1 Surrogate technologies for monitoring suspended-sediment transport in rivers

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Advances in technologies for suspended-sediment transport monitoring programs in rivers show varying degrees of promise toward supplanting traditional data-collection methods based on routine collection of physical samples and subsequent laboratory analyses. Mostly commercially available technologies operating on bulk-, laser-, and digital-optic, pressure-difference, and acoustic principles have been or are the foci of field or laboratory tests by the US Geological Survey (USGS) and other organizations. Advantages and limitations associated with each suspended-sediment-surrogate technology, considered with deployment-site sedimentological characteristics and monitoring objectives, can be factored into the design of program networks using the most appropriate technology. Examples of 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-concentration determinations, and suitability to the range of in-stream mass concentrations and particle-size distributions (PSDs). All of the *in situ* technologies require periodic site-specific calibrations to infer the sedimentary characteristics representative of the entire channel cross section.

In March 2009, the USGS endorsed bulk optics (turbidity) for use in operational suspended-sediment monitoring programs, the first sediment-surrogate technology to receive USGS endorsement. Other technologies are likewise being considered for USGS acceptance.

Nevertheless, hydroacoustic technologies show the most promise for use in operational suspended-sediment monitoring programs. A fixed-mounted, self-contained single-frequency acoustic backscatter instrument supported by appropriate deployment, calibration, and data-analyses protocols presents the prospect for automated collection of continuous time-series suspended-sediment-concentration data in selected river reaches. The anticipated adaption of a multi-frequency acoustic Doppler current profiler in fixed-mounted mode portends the potential for even more accurate monitoring of suspended-sediment concentration (SSC) and transport, possibly by particle-size classes. Laser-optic instruments deployed *in situ* or manually that provide PSDs and concentrations also show considerable promise.

Endorsement and broad-scale deployment of certifiably reliable sediment-surrogate technologies supported by operational and analytical protocols are revolutionary concepts in fluvial sedimentology. The benefits 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 resources.

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1.1 Introduction

Fluvial sediment and sorbed materials are the most widespread pollutants affecting US rivers and streams (US Environmental Protection Agency 2008). The need for reliable, comparable, cost-effective, spatially and temporally consistent data to quantify the clarity and sediment content of waters of the USA has never been greater. Yet resources dedicated to this need have been in decline for more than two decades. For instance, the number of sites at which the USGS collected nationally consistent daily sediment data in 2006 was about a quarter of the number operated in 1981 (David W. Stewart, USGS, personal communication 2008) (the USA has never had a federally funded, national sediment monitoring and assessment program analogous to the National Streamflow Information Program (USGS 2008a) for flow monitoring). This precipitous decrease in sediment monitoring over a quarter century by the USGS – the Federal agency tasked by the US Department of the Interior to collect, archive, and disseminate US water data, including fluvial sediment (Glysson & Gray 1997; USGS 2008b) – is due to several factors, principally cost (Gray *et al.* 2003). The decrease in monitoring is of particular concern, given that the physical, chemical, and biological damages attributable to fluvial sediment in North America alone are estimated to range from US$20 billion to US$50 billion annually (Pimental *et al.* 1995; Osterkamp *et al.* 1998, 2004; Gray & Osterkamp 2007). The relative dearth of adequate, consistent, and reliable data describing fluvial-sediment fluxes hinders development of technically supportable management and remedial plans around the world.

Historically, suspended-sediment flux data in the US have been produced by gravimetric analyses performed on physical samples collected by manual or automatic samplers (see Edwards & Glysson 1999; Bent *et al.* 2003; Davis 2005; Nolan *et al.* 2005; Gray *et al.* 2008). These traditional data-collection methods tend to be expensive, labor intensive, time-consuming, difficult, and under some conditions, hazardous. Specialized instruments and considerable training in their proper use are prerequisites for obtaining reliable samples. The characteristic paucity of the derived data – particularly at the higher flows that are most influential in mass transport of sediment – can lead to inadequate definition of the temporal variability in SSCs and suspended-sediment discharges, or loads (SSLs). Consequently, temporal interpolations and spatial corrections are commonly required to develop the requisite time series that is used with an associated time series of water-discharge data to produce sub-daily and daily records of SSL (Porterfield 1972; Koltun *et al.* 2006).

Sediment-surrogate technologies are defined as instruments coupled with operational and analytical methodologies that enable acquisition of temporally and (or) spatially dense fluvial-sediment data sets without the need for routine collection and analysis of physical samples other than for periodic calibration purposes. Selected sediment-surrogate technologies show varying degrees of promise toward providing the types, quality, and density of fluvial-sediment data needed to improve SSL computations. Potentially useful instruments and methods for inferring the physical characteristics of fluvial sediments (Bogen *et al.* 2003; Gartner *et al.* 2003; Gray *et al.* 2003a,b; Gray 2005; Topping *et al.* 2007; Gray & Gartner 2009) are being developed and tested worldwide. For example, through the informal USGS Sediment Monitoring Instrument and Analysis Research Program (Gray 2003; Gray & 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. These instruments, operating on bulk-, laser-, and digital-optic, pressure-difference, and acoustic principles are being evaluated in North American rivers and laboratories. To make the transition from research to operational monitoring applications, these new technologies must be rigorously tested with respect to accuracy and reliability in different physiographic and (or) laboratory settings as appropriate, and their performances must be compared with 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 identify potential bias and minimize differences in precision between the old and new technologies.

The *in situ* technologies presented herein 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 comparative 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 SSLs (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 (USGS 2005).

These are revolutionