methods of the suspended sediment and bedload samplers.

Sediment-surrogate technologies are defined as instruments coupled with operational and analytical methodologies that enable acquisition of temporally and (or) spatially dense fluvial sediment datasets without the need for routine

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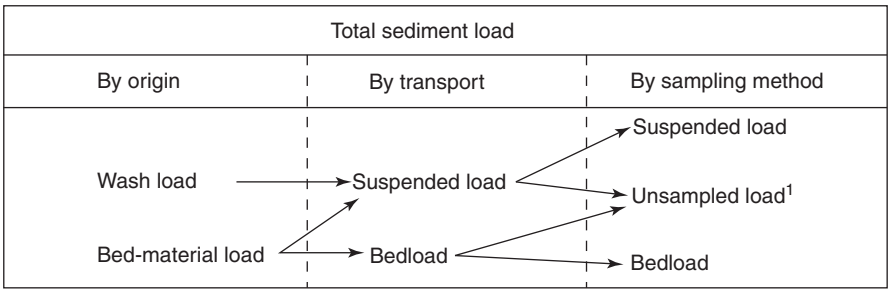

[1]That part of the sediment load that is not collected by the depth-integrating suspended-sediment and pressure-difference bedload samplers used, depending on the type and size of the sampler(s). Unsampled-load sediment can occur in one or more of the following categories: (a) sediment that passes under the nozzle of the suspended-sediment sampler when the sampler is touching the streambed and no bedload sampler is used; (b) sediment small enough to pass through the bedload sampler's mesh bag; (c) sediment in transport above, the bedload sampler that is too large to be sampled reliably by the suspended-sediment sampler; and (d) material too large to enter the bedload-sampler nozzle.

Figure 1 Components of total sediment load considered by origin, by transport, and by sampling method. Reproduced from Diplas, P., Kuhle, R. A., Gray, J. R., Glysson, G. D. and Edwards, T. K. (2008). Sediment transport measurements. In Garcia, M. (ed.) *Sedimentation engineering – Processes, measurements, modeling, and practice*. American Society of Civil Engineers Manual 110, ch. 5, pp. 307–353. Reston, Virginia: ASCE. Available at http://water.usgs.gov/osw/techniques/Diplas_Kuhnle_others.pdf (accessed on 18 May 2012).

collection and analysis of physical samples other than for calibration purposes. Although the traditional technologies described herein, with the exception of automatic samplers, are manually deployed, most of the surrogate technologies described can be deployed manually or *in situ*. The latter are capable of providing a continuous and dense time series of data to be empirically converted to the metric of interest.

1.10.1.2 Criteria for a Sediment Dataset

Collection of data to enable reliable sediment transport estimates is often difficult, time consuming, and expensive. It is frustrating to obtain data for a location and set of conditions of interest, only to subsequently discover that the collected data were incomplete (Glysson, 1989a) or were inappropriate for the requested laboratory analysis. The types of data required depend on the goals of the assessment and intended storage medium for the data. For example, suspended sediment concentration (SSC) and water discharge data are required to compute continuous records of suspended sediment discharge (Porterfield, 1972; Koltun et al., 2006). Other relevant data include particle-size distributions (PSDs) of suspended sediment and bottom material. The integrity of large-scale, long-term monitoring programs such as the Vigil Network (Osterkamp and Emmett, 1992), or that proposed for North America (Osterkamp et al., 1998, 2004), the US (Osterkamp and Parker, 1991; Gray and Shadie, 2010), and Canada (Day, 1991), is particularly dependent on the reliability and comparability of the data collected.

The most reliable databases accept only selected data types representing sediment and ancillary variables obtained using a consistent set of protocols. For example, sediment data stored by the USGS as part of the online National Water Information System (U.S. Geological Survey, 2012a) and other databases (Turcios et al., 2000; U.S. Geological Survey, 2012b) are collected by techniques described by the U.S. Geological Survey (1998a), Edwards and Glysson (1999), Nolan et al. (2005), and Gray et al. (2008); analyzed in a USGS-approved laboratory by techniques described by Guy (1969), Matthes et al. (1992), Knott et al. (1992, 1993), and U.S. Geological Survey (1999) with laboratory quality assurance verified by U.S. Geological Survey (1998b).

Glysson (1989a) divided dataset requirements for computing sediment transport using the more common sediment transport equations for noncohesive sediments into three categories: sediment, hydraulic, and others. **Table 1** summarizes and expands on those requirements. Parameter codes are available for storing most of these metrics in the USGS National Water Information System (NWIS) database (U.S. Geological Survey, 2012b).

1.10.1.3 Insights on Errors Associated with Measured SSCs and Loads

The 'best' (considered to be the most reliable and accurate) data describing SSCs and suspended sediment discharges are from analyses of physical samples collected using appropriate samplers and deployment methodologies with adequate

- temporal resolution for the ambient sediment-hydrologic conditions; and
- spatial resolution throughout the stream cross section.

Errors associated with measured load result from errors in quantifying stream discharge, sampling and analytical errors in the sediment samples, and errors in the calibration of fixed location samples based on flow-weighted cross-section samples. Water discharge errors at the 95% confidence limit are likely to be less than ± 5–8% at many riverine systems using these techniques (Kennedy, 1984; Sauer and Meyer, 1992). Laboratory analytical errors from gravimetric analysis of SSC are larger for very low concentrations and decrease rapidly with increasing SSC. Sampling errors for SSC measurements

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Table 1 Sediment, hydraulic, and operational parameters for a sediment dataset[a]

Sediment and related parameters include:	Operational and related parameters include:
*Suspended-sediment concentration	*Sample start and end times
*Suspended-sediment discharge	*Sample method of collection
*Bed load discharge	*Sampler type
*Total sediment discharge	*Sampler nozzle diameter and composi tion
*Suspended-sediment particle-size distribution	*Location of sample collection in cross section from left or right bank
*Bedload particle-size distribution	*Width of sampled vertical
*Bed-material particle-size distributions (in channel, overbank)	*Duration bedload sampler was deployed on bed
Turbidity	*Bedload sampler bag mesh size
Transparency	*Analyzing agency and laboratory
Mean specific gravity	Duration suspended-sediment sampler collected water
Particle shape	Sampler transit rate
Bed-roughness coefficient	Number of sampling points in a vertical
Total suspended solids	Number of verticals in composite sample
Specific conductance	Depth to compute isokinetic transit rate
Dissolved solids concentrations	Velocity to compute isokinetic transit rate
Hydraulic and related parameters[b] include:	Sample volume to compute isokinetic transit rate
*Water discharge	Number of bedload samples in a composite
*Watercourse stage	Tether line used for sampling
*Mean depth	
*Mean velocity	
*Water temperature	
*Surface width	
*Area	
Hydraulic radius	
Channel slope	

[a]The National Water Information System Parameter Code Definitions can be accessed at http://nwis.waterdata.usgs.gov/nwis/pmcodes/
[b]A site description that may include a morphometric assessment based on one or more channel classification schemes also should be included.
Note: Types of data collected are dependent on their intended use. Parameters marked with an asterisk are considered fundamentally important data types.

vary with SSC, PSD, sampler equipment, training and experience of the field crew, deployment techniques, and sampling conditions. However, analytical results from replicate field samples at SSCs above approximately 20 mg l^{-1} typically have differences estimated to be approximately $\pm 10\%$ (Edwards and Glysson, 1999; Horowitz et al., 2001; Horowitz, 2008). Based on published protocols for deployment of depth-integrated samplers (Edwards and Glysson, 1999; Topping et al., 2011, p. 45) found the maximum total uncertainty in sand SSCs to be approximately $\pm 7\%$. The accuracy of SSCs and loads cannot be generalized because of many factors including those mentioned here; however, for 'good' measurement conditions and data quality, measured load may have an expected accuracy of $\pm 15\%$ (Gray and Gartner, 2009, 2010b).

One commonly used analog for SSC data in the US is total suspended solids (TSS; American Public Health Association, American Water Works Association, and Water Pollution Control Federation, 1995). TSS data are not comparable to SSC data under some circumstances and are fundamentally unreliable when used to analyze samples collected from open-channel flows (Gray et al., 2000; U.S. Geological Survey, 2000; Glysson et al., 2000, 2001). TSS data tend to:

1. underestimate suspended solid-phase SSCs by a proportionate amount of 25–34% (Gray et al., 2000);
2. be least reliable under the very circumstances under which most suspended sediment transport typically occurs – at higher flows when percentages of suspended sand are comparatively large.

Based on the information above, Gray et al. (2000) concluded that the accuracy and comparability of suspended solid-phase SSCs determined in the US would be greatly enhanced if all such data were produced by the SSC analytical method (ASTM International, 1999). If TSS data are required to meet study objectives, then concurrent SSC analyses should be conducted and any bias associated with the TSS data quantified.

1.10.2 Traditional Suspended Sediment Measurement Techniques

The scope of this section includes a brief history of the development of traditional suspended sediment samples; descriptions of manual suspended sediment samplers and methods for their deployment; description, installation, and operation of automatic samplers; and a summary of equipment used for obtaining water–sediment subsamples.

1.10.2.1 History of Development of Traditional Sediment Sampling Equipment

The initial attempts to develop suspended sediment sampling equipment and deployment techniques were made by independent investigators, with the earliest such available records dated 1808–09 when Gorsse and Subuors sampled the Rhone river, Arles, France (Federal Interagency Sedimentation Project,

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1940). Baumgarten's samples collected in the River Garonne at Marmande, France, from 1839 to 1846 resulted in what were probably the first sediment discharge computations. Sediment-discharge measurements in the US began in 1838 when Captain Talcott sampled the Mississippi river. The fluvial sediment measurements made in the Rio Grande at Embudo, New Mexico, beginning 15 January 1889, represent the beginning of the USGS's sediment program (Glysson, 1989b). Fluvial sediment measurements have been made regularly in the Rio Grande since 1897, lower Colorado river since 1909, and upper Colorado river basin since 1925. A detailed investigation of sediment loads starting in 1942 as part of the Missouri River Project included determination of the feasibility of storage reservoirs on streams transporting heavy sediment loads. Beginning in about 1930, extensive sediment surveys have been made in many other streams of the US (Federal Interagency Sedimentation Project, 1940; Nelson and Benedict, 1950; Glysson, 1989b; Turcios et al., 2000).

After World War II, the number of sites at which the USGS collected daily suspended sediment data increased rapidly, peaking at approximately 364 in 1982 (Glysson, 1989b; Osterkamp and Parker, 1991). During the period 2006–10, an average of approximately 65 daily-record sediment sites were being operated by the USGS (U.S. Geological Survey, 2012d).

Before the mid-1940s, sediment samplers in the US lacked calibration and were deployed using widely different techniques. Most instruments were designed with limited attention to, or knowledge of, sediment transport concepts or the influence of the equipment on the local flow pattern (Glysson, 1989b). As a result, data obtained by different investigators before the mid-1940s were neither comparable nor could their accuracy be readily or reliably evaluated. It became apparent that collection of reliable suspended sediment data requires an understanding of the physics of sediment transport and of how the sediment–water mixture is affected by sampler and deployment characteristics.

In 1939, several US agencies organized an interagency program to study methods and equipment used in measuring the sediment discharge of streams and to improve and standardize equipment and methods where practicable (Federal Interagency Sedimentation Project, 1941). The FISP was created under the sponsorship of the Committee on Sedimentation of the Federal Water Resources Council (the functions of this council are now shared by two organizations: the Technical Committee that oversees the FISP; and the Advisory Committee on Water Information, Subcommittee on Sedimentation, 2012). The subsequent comprehensive study of sampling equipment included suspended sediment, bedload, and bed material samplers, their means of deployment, and sample analytical methods. As a result of research conducted by the FISP and others, an integrated system of standardized, quantifiably reliable sediment samplers, sampling, and analytical techniques has been developed and is widely used around the world.

1.10.2.2 Samplers and Sampling Methods

The purpose of a suspended sediment sampler is to obtain a representative sample of the water–sediment mixture moving in the stream in the vicinity of the sampler intake. There are two categories of traditional suspended sediment samplers: manually operated samplers and automatic samplers. Manually operated samplers include instantaneous and isokinetic samplers. Isokinetic samplers – those that collect a filament of river water without a change in the flow velocity or direction – include those with rigid sample bottles (bottle samplers) and with flexible bags (bag samplers). Additional information on manual sampler specifications, limitations, operation, and current costs are available in the online FISP catalog available through Federal Interagency Sedimentation Project (2012). FISP suspended sediment samplers range in (2012) price from $95 for a handheld US DH-81 to $7946 for a cable-deployed US P-63.

1.10.2.2.1 Manually operated samplers

1.10.2.2.1.1 Instantaneous samplers

Instantaneous samplers are applicable for sampling flows that fail to meet either of the following criteria for deployment of an isokinetic sampler: sampling depths exceeding approximately 0.3 m, and (or) mean velocities exceeding approximately 0.5 m s^{-1}. At shallow depths, the part of the stream from the streambed to the nozzle of an isokinetic sampler deployed at maximum depth, referred to as the unsampled zone, becomes unacceptably large with respect to the total depth. At small velocities, only silt- and clay-size material typically is in suspension, and these finer size fractions tend to be fairly uniformly distributed with depth (Colby, 1963; Guy, 1970). Under these circumstances, an instantaneous sample from the water column may provide a reasonably accurate estimate of the SSC at the sampled point or in the sampled vertical. Instantaneous samplers may also be deployed at flow velocities too swift to submerge an isokinetic sampler, or when the presence of debris renders normal sample collection dangerous or impossible.

Although nonisokinetic samplers may provide acceptable results under certain sediment-transport conditions, such as when fine material constitutes most or all of the sediment load, conditions for which nonisokinetic sampling are appropriate may not be apparent at the time of sample collection. The most reliable suspended sediment samples are obtained using isokinetic samplers.

The simplest instantaneous sampler is an open bottle used to obtain a surface, or dip, sample. The weighted-bottle, handheld (WBH)-96-weighted bottle sampler (Federal Interagency Sedimentation Project, 2012) can be deployed with a hand line in still or slow-moving water. The Van Dorn and Kemmerer samplers are thief-type samplers that are typically used for still-water sampling such as in lakes and reservoirs, but they also may be useful in sluggish streamflows U.S. Geological Survey, 2006.

1.10.2.2.1.2 Isokinetic samplers

Isokinetic samplers are designed to collect a representative velocity-weighted sample of the water–sediment mixture. Water approaching the nozzle of an isokinetic sampler undergoes essentially no change in speed or direction as it enters the nozzle orifice (**Figure 2**). When deployed using prescribed methods at preselected, strategic locations in a cross section, an isokinetic sampler integrates a sample

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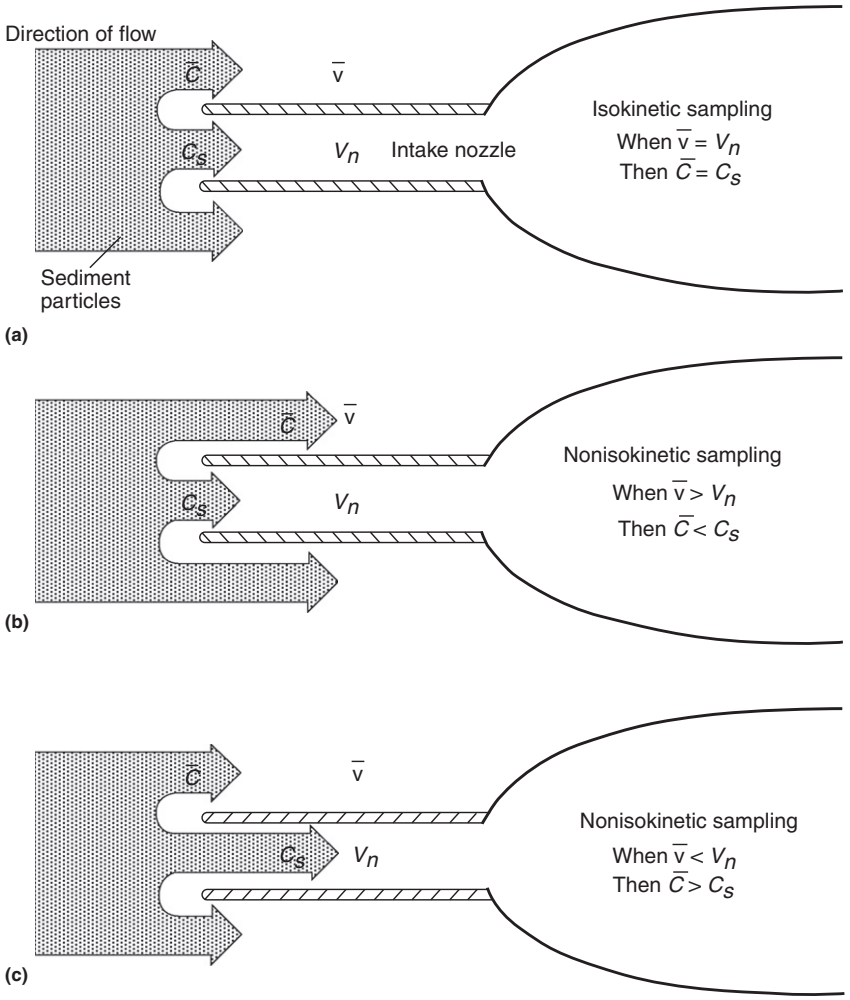

Figure 2 Relation between intake velocity and sample SSC for (a) isokinetic and ((b) and (c)) nonisokinetic sample collection of particles larger than 0.062 mm, where $\bar{v}$ is the mean stream velocity, V_n and $\bar{C}$ is the flow velocity and SSC incident on the sampler nozzle, respectively, and C_s is the sample SSC. Reproduced from Edwards, T. E. and Glysson, G. D. (1999). Field methods for measurement of fluvial sediment. U.S. Geological Survey Techniques of Water-Resources Investigations, Book 3, ch. C2, 89 pp. Available at http://water.usgs.gov/osw/techniques/sedimentpubs.html (accessed on 12 June 2012).

proportionally by velocity and area, resulting in a water discharge-weighted sample. A water discharge-weighted sample contains an SSC and a PSD representative of the material in transport in the sampled cross section at the time the sample was collected.

A list of isokinetic samplers available from the FISP is shown in Table 2. A sampler functions isokinetically when the relative sampling rate – the dimensionless ratio of the velocity through the nozzle divided by the approaching stream velocity – is equal to one. In practice, FISP isokinetic samplers are designed to ensure that the water velocity in the nozzle is within 10% of the ambient stream velocity throughout a sampler's operating velocity range (Broderick Davis, FISP, 2001, written communication).

SSC errors in samples collected with isokinetic-type samplers may stem from a combination of the size of the suspended material and the relative sampling rate (degree of departure from isokinetic sample collection). The relation between percent error in SSC and relative sampling rate for sediments with a density of 2.65 and median diameters of 0.45, 0.15, 0.06, and 0.01 mm in flows of 1.5 m s^{-1} is shown in Figure 3. Under these test conditions, relative sampling rates for 0.45 mm sediments may range from 0.75 to 1.3 without introducing more than about a 10% error in sample SSC values. Conversely, at relative sampling rates less than 0.25, resultant SSC errors for 0.45 mm sediments may exceed 100%. The range in errors tends to decrease with decreasing sediment size. For example, 0.01-mm size sediments have less than a 5% error for relative sampling rates ranging from approximately 0.2 to almost 5 (Figure 3). In each case, subunity relative sampling rates result in positive SSC bias; larger relative sampling rates result in zero or negative SSC bias.

The FISP's suite of depth- and point-integrating samplers (Davis, 2005; Table 2) are isokinetic samplers. A depth-integrating sampler is designed to isokinetically and continuously accumulate a representative sample from a stream vertical while transiting the vertical at a uniform rate (Federal

Table 2 Designations and characteristics for Federal Interagency Sedimentation Project (FISP) manually operated isokinetic samplers (Davis, 2005)

Sampler designation[a]	*Nozzle inner diameter, cm (in.)*	*Container type and capacity*	*Mode of suspension*	*Maximum depth, m (ft)*	*Minimum isokinetic velocity, m s^{-1} (ft s^{-1})*	*Maximum recommended velocity*[b]*, m s^{-1} (ft s^{-1})*	*Unsampled zone, cm (in.)*	*Mass, kg (weight, lbs)*
US DH-48	0.48 (3/16)[c], 0.64 (1/4)	Rigid bottle 0.47 l (pint)	Wading rod	2.7 (9)	0.5 (1.5)	2.7 (8.9)	8.9 (3.5)	2 (4)
US DH-59	0.48 (3/16)		Handline or cable reel	4.6 (15)		1.5 (5.0)	11 (4.5)	10 (22)
US DH-59	0.64 (1/4)			2.7 (9)				
US DH-76[d]	0.48 (3/16), 0.64 (1/4)	Rigid bottle 0.95 l (quart)		4.6 (15)		2.0 (6.6)	8.1 (3.2)	11 (25)
US DH-81	0.48 (3/16)	Rigid bottle1 l	Wading Rod	2.7 (9)	0.6 (2.0)	1.9 (6.2)	10 (4.0)	0.5 (1)
US DH-81	0.64 (1/4)					2.3 (7.6)		
US DH-81	0.79 (5/16)					2.1 (7.0)		
US DH-95	0.48 (3/16)		Handline or cable reel	4.6 (15)	0.6 (2.1)	1.9 (6.2)	12 (4.8)	13 (29)
US DH-95	0.64 (1/4)				0.5 (1.7)	2.1 (7.0)		
US DH-95	0.79 (5/16)				0.6 (2.1)	2.3 (7.4)		
US DH-2	0.48 (3/16)	Flexible 1-l bag		11 (35)	0.6 (2.0)	1.8 (6.0)	8.9 (3.5)	14 (30)
US DH-2	0.64 (1/4)			6.1 (20)				
US DH-2	0.79 (5/16)			4.0 (13)				
US D-74	0.48 (3/16)	Rigid bottle 0.47 l (pint) or 0.95 l (quart)		4.6 (15)	0.5 (1.5)	2.0 (6.6)	10 (4.1)	28 (62)
US D-74	0.64 (1/4)			2.7 (9) pint 4.6 (15) quart				
US D-74AL	0.48 (3/16)			4.6 (15)		1.8 (5.9)		19 (42)
US D-74AL	0.64 (1/4)			2.7 (9) pint 4.6 (15), quart				
US D-95	0.48 (3/16)	Rigid bottle 1 l		4.6 (15)	0.5 (1.7)	1.9 (6.2)	12 (4.8)	29 (64)
US D-95	0.64 (1/4)				0.6 (2.0)	2.0 (6.7)		
US D-95	0.79 (5/16)							
US D-96	0.48 (3/16)	Flexible 3-l bag		34 (110)	0.9 (3.0)	3.8 (12.5)	10 (4.0)	60 (132)
US D-96	0.64 (1/4)		Cable reel	18 (60)				
US D-96	0.79 (5/16)			12 (39)				
US D-96-A1	0.48 (3/16)			34 (110)		1.8 (6.0)		36 (80)
US D-96-A1	0.64 (1/4)			18 (60)				
US D-96-A1	0.79 (5/16)			12 (39)				
US D-99	0.48 (3/16)	Flexible 6-l bag		67 (220)	1.1 (3.5)			
US D-99	0.64 (1/4)	Flexible 6-[d] or 3 l (6.3- or 3.2-quart) bag[e]		37 (120)	1.1 (3.5)[c] or 0.6 (2.0)[d]	4.6 (15.0)	24 (9.5)	125 (275)
US D-99	0.79 (5/16)			24 (78)				
US P-61-A1	0.48 (3/16)	Rigid bottle 0.47 l (pint) or 0.95 l (quart)		55 (180), pint 37 (120), quart	0.5 (1.5)	3.0 (10.0)	11 (4.3)	48 (105)
US P-63	0.48 (3/16)					4.6 (15.0)	15 (5.9)	91 (200)
US P-72	0.48 (3/16)			22 (72), pint 16 (51), quart		1.6 (5.3)	11 (4.3)	19 (41)
US P-6	0.48 (3/16)	Rigid bottle 0.95 l (quart)[f]		49 (160), quart	0.5 (1.5)	4.0 (13)	8.9 (3.5)	~45 (~100)

[a]Samplers designated in italics may also be used for water quality sampling as described in the US Geological Survey National Field Manual for the Collection of Water Quality Data (variously dated).

[b]For rigid-bottle samplers, the maximum recommended velocity for sampler deployment is based either on measured isokinetic limitations, or, for prototypes of samplers tested at Anthony Falls Hydraulic Laboratory flume, on the maximum velocities used in tests. Bag samplers were determined to retain isokinetic characteristics at the highest velocities tested. Their maximum recommended velocity was selected to correspond with the velocity at which the angle of the suspension cable was drawn back just shy of 'excessive' by testing personnel – from 25° to 30° – and on safety considerations.

[c]The 0.48-mm (3/16-in.) internal diameter nozzle is designated for use in high-velocity flows.

[d]A minimum isokinetic velocity of 1.1 m s^{-1} (3.5 ft s^{-1}) applies to the D-99 sampler using a 6-liter flexible bag and a 0.48-mm (3/16-in.) internal diameter nozzle.

[e]A minimum isokinetic velocity of 0.61 m s^{-1} (2 ft s^{-1}) applies to the D-99 sampler using a 3-l flexible bag and 0.64-mm (1/4-in.) or 0.79-mm (5/16-in.) internal diameter nozzle.

[f]The sampler is designed to use various sizes of bottles as sample containers. The 1-ll HDPE bottle, Item # 621-0032 sold by Dynalab Corp., has been found to work well with the sampler (FISP, 2011, written communication).

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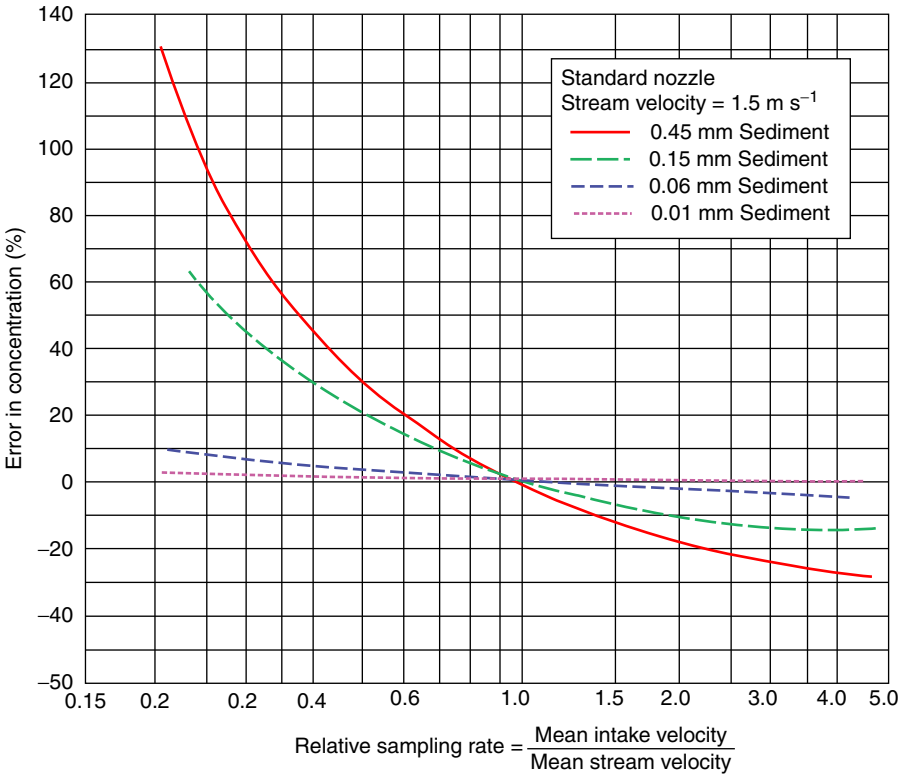

Figure 3 Effect of sampling rates on measured SSCs for four sediment-size distributions. Reproduced from Gray, J. R., Glysson, G. D. and Edwards, T. E. (2008). Suspended-sediment samplers and sampling methods. In Garcia, M. (ed.) *Sediment transport measurements. Sedimentation engineering – Processes, measurements, modeling, and practice*. American Society of Civil Engineers Manual 110, ch. 5.3, pp. 320–339. Available at http://water.usgs.gov/osw/techniques/Diplas_Kuhnle_others.pdf (accessed on 18 May 2012) and adapted from Federal Interagency Sedimentation Project (1941). Laboratory investigation of suspended-sediment samplers. *Interagency Report No. 5*, Hydraulics Laboratory, Iowa University, Iowa City, 99 pp. Available at http://water.usgs.gov/fisp/docs/Report_5.pdf (accessed on 12 June 2012).

Interagency Sedimentation Project, 1952). A depth-integrating sampler collects and accumulates a velocity- or water discharge-weighted sample as it descends and ascends at a constant rate through the sampling vertical provided that the appropriate transit rate is not exceeded and the sample container is not overfilled.

Point-integrating samplers are more versatile than the depth-integrating types. Point-integrating samplers are designed for depth integration of streams too deep (or too swift) to be sampled in a continuous round-trip integration. They are equipped with an electrically activated valve that enables the operator to isokinetically sample points in, parts of, or the entire vertical. For stream cross sections less than 9 m deep, the full depth can be traversed in one direction at a time by opening the valve and depth integrating either from surface to bottom or vice versa. Stream cross sections deeper than 9 m can be integrated in segments of 9 m or less by collecting integrated sample pairs consisting of one or more downward integration(s) and a corresponding upward integration(s) in separate containers (Federal Interagency Sedimentation Project, 1963).

1.10.2.2.1.2.1 Rigid-bottle samplers When a rigid-bottle suspended sediment sampler is submerged with the nozzle pointing directly into flow within the sampler's calibrated velocity range, a part of the streamflow enters the sampler container via the nozzle and air in the container exhausts under the combined effect of three forces:

1. A positive dynamic head at the nozzle entrance due to the flow.
2. A negative head at the outlet of the air exhaust tube due to flow separation.
3. A positive pressure due to difference in elevation between the nozzle entrance and the air exhaust tube outlet.

Under these conditions, a calibrated isokinetic sampler will collect a sample with an SSC and a PSD essentially unchanged from those at the sampling point in the stream and a representative sample will result. However, when the sample in the container reaches the level of the air exhaust, the intake flow rate drops and circulation of the streamflow into the nozzle and out of the air exhaust tube occurs. Because the velocity of the water flowing through the bottle is less than the stream velocity, some sediment – particularly coarser particles – tend to settle in the sample bottle resulting in a large-biased SSC value. Additionally, the resulting subefficient sampling rate may favor positive SSC bias (**Figure 3**). Substantial errors in an SSC and a PSD can result from samples collected using an incorrect or uncontrolled sample rate. The magnitude of errors tends to increase concomitantly with increases in the percentage and size of suspended sand-size material (Federal Interagency Sedimentation Project, 1941; **Figure 3**). Edwards and Glysson (1999) and the U.S. Geological

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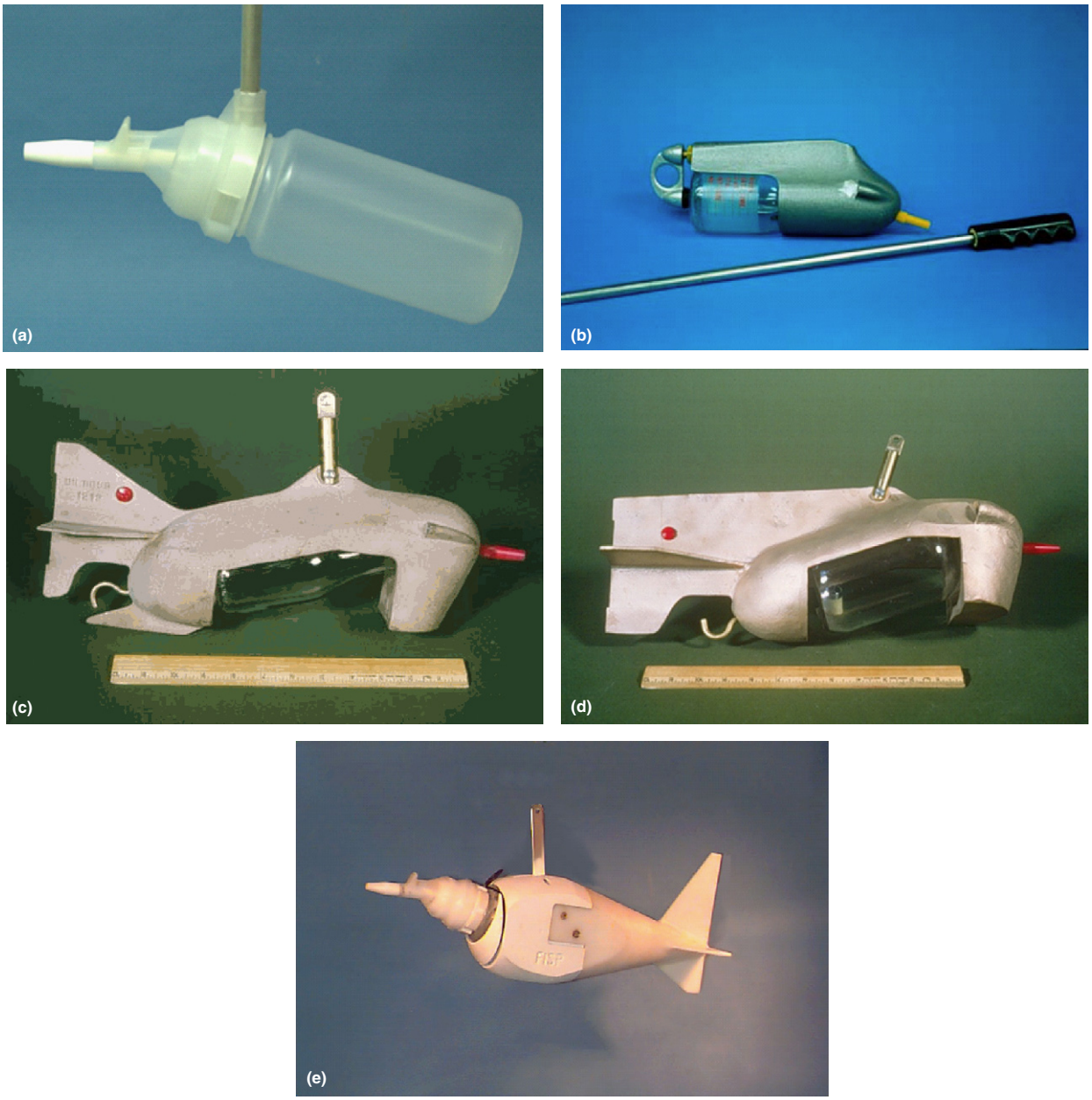

Figure 4 Handheld and handline samplers. (a) The US DH-81 suspended sampler with an attached wading rod (the D-77 cap and nozzle is located to the left of the bottle and sampler body). (b) The US DH-48 suspended sediment sampler with an unattached wading rod. (c) The US DH-59 suspended sediment sampler with hanger bar. (d) The US DH-76 suspended sediment sampler with hanger bar. (e) The US DH-95 suspended sediment sampler with hanger bar.

Survey (1998a) provided more information on ranges in transit rates required for isokinetic sampling.

1.10.2.2.1.2.2 Handheld and handline samplers US depth-integrating, hand-held (DH)-81, US DH-48, US DH-59, US DH-76, and US DH-95: where streams are wadable or access can be obtained from a culvert, low-bridge span, cableway or boat, and any of six lightweight samplers (Table 2) can be used to obtain suspended sediment samples via a wading rod or hand line. The US DH-81 sampler (Figure 4(a); Table 2), which is deployed by a wading rod, consists of a US DH-81A adapter and US D-77 cap and nozzle (U.S. Geological Survey, 2006; Edwards and Glysson, 1999; Gray et al., 2008). All parts can be autoclaved, enabling the collection of a depth-integrated sample for a flow-weighted, unbiased bacterial analysis. Any bottle having standard Mason jar threads can be used with the US DH-81 sampler. The unsampled zone – the distance from the centerline of the nozzle to the streambed when the sampler contacts a flat bed – varies depending on the size of bottle used.

The US DH-81 is advantageous for sampling in subfreezing temperatures because the plastic sampler head and nozzle

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attach directly to the plastic or glass bottle. Sampler bodies constructed of metal are relatively efficient at conducting heat away from the nozzle, air exhaust, and bottle, resulting in increased potential for ice blockage of the nozzle and (or) the exhaust port and likely subsequent negation of isokinetic sampling properties.

The rod-suspended US DH-48 sampler (Figure 4(b); Table 2) features a streamlined aluminum casting that partially encloses the sample container (Federal Interagency Sedimentation Project, 1952; Edwards and Glysson, 1999; Gray et al., 2008). The container, usually a 0.45-l glass milk bottle, is sealed against a gasket recessed in the head cavity of the sampler by a hand-operated, spring-tensioned pull-rod assembly at the tail of the sampler.

The US DH-59 and US DH-76 samplers (Figures 4(c) and (d), respectively; Table 2) are designed for use in unwadable streams with maximum depths less than 4.6 m and flow velocities up to approximately 1.5 m s^{-1}. The fundamental difference between the samplers is that the US DH-59 accommodates a 0.45-l sample bottle, whereas the US DH-76 uses a 0.9-l container. The tailfin assembly for each sampler ensures sampler alignment parallel to the direction of the ambient flow with the intake nozzle entrance-oriented upstream.

The US DH-95 sampler (Figure 4(e); Table 2) is designed to enable collection of unbiased 1 l samples for trace element analyses in addition to samples for suspended sediment analyses (McGregor, 2000a) in depths less than 4.6 m and flow velocities up to approximately 2.4 m s^{-1}. The sample bottle, nozzle cap, and nozzles are available in plastic or, for trace-element sampling, teflon. The bottle cavity is machined from a low-lead bronze casting and is plastic coated. The tail section is constructed from plastic.

1.10.2.2.1.2.3 Cable-and-reel samplers US D-74, US D-95, US P-61A1, US P-63, US P-72: the US D-74 (Figures 5(a) and (b)), US D-74AL, and US D-95 (Figure 5(c)) depth-integrating samplers can be used to obtain suspended sediment samples in unwadable streams less than 4.6 m deep (Table 2).

The bronze US D-74 and aluminum US D-74AL are designed to be suspended from a bridge, cableway, or boat. The US D-74 sampler completely encloses a 0.9-l sample container or a standard 0.45-l milk bottle when an adapter is used. The sampler head is hinged at the bottom and swings downward to provide access to the sample container chamber. The body includes tail vanes that serve to align the sampler and intake nozzle with the flow.

The US D-95 (Figure 5(c)) sampler, like the US DH-95 (Figure 4(e)), is designed to make possible collection of unbiased samples for trace element analyses in streams not exceeding 4.6 m in depth (McGregor, 2000b) at stream velocities ranging from 0.5 to 2.3 m s^{-1}. The bronze body casting is coated with plastic, and the tail section is constructed from plastic to help avoid metal contamination during water quality sampling.

Point-integrating suspended sediment samplers in wide use are the US P-61A1 (Figure 5(d)), US P-63, and US P-72 (Table 2). Each is equipped with an operator-controlled sampler solenoid valve powered by a nonsubmersible battery pack, which makes possible collection of a sample at a discrete depth or can start and stop depth-integrated sample collection. Automatic pressure equalization at depth precludes a sudden inrush of sample due to a static head differential when the valve is opened. All point-integrating samplers can be used in depth-integration mode.

The US P-61A1 (Figure 5(d); Table 2) is calibrated for use in velocities up to 2 m s^{-1}, but there is evidence to suggest that it can collect samples isokinetically at velocities of at least 3 m s^{-1} (Wayne O'Neal, FISP, 2000, written communication). The US P-63 and US P-72 are heavier and lighter versions and have higher and lower flow-velocity limits, respectively, but otherwise are functionally similar to the US P-61A1. The newest of the FISP series of point-integrating samplers – the US P-6, approved for use in 2010 – has operational range similar to the US P-61A1 but with a simpler valve assembly.

Because of the comparatively complex nature of point-integrating samplers, the user may find it useful to seek additional information given in FISP reports (Federal Interagency Sedimentation Project, 1952, 1963; Davis, 2005) or to obtain information directly from the Federal Interagency Sedimentation Project (2012).

1.10.2.2.1.2.4 Bag samplers Samplers using collapsible bags as the sample container have been used since the 1970s (Stevens et al., 1980). Nordin et al. (1983) tested a large-volume bag sampler in the Rio Orinoco and Rio Amazonas, South America. Moody and Meade (1994) deployed a bag sampler of the type devised by Stevens et al. (1980) in the Mississippi river and selected tributaries.

As with rigid-bottle isokinetic samplers, water enters the bag sampler through a nozzle. However, a bag sampler has no exhaust port, and the sample container is a collapsible bag. Air is manually expelled from the bag before submersion of the sampler. The empirically determined minimum transit rate for a bag sampler is constrained by the intake nozzle and bag volume; and the maximum transit rate is 0.4 times the mean flow velocity in the vertical. When a Teflon bag is used, bag samplers are capable of collecting unbiased samples for trace element analyses in addition to those collected for suspended sediment analyses.

The US D-96 collapsible bag sampler (Figures 5(e) and (f); Table 2) was developed in part to address the limitations and disadvantages associated with bottle and previous bag samplers (U.S. Geological Survey, 2006; Davis, 2001, 2005). This cable-suspended sampler can provide up to 3 l of sample for subsequent unbiased trace element analyses in addition to physical sediment analyses. It is fabricated from bronze and aluminum castings with a high-density polyethylene tail. All metal parts are plastic coated with commercially available 'PlastiDip.' A sliding tray (Figure 5(f)) in the sampler holds the nozzle holder with nozzle in place and supports a perfluoroalkoxy bag. The US D-96 sampler can collect velocity-weighted samples in streams with velocities from 0.6 to 3.8 m s^{-1}, although minimum velocities require the larger diameter nozzles. At a maximum transit rate of 0.4 times the mean flow velocity in the vertical, the US D-96 sampler is capable of sampling to a depth of 34 m with a 4.8-mm diameter nozzle (Davis, 2001; Table 2). Bag samplers with smaller and larger capacities than the US D-96 sampler are also available. The 13-kg US DH-2 is a

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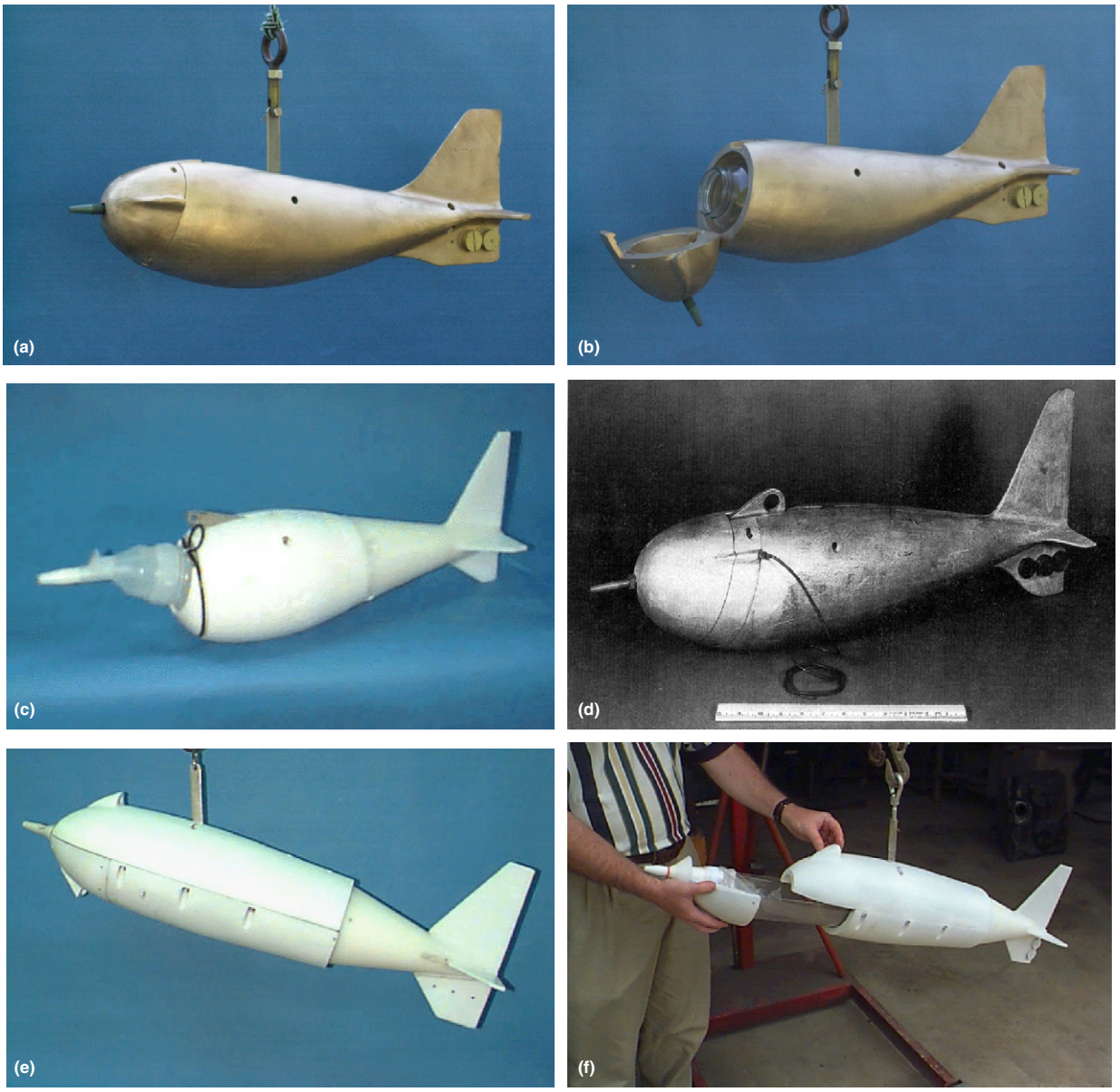

Figure 5 (a) The US D-74 suspended sediment sampler. (b) The US D-74 suspended sediment sampler open. (c) The US D-95 suspended sediment sampler. (d) The US P-61A1 point-integrating suspended sediment sampler. (e) The US D-96 suspended sediment sampler. (f) The US D-96 suspended sediment sampler with tray extended.

handline sampler capable of collecting a 1 l sample. The heaviest FISP sampler at 125 kg – the US D-99 – is capable of collecting a 6 l sample at a maximum depth of 67 m when a 4.8-mm diameter nozzle is used.

1.10.2.2.2 Manual sampling methods

The most common purpose of sediment sampling is to determine the instantaneous mean water discharge-weighted SSC at a cross section. Derived SSC values are combined with water discharge to compute the measured suspended sediment discharge. A water discharge-weighted SSC representative of the mean value in the cross section is desired for this purpose and for the development of coefficients to adjust data collected by observers, automatic samplers, and selected suspended sediment surrogate instruments.

Ideally, the best method for sampling any stream to determine suspended sediment discharge would be to collect the entire flow of the stream over a given time period, and extract, dry, and weigh the sediment. This method is rarely feasible. Instead, the SSC in the flow is determined by collecting depth-integrated suspended sediment samples that define the mean water discharge-weighted SSC in the sample vertical, and collecting samples from sufficient verticals to define the water-mean discharge-weighted SSC in the cross section (Edwards and Glysson, 1999; Nolan et al., 2005; Gray et al., 2008).

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1.10.2.2.2.1 Single-vertical sampling

The objective of collecting a single vertical sample is to obtain an SSC value representative of the mean water discharge-weighted SSC in the vertical being sampled at the time the sample was collected. An isokinetic sampler deployed at a constant rate in a downward and an upward transit will collect a sample weighted for the variations in velocity and SSC in the vertical from the surface to the top of the unsampled zone. The following equation demonstrates this concept:

$$C_i = \frac{\int_{B_i+UZ}^{D_i} c_i(s)v_i(s)\mathrm{d}s}{\int_{B_i+UZ}^{D_i} v_i(s)\mathrm{d}s} \quad [1]$$

where C_i is the mean SSC in vertical i, B_i the elevation of the stream bed in vertical i, UZ the distance from the bed to the nozzle of a sampler resting on the bed (unsampled zone), D_i the elevation of the water surface in vertical i, $c_i(s)$ the SSC at depth s in vertical i, s the depth in the vertical, and v_i the velocity at depth s in vertical i.

The method used to obtain the mean SSC in a vertical depends on the flow conditions and PSD of the sediment in transport. These conditions can be generalized to four types of situations (Edwards and Glysson, 1999), where $\bar{v}$ equals the mean ambient velocity in the sampled vertical:

1. Low velocity ($\bar{v} < 0.6$ m s^{-1}) when little or no sand is being transported in suspension.
2. High velocity ($0.6 \leq \bar{v} \leq 4.6$ m s^{-1}) when depths are less than 4.6 m.
3. High velocity ($0.6 \leq \bar{v} \leq 4.6$ m s^{-1}) when depths are greater than 4.6 m.
4. Very high velocity ($\bar{v} > 4.6$ m s^{-1}).

1.10.2.2.2.1.1 First case When the mean ambient velocity in the sampled vertical is less than 0.6 m s^{-1}, barring very shallow depths, the velocity is low enough so that little if any sand is in suspension. The distribution of any silt- and clay-size material (<0.062 mm in diameter; Guy, 1969) in transport is likely to be relatively uniform from stream surface to bed (Guy, 1970). The sampling error for this case is 10% or less with relative sampling rates in a range from approximately 0.2 to at least 5 (**Figure 3**). Consequently, it is less important to collect the sample isokinetically with fines in suspension than it is when sand-size particles (0.062–2 mm in diameter; Guy, 1969) are in suspension. In shallow streams, a sample may be collected by manually submerging an open-mouthed bottle into the stream to obtain a 'grab' sample. There are at least two ways to collect a proper 'grab' sample; the sample bottle should be:

1. held tilted upward at an approximate 45° angle from vertical in the upstream direction. The bottle should be filled by moving it from the surface vertically toward the streambed and back at a constant rate, or
2. inverted and thrust vertically through the water column to a depth no closer than approximately 8 cm of the bed; tilted upward; and filled as it is raised at a constant rate to the surface.

In neither case should the bottle be filled to the brim, nor should the bottle mouth come closer than approximately 8 cm from the bed (the unsampled zone) to obtain samples that are compatible with those obtained using depth-integrated samples at higher velocities. In exceptionally shallow water where the 8-cm unsampled zone limitation might preclude sampling in a substantial proportion of the vertical, an effort should be made to sample a substantial proportion of the vertical without disturbing the bed material.

1.10.2.2.2.1.2 Second case When $0.6 \leq \bar{v} \leq 4.6$ m s^{-1} and the depth is less than 4.6 m, a depth-integrating sampler described in **Table 2** that is suitable for the ambient streamflow condition should be used. Note that for many samplers, the maximum velocity for this case is less than 4.6 m s^{-1} (**Table 2**). The method of sample collection is basically same for all of the aforementioned samplers, whether used while wading or deployed from a bridge, cableway, boat, or other platform:

1. Insert a clean container into the sampler and ensure that the nozzle and the air exhaust tube (where applicable) is unobstructed.
2. Lower the sampler to the water surface, so that the nozzle is above the water and the lower tail vane or back of the sampler is in the water with the nozzle pointing directly into the oncoming flow.
3. Lower the sampler at a constant rate until it touches the bottom (see following caveat), and immediately retrieve it at a constant rate until it clears the water surface.

In rare cases, site conditions are such that it is unadvisable for the descending sampler to contact the bed. For example, the presence of anchored or mobile bed features capable of snagging or engulfing the sampler can present unacceptable safety concerns or at least the prospect of losing the sampler. Also, the presence of a soft bed into which the sampler sinks – or a bedform that the sampler nozzle gouges – can result in contamination of the sample with bed material. Under these and perhaps other extenuating circumstances, it may be acceptable or necessary to sound the depth before sampling and reverse direction of the sampler before contacting the bottom. Some USGS hydrographers sound bottom at a vertical with an echo sounder or sounding weight so as to determine the depth from which to retrieve the sampler before contacting the bed. Some samplers used in the lower Mississippi river and Atchafalaya rivers, for example, are deployed no lower than the 0.9 depth due to safety or sample contamination concerns (Paul Frederick and Michael Manning, USGS, written communications, 2012). Theoretically, partial-depth samples would tend to have low-biased SSC values compared to those obtained in the full-sampled depth due to SSC gradients that favor larger SSC values with depth, particularly when sand-size fractions are in suspension (American Society of Civil Engineers, 2006).

Those who consider using this modified 0.9-depth sampling method (or another user-determined sampling depth using a

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technically supportable rationale, such as the 0.95 depth) in lieu of the standard sampler-deployment procedure (Edwards and Glysson, 1999) should be cognizant of the objective to balance the unequivocal need for sampling safely and representatively, with the desire to minimize the size of the unsampled zone over that associated with a sampler contacting the bed. If a modified procedure of this type is used, it must be fully documented. Additionally, it is advisable to measure SSC profiles in verticals with a point-integrating sampler (or to collect depth-integrated samples from the full depth to compare to those collected at the 0.9 depth when it can be done safely, checking carefully for evidence of excess or inordinately coarse sediment in the full-depth sample) to aid in estimating errors in the mean SSC from use of the nonstandard technique.

For streams that transport substantial suspended sand loads or otherwise exhibit marked spatial SSC heterogeneity in the cross section, at least two complete depth integrations of the sample vertical should be made as close together in time as possible, one bottle for each integration. Each bottle then constitutes a sample and can be analyzed separately or, for the purposes of computing the sediment record (a time series of sediment discharges often reported as daily values), SSC values representing two or more bottles can be averaged as a set and tagged with a single time of collection. This set is used as a single SSC value for computing the sediment record. In an analysis of uncertainties arising from potential inadequate time averaging in sample collection at a verticals and over a cross section, Topping et al. (2011) recommend collecting a total of four water-column transits in as many verticals as practical, with each transit consisting of lowering and raising the sampler at a constant rate between the surface and river bed.

1.10.2.2.2.1.3 Third case When $0.6 \leq \bar{v} \leq 4.6\ \mathrm{m\ s^{-1}}$ and the depth is greater than 4.6 m, rigid-bottle depth-integrating samplers cannot be used because the depth exceeds the maximum allowable depth for these samplers (some rigid-bottle depth-integrating samples are limited to deployment in depths less than 4.6 m; see **Table 2**). In this case, a point-integrating or bag-type sampler must be used. The method for collection of a sample using the bag-type sampler is similar to that used with the depth-integrating samplers.

A point sampler may be used to collect depth-integrated samples in verticals where the depth is greater than 4.6 m. For streams with depths of 4.6–9.1 m, a procedure for sampling modified from that described by Edwards and Glysson (1999) is as follows:

1. Insert a clean bottle in the sampler and close the sampler head.
2. Lower the sampler to the streambed, keeping the solenoid valve closed; note the depth to the bed. If there is a high probability of contaminating the sample with bottom material gouged from the bed, then it is acceptable to sound the depth before sampling and initiate sample collection as shallow as the 0.90 depth.
3. Simultaneously, open the valve and start raising the sampler to the surface, using a constant transit rate.
4. Keep the valve open until after the sampler has cleared the water surface. Close the valve.
5. Remove the bottle containing the sample, check the volume of the sample, and mark the appropriate information on the bottle. (If the sample volume exceeds allowable limits, discard the sample and repeat depth integration using a faster transit rate that does not exceed 0.4 times the mean velocity in the vertical.)
6. Insert a clean bottle into the sampler and close the sampler head.
7. Lower the sampler until the nozzle above water but with the lower tail vane touching the water, allowing the sampler to align parallel into the flow.
8. Open the valve and lower the sampler at a constant transit rate until the sampler to the same depth at which the initial sample was collected (the bed, or to as shallow as the 0.9 depth).
9. Close the valve when the sampler touches the bed or at the same minimum depth at which the first sample was collected (by noting the depth to the streambed in step 2 above, the operator will know when the sampler is approaching the bed under all but the most dynamic bed-load-transport conditions).

If the stream depth is greater than 9.1 m, the process is similar, except that the descending and ascending integrations are broken into segments no larger than 9.1 m. Samples collected by this technique may be composited for each vertical if the same transit rate is used. Otherwise, samples should be analyzed separately. A single mean SSC is computed for the vertical (as described in the second case (above), the hydrographer might opt to retrieve the sampler before touching bottom due to safety considerations, or if there is a high probability of contaminating the sample with bottom material).

1.10.2.2.2.1.4 Fourth case When $\bar{v} > 4.6\ \mathrm{m\ s^{-1}}$, the velocities are too large to deploy a US D-99 or a US P-63, which share the highest velocity rating of the FISP suite of isokinetic samplers. In this case, when the presence of entrained debris or ice, or other factors, makes normal sample collection dangerous or impossible, a surface or dip samples, or, better yet, a partial-depth isokinetic sample may be collected.

A surface sample is one taken on or near the surface of the water, with or without an isokinetic sampler. At some locations and at certain times, such as during floods, stream velocities and depths can be so large that even the heaviest, most streamlined samplers will not reach the streambed in one or more sampled verticals. Under such conditions, it can be expected that all but perhaps the largest sediment particles in suspension will be well mixed within the flow; and, therefore, a sample from near the surface, nondepth integrated, may contain an SSC and size distribution representative of the entire vertical. However, results from these samples should be correlated with those from depth-integrated samples collected under more normal flow conditions as soon as possible after the large velocities diminish. Along with the depth-integrated sample, a sample should be collected in a manner duplicating the sampling procedure used to collect the surface or dip sample. Analytical results from these samples will be used to adjust those from the surface or dip sample collected during the

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higher flow, if necessary, to facilitate the use of these data in sediment discharge computations and data analyses.

A partial-depth isokinetic sample also requires correlation to proper depth-integrated samples collected at more normal flows. If done rigorously, it can be used as a relatively reliable analog to a full-depth sample. For example, one can only sample to 4 m or 50% of the 8 m depth at a given vertical during a flood peak. At the next site visit when the flood has receded to a maximum depth of 4 m, isokinetic samples are collected at the same vertical throughout the full depth of 4 m, and also at 2 m, or 50% of the full depth. The SSC from the sample collected in the full 4-m depth during the recession is divided by that at 2 m collected during the same site visit. The resulting ratio is multiplied by the flood peak SSC determined from the sample collected in the top half of the vertical. The product is an empirically derived estimate of the actual full-depth, flow-weighted SSC during the flood peak. This approach would have to be repeated using appropriate ratios for each vertical sampled during the flood peak.

1.10.2.2.2.2 Multivertical sampling

A depth-integrated sampler collected using the manual-sampling methods described in Section 1.10.2.2.2 will accurately represent the water discharge-weighted SSC in a vertical at the time of the sample collection. Samples collected at appropriately spaced verticals can be used to calculate the instantaneous SSC at a cross section. The International Standards Organization (ISO, 2002) lists three methods for suspended sediment data collection in a cross section: the equal-discharge-increment (EDI), equal-width-increment (EWI), and equal-area-increment methods. The equal-area-increment method is rarely used in the US. The first two methods are described in the following sections (Edwards and Glysson, 1999; Nolan et al., 2005; Gray et al., 2008).

1.10.2.2.2.2.1 EDI method With the EDI method, samples are obtained from the locations representing equal increments of water discharge. The EDI method is predicated on three criteria:

1. Samples are collected isokinetically (river conditions permitting).
2. The vertical represents the mean SSC and PSD for the subsection sampled.
3. The water discharges on either side of the sampling vertical are predetermined proportions of the total water discharge, which requires information on the lateral distribution of water discharge in the cross section. The lateral distribution of water discharge is usually obtained by a prior discharge measurement or a relation developed between river stage and the lateral distribution of discharge if the channel geometry is stable.

The mean water discharge-weighted SSC in a cross section using the EDI method is calculated from the mean SSC values from individual verticals (see Section 1.10.2.2.2.1) as follows:

$$C_{xs} = \frac{1}{n}\sum_{i=1}^{n} C_i \qquad [2]$$

where C_{xs} is the mean water discharge-weighted SSC in the cross section, n the number of verticals used in the EDI measurement, and C_i the mean SSC in the vertical i.

The lateral distribution of water discharge can be derived from a discharge measurement made immediately before selecting sampling verticals (Rantz, 1982), or, if the channel is relatively stable on an analysis of the lateral distribution of water discharges measured over a range of historical flows. If such knowledge can be obtained, the EDI method can save time and labor (compared to the EWI method, discussed in the next section), because fewer verticals are required (Hubbell et al., 1956, p. 35). This conclusion would be particularly applicable to larger streams.

The inverse of the number of verticals, n, to be sampled by the EDI method is multiplied by 100% to derive q percent, the percentage of water discharge to be represented in samples collected in each vertical. The location of a vertical nearest the left bank is selected at-a-point at which the cumulative water discharge to the left of the vertical is one-half of the total water discharge times q percent. Similarly, the location of a vertical nearest the right bank is selected at-a-point at which the cumulative water discharge to the right of the vertical is one-half of the total water discharge times q percent. All other verticals are selected at points where the cumulative water discharge between adjacent verticals is equal to the total water discharge times q percent.

For example, samples are to be collected from eight increments of equal water discharge from a 100-m wide cross section of a river flowing at 500 $m^3\,s^{-1}$. The percentage of the total water discharge to be represented in samples collected from each vertical is one-eighth times 100% or 12.5%. The location of the vertical nearest the left bank is selected at the point at which the cumulative water discharge to the left of that vertical is one-half the product of 500 $m^3\,s^{-1}$ times 12.5%, or at the point in the cross section where approximately 31 $m^3\,s^{-1}$ flows between the vertical and left bank. Likewise, the vertical nearest the right bank is selected at the point at which approximately 31 $m^3\,s^{-1}$ flows between the vertical and right bank. The other six verticals are located at points separating adjacent verticals by water discharges of 62.5 $m^3\,s^{-1}$, the product of the total river discharge of 500 $m^3\,s^{-1}$, times q percent, 12.5%. The location of each vertical represents the centroid of the water discharge in its respective subarea, with each subarea containing equal increments of water discharge. The lateral locations of the sampling verticals in natural settings are at irregular intervals due to a typically uneven channel morphology and variable velocity distribution.

Samples are collected from each EDI method vertical as described previously in the Section 1.10.2.2.2.1. Although a given one-way transit rate must be constant, neither the descending and ascending transit rates in any one vertical need to be equal nor do the transit rates need to be equal among verticals. The number of transits in each vertical can vary as long as no sample bottle overfills. Although different diameter nozzles for the isokinetic sampler can be used from vertical to vertical, it may complicate the data collection procedure, hence, the practice is discouraged.

The EDI method requires 4–9 verticals. At least two separate samples are recommended to be collected at each

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vertical. The greater the potential heterogeneity in the distribution of SSC and PSDs in the cross section, the more verticals should be selected. If an equal amount of sample is collected at each vertical, the samples can be composited and analyzed as a single sample. However, to realize the full benefits of the EDI method, samples should be analyzed separately and the resulting SSC values summed and then divided by the number of subsections to derive a mean water discharge-weighted SSC. One advantage of this method is that data describing the cross-sectional variation in SSC are produced. Additionally, a bottle containing an abnormal amount of sediment – particularly sand – compared to others in the set (because of recirculation or to gouging the nozzle into the bed) can be identified and excluded from the calculated mean cross-sectional SSC to minimize the potential for bias.

The bed of a sand channel can shift substantially at single points and across segments of the width and at timescales as short as fractions of an hour. This not only makes it difficult at best to establish a relation between stage and the distribution of the cross-section water discharge distribution from one visit to the next but also makes it impossible to be certain that the water discharge distribution does not change between the time of the water discharge measurement and sample collection (see Guy, 1970). Under conditions where the lateral distribution of flow changes rapidly or on rapidly rising or falling hydrographs, the EDI method may yield unreliable results.

1.10.2.2.2.2.2 EWI method A cross-sectional suspended sediment sample obtained by the EWI method requires a sample volume proportional to the amount of flow at each of 10 or more equally spaced verticals in the cross section (Edwards and Glysson, 1999; Nolan et al., 2005; Gray et al., 2008). Equal spacing between EWI verticals across the stream and sampling at an equal transit rate at all verticals yields a cumulative sample volume proportional to the total water discharge. This method first was used by Colby in 1946 (Federal Interagency Sedimentation Project, 1963) and is used most often in relatively shallow, wadable streams, and (or) alluvial streams where the distribution of water discharge in the cross section is temporally unstable or unknown. It also is useful where SSCs in the cross section are markedly heterogeneous, such as at sites where inflow from an upstream tributary has yet to fully mix with the main channel flow.

The mean water discharge-weighted SSC in a cross section using the EWI method is calculated from the mean SSC from individual verticals (see Section 1.10.2.2.2.1) as follows:

$$C_{xs} = \frac{\sum_{j=1}^{J} \mathrm{Vol}_j C_j}{\sum_{j=1}^{J} \mathrm{Vol}_j} \qquad [3]$$

where C_{xs} is the mean water discharge-weighted SSC in the cross section, J the number of sample bottles used in the EWI measurement, C_j the SSC in the sample bottles j, and Vol_j the total volume of water collected in sample bottle j.

The number of verticals required for an EWI sediment-discharge measurement depends on the distribution of SSC and flow in the cross section at the time of sampling, as well as on the relative assessment of the desired accuracy of the result. For many streams, statistical approaches and experience are needed to determine the desirable number of verticals. Until such experience is gained, the number of verticals used should be somewhat larger than that deemed to be minimally necessary. In all cases, a minimum of 10 verticals should be used for streams exceeding 1.5 m wide. For streams less than 1.5-m wide, adjacent verticals should be separated by at least 8 cm to allow discrete sampling of each vertical while avoiding overlaps. Through general experience with similar streams, field personnel can estimate the required minimum number of verticals to yield a desired relative level of accuracy. For all but the widest and shallowest streams, or when flood flows result in consequential floodplain flows, 20 verticals usually are ample.

The width of the increments to be sampled, or the distance between verticals, is determined by dividing the stream width by the number of verticals, n, considered adequate to collect a water discharge-weighted suspended sediment sample representative of the SSC of the flow in the cross section. The locations of the two verticals nearest to the banks are at a distance of one-half of the total width divided by n. The locations of the other verticals are separated from adjacent verticals by a distance equal to the total width divided by n. The locations of these verticals represent the centroid of subareas with boundaries one-half the distance to adjacent verticals. Hence, only the widths of the subareas necessarily are equal.

The EWI sampling method requires use of the same size nozzle for a given measurement, and all verticals must be traversed using a transit rate that will not result in overfilling the sample bottle at any vertical. The descending and ascending transit rates must be equal for all verticals and during the sampling traverse of each vertical. By using this equal transit rate technique with a standard depth- or point-integrating sampler at each vertical, a volume of water proportional to the flow in the vertical will be collected.

For example, from the previous paragraphs, samples from 12 verticals are to be collected from a 120-m wide stream. The location of the leftmost vertical is at a distance of one-half of the 120-m width divided by 12 (the number of verticals) or at 5 m from the left bank. Each of the 12 verticals are located 10 m apart with the rightmost vertical at 115 m from the left bank (5 m from the right bank).

The maximum transit rate must not exceed 0.1, 0.2, or 0.4 (a 0.4, transit rate applies to all bag samplers) depending on the sampler nozzle and bottle size (Edwards and Glysson, 1999). The minimum transit rate must be sufficiently fast to keep from overfilling the sample container. Therefore, the minimum transit rate to be used at all verticals is limited by conditions at the vertical that represents the largest water discharge per unit width, or, in operational terms, that vertical with the largest product of depth times mean velocity. A discharge measurement can be made to identify the location of this vertical. In practice, this location often is estimated from experience or by sounding for depth and acquiring a feel for the relative velocity with a deployed sampler, sounding weight, or wading rod. The transit rate required at the maximum water discharge vertical then must be used at all other verticals in the cross section and often is set to provide the maximum sample volume in a round-trip transit. It is

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permissible to sample at multiple verticals using the same bottle as long as the bottle is not overfilled. If a bottle is overfilled, the contents must be discarded and all verticals sampled using that bottle must be resampled, using at least two bottles to avoid overfilling.

1.10.2.2.2.2.3 Number of cross sections required to quantify a suspended sediment discharge The requisite number of EDI and (or) EWI cross sections to compute a reliable suspended sediment discharge is dependent on at least two factors:

1. Whether or not the purpose of the measurements is to define a coefficient to estimate cross-section SSC using samples collected at discrete locations such as at a single vertical by an observer, by pumping sampler, or by an *in situ* suspended sediment surrogate technology.
2. The risk associated with producing an incorrect result due to errors in the sampling process.

In the first case, Guy and Norman (1970, p. 38) stated that, "it is desirable to obtain…two or more mean SSCs [i.e., EDI and (or) EWI cross sections] …for a cross section." Edwards and Glysson (1999, p. 60) implicitly concur, stating that, "Samples should be collected at the observer's single vertical using the observer's equipment, both before and after each cross-section samples is taken."

In the second case, it is an unfortunate truism (based on the authors' cumulative 65 years of experience in hydrology and sedimentology in 2012) that imprecise or erroneous sediment data are occasional if inadvertently produced as a result of mistakes in the sampler selection/sample collection/processing/transportation/analysis continuum. Production of spurious data can arise from a number of sources, including inadequate definition of the SSC in a vertical due to an insufficient number of transits (Topping et al., 2011), incomplete transits, or use of inappropriate transit rates; gouging the sampler nozzle or sinking the sampler into the streambed; alterations arising from subsampling and transport to the sediment laboratory; and, however infrequent, analytical or computational errors. Regardless of the source of the error, an incorrect value from a sample is arguably worse than no data. Incorrect data nullify the benefits of the resources expended in their collection and may result in added time and resources in an attempt to identify and purge the erroneous data.

Based on the facts and rationale above – and on the findings of Topping et al. (2011) – when the objective is to define a cross-section SSC coefficient, at least two sets of samples collected by the EDI and (or) EWI methods are required in the measurement of suspended sediment discharge. Additionally, multiple samples need to be collected from the instrument to be calibrated, usually double the number of cross sections sampled. For other purposes, multiple EDI and (or) EWI sample sets are strongly recommended to minimize the potential for spurious data to remain undetected.

In the case of the EDI method, one may collect multiple samples at each vertical in a single pass across the stream. The first sample at each vertical may be designated 'cross section A,' the second, "cross section B," etc. Separate mean SSC values are produced for each cross section, and, if the streamflow conditions have remained more or less the same during both cross sections and the SSC values are similar among the cross sections, the mean SSC values from each cross section are averaged and multiplied by the water discharge and a constant units conversion factor to produce a value of suspended sediment discharge.

This process to derive a single suspended sediment discharge value from EWI samples is more straightforward. The mean SSC values produced from each cross section are averaged to produce a single mean SSC value for subsequent suspended sediment discharge computation. There are no restrictions with respect to the starting location for EWI suspended-sediment sampling in a cross section. The most common approach is to begin sampling from near one side of the stream and progress to the opposite bank, and to collect subsequent EWI sample set(s) starting at or near the location of the last sample from the previous sample set.

EDI and EWI methods can be used in tandem. For example, an EWI sample set may be used to produce a PSD and a mean SSC, and an EDI sample set used to describe SSC. The benefits of this approach are from the detailed cross section distribution of SSC, which can readily identify outliers; and a PSD that is representative of that in the cross section.

In rare cases, a combination of depth-integrated sampling and dip sampling to quantify suspended sediment transport may be appropriate. For example, in the mid-2000s, the right third of the Rio Grande at Albuquerque, New Mexico (USGS streamgage 08330000) averaged approximately 0.6-m deep with mean velocities exceeding 0.6 m s^{-1} – conditions amenable for depth-integrated sampling. The left two-thirds of the channel had a more-or-less uniform 0.2 m depth – conditions amenable to dip sampling. A 10-section EDI measurement – those samples in the deeper section collected with a depth-integrating sampler and those in the shallow section dipped – was used to quantify suspended sediment discharge. Note that an EWI measurement would be inappropriate under these circumstances, because of the unmet requirement for uniform transit rates with an isokinetic sampler over the entire cross section.

1.10.2.2.2.2.4 Advantages of the EDI and EWI methods Some advantages and disadvantages of both the EDI and EWI methods have been noted in the previous discussion. It must be remembered, however, that both methods, if properly used, will yield similar cross-sectionally averaged results.

The advantages of the EDI method are as follows:

1. The fewer requisite verticals typically result in a reduced collection time, which is particularly advantageous during periods of rapidly changing water discharge.
2. Bottles composing a sample set may be composited for single laboratory analysis when equal volumes of sample are collected from each vertical.
3. The cross-sectional variation in SSC can be determined if samples are analyzed individually, and errors often can be readily identified by a comparison of SSC values in the cross section.
4. Multiple cross-sectional samples can be collected at each vertical during a single traverse of the stream.
5. A variable transit rate can be used among verticals although the rate of a single-direction transit must remain constant.

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The advantages of the EWI method are as follows:

1. No antecedent knowledge of flow distribution in the cross section is required.
2. Variations in the distribution of SSC in the cross section may be better integrated in the composite cross section sample due to the larger number of verticals sampled.
3. Analytical time and costs are minimized as sample bottles are composited for single laboratory analysis.
4. This method is easily learned and used due to the straightforward spacing of sample verticals based on stream width, rather than on the cross-sectional distribution of water discharge.
5. Generally, less total time is required on site if no discharge measurement is deemed necessary and the cross-section geometry is relatively stable during the measurement.

The advantages of one method are, in many cases, the disadvantages of the other. The U.S. Geological Survey (1998a) considered the EDI method the most universally applicable and useful water discharge-weighted sampling method.

1.10.2.2.2.2.5 Transit rates for suspended sediment sampling A sample obtained with an isokinetic sampler using depth integration is quantitatively weighted according to the velocities through which it passes. Therefore, if the sampling vertical represents a specific width of flow, the sample is considered to be water discharge-weighted because, with a uniform transit rate, the suspended sediment conveyed at varying velocities throughout the sampled vertical is given equal time to enter the sampler.

The transit rate used with any depth-integrating sampler must be regulated to make possible the collection of representative samples (i.e., isokinetically collected). Although the descending and ascending transit rates need not be equal, in practice it is simpler, ergo less prone to error, for the transit rates to be equal in both directions. Regardless, the rate of any one-direction transit must be constant to obtain a valid velocity- or water discharge-weighted sample. The goal in selecting transit rates is to fill the sample bottle to its optimum level (Johnson, 1997; Edwards and Glysson, 1999; Nolan et al., 2005; Gray et al., 2008).

An insufficient transit rate can result in an unacceptable sample due to overfilling of the sample container. An excessive transit rate can result in intake velocities less than the stream velocity due to a large entrance angle between the nozzle and streamflow lines caused by the vertical movement of the sampler in the flow (Federal Interagency Sedimentation Project, 1952). Transit rates should never exceed the product of 0.4 and the mean velocity ($0.4\,\bar{v}$) in a vertical with any isokinetic sampler.

Additional limitations may be imposed on maximum transit rates for rigid-bottle depth-integrating samplers due to changes in hydrostatic pressure during deployment. The maximum allowable transit rate is attained when the rate of change in the internal pressure due to filling equals the rate of change of hydrostatic pressure. If the sampler is lowered too fast in the vertical, inflow through the nozzle is insufficient to increase the pressure in the container at the same rate; consequently, hydrostatic pressure increases at a greater rate than pressure in the container. The resulting pressure imbalance causes the sample to enter the nozzle at a velocity greater than the ambient stream velocity. Stream water can also enter the exhaust port under these circumstances. Both potential outcomes result in violation of isokinetic sampling principles (Stevens et al., 1980). Likewise, if the sampler is raised too rapidly, the hydrostatic pressure will decrease at a greater rate than the pressure inside the container. This pressure imbalance will result in reduced flow of sample into the container with respect to the ambient stream velocity. Either outcome – larger or smaller intake velocities with respect to the ambient stream velocity – can result in collection of a sample that contains neither a representative SSC nor PSD of suspended sediment.

The maximum allowable transit rate for rigid-bottle samplers can be determined with knowledge about the:

1. depth of the sample vertical,
2. mean velocity of the vertical,
3. sampler nozzle size, and
4. bottle size used in the sampler.

Different combinations of nozzle diameters and bottle volumes result in maximum transit rates ranging from approximately $0.1\,\bar{v}$ to $0.4\,\bar{v}$. Tables providing isokinetic transit rates as a function of nozzle diameters and bottle volumes are provided by the U.S. Geological Survey (1998a). Graphs delineating permissible and optimal transit rates for a combination of sample container and nozzle sizes as a function of stream depth and mean velocity are provided by Edwards and Glysson (1999).

When using a cable-deployed sampler, there are at least two options toward maintaining constant transit rates: use of a power-regulated reel (Jelinski, 2008) or an electronic metronome such as the US vertical transit pacer (VTP)-99 Vertical Transit Rate Pacer (Federal Interagency Sedimentation Project, 2012).

1.10.2.2.2.2.6 Inspecting samples Inspecting individual samples is fundamentally important toward evaluating the magnitude and potential sources of variations in sediment content of sample bottles during a site visit. The primary objective is to identify samples collected consecutively from the same vertical or from adjacent verticals in which SSCs differ markedly. Such checks should be done routinely as part of the data collection process.

Immediately after collection, each sample should be inspected by briefly swirling or agitating the container and then observing the quantity of sand particles that collect in the bottom of the tilted container. If it is perceived that the concentration of sand inexplicably differs among the bottles when visually correcting for differences in sample volumes, or the sand in a sample bottle is inordinately coarse, it is possible that the sampled concentration is an artifact of the sampler nozzle gouging or sinking into the bed. In this case, the vertical should be immediately resampled at least once and additional times until the hydrographer can ascertain if any samples are contaminated with bed material. Any sample container perceived to contain anomalously large quantities,

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or abnormally coarse size fractions of sand should be marked as such, or, if the hydrographer lacks confidence in a sample's validity, the sample should be summarily discarded. If a container is overfilled or if water ejects from the nozzle during sampler retrieval, the sample should also be discarded. A clean container must be used to resample the vertical.

1.10.2.2.2.3 Point-integrated sampling

A point-integrated sample is a sample of the water–sediment mixture collected isokinetically from a single point in the cross section. Point-integrated samples are collected using one of the point-integrating samplers previously presented (**Figure 5(d)**). Multiple point samples may be used to define the distribution of sediment in a vertical, the vertical and horizontal distributions of sediment in a cross section, and the mean cross-sectional SSC.

The purpose for which point samples are to be collected determines the collection method to be used. If samples are collected for the purpose of defining the horizontal and vertical distribution of SSC and (or) PSDs, samples collected at numerous points in the cross section with any of the 'P' type samplers will be sufficient. Vertical distributions can be adequately defined by obtaining samples from a number of points in each sample vertical. Specifically, samples should be taken with the sampler lightly touching (or, if the nozzle might gouge the bed, suspended a short distance above) the bed, 0.3 m off the bed, from 5 to 10 additional points in the vertical above that point, and from near the surface.

The sampling time for each sample (the elapsed time that the nozzle is open) must be equal. This result will ensure that sample volumes collected are proportional to the flow at the point of collection. These samples may be composited for a single laboratory analysis. If the EDI method is used to define the stationing of the verticals, the sampling time may be varied among verticals. If the EWI method is used, a constant time for collecting samples from all verticals must be used. In most cases, it is necessary to analyze each point sample separately.

The mean water discharge-weighted SSC in a cross section using the point-integration method is calculated from the mean SSCs from individual sampling points as follows:

$$C_{xs} = \frac{1}{n}\sum_{i=1}^{n}\left\{\frac{\sum_{d=1}^{D_i}\mathrm{Vol}_{id}C_{id}}{\sum_{d=1}^{D_i}\mathrm{Vol}_{id}}\right\} \qquad [4]$$

where C_{xs} is the mean water discharge-weighted SSC in the cross section, D_i the total number of points sampled in vertical i, n the number of verticals in which point samples are collected, C_{id} the SSC in a sample from point d of vertical i, and Vol_{id} the volume of sample collected from point d of vertical i.

If multiple points are sampled with a single bottle, computation of the mean sample SSC is accomplished by treating the contents of the bottle as if collected at a single point.

1.10.2.2.3 The case for depth-integrated sampling with isokinetic samplers

The natural environment presents a variety of challenges to the hydrographer responsible for measuring riverine suspended sediment transport rates. The temporal and spatial variability of sediment transport can be and typically is substantial. Quantification of sediment transport over time requires a sufficient number of measurements (Porterfield, 1972), each of which adequately accounts for the spatial variability of sediment transport in the cross section. Because of the non-uniformity in velocity and SSC profiles in a cross section, the spatial distribution of sediment discharge per unit area creates a measurement conundrum: How to measure and properly weight velocity and SSC variations in the cross section to derive the correct value for suspended sediment discharge in the cross section at the time of the site visit.

Spatial variations in sediment concentrations can result from a number of factors including the dynamic site characteristics of proximity and relative sedimentary content of tributary inflows, channel roughness characteristics, hydraulic radius, flow energy, turbulence, sloughing banks; and the sedimentary characteristics of specific gravities, shapes, and size distributions. Even at a cross section with relatively well-mixed flow and sediments of consistent specific gravities and shapes, spatial SSC variations can be expected due to the propensity for larger particles to fall at a faster rate than smaller particles as described by Stokes Law (American Society of Civil Engineers, 2006). In the absence of coarser (sand size) particles and with even moderate turbulence, the effect of Stokes Law can be negligible, yielding a relatively uniform distribution of silt- and clay-size particles in the cross section. However, sand-size material in suspension coupled with minimal to moderate turbulence usually results in a vertical SSC gradient, with SSCs increasing with depth.

The effects of Stokes Law and other factors that result in unequal mixing of suspended sediments – ergo the need for depth-integrated sampling with FISP isokinetic samplers when their deployment criteria are met – can be demonstrated using suspended sediment SSC and PSD data collected at the Rio Grande Floodway near Bernardo, New Mexico, USA (USGS streamgage 08332010) on 4 May 1966 (Culbertson et al., 1972). These data were used to generate lines of equal SSC in the measured cross section (**Figures 6(a)** and **(b)**), as distributions of silt-size material (0.004–0.062 mm) and sand-size material (0.062–2 mm), respectively. The data were obtained using a DH-48 suspended sediment sampler modified for point-integration sampling, with SSCs reported per ranges of phi diameters. With the exception of one measurement of 2 mm sand at an SSC of 31 mg l^{-1}, all of the remaining 63 point-integrated samples contained material finer than 1 mm.

The silt–clay-size range in SSC data from the six verticals sampled (**Figure 6(a)**) based on individual samples (Culbertson et al., 1972; USGS, written communication, undated) is 820–1080 mg l^{-1}, with a mean silt–clay SSC of 930 mg l^{-1}. The maximum silt–clay SSC deviation from the mean value is approximately 14%. If one were to obtain an open-bottle grab sample from near the water surface at the rightmost sampled vertical (**Figure 6(a)**) and use the derived SSC silt–clay SSC value – 860 mg l^{-1} – with river discharge to compute suspended sediment discharge, the result would be a suspended silt–clay discharge equal to approximately 92% of the actual value. Alternately, if the silt–clay SSC value from an unbiased sample pumped from near the right bank at a depth of approximately 1 m, the resulting silt–clay SSC of

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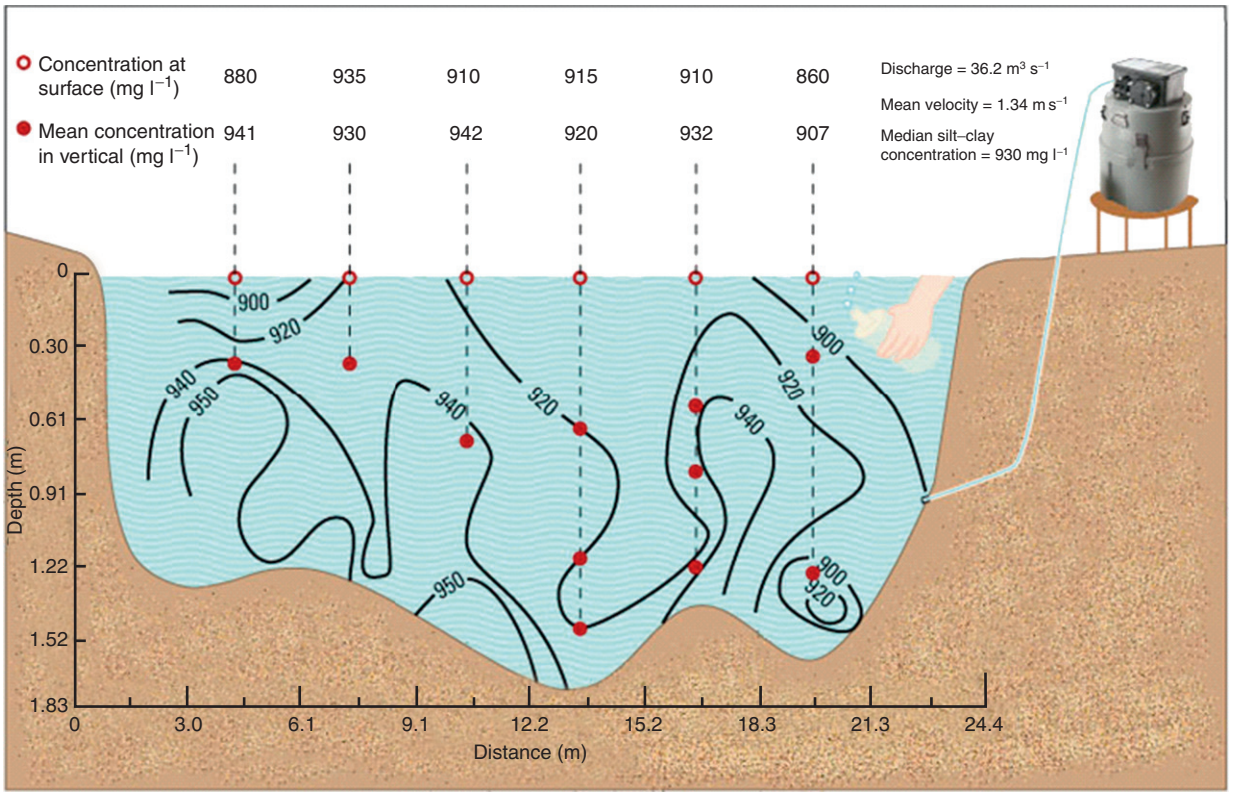
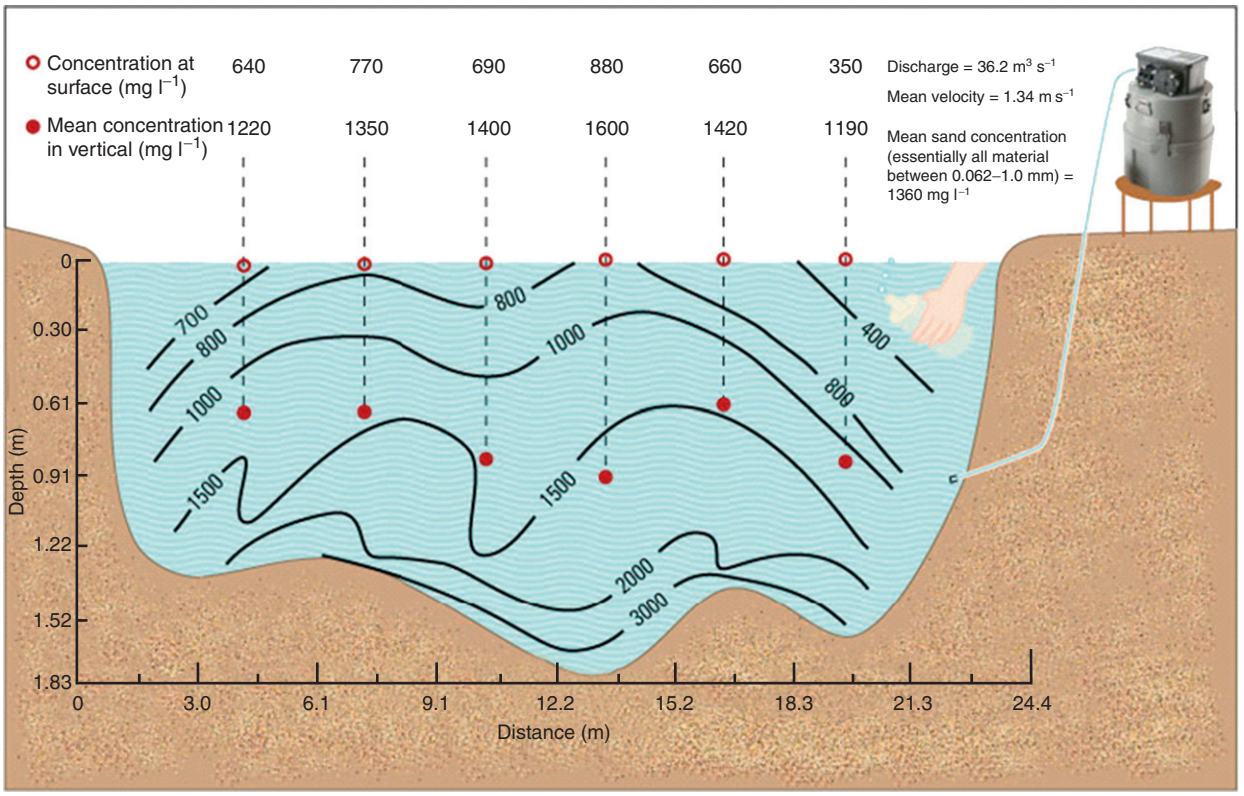


(a)



(b)

Figure 6 SSCs as (a) silt–clay and (b) sand-size material in the Rio Grande Floodway near Bernardo, New Mexico, USA (USGS streamgage 08332010) interpolated from data collected on 4 May 1966 (Culbertson et al., 1972). Base graph developed by an anonymous hydrographer before 1996. Photographs of the ISCO 3700 sampler with jumbo base are reproduced by courtesy of Teledyne Isco, © 2012 (use of any trade or firm names in this report is for identification purposes only and does not constitute endorsement by the US Government).

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900 mg l^{-1} would yield a suspended silt–clay discharge value equal to approximately 103% of the actual value. Based on standard protocols for deployment of depth-integrated samplers (Edwards and Glysson, 1999), Topping et al. (2011, p. 43), showed that the maximum total uncertainty in silt–clay SSCs (four verticals and two transits/vertical) to be approximately 3%. Hence, collection of a nonisokinetic sample near the stream's edge or via an unbiased pumping sampler, with only silt–clay-size material in suspension may provide a reasonable estimate (within several percent) of the actual mean cross-section SSC value. This statement is necessarily predicated on the assumption that only silt–clay-size material is in suspension in a river cross section at a given time. However, it is important to note that only the more experienced hydrographer can ascertain the relative contribution of suspended sand to the total SSC with even a modicum of certitude.

Figure 6(b) depicts a markedly different SSC cross-sectional distribution for sand-size material (in this case, essentially all material in the range of 0.062–1 mm). The sand-size range in SSC data from the six verticals sampled (**Figure 6(b)**) based on individual samples (Culbertson et al., 1972; USGS, written communication, undated) is 255–8380 mg l^{-1}, with a mean sand SSC of 1360 mg l^{-1}. The maximum sand SSC deviation from the mean value is approximately 616%. If one were to obtain an open-bottle grab sample from near the water surface at the rightmost sampled vertical and used the derived SSC value – approximately 350 mg l^{-1} – with water discharge to compute the suspended sand discharge, the result would equal approximately 26% of the actual value. Alternately, if the sand SSC value from an unbiased sample pumped from the right bank at a depth of approximately 1 m equaled approximately 700 mg l^{-1}, the resulting suspended sand discharge value would equal approximately 194% of the actual value. In comparison, Topping et al. (2011, p. 45) showed that the maximum total uncertainty in sand SSCs using standard USGS protocols (Edwards and Glysson, 1999) is approximately 7%.

The previous paragraphs provide the underpinning for the answer to the question, 'How does one measure and properly weight velocity and SSC variations in the cross section to derive the correct value for suspended sediment discharge in the cross section at the time of the site visit?' When substantial variations in the distribution of flow and SSC in a cross section exist, proper deployment of a suitable depth-integrating sampler – the EDI or EWI methods – is required to obtain samples representative of the flow-weighted sediment content in the cross section. Such unmixed conditions are typical for sand- and gravel-bed rivers at most flows; and for rivers with finer grained or cohesive beds at medium-to-higher flows. When it is unknown if substantial spatial SSC variations exist, the same sampling approach should be used to preclude inaccuracies resulting from nonflow weighting a sample from a potentially heterogeneous mixture of suspended sediment. Only when the experienced hydrographer determines unequivocally that the amount of sand in suspension is insignificant with respect to total SSC – or when the limitations of an isokinetic sampler are exceeded – samples should be collected with other than isokinetic samplers and their appropriate deployment techniques.

1.10.2.2.4 Automatic samplers

Some sediment-monitoring programs and studies include sites where collection of sediment samples is required at a frequency, at a time, and (or) under a set of conditions that cannot be accommodated through manual sampling. Safety considerations, remoteness or inaccessibility of site location, flow conditions, operational costs, and other factors may render manual collection of sediment and flow data at a site impractical or impossible. In lieu of manual sampling, automatic samplers collect a sample for subsequent analysis, and possibly one or more surrogate technologies may be deployed to accommodate sediment data collection needs at some sites. As noted previously and described later, emerging surrogate technologies for monitoring suspended sediment are being tested and, in the case of turbidity, incorporated into operational programs of the USGS (Rasmussen et al., 2009).

Automatic samplers are useful for collecting suspended sediment samples during periods of rapid water discharge changes from storm runoff and in reducing the need for manual measurements associated with intensive sediment-collection programs (Federal Interagency Sedimentation Project, 1981). However, under some circumstances, use of automatic samplers to collect data can actually result in costs greater than those for an observer (Johnson, 1997) at the same site. Automatic samplers, and particularly pumping samplers, often require more frequent site visits by the field personnel than would be required at the conventional observer station owing to their mechanical complexity, power requirements, and limited sample capacity. Use of automatic samplers does not preclude the need for collecting medium- and high-flow cross-sectional samples. Additionally, use of automatic samplers typically results in reduced data quality because the samples are rarely, if ever, withdrawn isokinetically. This conclusion is particularly true for automatic sample collection from streams conveying high percentages of suspended sand-size material.

The most commonly used automatic samplers are automatic pumping samplers, which require power to obtain water samples. Single-stage samplers, which rely on changes in stream stage and (or) velocity to collect water–sediment samples passively on the rising phase of a hydrograph, also are available.

1.10.2.2.4.1 Automatic pumping samplers

Automatic pumping samplers generally consist of a pump, bottle container unit, sample distribution, activation, and intake systems. Ideally, this combination of components should be designed to meet the following criteria (Bent et al., 2003; Edwards and Glysson, 1999):

1. Stream velocity and sampler intake velocity should be equal to allow for isokinetic sample collection if the intake is aligned into the approaching flow.
2. A suspended sediment sample should be delivered from stream to sample container without a significant change in SSC or PSD.
3. Cross contamination of samples caused by residual sediment in the sampler plumbing between sample collection periods should be prevented.

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4. The sampler should be capable of sampling over the full range of SSCs and particle sizes.
5. Samples should meet minimum sample analysis volume requirements.
6. The inside diameter of the intake should be at least three times the diameter of the largest particles sampled, although small enough to maintain a mean sample velocity that will substantially exceed the fall velocity of largest particles.
7. The sampler should be capable of vertical pumping lift heights of approximately 10 m from intake to sample container for clear water (in most cases, the lift elevation for river water is a function of sediment concentration, water temperature, and atmospheric pressure).
8. The sampler should be capable of collecting a reasonable number of samples – usually at least 24 – dependent on the purpose of sample collection and the flow conditions.
9. Some provision should be made for protection against freezing, evaporation, and dust contamination of collected samples.
10. The sample container unit should be constructed to facilitate removal and transport as a unit.
11. The sampling cycle should be initiated in response to a timing device, flow or stage change, or external signal based on a set of criteria that maximizes the potential for collecting samples at desired points over one or more hydrographs.
12. The capability of recording the sample collection date and time should be present.
13. The provision for operation using alternating current (AC) power or direct current (DC) battery power should be present.

Nearly all of the automatic pumping samplers in use at present are commercially produced. The ISCO 6700 and American Sigma 900 automatic pumping samplers, for example, share various features for collecting water samples. Both are computer controlled and capable of collecting up to 24 1 l samples based on time, flow, and (or) other user-selected criteria. They use built-in peristaltic pumps and operate on AC power or DC battery power. Both samplers feature a back-flush cycle to preclude or minimize cross contamination between consecutively collected samples.

Neither sampler is capable of sampling clear, cold freshwater if the peristaltic pump is at a height greater than approximately 10 m above the water surface at normal sea level barometric pressures. Cavitation can occur at smaller heads with larger specific gravities associated with increasing SSCs and (or) lower barometric pressures and (or) larger water temperatures. Where lift requirements potentially exceed the capacity of a sampler, an auxiliary pump may be used to pump water to the sampler under a positive pressure.

Gray and Fisk (1992) described an automatic pumping sampling system used to collect samples of highly concentrated and hyperconcentrated streamflows in Arizona and New Mexico, USA. An auxiliary pump in a diving bell affixed at a height of 1–2 m above that of the water surface at low-flow pumped stream water to a gaging station. In the gaging station, a commercial sampler modified to collect 9 l samples periodically drew an aliquot of the pumpage from the auxiliary pump via a Y connector in the intake line. A data collection platform controlled collection of up to 24 samples based on time, stage, and rate-of-stage-change criteria. The data collection platform recorded hydrologic information and data related to the number and times of samples collected and periodically updated a USGS database via satellite. Such capabilities are relatively common in 2012.

1.10.2.2.4.1.1 Installation and use criteria Physical and fiscal criteria usually drive the decision to use a pumping sampler for collection of sediment samples. Installation of an automatic pumping sampler requires careful planning including selection of the sampler site location and an evaluation of available or newly collected data to maximize the potential to obtain useful data from the pumped samples.

Before installation of an automatic pumping sampler, many of the problems associated with installing streamgaging equipment must be addressed. In addition, specific data concerning the sediment-transport characteristics at the proposed sampling site must be obtained and evaluated before emplacement of the sampler and location of the intake within the streamflow. Logistically, the sample site must be evaluated as to accessibility, availability of electrical power, access to a bridge, cableway, or other platform from which to safely obtain manual measurements and range in air temperatures characteristic for the site. The availability of a local observer to collect periodic reference samples also should be considered. The sediment-transport characteristics should include detailed information on the distribution of SSCs and PSDs throughout the sampled cross section over a range of water discharges. Additional information is contained in Section 1.10.1.2 (Table 1).

1.10.2.2.4.1.2 Placement and orientation of sampler intake The primary concept to consider when placing a sampler intake in the streamflow at a sample cross section is that only one point in the flow is being sampled. Therefore, to yield the most reliable and representative data, the intake should be placed at the point where the SSC and PSD are most representative of the mean SSC for the cross section over the full range of flows. This idealistic concept has great merit, but the mean cross-section SSC rarely, if ever, exists at the same point under varying streamflow conditions. It is even less likely that specific guidelines for locating an intake under given stream conditions at one stage would produce the same intake location relative to the flow conditions at a markedly different stage. These guidelines would have even less transfer value from cross section to cross section and from stream to stream. For these reasons, some generalized guidelines are outlined here and should be considered on a case-by-case basis in placing a sampler intake in the streamflow at any given cross section (Edwards and Glysson, 1999):

1. Select a stable cross section in a reach with reasonably uniform depths and widths to maximize the stability of the relation between the at-a-point SSC and the mean SSC in the cross section. This guideline is of primary importance

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in the decision to use a pumping sampler in a given situation; if a reasonably stable relation between the at-a-point SSC and mean SSC in the cross section cannot be attained by the following outlined steps, an alternate location for the installation should be considered.

2. Consider only the part of the vertical that could be sampled using a standard US series depth- or point-integrating isokinetic suspended sediment sampler, excluding the unsampled zone, because data collected with a depth- or point-integrating sampler will be used to calibrate the pumping sampler.
3. Determine, if possible, the depth of the point of mean SSC in each vertical for each size class of particles finer than 0.25 mm from a series of carefully collected point-integrated samples.
4. Determine, if possible, the mean depth of occurrence of the mean SSC in each vertical for all particles finer than 0.25 mm.
5. Use the mean depth of occurrence of the mean SSC in the cross section as a reference depth for placement of the intake.
6. Affix the intake at the desired location in flow. It should remain stable and free of debris throughout the range of flows. Its depth should be sufficiently high to avoid interference by dune migration or contamination by bed material but low enough to collect samples at the lowest flows of interest.
7. Locate the intake in the flow at a distance far enough from the bank to eliminate any possible bank effects. Never place the intake in an eddy.
8. Place the intake in a zone of high velocity and turbulence where the sediment will be relatively well mixed, the potential for deposition on or near the intake is minimal, and to provide for rapid elimination of any particles during a purge cycle.
9. Situate the intake line to maintain a downward slope from the sampler to the orifice without dips, which may retain water and sediment after a pumping cycle.

Because of the generalized nature of these guidelines and because selected guidelines may prove to be mutually exclusive, it will rarely be possible to satisfy them all when positioning a pumping sampler intake into stream flows. The investigator is encouraged to identify those guidelines that are most crucial to the success of the installation and endeavor to satisfy them first.

The orientation of the pumping sampler intake nozzle can drastically affect sampling efficiency. There are five ways in which an intake could be oriented to the flow (see **Figure 7**): (a) pointing directly upstream (**Figure 7(a)**), (b) perpendicular to the flow and horizontal (**Figure 7(b)**), (c) vertical with the orifice up (**Figure 7(c)**), (d) vertical with the orifice pointing down (**Figure 7(d)**), and (e) pointing directly downstream (**Figure 7(e)**). Of these five orientations, (a), (c), and (d) should be avoided because of high sampling errors and trash collection problems. Orientation (b), with the nozzle positioned perpendicular to the flow and horizontal, is the most common alternative used. The major problem with orientation (b) is that sand-size particles may not be adequately sampled. Orientation (e), pointing directly downstream, may be advantageous over orientation (b) (Winterstein and Stefan, 1986). When the intake is pointing downstream, hydraulic theory supports the presence of a small eddy at the intake, which captures sand particles and thus enables withdrawal of a more representative sample of the coarse load (the fine load tends to be more representatively sampled regardless of intake orientation). Regardless of the intake orientation selected, the ratios of SSCs representative of the mean cross-sectional SSC and those from pumped samples are required to define the sampling efficiency over a range of flows with an emphasis on medium-to-high flows.

1.10.2.2.4.1.3 Activation The availability of a microprocessor as an integral part of the sampler, or as an external controller, provides many options for controlling pumping samplers that can be tailored to data collection requirements on hand. As noted previously, Gray and Fisk (1992) described a method for controlling an automatic water sampler based on time, stage, and rate-of-stage-change criteria. Their technique is designed to provide adequate definition of the flood hydrograph to make possible reliable computations of daily sediment and associated solid-phase radionuclide discharges.

Lewis (1996) described a means for controlling an automatic sediment sampler based on real-time turbidity measurements. A technique for controlling an automatic water sampler that provides unbiased estimates of suspended sediment discharges, based on time-stratified sampling and selection at list time, is described by Thomas (1985, 1991) and Thomas and Lewis (1993).

1.10.2.2.4.2 Single-stage samplers

Single-stage samplers were developed to meet the needs for instruments useful in obtaining sediment data on streams where remoteness of site location and (or) rapid changes in stage make it impractical to use a conventional depth-integrating sampler. They are generally less reliable, both in operation and in data accuracy, than depth-integrating samplers. However, even approximate information on the SSCs between visits to the stream can be useful if nothing better is available (Federal Interagency Sedimentation Project, 1961; Edwards and Glysson 1999).

The US U-59 series single-stage samplers designed and tested by the FISP consist of a 0.45-l milk bottle or other sample container, a 4.7-mm inside diameter air exhaust, and a 4.7- or 6.4-mm inside diameter intake constructed of copper tubing. Each tube is bent to an appropriate shape and inserted through a stopper sized to fit and seal the mouth of the sample container.

There are four models of US U-59 samplers (Federal Interagency Sedimentation Project, 1961). That designated US U-59A is designed for collection of silt- and clay-size sediments in low, less than approximately 0.7 m s^{-1}, stream velocities. Those designated US U-59B, US U-59C, and US U-59D are for collection of sand-size and finer material in stream velocities less than 1.0, 1.6, and 2.1 m s^{-1}, respectively. A US U-59D single-stage suspended sediment sampler is shown in **Figure 8(a)**.

The US U-59 series of samplers obtain a sample on the rising phase of the hydrograph from a point near the water surface when the water level inside the intake tube reaches the

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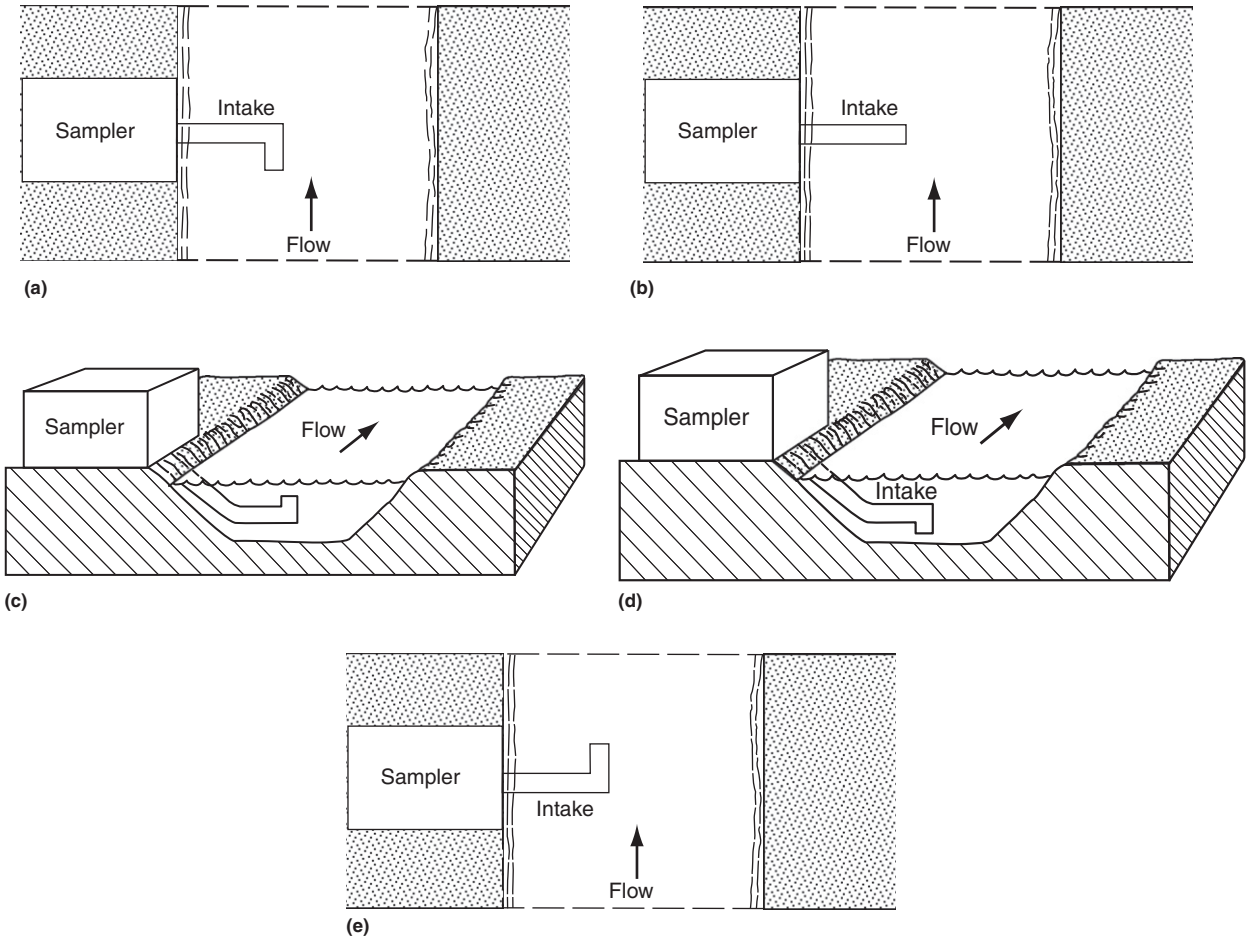

Figure 7 Examples of pumping-sampler intake orientations. (a) Pointing directly upstream, (b) Perpendicular to flow and horizontal, (c) Vertical with the orifice up, (d) Vertical with the orifice down, and (e) Pointing directly downstream.

weir height. As the sample siphons from the intake orifice into the sample bottle, air from the sample bottle vents out of the exhaust tube. The sampler is designed to cease filling when the sample height reaches the inner exhaust tube orifice. The sample velocity in the intake tube is a function of various factors including stream velocity on the orifices, intake orifice orientation, turbulence, and the presence of obstructions in either tube.

The sampling operation just described is somewhat idealistic because, in reality, the operation is affected by various factors including flow velocity and turbulence. These factors alter the effective pressure at the entrance and exit nozzles, which in turn alters the sampler's intake velocity.

The US U-59 sampler has many limitations with respect to desirable sampling objectives. It is a type of point sampler because it samples a single point in the stream at whatever stage the intake nozzle is positioned when immersed in flow. Its primary purpose is to collect a sample automatically, and the US U-59 usually is used on flashy streams or other locations that are difficult to visit in time to manually collect samples. Besides being automatic, the US U-59 is simple and inexpensive compared to automatic pumping samplers; a bank of them can be used to obtain a sample at various depths during the rising hydrograph. However, despite these seemingly important advantages, the US U-59 sampler has many limitations. Following are the more important of these limitations:

1. Samples are collected at or near the stream surface, so that, in the analysis of the data, theoretical adjustments for vertical distribution of SSCs or size are necessary.
2. Samples usually are obtained near the edge of the stream or near a pier or abutment; therefore, theoretical adjustments for lateral variations in sediment distribution are required.
3. Even though combinations of size, shape, and orientation of intake and air exhaust tubes are available, the installed system may not result in intake ratios sufficiently close to unity to sample sands accurately at parts of the runoff hydrograph.
4. Covers or other protection from trash, drift, and vandalism often create unnatural flow lines at the point of sampling.
5. Water from condensation may accumulate in the sample container before sampling.
6. The sediment content of a sample may change during subsequent submergence.

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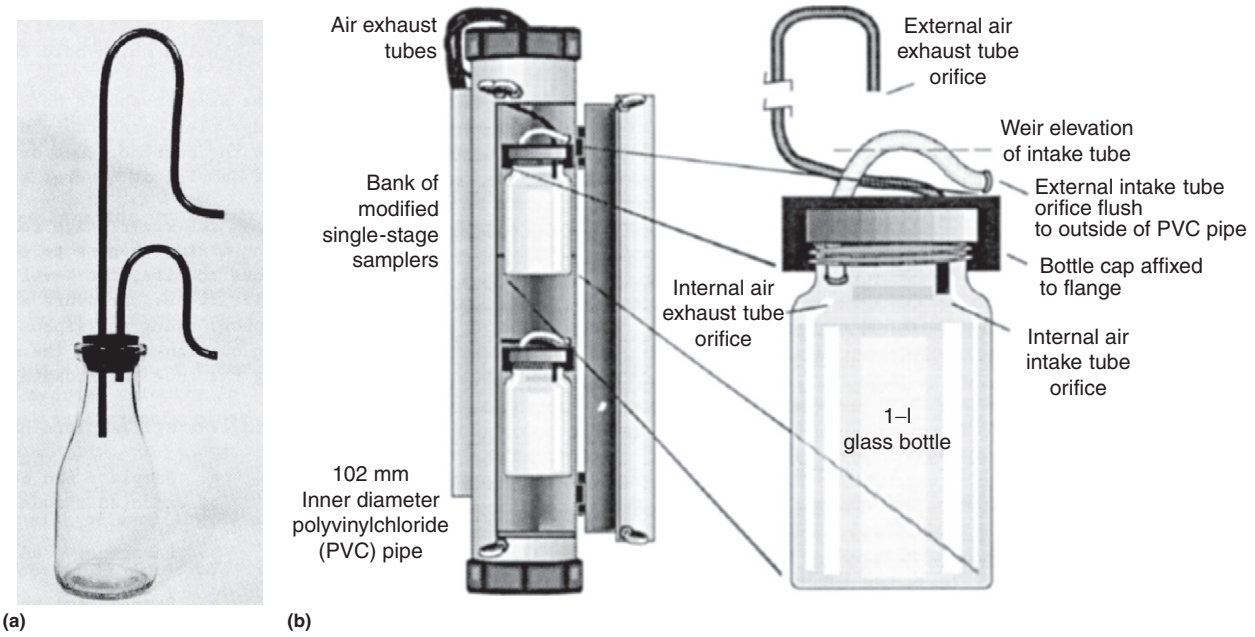

Figure 8 (a) US U-59D single-stage suspended sediment sampler and (b) Modified single-stage sampler. Reproduced from Gray, J. R. and Fisk, G. G. (1992). *Monitoring radionuclide and suspendedsediment transport in the little Colorado river basin, Arizona and New Mexico, USA*. IAHS Publication No. 210, pp. 505–516. Wallingford, OX: IAHS Press, Institute of Hydrology.

7. The device is not adapted to sampling on falling stages or on secondary rises.
8. No specific sampler design is best for all stream conditions.
9. The time and stage at which a sample was taken is often unknown.
10. At high velocities, flow can circulate into the intake nozzle and out the air exhaust. This can result in an increase in the SSC of coarse material in the sample by at least an order of magnitude.

Gray and Fisk (1992) developed a modified single-stage sampler that provides a measure of protection against vandalism and flood damage while minimizing the potential for water circulation (**Figure 8(b)**). Various single-stage samplers are arranged vertically inside a protective polyvinyl chloride (PVC) pipe capped at both ends. Screw cap 0.9 l bottles are used to provide a larger sample volume and a more positive seal. External air exhaust orifices extend through the top cap to the highest elevation feasible for the site, reducing the potential for its inundation. External intake orifices are set flush with the exterior PVC pipe so that debris cannot snag on them. A hinged lockable door provides access to the 0.9-l sample bottles.

The investigator using single-stage samplers may find protective measures necessary to avoid blockage of intakes or air exhausts due to nesting insects. In freezing temperatures, precautions against sample container breakage due to expansion of a freezing sample are advised. The percent sand-size material should be analyzed for all samples collected by single-stage samplers. This analysis will help identify instances of bias in SSCs resulting from sample recirculation.

1.10.2.2.5 Sediment subsampling equipment

Samples of water–sediment mixtures are sometimes subsampled or split into multiple aliquots to make possible different analytical determinations on the subsamples. The validity of data obtained from subsamples depends on the comparability of to the SSC of the original sample. Subsamples tend to have larger constituent variances than the original and also may be biased. Subsampling should be avoided unless it is necessary to achieve the ends of the sampling program.

Before 1976, USGS guidelines on manual sample splitting required compositing the water sample into a large, clean jug or bottle, shaking it for uniform mixing and then withdrawing the required number of samples (U.S. Geological Survey, 1976). In 1976, the 14-l Scienceware® Churn Sample Splitter (churn splitter) (**Figure 9(a)**) was introduced to facilitate the withdrawal of a representative subsample of a water–sediment mixture (Capel and Larsen 1996; Lane et al. 2003). A fluoropolymer version of the churn splitter for trace element subsampling is also available (Federal Interagency Sedimentation Project, 2012). The cone splitter (**Figures 9(b)** and **(c)**), a device developed to split water samples for suspended sediment and other water quality constituents into approximately 10 equal and representative aliquots, was introduced for widescale use in 1980 (Capel and Nacionales, 1995; Capel and Larsen, 1996).

Based on test results on the sediment-splitting efficiency of the churn and cone splitters (U.S. Geological Survey, 1997), the USGS has approved the use of the churn splitter for providing subsampling when the original sample's SSC is less than 1000 mg l^{-1} at mean particle sizes less than 0.25 mm. The cone splitter is approved for providing subsamples at SSCs up to 10 000 mg l^{-1} at mean particle sizes less than 0.25 mm. The

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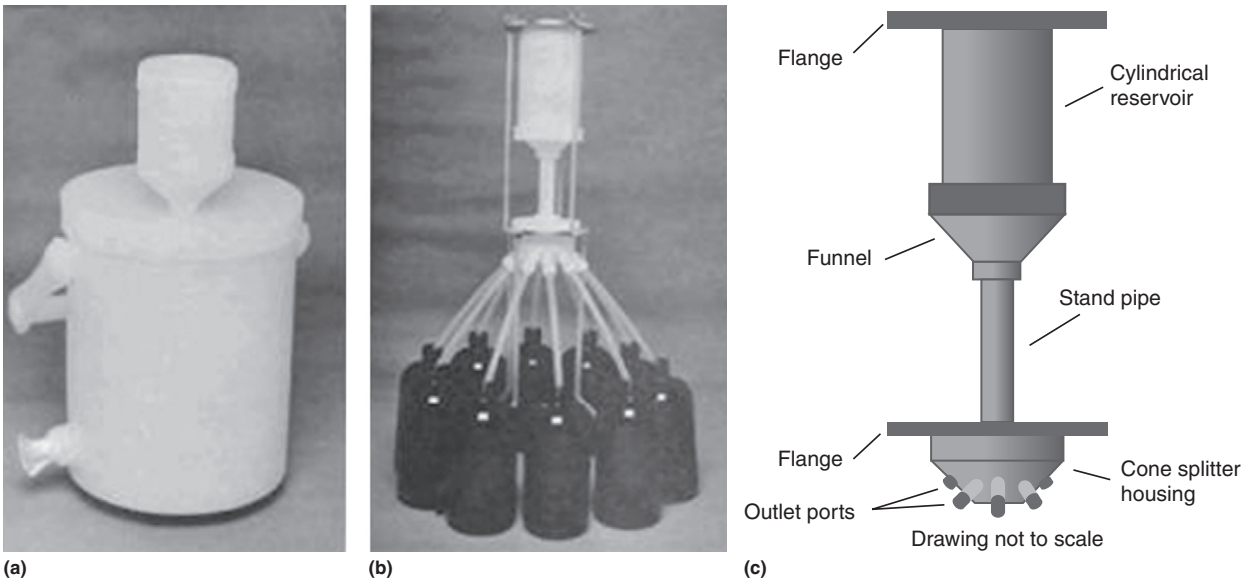

Figure 9 The14-I churn splitter (a), and the cone splitter ((b) and (c)). Permission to reproduce the photograph of the Scienceware® Churn Sample Splitter is by courtesy of Bel-Art Products (2012). Churn sample splitter. Available at http://www.belart.com/shop/advanced_search_result.phpkeywords=churn + splitter&x=6&y=3 (accessed on 18 July 2012) and the photograph and diagram of the cone splitter is reproduced by courtesy of Geotech Environmental Equipment, Inc. (2012). Dekaport sample splitter. Available at http://www.geotechenv.com/pdf/ground_water_sampling_equipment/dekaport_sample_splitter.pdf (accessed on 18 July 2012).

test data suggest that the cone splitter's acceptable SSC range exceeds 10 000 mg l^{-1} and may be as large as 100 000 mg l^{-1}.

1.10.3 Surrogate Suspended Sediment Measuring Techniques

The scope of this section includes an introduction to advances in suspended sediment surrogate technologies, calibration issues, data acceptance criteria, and descriptions of four surrogate technologies that are being or may be used in large-scale operational monitoring programs. Descriptions of the theory, applications, some advantages, limitations, and costs of each surrogate technology are presented and compared. This is followed by an evaluation of the efficacy of each technology for riverine suspended sediment transport monitoring.

All of the surrogate methods described herein must be calibrated using representative physical samples to obtain mass SSC and in some cases PSD, with the possible exception of the manually deployed version of the described laser technology. The reader is thus encouraged to become familiar with the information under Section 1.10.2. Those interested in surrogate technologies for measuring bedload may opt to access Gray et al. (2010) and (or) Gray and Gartner (2010a); and for bed material and other surrogate technologies, Gray (2005).

The prospect of continuous and quantifiably accurate monitoring of riverine suspended sediment transport is a revolutionary concept when considered from an operational perspective. The benefits of such applied capability could be enormous, providing for safer, more frequent and consistent, arguably more accurate, and ultimately less expensive fluvial sediment data collection for use in managing the world's sedimentary and related resources.

1.10.3.1 Overview of Selected Suspended Sediment Surrogate Measurement Techniques, Metrics, and Requirements

Advances in suspended sediment surrogate techniques for transport monitoring programs in rivers show varying degrees of promise toward supplementing and (or) supplanting traditional data collection methods based on routine collection of physical samples and subsequent laboratory analyses. Research-based and commercially available technologies operating on turbidity (transmissometry and nephelometry)-, laser-, and digital optics; pressure-difference; and acoustic principles have been or remain the foci of field or laboratory tests by the USGS and other organizations. Advantages and limitations associated with each suspended sediment-surrogate technology should be factored into monitoring program network design to select the most appropriate technology. General considerations should include deployment site physical, flow, sedimentological characteristics, and monitoring objectives. Examples of specific factors that can limit or enhance the efficacy of a surrogate technology include cost (purchase, installation, operation, and data analysis), reliability, robustness, accuracy, measurement volume, susceptibility to biological fouling, volumetric versus mass-SSC determinations, and suitability to the range of in-stream mass SSCs and PSDs.

Selected sediment-surrogate technologies have been shown to provide the types, quality, and density of fluvial sediment

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data needed to improve suspended sediment discharge computations in research settings and in limited operational deployments. Potentially useful instruments and methods for inferring the physical characteristics of fluvial sediments (Wren et al., 2000; Gartner et al., 2003; Bogen et al., 2003; Gray et al., 2003; Gray, 2003b; Gray and Glysson, 2004; Gray, 2005; Topping et al., 2007; Gray and Gartner, 2009, 2010a, 2010b, 2010c; Gray et al., 2010) are being developed and tested worldwide. For example, through the informal USGS Sediment Monitoring Instrument and Analysis Research Program (Gray, 2003a, 2003b; Gray and Simões, 2008), the USGS and collaborators in other government agencies, academia, and the private sector are testing several instruments for measuring SSCs and, in some cases, PSDs. To make the transition from research to operational monitoring applications, these new technologies must be rigorously tested with respect to accuracy, robustness, and reliability in different physiographic and (or) laboratory settings as appropriate, and their performances must be compared to data obtained by the aforementioned traditional methods and to available quality control data. In most cases, performance comparisons should include concurrent collection of data by traditional and new techniques for a sufficient period – probably years – and in a variety of river types and flow conditions to optimize calibration and identify potential bias between the old and new technologies.

Calibrations must cover the range of SSC and PSD observed in the system and, once established, must be verified periodically to test for temporal changes. Also, the *in situ* technologies presented herein measure a fixed point in a stream and require periodic site-specific calibrations to infer the sedimentary characteristics representative of the entire channel cross section or reach segment. This requirement is anticipated to be substantial for new river-monitoring applications but may diminish as calibration data accumulate.

None of the technologies represents a panacea for sediment monitoring in all rivers under all flow and sediment-transport conditions. However, with careful matching of surrogate monitoring technologies to selected river reaches and objectives, it is becoming possible to remotely, continuously, and accurately monitor SSCs and suspended sediment discharges (and in some cases, PSDs) in a variety of river types, flow conditions, and sedimentological regimes. In some cases, the computed SSC values and perhaps other data types may be qualified with estimates of uncertainty (U.S. Geological Survey, 2005).

1.10.3.1.1 Calibration of suspended-surrogate metrics to representative SSC

All of the surrogate methods described use metrics that must be calibrated using physical samples representative of the cross section to obtain mass SSC or PSD. The reliability and efficacy of data produced by a sediment-surrogate technology are predicated on the adequacy of its calibrations. Three general types of calibrations may be used, depending on the metric of interest. These are calibration of:

1. the surrogate instrument metric to some standard such as blank water, a turbidity standard, or a single- or double-blind standard reference sediment sample (U.S. Geological Survey, 1998b);
2. the surrogate metric to representative physical environmental samples of SSC and/or PSD; and
3. the monitored volume to cross-section average volume.

Calibration of the surrogate instrument metric to a standard or blank water provides a test for instrument drift, fouling, or malfunction and typically follows manufacturer recommendations. Calibration to measured SSC and/or PSD is a primary analytical component of using any surrogate parameter and requires concurrent physical samples and surrogate measurements over the range of sediment conditions for the period of monitoring. The calibration will typically use statistical methods and inclusive of model uncertainty, which should be carefully documented. The surrogate measurements may be calibrated to representative physical samples taken from the stream cross section or may be calibrated to samples collected at the point or within the volume being measured by the surrogate. In the latter case, the point-estimated SSC must be calibrated to the cross-sectionally averaged SSC.

Calibration of surrogate metrics to PSDs can be more difficult than to SSCs because the analytical results of PSD analyses are somewhat dependent on the methods used to measure and analyze the PSD and on handling of water samples between the stream and location of analysis. Gravimetric PSDs determined by sieving and/or settling velocity methods would not be expected to be the same as volumetric PSD obtained by laser diffraction methods. PSD determined by multifrequency acoustics methods will depend on the frequencies used in the analysis. Furthermore, *in situ* PSD would not be expected to be the same as laboratory PSD where samples are affected by handling and potential disaggregation of flocs due to sonic or chemical dispersant. Nonetheless, for data continuity in sediment studies, the results need to be quantitatively comparable. Preliminary results from recent studies indicate that PSD can be quantified or qualified using surrogate technologies, although the results may require important metadata on assumptions and limitations.

1.10.3.1.2 Acceptance criteria for SSC and PSD data produced by suspended sediment-surrogate technologies

Validation of a suspended sediment-surrogate technology requires evaluation criteria and a well-conceived and well-administered testing program (Gray et al., 2002; Gray and Glysson, 2005; Gray et al., 2010). Following are some qualitative criteria for selecting and deploying a surrogate technology.

- Capital and operating costs should be affordable with respect to the objectives of the monitoring program in which the surrogate instrument is deployed.
- The technology should be able to measure SSCs, and, if sought, PSDs, throughout the range of interest (but not necessarily throughout the entire potential environmental range).
- The equipment should be robust and reliable, that is, prone to neither failure nor signal drift.
- The method should be sufficiently simple to deploy and operate by a field technician with a reasonable amount of appropriate training.

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- The derived data should be relatively simple and straightforward, or rendered so with advanced computational tools, to use in subsequent computations and (or) accompanied by standard analytical procedures as computational routines for processing the data.

Quantitative criteria for acceptable accuracies of the derived data are difficult to develop for all potential applications, in part, because of substantial differences in river sedimentary and flow regimes. For example, accuracy criteria for rivers transporting mostly silt and clay can and should be set more stringently (intolerant of larger-magnitude uncertainties) than those for rivers that transport comparatively large fractions of sand. However, there is a clear need for consistency in SSC criteria on the part of instrument developers, marketers, and users.

To this end, quantitative acceptance criteria developed for PSD and SSC data produced by a laser diffraction instrument (Gray et al., 2002) have been generalized for evaluating data from other suspended sediment surrogate instruments. At least 90% of PSD values between 0.004 and 0.5 mm median diameter are required to be $\pm 25\%$ of true median diameters. Absent a more rigorous evaluation, this criterion has been applied to all particle sizes in suspension (Gray et al., 2010).

SSC acceptance criteria range from $\pm 50\%$ uncertainty at lowest SSCs to $\pm 15\%$ uncertainty for SSCs exceeding 1000 mg l^{-1}. The criteria presented in **Table 3** are adapted from Gray et al. (2002, 2008), and Gray et al. (2010).

These criteria pertain solely to the performance of a surrogate technology within its physical realm of measurement. Routine calibrations to correlate instrument signals to mean cross-sectional SSC values are required for all of the *in situ* instruments presented herein.

1.10.3.2 Technological advances in suspended sediment-surrogate monitoring

The following sections in this sub-chapter describe theoretical principles (Gray and Gartner, 2004, 2010b), capital costs, examples selected field applications, and advantages and limitations of four suspended sediment-surrogate technologies that cover a range of transport conditions that are being used or considered promising by the USGS. Capital cost information provided herein is in 2012 US dollars relative to the approximate purchase price of an *in situ* turbidimeter with sonde (sensor), wiper, and controller, totaling approximately $5500 US in 2012.

Table 3 Acceptance criteria for suspended sediment concentration (SSC) data. The data are considered acceptable when they meet these criteria 95% of the time with any deviant values randomly distributed over the range in SSCs

SSC		*Acceptable uncertainty*
Minimum, mg l^{-1}	*Maximum, mg l^{-1}*	*Percent, ±*
0	<10	50
10	<100	50–25 computed linearly
100	<1000	25–15 computed linearly
1000	–	15

1.10.3.2.1 Turbidity

1.10.3.2.1.1 Background and theory

Turbidity is an expression of the optical properties of a sample that causes light rays to be scattered and absorbed rather than transmitted in straight lines through the sample (Ziegler, 2003; Anderson, 2005). Turbidity was the most common surrogate used for determining water clarity and computing SSCs in US rivers in 2003 (Pruitt, 2003) and remained so in 2012.

A number of commercially available optical instruments operate on one of two physical principles: transmissometry and nephelometry. Transmissometers employ a light source beamed directly at a light detector. The instrument measures the fraction of visible light from a collimated light source (typically at approximately 660 nm) that reaches the detector. The fraction of light reaching the detector is converted to a beam attenuation coefficient, which is related to SSC.

Nephelometry is the measurement of light scattering usually with a light detector at 90° from the incident light (adapted from U.S. Environmental Protection Agency, 1999) in visible or infrared (IR) spectra. Most laboratory turbidimeters measure 90° scattering. According to D&A Instrument Company (1991), optical backscatterance (OBS) instruments collectively are a type of nephelometer designed to measure backscattered (140°–165°) IR in a small (concentration-dependent) volume on the order of a few cubic centimeters. Transmittance and scatterance are functions of the number, size, color, index of refraction, and shape of suspended particles (Conner and De Visser, 1992; Sutherland et al., 2000).

Figure 10 shows examples of five types of nephelometry sensors.

A wide variety of turbidimeters are available, most of which operate on the nephelometric principle. For example, Landers (2003) described bench tests as part of a workshop at which variances in measurements from nine different types of turbidimeters using blind reference samples were evaluated. One instrument that was first described in the early 1980s (Downing et al., 1981; Downing, 1983) and is now widely used for *in situ* applications is the OBS-3 (originally manufactured by the D&A Instrument Company, now by Campbell Scientific, Inc.).

Turbidity instruments lack moving parts (unless outfitted with optical wipers) can be deployed *in situ* and provide rapid sampling capability. Site-specific empirical calibrations are required to convert measurements to reliable cross-sectional SSC estimates. The technology is relatively mature, and has been shown to provide reliable data at a number of USGS streamgages (Uhrich, 2002; Schoellhamer and Wright, 2003; Melis et al., 2003; Uhrich and Bragg, 2003; Wright and Schoellhamer, 2005; Rasmussen et al., 2005; 2009; Schoellhamer et al., 2007; Buchanan and Morgan, 2011) and other sites (Pratt and Parchure, 2003; Lewis, 2002). As noted previously, the cost of an *in situ* turbidimeter with sonde (sensor), wiper, and controller in 2012 is approximately $5500. The purchase price of an OBS without a wiper but with cable is about equal to the fully equipped *in situ* nephelometric turbidimeter cost.

Maximum SSC limits for these instruments depend in part on PSDs. The OBS has a generally linear response at SSC less than approximately 2000 mg l^{-1} for clay and silt and

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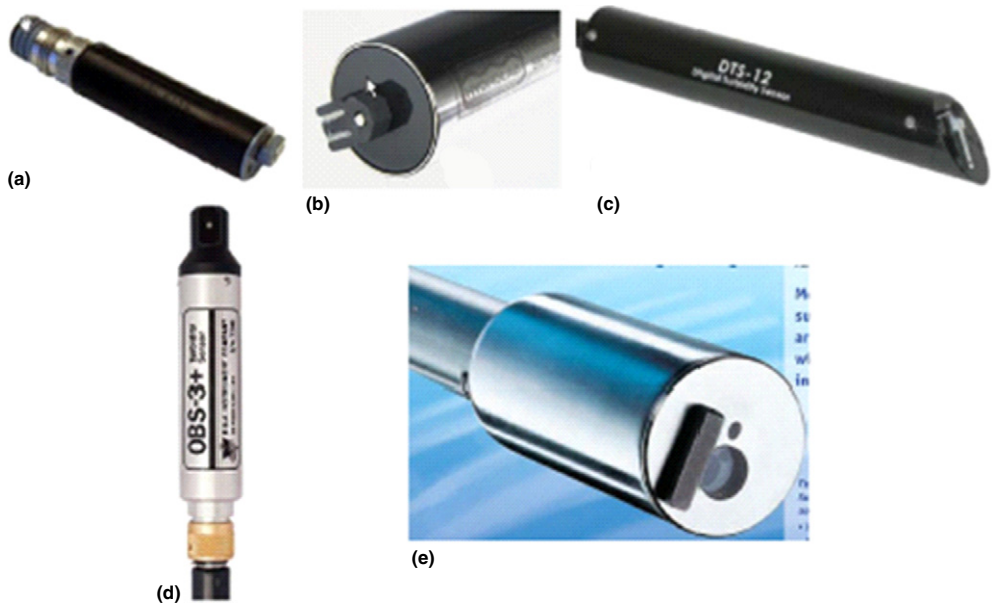

Figure 10 Photographs showing nephelometry sensors: (a) YSI model 6136, (b) Hydrolab turbidity sensor with wiper, (c) Forrest Technology Systems model DTS-12, (d) D&A Instrument Company model OBS 3+, and (e) Hach OptiQuant with wiper.

10 000 mg l^{-1} for sand (Ludwig and Hanes, 1990), although Kineke and Sternberg (1992) described the capability to measure SSC up to approximately 320 000 mg l^{-1} (in the nonlinear region of the OBS response curve). The specification sheet for the OBS-5+ manufactured by Campbell Scientific (2008) lists an applicable range of up to approximately 500 000 mg l^{-1} (specific gravity 1.3). The upper SSC limit for transmissometers depends on optical path length but may be as low as approximately 50 000 mgl^{-1} (D&A Instrument Company, 1991). Thus, transmissometers are more sensitive at low SSC, whereas optical backscatter sensors have superior linearity in turbid water (Downing, 1996). In general, the wider a turbidimeter's turbidity-measurement range, the less precise the within range derived turbidity data and vice versa.

Biological fouling of sensor optical windows can be problematic, particularly in warmer, nutrient-rich waters. Biological fouling results in a tendency for the output to shift from the calibration curve to spuriously larger values over timescales of days or more, particularly in warmer, microbiologically active waters. Commercially available mechanical wiper systems available with some sensors may alleviate this problem.

Because of the relation between OBS signal response and PSD, OBS (like all single-frequency optical instruments) is best suited for application at sites with relatively stable PSDs. For a given mass SSC, OBS response increases with decreasing particle size (Conner and De Visser, 1992; Downing, 1996; Sutherland et al., 2000). OBS signal response is minimally affected by changes in PSD in the range of 200–400 μm and greatly affected by changes when particles are smaller than approximately 44 μm (Conner and De Visser, 1992). Conner and De Visser (1992) caution against using OBS in environments where changes in PSDs occur and particle sizes are less than 100 μm. Additionally, the OBS signal can vary as a function of particle color. Sutherland et al. (2000) found a strong correlation between observed and predicted OBS measurements of varying SSC and ratios of black and white suspended sediment. They found the smallest OBS signal-gain response for black sediment and the largest for white sediment, with responses from other colors falling between. They suggest that the level of blackness of particles acts to absorb the near-IR signal of the OBS, thus modifying its output. Hence, caution should be exercised in deployments under varying particle-size and particle-color conditions, unless the instrument is recalibrated for ambient conditions.

1.10.3.2.1.2 Example field evaluation

Continuous turbidity measurements have been shown to provide reliable continuous SSC values with a quantifiable uncertainty at the USGS streamgage on the Kansas river at DeSoto, KS, USA, since the 1990s. Simple linear regression analysis explained in Christensen et al. (2000) was used to develop a site-specific univariate model using turbidity to compute SSC (**Figure 11**). The model explains approximately 93% of the variance in SSC. Continuous suspended sediment discharge values computed from the model and subdaily time series water discharge data are available online (U.S. Geological Survey, 2005). The advantages of regression-based estimates using continuous turbidity measurements over discrete sample collection are that regardless of flow conditions, SSC and sediment-discharge values are obtained essentially continuously at the interval in which water discharges are recorded.

Some researchers are using turbidity in conjunction with other variables to compute time series of SSC. Jastram et al. (2009) had monitored turbidity at a USGS streamgage on the James river at Cartersville, VA, USA, since 2003. **Figure 12** shows a time series of computed SSC, sampled SSC, and streamflow data for this station from 22 October 2006 to 30 April 2007. The continuous SSC data were computed by using

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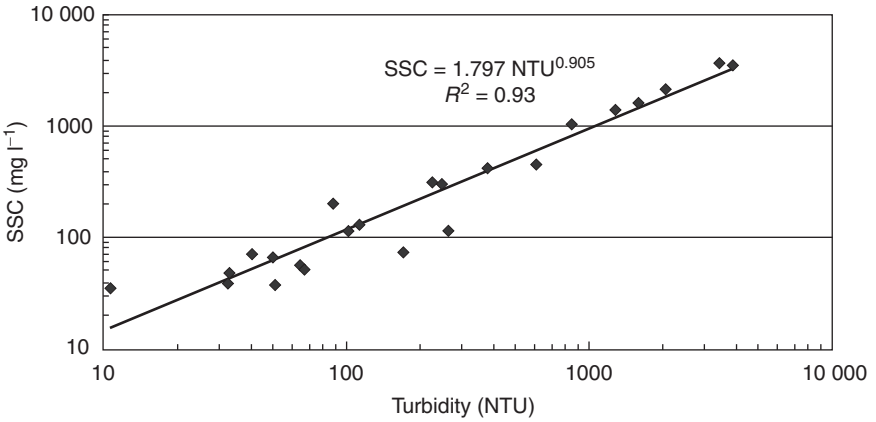

Figure 11 Linear regression comparing field turbidity in nephelometric turbidity units and instantaneous SSCs in milligrams per liter for the Kansas river at DeSoto, KS, USA, 1999 through 2002. Reproduced from Gray, J. R., Gooding, D. J., Mellis, T. S., Topping, D. J. and Rasmussen, P. P. (2003). U.S. Geological Survey suspended-sediment surrogate research, Part II: Optic technologies. In: Jane W. and Judy P. (eds.) *Proceedings of the Virginia Water Research Symposium 2003, Water Resource Management for the Commonwealth*. Virginia Polytechnic Institute and State University, Blacksburg, 8–10 October, pp. 58–64. Available at http://vwrrc.vt.edu/pdfs/proceedings/2003WaterResearchSymposium_proceedings.pdf (accessed on 13 June 2013).

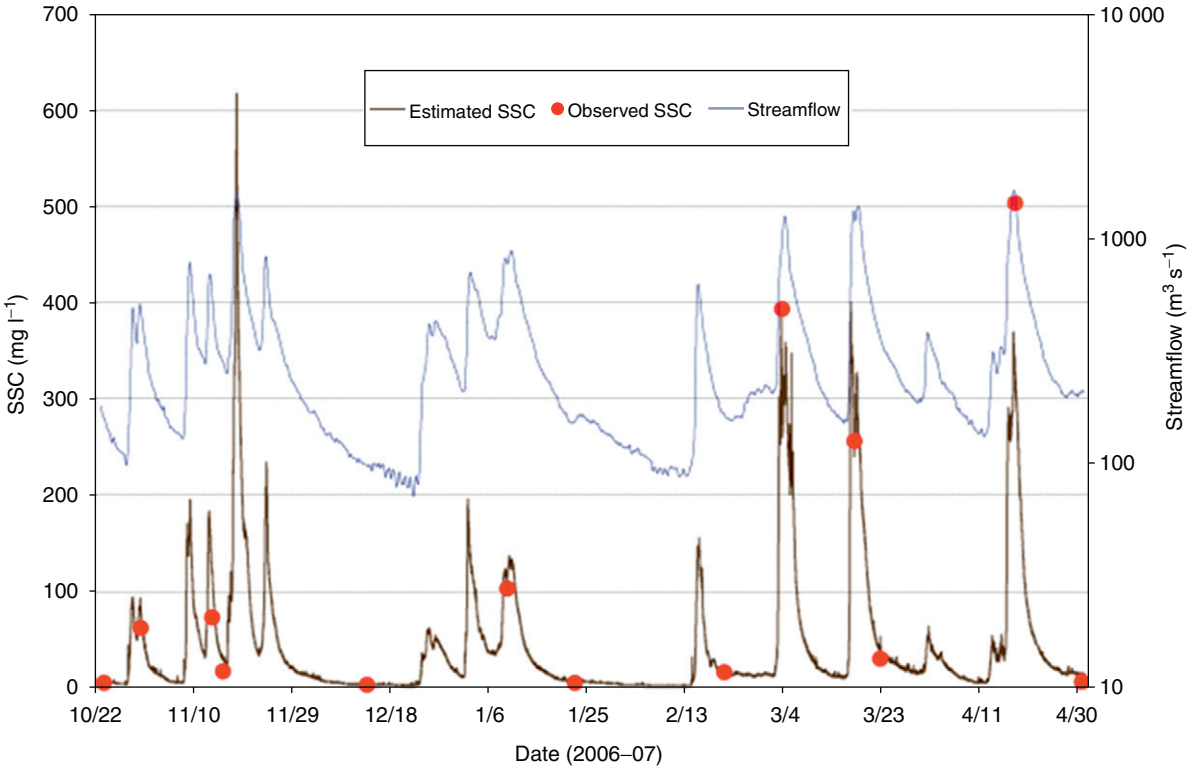

Figure 12 Time series plot of continuous SSCs (computed by multiple linear regression from square root-transformed time series of turbidity, streamflow, and water temperature data), sampled SSCs in milligrams per liter, and streamflow in cubic meters per second for the James river at Cartersville, VA, USA, 22 October 2006–30 April 2007. Reproduced from Jastram, J. D., Moyer, D. L. and Hyer, K. E. (2009). A comparison of streamflow-based and turbidity-based estimates of suspended sediment concentrations in three Chesapeake bay tributaries. *U.S. Geological Survey Scientific Investigations Report 2009-5165*. Available at http://pubs.usgs.gov/sir/2009/5165/ (accessed on 14 June 2012).

a multiple regression technique from square root-transformed time series data describing turbidity, streamflow, and water temperature. The model explains approximately 97% of the variance in SSC.

Schoellhamer et al. (2007) described a multistation, multiyear field investigation to continuously monitor SSC in California's San Francisco Bay and Delta system that began in 1991. As of 2010, the program consisted of 13 monitoring

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stations (with turbidity sensors at multiple depths) at which a cumulative 280 years of sensor data have been collected. Turbidity sensors are calibrated with water samples collected by a Van Dorn sampler after sensor cleaning at each site. As an example of data quality, results from the 2008 water year (1 October 2007–30 September 2008) from 9 records at 5 stations in San Francisco bay had an average of approximately 82% data considered acceptable (after deletion of records compromised by biological fouling and other factors) (Buchanan and Morgan, 2011). Improved self-cleaning sensors have increased the fraction of acceptable data from approximately 50% in the 1990s. Calibration curves indicated generally good correlations between SSC samples and turbidity readings. Before October 1997, calibrations were performed using ordinary least-squares regressions; starting with water year 1998, a robust, nonparametric, repeated median method was used (see Buchanan and Morgan, 2011, for a description of the method). San Francisco bay sensors are calibrated to point measurements and Delta sensors are calibrated to discharge-weighted, cross-sectionally averaged SSC values. Suspended sediment discharge is determined by multiplying the discharge-weighted, cross-sectionally averaged SSC by water discharge, accounting for tide-driven bidirectional flow (Wright and Schoellhamer, 2005).

1.10.3.2.1.3 Advantages and limitations of turbidity

Advantages:

- As the most ubiquitous of the field-deployed surrogate technologies, results from a large number of field settings are available for evaluation.
- The technology is relatively mature and reliable.
- Calibration techniques are documented and largely straightforward.
- At a cost for a fully equipped turbidimeter of approximately $5000, this is one of the more affordable sediment-surrogate technologies.

Limitations:

- The at-a-point turbidity time series data may not be representative of the sedimentary conditions in the river cross section.
- Saturation of the turbidimeter signal can occur resulting in erroneous (constant) values for all SSC values that exceed a maximum value.
- Biological fouling or damage to optical windows may require frequent site visits to service the instrument.
- Instrument response to grain size, composition, color, shape, and coating can be variable and, hence, can reduce the accuracy of derived SSC values without additional calibration.
- A lack of consistency in measurement characteristics among commercially available instruments impinges on the comparability of turbidity measurements made with different types of instruments.

1.10.3.2.2 Laser diffraction

1.10.3.2.2.1 Background and theory

Laser diffraction instruments exploit the principles of small-angle forward scattering to infer volumetric PSDs. At small forward scattering angles, laser diffraction by spherical particles is essentially identical to diffraction by an aperture of equal size (Agrawal and Pottsmith, 1994). Thus, this method of determining PSDs (and, by inference, volumetric SSC values) is mostly insensitive to changes in particle color or composition, although departure from sphericity produces a bias in the computed PSD compared to that for sieving. For example, Agrawal et al. (2008) had shown that natural particles measured by laser diffraction are inferred to be approximately 20–40% larger than sieved spheres of known sizes. They reported a new method that permits computation of PSDs of equivalent sieved sizes.

At present, an *in situ* version of this type of instrument is commercially available from only one manufacturer (Sequoia Scientific, Inc., 2012). First used in the early 1990s (Agrawal and Pottsmith, 1994), the present version of a laser diffraction instrument that can be deployed unattended to provide a time series of PSD and volume SSC values is the laser *in situ* scattering and transmissometry (LISST)-100X, shown in **Figure 13(a)** (Sequoia Scientific, Inc., 2012). LISST instruments use a 32-ring detector to sense light scattered by particles illuminated by a laser beam into small forward angles. These data are inverted to determine PSDs in 32-size classes between 1.25–250 and 2.5–500 μm (limits that are not fundamental and which may be expanded in the future). The standard sample path of this device is a cylindrical volume with a diameter of approximately 6 mm and a length of 50 mm (essentially a point measurement). An isokinetic, cable-suspended, streamlined version of the LISST-100X, the

(a) (b)

Figure 13 LISST: (a) an LISST-100X *in situ* instrument and (b) an LISST-SL (streamlined) manually deployable instrument. Photographs courtesy of Sequoia Scientific, Inc.

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LISST-SL shown in Figure 13(b), features the capability of real-time velocity measurement. This measurement is, in turn, used to control a pump to withdraw a filament of water and route it through the laser beam at the ambient current velocity (Gray et al., 2002; Gray and Gartner, 2004; Gray et al., 2004; Agrawal and Pottsmith, 2006; Gray and Gartner, 2009; Gray et al., 2010). The performance of the LISST-SL has been evaluated by the Federal Interagency Sedimentation Project (2012) in a laboratory, a flume, and by USGS researchers in rivers in Washington and Illinois, USA. The purchase price of one of the LISST instruments (*in situ* or manually deployed) described in this section ranges from approximately 2–6 times that for a fully equipped turbidimeter, depending on the instrument of interest.

Because an LISST determines PSD for all measurements, it is not subject to potential inaccuracies in the calculation of SSC associated with single frequency (optical and acoustic) instruments that occur due to changes in PSDs as long as particle sizes fall within the instrument measurement range (Agrawal and Pottsmith, 2000).

Field and laboratory tests have shown the LISST-100X to be capable of determining PSDs of natural materials and the size of monosized particle suspensions with an accuracy of approximately 10% (Traykovski et al., 1999; Gartner et al., 2001). The LISST-100X can also be used to determine mass SSC from volume SSC if mean particle density is known from field calibrations or some other means (Gartner et al., 2001). Size-dependent mass density (as can happen due to flocculation) can be used to convert volume to mass SSC.

As is the case with all types of *in situ* optical instruments, biological fouling can degrade measurements. Antifouling shutters for some LISST instruments are available from the manufacturer. In addition, the technology has an SSC range limitation associated with multiple scattering in the presence of high SSCs. The LISST-100X requires approximately 30% or more laser optical transmission. The range limitation is a function of the laser path length, PSDs, and SSCs. For SSC, the usable limits range from tenths of a $g\,l^{-1}$ for small particle sizes to several thousand $mg\,l^{-1}$ for larger particle sizes. Optical blocks that reduce the path length of LISST-100X by 50%, 80%, or 90% are available, reducing the optical path from the standard 5 cm to 5 mm can extend measurement limits approximately from 500 to 5000 $mg\,l^{-1}$ for 25 μm particles (Yogesh Agrawal, Sequoia Scientific, Inc., written communication, 2008; Agrawal et al., 2008). A prototype LISST-Infinite has been tested by the USGS (Konrad et al., 2006) for application in very high SSCs. The system pumps a water–sediment mixture sample to the instrument and then uses automated multistage dilution (if necessary) before measuring PSDs and SSCs with built-in LISST-100X optics. However, as is the case with any nonisokinetic point sampler, pumping a water sample from a fixed point in the channel may result in a PSD and an SSC that is nonrepresentative of that in the cross section. The same is true for the LISST-Streamside, which was developed specifically for monitoring applications such as for real-time continuous sediment monitoring in shallow streams and rivers, including periods of storm runoff.

A somewhat simpler and less expensive version of the LISST-100X instrument – the LISST-25X – measures mean SSC and a mean particle size (Sauter mean size) in two size classes (0.0025–0.062 and 0.062–0.5 mm) (Sequoia Scientific, Inc., 2012). This device is also based on the same small-angle scattering principles as the LISST-100X, but it obtains the SSC through a weighted summation of the output of ring detectors, bypassing the inversion step from rings output to PSD. The cost of the LISST-25X is about double that of a fully equipped *in situ* turbidimeter.

1.10.3.2.2.2 Example field evaluation

Laser sensors are being investigated as an alternative monitoring protocol for tracking reach scale suspended sediment supply at a USGS streamgage on the Colorado river near Grand Canyon, AZ, USA, located 164 km downstream from Glen Canyon dam (Topping et al., 2004). A canyon wall-mounted LISST-100B provides continuous suspended sediment transport data (SSCs and PSDs in the range of 0.0012–0.25 mm) that may reduce uncertainty in estimates of the transport of sand and finer material.

An example of data collected by a LISST-100B at a fixed-depth, canyon wall mounted installation on the Colorado river is shown in Figure 14. Data were obtained averaging 16 measurements at 2-min intervals during a 24-h deployment in July 2001. The time series of 720 LISST at-a-point measurements are compared with cross-sectional data obtained by US D-77 isokinetic bag sampler (the US D-77 bag sampler has been phased out of use by the U.S. Geological Survey (2002)) concurrent with some of the LISST measurements using techniques described by Edwards and Glysson (1999) and Nolan et al. (2005) (more recent calibrations are performed using the US D-96 bag sampler). In addition to accurately tracking sand-size SSCs, the LISST-100B also recorded the increase of variance in the SSCs of sand-size particles expected with increasing flows; peak sand-size SSC values ranged up to 150 $mg\,l^{-1}$ (Figure 14).

The FISP has performed laboratory bench tests of the sedimentological characteristics of a LISST-SL. The range in SSC used in tests was 10–3000 $mg\,l^{-1}$. Material used for testing was primarily less than 0.15 mm, although some tests included coarser material that was difficult to keep suspended in the test system. Sedimentological results from these LISST-SL tests fall within the acceptable uncertainty values for the corresponding SSC levels shown in Table 2 (Broderick Davis, FISP, written communication, 2008).

1.10.3.2.2.3 Advantages and limitations of laser-optic technology

Advantages:

- The instrument provides *in situ* or real-time PSD measurements in 32 size classes.
- Calculated volumetric SSC values are not affected by changes in PSD.
- A manually deployed isokinetic version of the LISST technology is available.

Limitations:

- *In situ* laser measurements may not be representative of sedimentary conditions in the river cross section.

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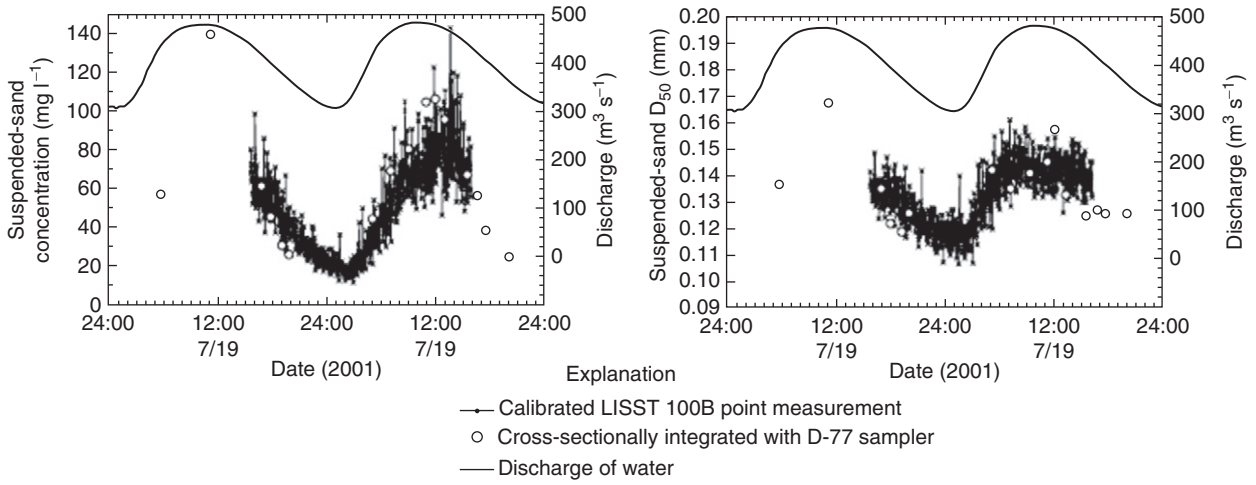

Figure 14 Comparison of sand concentrations in milligrams per liter and median grain sizes in millimeters measured at the USGS streamgage at the Colorado river near Grand Canyon, AZ, USA, using a LISST-100B and a US D-77 bag sampler. Reproduced from Melis, T. S., Topping, D. J. and Rubin, D. M. (2003). Testing laser-based sensors for continuous *in situ* monitoring of suspended sediment in the Colorado river, Arizona. In Bogen, J., Fergus, T. and Walling, D. E. (eds.) *Erosion and sediment transport measurement in rivers, technological and methodological advances*. International Association of Hydrological Sciences Publication 283, pp. 21–27.

- Saturation of the laser-optic signal can occur at a SSC level of about half of that at which a standard *in situ* turbidimeter saturates.
- As with turbidimeters, frequent field visits may be required to clean the optics if antifouling shutters are not used.
- The cost of a LISST instrument is 2–6 times that for a fully equipped *in situ* turbidimeter depending on the instrument of interest.

1.10.3.2.3 Pressure difference

1.10.3.2.3.1 Background and theory

The pressure-difference technique for monitoring SSC relies on simultaneous measurements from exceptionally sensitive pressure transducer sensors arrayed at different fixed depths in a water column. The difference in pressure readings is converted to a water density value from which SSC is inferred after correcting for water temperature (dissolved-solids concentrations in freshwater systems are rarely of consequence in the density computation).

The following equation describes this conversion for a 2-orifice instrument (refer to **Figure 15(d)**):

$$\gamma = (\rho_1 - \rho_2)/(z_1 - z_2) \qquad [5]$$

where γ is the specific weight of the fluid, which is an analog for SSC in many freshwater systems, ρ_1, ρ_2 the simultaneous pressure measurements at orifices 1 and 2, respectively, and z_1, z_2 the depths below water surface of orifices 1 and 2, respectively.

Implicit assumptions are that the same water surface location is measured by all sensors, and that the density of the water–sediment mixture above the lowest sensor is more or less constant at a given instant. The technology has both laboratory and field applications (Lewis and Rasmussen, 1999). One of the first uses of the pressure-difference technique was for monitoring the density of crude oil in pipes (William Fletcher, D&A Associates, oral communication, 1999).

The instrument produced by Design Analysis Associates (2012) and evaluated by the USGS in Puerto Rico and Arizona, USA – the Double Bubbler Differential Instrument (Double Bubbler) – was based on a dual sensor configuration (**Figure 15**). Although the Double Bubbler is no longer manufactured, an Accubar® Constant Flow Dual Orifice Bubble Gauge/Recorder produced by Sutron Corporation (2012) is available in two- and three-sensor configurations. The accuracy of the three-sensor version is advertised as thrice that of the dual sensor unit.

The technique has been applied in the laboratory with promising results of better than 3% accuracy (543 ± 14 mg l^{-1}) for determining mass concentrations of suspensions of glass microspheres (Lewis and Rasmussen, 1999). However, application of this technique in the field can be complicated by small signal-to-noise ratios associated with small SSCs, turbulence, substantially large dissolved solids concentrations, and (or) water temperature variations. Additionally, analyses may be complicated by density variations in the suspended material. These complications coupled with the sensitivity limitations of the pressure transducer sensors may render this technology unreliable at concentrations below 10 000–20 000 mg l^{-1}.

1.10.3.2.3.2 Example field evaluation

Information on the field performance of the pressure-difference technology is available from USGS streamgages on the lower Río Caguitas in Puerto Rico (Larsen et al., 2001; Gray and Gartner, 2010b) and the Paria river in AZ, USA (Gray and Gartner, 2010b). Continuous pressure-difference data were collected during October–December 1999 at the Río Caguitas streamgage using a Double Bubbler, composed of a digital recorder, bubbler system, and two precision pressure sensors with orifices anchored at fixed depths in a vertical (Design Analysis Associates, Inc., 2008) (**Figure 15**). Most of the annual suspended sediment discharge in the lower Rio Caguitas occurs as runoff from a few storms during which SSCs exceed

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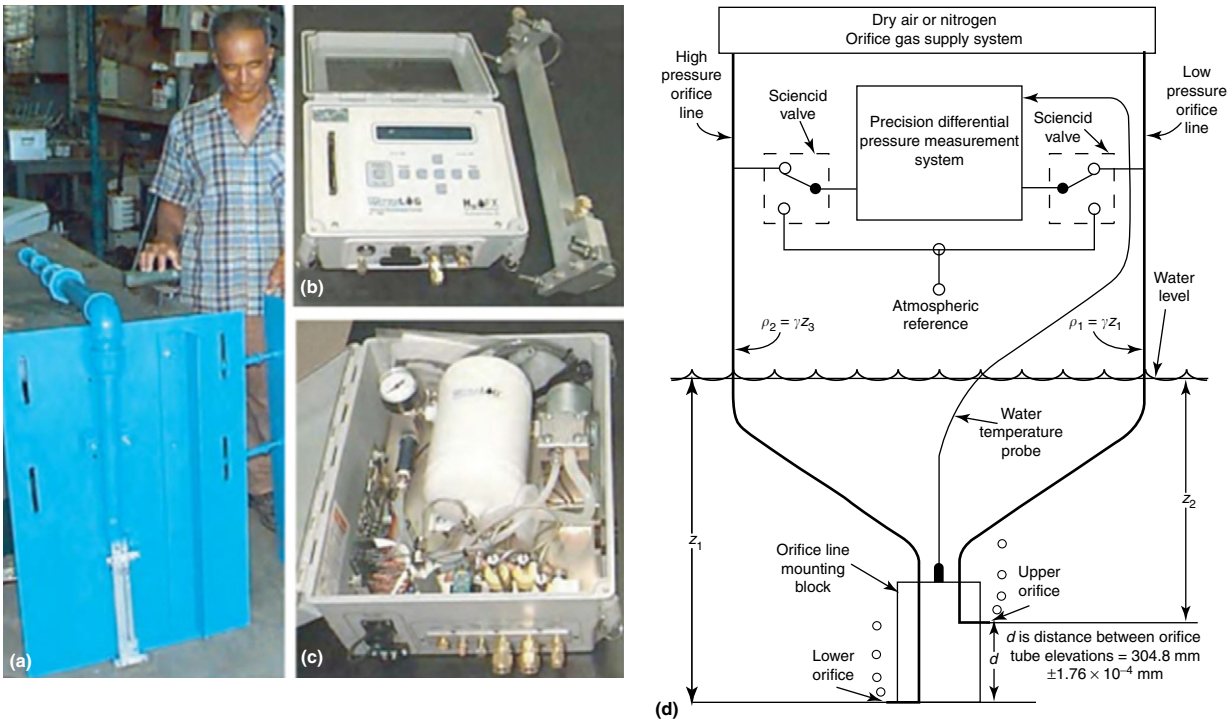

Figure 15 Double Bubbler pressure differential instrument (a) in-stream components before installation, (b) controller and orifice bar, (c) air compressor and tank assembly, and (d) schematic. Photographs (b) and (c) courtesy of Design Analysis Associates (2012). Home page. Available at http://www.waterlog.com/ (accessed on 14 June 2012).

approximately 500 mg l^{-1}. The maximum SSC measured at the streamgage during the Puerto Rico Double Bubbler tests based on water samples collected by an autosampler (Edwards and Glysson, 1999) was 17 700 mg l^{-1}.

Data analyses involved data smoothing and removal of outliers. To calculate the weight density of suspended sediment and dissolved solids, the weight density of pure water at 27 °C was subtracted from the smoothed data values. Even with these manipulations, the tests of the Double Bubbler instrument at the Puerto Rico site during October–December 1999 showed relatively poor agreement with water discharge, SSC, and water density (**Figure 16**). The Double Bubbler data contained a large amount of signal noise, making interpretation difficult. Lacking a thermistor for temperature compensation, 12 of 15 base-flow instrument measurements inferred negative SSC values (an impossibility) concurrent with in-stream measured SSC values of 10 000–100 000 mg l^{-1}. However, all but two of the samples collected during seven higher flow periods showed concomitant increases in inferred positive SSC values.

A complicating factor in the pressure-difference method is in-stream turbulence, which introduces noise about equal to the magnitude of the signal of interest, particularly during high flows that occur more or less concomitant with the largest SSCs. Additionally, diel and storm-related fluctuations in water temperatures resulted in a daily range as much as 10 °C. The high relative humidity characteristic of this humid tropical site may also complicate the use of the Double Bubbler because of the sensitivity of the narrow diameter bubbler gas lines to moisture, unless the gas lines are equipped with dryer tubes. This test of the Double Bubbler instrument showed the need for temperature compensation, and possibly the need to deploy the instrument at a site where the range in the density of the water–sediment mixture is substantially larger than the 1–1.02 range occurring in the Double Bubbler evaluation at the Río Caguitas streamgage.

In 2004, the Puerto Rico Double Bubbler system was relocated to the USGS streamgage on the Paria river at Lees Ferry, AZ, USA, where SSCs as high as 10^6 mg l^{-1} have been measured during storm runoff (Beverage and Culbertson, 1964). Deployment of the Double Bubbler in the Paria river was predicated on the hypothesis that Paria river SSCs, commonly exceeding peak measured Rio Caguitas SSCs by a factor of at least three and in some cases by 1–2 orders of magnitude, would subject the instrument to a substantially larger density range than that inferred for higher flows at the Rio Caguitas streamgage in Puerto Rico. However, even with the addition of a thermistor for monitoring water temperatures, results were inconclusive (Gray and Gartner, 2010b).

Double Bubbler data were collected, at 5-min intervals, during periods of elevated flow at the Paria river streamgage from July 2004 through September 2006. Data collected from more than 14 storm-runoff hydrographs were examined and compared to SSCs from samples collected during storm runoff. The elevated flows had peaks ranging from approximately 7–90 m^3 s^{-1}; the maximum SSC measured was 382 000 mg l^{-1} from a sample collected using an autosampler. Of the 261 suspended sediment samples collected during the 14 storm-runoff periods, 86% had SSC values larger than 50 000 mg l^{-1} (Nancy Hornewer, USGS, written communication, 2008).

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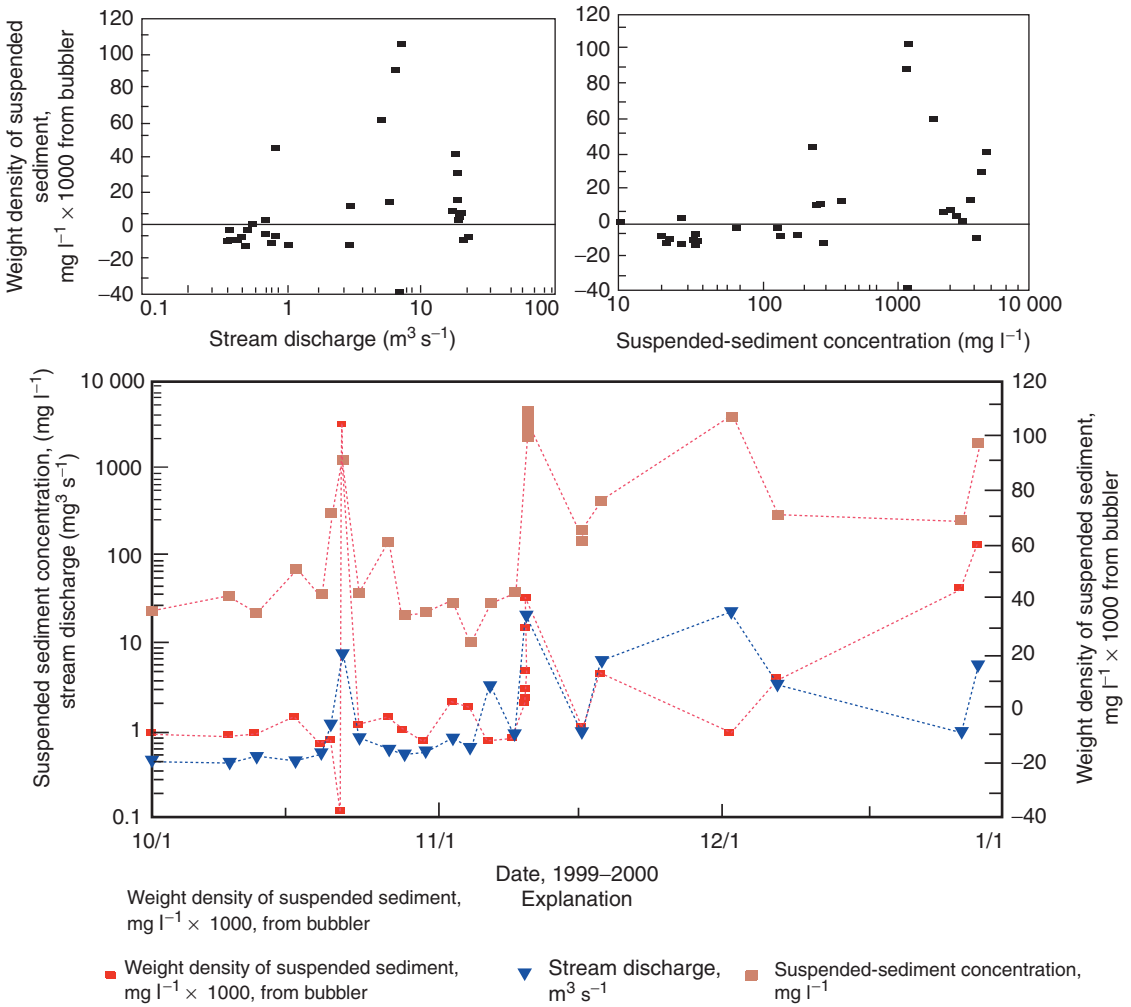

Note: Only symbols denote measure values; dashed interpolation lines are included for viewing purposes only

Figure 16 Scatter plots and time series of stream discharges, SSCs, and weight density of suspended sediments and dissolved solids measured with a Double Bubbler (Design Analysis Associates (2012)), 1 October 1999–1 January 2000, lower Rio Caguitas, Puerto Rico. Water discharge and sediment data are instantaneous values in cubic meters per second and milligrams per liter, respectively; Double Bubbler weight density values are expressed in milligrams per liter as 30-min mean values of measurements made at 5-min intervals. Reproduced from Larsen, M. C., Figueroa-Alamo, C., Gray, J. R. and Fletcher, W. (2001). Continuous automated sensing of streamflow density as a surrogate for suspended-sediment concentration sampling. *Proceedings of the 7th Federal Interagency Sedimentation Conference*, Reno, NV, 25–29 March, vol. I, pp. III-102–III-109. Available at http://pubs.usgs.gov/misc_reports/FISC_1947-2006/pdf/1st-7thFISCs-CD/7thFISC/7Fisc-V1/7FISC1-3.pdf (accessed on 14 June 2012).

Similar to data collected at the Rio Caguitas in Puerto Rico and contrary to the aforementioned hypothesis, the Double Bubbler data collected at the Paria river at Lees Ferry streamgage seemed to have a large amount of signal noise, also making interpretation difficult (Gray and Gartner, 2010b). The Double Bubbler data were collected only during periods of elevated stages (water discharges) because the instrument was not fully submerged during normal shallow flows. Data were filtered in a manner similar to that for the Río Caguitas data but not smoothed. Relations between measured SSCs and those calculated from bubbler data tended to be inconsistent. It is likely that bed movement caused the lower orifice to become partially or fully blocked at times, contributing to erroneous data. Also, the paired stage readings necessary for the density calculation could not always be obtained because both orifices were only submerged during infrequent periods of high flow. Neither condition constitutes a fair test of the technology.

The performance of the Double Bubbler has been proven neither inadequate nor adequate for USGS data collection purposes in streams with large SSCs (Gray and Gartner, 2010b). Regardless, due to its strong theoretical underpinnings, continuous monitoring capability, and – not unimportantly – a lack of any other proven technology for monitoring SSCs in high- and hyperconcentrated streamflow conditions the technology is considered worthy of additional testing. To this end, a 3-orifice pressure-differential system (Sutron Corporation, 2012) is being tested at the USGS streamgage Rio Puerco near Bernardo, New Mexico, USA.

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Beverage and Culbertson (1964) indicated that hyperconcentrated streamflows of at least 560 000 mg l^{-1} have occurred at this site.

1.10.3.2.3.3 Advantages and limitations of the pressure-difference technology

Advantages:

- The pressure-difference technology's inference of SSC in a single vertical is an improvement over at-a-point measurements but still may not provide SSC data representative of mean cross-sectional values.
- The technology is relatively robust, being prone to neither signal drift nor biological fouling.
- The technology doubles as a redundant stage sensor for the site.
- The technology may be unique in that the accuracy of its measurements theoretically improves with concentrations increasing above approximately 10 000–20 000 mg l^{-1}.
- The theoretical underpinnings of the technology are relatively simple and straightforward.

Limitations:

- The required computational scheme presupposes that the SSC in the vertical profile above the lower pressure sensor is more or less constant to the surface. This assumption, which is difficult to verify, may not be valid.
- The technology may be incapable of measuring SSCs below approximately 10 000–20 000 mg l^{-1} in turbulent flows and where the bedforms cover one or both orifices. The field performance of the technology has yet to be adequately resolved at any SSC.
- The technology is incapable of measuring SSC when the top orifice is not submerged or the bottom orifice is buried in sediment.
- Spurious data are numerous and are believed to be associated with flow turbulence.
- The Double Bubbler (Design Analysis Associates, Inc., 2008) is no longer marketed; however, three versions of the Accubar® Bubble Gauge Recorder are marketed by Sutron (2012). The third version, employing three precision pressure sensors, is reputed to be thrice as accurate as those composed of dual density sensors.

1.10.3.2.4 Acoustic surrogates

Hydroacoustics is a compelling technology that can provide surrogate measurements of SSC with several advantages including large sample volumes, potential for simultaneous velocity measurements, and environmental robustness (Landers et al., 2012). Characterization of suspended sediment using backscatter and attenuation of acoustic signals in water has been described and developed for several decades (Urick, 1948, 1975; Flammer, 1962; Hay, 1983; Sheng and Hay, 1988; Flagg and Smith, 1989; Thorne et al., 1991; Hay and Sheng, 1992; Lynch et al., 1994; Holdaway et al., 1999; Gartner, 2004; Wall et al., 2006; Gray and Gartner, 2009; Simmons et al., 2010; Gray and Gartner, 2010b; Guerrero et al., 2011; Thorne et al., 2011). The basic principles are that acoustic waves passing through a water–sediment mixture will scatter and attenuate as a function of sediment, fluid, and instrument characteristics. The acoustic metrics of backscatter and attenuation relate functionally to sediment characteristics (SSCs, PSDs, and shapes) within an ensonified volume after adjusting for the influence of fluid and instrument characteristics.

Early investigations of acoustic surrogates relied on instruments with a separate sound source and receiver, rather than a combined source and receiver such as modern transceivers (referred to here and typically as transducers). The transducer emits an acoustic pulse and then, after an interval just long enough to stop 'ringing,' it receives the echoes backscattered from particles suspended in the acoustic path as illustrated in the simplified cartoon of Figure 17. Acoustic Doppler velocity meters measure the Doppler shift in the frequency of the backscattered signal to determine the velocity of the particles scattering the signal (the assumed water velocity) relative to the transducer. Two or three transducers at fixed beam angles may be used to resolve a 2- or 3-dimensional flow velocity vector. As acoustic Doppler velocity meters are now ubiquitous in streamflow monitoring, the acoustic backscatter provides tremendous potential for sediment monitoring using existing instrumentation.

1.10.3.2.4.1 Acoustic backscatter

The amplitude of the backscattered acoustic signal depends on several factors including SSC, PSD, acoustic frequency, range from the transducer to the ensonified particles, the volume of sediment-water ensonified, water temperature, sediment density, and sediment shape. In order to use acoustic surrogates, the effects of all of these factors must be measured, modeled, or assumed. Physically, the acoustic signal to sediment interaction involves both acoustic scattering and attenuation. Because there are unique physical mechanisms driving backscatter and attenuation, these two metrics can

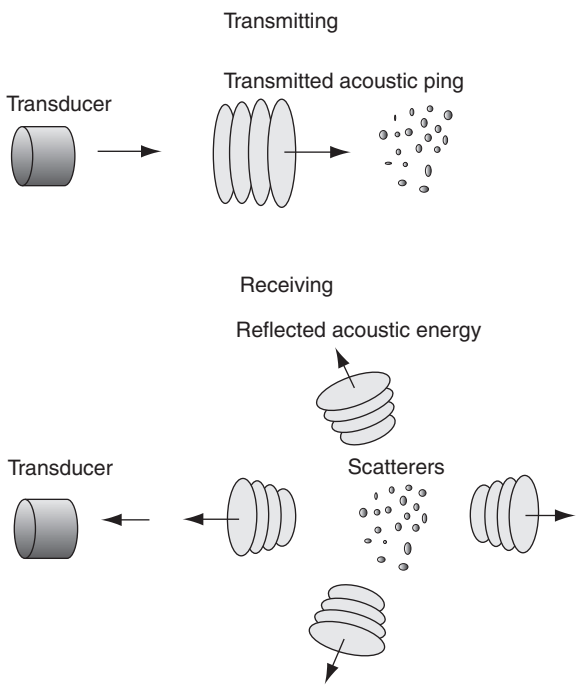

Figure 17 Acoustic backscatter from suspended particles.

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provide independent information relating to SSC and PSD. In many applications, the acoustic backscatter is calibrated to measure SSC, as described in the following paragraphs, and the effect of changes in the sediment size, shape, and density are assumed to be negligible.

1.10.3.2.4.2 Acoustic attenuation

Acoustic absorption due to sediment (α_s) in decibel per meter varies linearly with SSC for a given frequency and sediment size, shape, and density. The physical process driving acoustic attenuation for a given SSC include shear (or viscous) energy losses at the sediment particle-to-water boundary and energy transference due to scattering. Viscous losses are primarily due to the SSC of finer particles (viscous loss size range), whereas scattering losses are primarily due to coarser particles (scattering loss size range). The acoustic attenuation due to viscous loss is caused by shear at the fluid–particle boundaries because of a lag between the sound wave-induced vibration of the particle and that of the fluid. The magnitude of the viscous loss is a function of the particle surface area, sound frequency, fluid viscosity, and the ratio of particle to fluid density. The scattering loss is due to reradiation of the acoustic energy incident on a particle. Scattering loss is a function of the ratio of acoustic wavelength, λ, to particle circumference $2\pi a_s$. The scattering attenuation reaches a maximum at particle diameters of approximately 1050, 840, and 420 μm for frequencies of 1.2, 1.5, and 3 MHz, respectively.

The minimum acoustic attenuation occurs at the transition between viscous and scattering losses. The particle size associated with this minimum attenuation increases with wavelength (decreasing frequency). For example, the minimum acoustic attenuation occurs at particle diameters of 90, 74, and 42 μm for frequencies of 1.2, 1.5, and 3 MHz, respectively, using 1484 m s^{-1} as the speed of sound in water. These particle diameters are in the silt to very fine sand range. Knowledge of this transition particle size is relevant to using multifrequency acoustics to assess characteristics of the sediment PSD. Acoustic attenuation may be computed using forms of the equations by Urick (1948) or Sheng and Hay (1988) as described in Thorne and Hanes (2002) or Landers (2012). Acoustic attenuation may be measured with much greater potential accuracy than available by computations using multicell acoustic Doppler current profilers or by using the method developed by Topping et al. (2007).

1.10.3.2.4.3 Acoustic surrogate methods for SSC

A semiempirical backscattering theory and acoustic surrogate methodology was progressively developed by several researchers working in fluvial (Urick, 1948, 1975; Flammer, 1962; Gartner, 2004; Topping et al., 2007; Wall et al., 2006; Gray and Gartner, 2009; Simmons et al., 2010) and marine environments (Sheng and Hay, 1988; Thorne et al., 1991; Hay and Sheng, 1992; Downing et al., 1995; Crawford and Hay, 1993; Thorne and Hanes, 2002; Thorne et al., 2011). The methods developed in fluvial and marine environments are distinct, yet similar and can be equated mathematically. For the purposes of this summary, the form of equations presented is that developed and used primarily by researchers in fluvial systems.

The acoustic sediment surrogate methods used primarily in fluvial systems begins with Urick's (1975) sonar equation and has been used by several authors (Thevenot and Kraus, 1993; Reichel and Nachtnebel, 1994; Gartner, 2004; Wall et al., 2006; Topping et al., 2007). The sonar equation is written in logarithmic units of decibels as:

$$\mathrm{RL} = \mathrm{SL} - 2\mathrm{TL} + \mathrm{TS} \qquad [6]$$

where

$$2\mathrm{TL} = 20\log_{10}(r) + 2r(\alpha_s + \alpha_w) \qquad [7]$$

In this method, RL is the reverberation level (measured backscatter intensity at the transducer face recorded by the acoustic velocity meter) of the received signal, SL is the source level of the emitted signal, 2TL is the two-way transmission loss equal to the sum of the spherical energy spreading and attenuation, and TS is the intensity of the signal echoed by the particles in the ensonified volume equal to 10 $\log_{10}$ (SSC).

In the equation for TL, r is the range from the transducer to the ensonified volume, acoustic attenuation is expressed in the coefficients for acoustic absorption, α_s, and water absorption, α_w. The first term to the right of the equality in the TL equation accounts for physical spreading of the acoustic energy as the signal propagates from its source and spreading is linear in logarithmic space. Attenuation in pure water at depths less than 100 m is a function of temperature and acoustic frequency only and may be computed using standard equations such as that by Fisher and Simmons (1977). Water temperatures are measured and stored by most acoustic meters at each measurement interval, so continuous time series of α_w can be computed. The relative backscatter (RB) is computed as RB = RL + 2TL, which is equivalent to the total scattering by suspended particles. Then, $\log_{10}$ (SSC) is a function of RB and:

$$\mathrm{SSC} = 10^{(A+B*\mathrm{RB})} \qquad [8]$$

The coefficients A and B are evaluated using regression for paired physical SSC and acoustic measurements. Source level is evaluated in the regression coefficient for this method (Thevenot and Krause, 1993; Gartner, 2004), and sediment acoustic attenuation is sometimes assumed to be negligible for low-concentration systems (Gartner et al., 2001; Wall et al., 2006).

Measurements of the acoustic return signal can be digitally sliced into specific range-gated 'cells' to provide data on velocity and acoustic metrics at integral points along the acoustic beam. Most commercially available acoustic velocity meters have this profiling capability. These multicell data offer an effective means to directly measure the sediment acoustic attenuation at a high temporal resolution. **Figure 18** shows the acoustic backscatter in decibels measured by a 1.5 MHz unit with 10 cells of 20 cm axial distance each measured between 0.2 and 2.2 m from the transducer face for a river with an average SSC in the channel cross section of approximately 694 mg l^{-1} at the time of this acoustic measurement (Landers, 2012). The RL line is the measured backscatter intensity and its slope is the combined two-way signal strength loss due to spherical spreading plus fluid and sediment acoustic attenuation. The (RL + 20$\log_{10}(r)$) line is the measured backscatter intensity corrected for spherical spreading, and the

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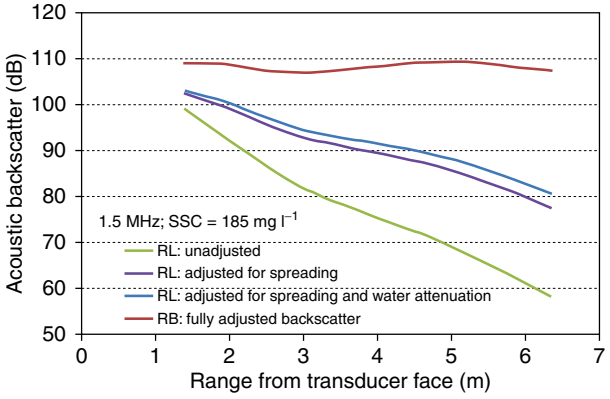

Figure 18 Acoustic backscatter amplitude profiles along beam axis for 1.5 MHz.

$(\mathrm{RL} + 20\log_{10}(r) + 2r\alpha_w)$ line is further corrected for fluid attenuation. Solving for the slope of this line provides the two-way acoustic attenuation, $2\alpha_s$. Topping et al. (2007) first used this method to solve for α_s. This multicell method has the powerful advantages of measuring α_s and of normalizing for the effects of sediment scattering properties and transducer-specific characteristics.

Methods to obtain SSC using acoustic surrogates include/involve elements common to all sediment monitoring studies (identifying information goals and accuracy requirements, budgets, site selection, training) and elements specific to acoustic surrogates (selection of monitoring section, instrument set-up, data retrieval, data processing, concurrent physical sampling, and calibration). The acoustic meters may be mounted *in situ* for time series data or used from a mobile platform for discrete measurements. The ensonified volume for *in situ* monitoring should be selected to maximize the measured volume for all flow conditions and generally limited by low-flow conditions. The system should be set up to collect multicell data with initial set up using at least 10 cells to optimize calibration with measured SSC. Once the instrument set up is complete and deployed, concurrent acoustic and physical sample measurements are required over the range of sedimentological conditions that occur for the monitoring period. The TL data are computed for each cell using the range to the cell, computed α_w, and measured or computed α_s. The RB is computed for each time step (for *in situ*) or location (for mobile) using the measured backscatter (RL) and the TL as $\mathrm{RB} = \mathrm{RL} + 2\mathrm{TL}$. This analysis is performed for each time step to obtain a time series of the acoustic surrogates of acoustic attenuation by sediments and normalized acoustic backscatter.

The acoustic surrogates RB and α_s are then calibrated using concurrent measurements of cross-section representative SSC. Sensitivity analyses may be performed to determine whether to use the entire ensonified profile or selected cells to best represent the SSC. Sensitivity analyses should also be done to determine whether using both RB and α_s provide statistically significant and independent data explanatory variables or whether RB should be used alone as the acoustic surrogate. Computed estimates of SSC should be reported with the SSC-acoustic surrogate model error, as well as assessments of the calibration dataset uncertainty.

1.10.3.2.4.4 Multifrequency acoustic surrogates for sediment size

A major limitation of single-frequency systems is that the metrics of acoustic attenuation and RB change in response to changes in both SSC and PSD, creating a SSC–PSD ambiguity. Relative acoustic backscatter from sediment may increase with increased concentration at a fixed size distribution or with increased sediment size at a fixed SSC, and acoustic attenuation also varies with size. Multifrequency acoustic systems, however, have been successfully used to estimate both sediment concentration and general size characteristics (Crawford and Hay, 1993; Gartner, 2004; Hay and Sheng, 1992; Thorne et al., 1991; Smith et al., 2006; Topping et al., 2007). Two approaches have been developed that use multifrequency acoustics to evaluate sediment size, one by Hay and Sheng (1992), which is effectively summarized in Thorne and Hanes (2002) and one by Topping et al. (2007). Three frequencies have been used in most multifrequency sediment surrogate studies.

Topping et al. (2007) observed the transition from viscous to scattering losses in sediment acoustic attenuation, as noted in Section 1.10.3.2.4.3 for Urick's equation and from this describe two acoustic size classes of sediment – a finer acoustic size class in which viscous attenuation is dominant and a coarser acoustic size class in which scattering attenuation is dominant and backscatter is more significant. Applying this method, Topping et al. (2007) report computed concentrations within 5% of the values computed using conventional data and median sand grain size typically within 10% of the values obtained by conventional measurement.

1.10.3.2.4.5 Examples of deployments

Landers (2012) used horizontally mounted, *in situ* 1.2, 1.5, and 3.0 MHz systems at a site on the Yellow river near Atlanta, GA, USA. Acoustic, turbidity, and laser-diffraction surrogates were compared with traditional SSC measurements and computed sediment flux. **Figure 19** shows a time series plot of measured SSC (from physical samples), RB, and attenuation for a 1.5-MHz system for a small storm in April 2010 at the Yellow river site.

More than 180 representative, concurrent SSC measurements were obtained during 2009–10 for calibration with the acoustic surrogates. Both RB and α_s proved statistically significant and independent as explanatory variables. The regression fit between these variables and measured SSC had R^2 values from 0.79 to 0.80 for the three frequencies tested, with model standard errors from 34% to 40%, as indicated in **Figure 20** for the 1.5 MHz acoustic Doppler current profiler. By comparison, a traditional model using streamflow discharge as the explanatory variable for these data had a model standard errors of 73%. The measured SSC calibration dataset was estimated to have an uncertainty of $\pm 10\%$. However, as noted previously, the surrogate measurements can measure at very high resolution compared with physical sampling over time, thus providing improved accuracy and information over time.

Sediment flux measured by detailed samples was estimated using all three frequency acoustic surrogates with an error of prediction of less than 10%, which is within the estimated uncertainty of the sediment flux calibration dataset. Landers

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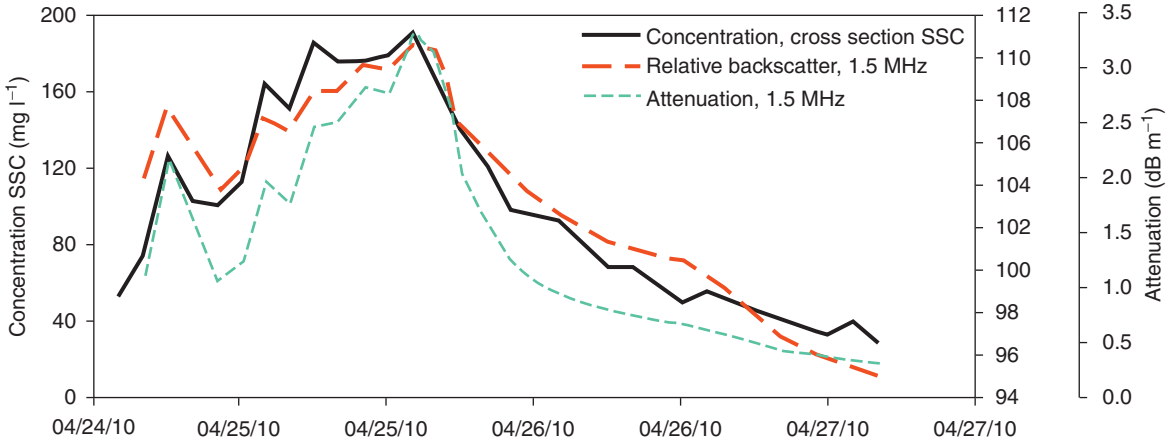

Figure 19 Measured SSC, acoustic attenuation, and relative acoustic backscatter during runoff on the Yellow river near Atlanta, GA, USA.

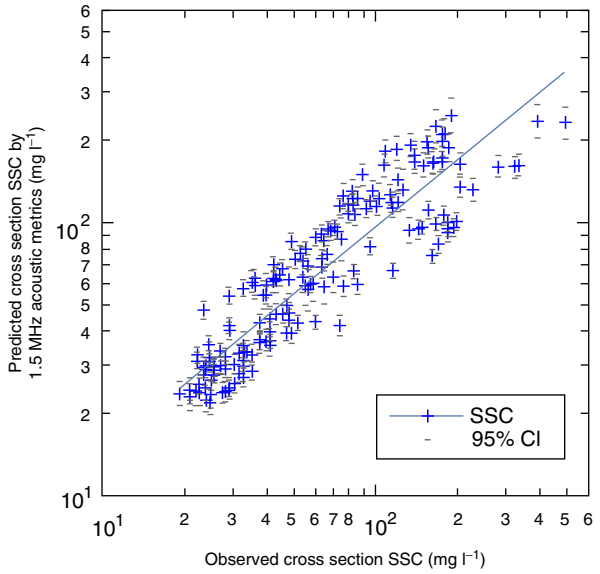

Figure 20 Observed and predicted SSC using acoustic backscatter and attenuation from 1.5 MHz acoustic Doppler current profiler. Reproduced from Landers, M. N. (2012). Fluvial suspended sediment characteristics by high-resolution, surrogate metrics of turbidity, laser-diffraction, acoustic backscatter, and acoustic attenuation. Ph.D. Dissertation, Georgia Institute of Technology. Available at http://hdl.handle.net/1853/43747 (accessed on 14 June 2012).

(2012) also found that ratios of measured acoustic attenuation for 1.2, 1.5, and 3 MHz systems are significantly related to PSD, with increasing significance for smaller size fractions.

Wall et al. (2006) used a bottom-mounted, broadband, 4 beam, 0.614 MHz acoustic Doppler current profiler on the Hudson river below Poughkeepsie, NY, USA (USGS streamgage 01372058). They collected concurrent SSC samples from the ensonified volume to calibrate the sonar equation. They also measured depth- and width-integrated SSC for the stream cross section and developed the relation between sediment flux in the acoustic sampling area and in the river cross section. Their work resulted in the computation of daily sediment flux for this tidally affected location of the Hudson river and is included in near real time as part of the USGS National Water Information System (U.S. Geological Survey, 2012a).

1.10.3.2.4.6 Advantages and limitations of acoustic surrogates

Advantages:

- Acoustic velocity meters are used broadly in streamflow monitoring to collect acoustic backscatter data, which can generally be used with calibration and analysis to infer sediment characteristics.
- Acoustic meters are highly robust in the stream environment requiring little cleaning and maintenance.
- Acoustic meters measure a substantially large volume of the flow compared to the other described surrogate technologies.
- Most commercially available acoustic velocity meters measure profiles of backscatter, which can be used to indicate acoustic attenuation as well as backscatter.
- As with other surrogate technologies, acoustic meters can operate at very high temporal resolutions that provide improved accuracy and information for dynamic sediment characteristics.
- Multifrequency acoustic instruments can provide information on PSD as well as SSC.

Limitations:

- As with turbidimeters, acoustic metrics from single-frequency systems may change due to changes in sediment concentration or sediment size, creating a size–concentration ambiguity.
- Acoustic metrics are sensitive to the ratio of sediment size to acoustic wavelength and a somewhat narrow frequency is optimal for evaluation of PSD using multifrequency acoustics.
- The sensitivity of acoustic surrogates of suspended sediment is limited for low concentrations and generally may not be applicable for concentrations less than approximately 10 mg l^{-1} for frequencies in the 0.5–5 MHz frequency range.
- All methods that use measurements of a subsection or single point of the channel cross section require concurrent point and cross-section SSC measurements for calibration

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to the entire cross section and assumed stability of those calibrations. This limitation is more restrictive for surrogates based on small at-a-point volume measurements than for acoustic surrogates, which typically are based on a much larger volume than point measurements.

1.10.4 Summary and Conclusions

The efficient and proper management of river systems is predicated on the availability of sufficient high-quality fluvial sediment and ancillary data. Two general means for obtaining sediment data have been described: those based on traditional instruments and techniques and those using technologically advanced instruments. Traditionally, collected data tend to be spatially robust but temporally deficient. The opposite is true for *in situ* surrogate technologies. Some of the surrogate technologies are being incorporated into operational programs and show considerable promise toward providing the temporally dense and, in some cases, spatially robust fluvial sediment data needed to increase and bring more consistency to sediment-discharge measurements worldwide.

1.10.4.1 Traditional Technologies

The previously described in Section 1.10.2.2 traditional FISP samplers and techniques, which debuted in the mid-twentieth century, are grounded on sound physical and statistical principles and form the basis for production of the bulk of fluvial suspended sediment data in the US and in selected countries of every continent other than Antarctica (Federal Interagency Sedimentation Project, 1941; Edwards and Glysson, 1999; Nolan et al., 2005). The key for collection of representative, unbiased physical samples is the use of any one of a suite of FISP isokinetic samplers – devices capable of collecting a filament of flow without change in the ambient velocity or direction – using the EDI or EWI methods deployment techniques. The derivative data are used to directly quantify instantaneous suspended sediment discharges and calibrate physical and surrogate intermittent or time series data collected by *in situ* devices. Failure to use flow integrating instruments and techniques often results in production of data of unknown veracity. Additionally, even if *in situ* surrogate technologies become operationally ubiquitous, they will continue to require empirical calibrations with traditional technologies. Ergo, traditional instruments and technologies will remain necessary and relevant for the foreseeable future.

1.10.4.2 Surrogate Technologies

Four advanced *in situ* technologies for monitoring fluvial suspended sediment transport are among instruments and techniques being tested by the USGS: turbidity (nephelometry and transmissivity), laser optics, pressure difference, and acoustic backscatter. Although none is a panacea for sediment monitoring needs in all rivers, the capability for consistent, large-scale monitoring of suspended sediment transport in many of the world's rivers may be possible.

Table 4 summarizes selected attributes of the four technologies that are germane to their potential use as a sediment-surrogate technology. Each technology, with the possible exceptions of manually deployed laser-optic instruments, requires periodic calibration with data produced from traditionally collected water samples to calculate the mean value in the cross section. When properly configured and deployed, each is capable of providing a dense and continuous time series of SSC for use in computation of continuous suspended sediment transport. Laser optics and possibly multifrequency acoustic backscatter may provide the added capability of sediment discharge computations by particle-size class. The ability to determine continuous, high frequency, time series of SSC is a major advantage over traditional data collection techniques, obviating the need for routine, potentially subjective interpolations between sample values, and providing the capability to determine high-frequency SSC and PSD fluctuations not revealed by traditional measurements. Calibrations with somewhat larger uncertainty bounds might be considered more acceptable in that the vastly increased derived data density preclude the routine need for interpolations between infrequent discrete measurements.

The applicability of each technology is dictated in part based on the physical and hydrological characteristics of the monitoring site, monitoring objectives, and on the instrument's advantages and limitations. Each deployed surrogate instrument provides time series data representative of the sedimentological characteristics in but a fraction of the cross section. Both optical technologies provide at-a-point SSC data during periods when in-stream SSC values remain below the instrument's saturation limit. The SSC data provided by laser optics are computed from PSDs associated with each measurement.

The location and volume of flow measured by an instrument is an important factor in correlating the measurements to mean cross-sectional SSC values. Assuming production of reliable data collected from the instrument's measurement realm, SSCs computed utilizing acoustic-backscatter technology (employing a profile of vertical or horizontal measurements) may correlate better with the mean SSC value for the river cross section than those computed with the pressure-difference method, which in turn may be better than those computed from at-a-point turbidity or laser-optic measurements.

Nevertheless, the most ubiquitous *in situ* surrogate technology utilizes turbidimeters, which have been shown to provide useful data for computing SSCs in a number of field settings. However, issues associated with instrument sensor saturation can result in failure to record reliable data at the higher values of SSCs that tend to be the most influential in sediment transport. SSCs computed from at-a-point turbidity data may not be representative of the mean cross-sectional SSC, particularly when sand-size material composes an appreciable fraction of total suspended sediment transport. Biological fouling can reduce signal integrity in the absence of a mechanical wiper or manual cleaning to keep the optical window clean. Turbidimeter costs are a small fraction of the annual cost of monitoring suspended sediment transport using traditional techniques, but the potential for increased

Table 4 Summary of selected attributes of four suspended sediment surrogate technologies

Technology	*Turbidity (bulk optics)*		*Laser*		*Pressure difference*	*Hydroacoustics*	
Instrument or type	*In situ* turbidimeter	*In situ* OBS	*In situ* LISST-100 or LISST-streamside (pumping)	Manually deployed LISST-SL	*In situ* Double Bubbler	*In situ* single-frequency acoustic Doppler profiler	*In Situ* Multiple-frequency acoustic Doppler profiler
Price relative to *in situ* turbidimeter	$5000 and up (summer 2011)	Approximately 1X	Approximately 5X	Approximately 6X	Approximately 1X	Approximately 2X–3X	Approximately 3X–6X
Approximate concentration measurement range	Standard 0–2 g l^{-1} Available at larger ranges. Sensor saturation (censoring) occurs above maximum	Standard 0–5 g l^{-1} Available at larger ranges	Depending on versions: 0–2 g l^{-1} (particle size dependent)	Approximately 0–2 g l^{-1} (particle size dependent)	Larger than approximately 10 g l^{-1}, but needs more research; no upper limit	0.02–5 g l^{-1} Variable as function of PSD and frequency	0.02–5 g l^{-1} Variable as function of PSD and frequency
Approximate measurement range, PSD in mm	Does not measure PSD	Does not measure PSD	0.0025–0.5 or 0.0025–0.38	0.002–0.38 or 0.00125–0.25	Does not measure PSD	Does not measure PSD	May measure or qualify PSD
Measurement metrics	Formazin nephelometric or nephelometric turbidity units	Optical Backscatter in millivolts	Volumetric particle concentration and PSD within instrument sediment size limits	Volumetric particle concentration and PSD within instrument sediment size limits	Calibrated to concentrations from physical samples in mass units	Relative acoustic backscatter and attenuation	Relative acoustic backscatter and attenuation for multiple frequencies
Ancillary measurements	None	None	Depth and water temperature	Depth, ambient velocity, and water temperature	Stage	Velocity, temperature, stage or depth, if oriented down	Velocity, temperature, stage or depth, if oriented down
Reliability, robustness, and frequency of servicing	Reliable technology. For wiped sensor models, cleaning every 2–6 weeks depending on stream and temperature	Reliable technology. For wiped sensor models, cleaning every 2–6 weeks depending on stream and temperature	Robustness and reliability is variable to low, depending on stream. Cleaning every 1–3 weeks	Robustness and reliability is variable to low, depending on stream. Cleaning every use.	Low concentration data unreliable; veracity of higher concentrations unresolved	Very reliable and robust. More or less unaffected by fouling	Very reliable and robust. More or less unaffected by fouling

(*Continued*)

Table 4 Continued

Technology	*Turbidity (bulk optics)*		*Laser*		*Pressure difference*	*Hydroacoustics*	
Region of measurement	Fixed point	Fixed point	Fixed point (100X) or pumping (streamside)	Point, vertical, or multiple verticals	Single fixed vertical, mean concentration value	Conic beam with data available at selected distances from the sensor	Conic beam with data available at selected distances from the sensor
Accuracy for derivation of suspended sediment data	When within measurement range has been used to develop reliable SSC-turbidity regression relations	When within measurement range has been used to develop reliable SSC-turbidity regression relations	Deemed reliable in some field applications	Deemed reliable in some field applications	Unresolved based on two field tests; additional work planned	Shown useful in field applications where size distribution does not change dramatically	Shown to provide accurate silt–clay versus sand-size fractions
Potential for application in large-scale monitoring programs	Very high (given appropriate in-stream sedimentological conditions, calibration, and ability to maintain instruments)	Very high (given appropriate in-stream sedimentological conditions, calibration, and ability to maintain instruments)	High (given appropriate in-stream sedimentological conditions, known density, and ability to maintain instruments)	High (used for calibrating *in situ* instruments)	Unknown pending additional testing using modifications of the physical system and algorithms	High for SSC for systems with relatively stable PSD	High for SSC; Moderate for silt–clay versus sand-size fractions

Abbreviations: LISST, laser *in situ* scattering and transmissometry; OBS, optical backscatterance; PSD, particle-size distribution; SSC, suspended sediment concentration.

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site visits for maintenance may result in increased operating costs.

In situ laser-optic instruments also suffer from the drawbacks associated with sensor saturation, biological fouling, and at-a-point measurement limitation characteristics of *in situ* turbidimeters. Additionally, laser data are in the form of volume SSC and mass SSC may be calculated only if particle density is known or can be reliably inferred. The purchase price of an *in situ* laser-optical instrument (LISST-100) is approximately 5 times the cost of a fully equipped *in situ* turbidimeter. However, these instruments have the major advantage in providing continuous PSDs from which the volumetric SSCs are inferred.

The pressure-difference technology is designed for monitoring SSCs exceeding approximately 10 000 mg l^{-1} in a single vertical, which is near or above the maximum range of the other technologies examined herein. The purchase price of this relatively uncomplicated technology is similar to that for a turbidimeter. It is relatively robust in that it integrates the density of a water column as opposed to a single vertical, and it is not subject to biological fouling. The theoretical underpinnings of this technology are straightforward. However, performance of the pressure-difference technology has been marginal at best in field tests in Puerto Rico (maximum SSCs of approximately 17 700 mg l^{-1}) and Arizona (maximum concentrations of approximately 380 000 mg l^{-1}). Because this technology addresses a unique monitoring niche for measurements in highly or hyperconcentrated flows and because of large benefits associated with the production of a dense time series of surrogate measurements, it remains under consideration for future testing and use.

Acoustic backscatter technology shows the most promise for meeting the needs of large-scale fluvial sediment monitoring programs. The technology measures several orders of magnitude more flow than those technologies associated with point measurements. SSC data computed from backscatter data obtained using a three-frequency instrument array and appropriate postprocessing techniques range from 10 to 20 000 mg l^{-1} (silt- and clay-size material) and 10–3000 mg l^{-1} (sand-size material). These data are deemed by the principal investigators to be at least as accurate – within 5% – as measurements made by traditional techniques. At present, the cost of using a three-frequency Doppler array (three separate instruments) is approximately sixfold that of a fully equipped *in situ* turbidimeter. Although at least one multifrequency acoustic backscatter meter is commercially available, it lacks Doppler velocity capability. Multifrequency Doppler velocity profiler is becoming commercially available; however, the signal processing does not as yet support analysis for sediment properties. Fortunately, there are indications that development of applicable, self-contained, multifrequency Doppler velocity units are planned, making more economic monitoring of sediment transport possible in the future, at least under some hydrological and sedimentological conditions.

Most suspended sediment data obtained by Federal agencies at present have their underpinnings in instruments and techniques conceived before the mid-1940s. Hence, the prospect of broad application of one or more suspended sediment surrogate technologies presented herein – and perhaps others in development – is a revolutionary concept in fluvial sedimentology. The benefits of such applied capability could be enormous, providing for safer, more frequent and consistent, arguably more accurate, and ultimately less expensive fluvial data collection for use in managing the world's sedimentary resources.

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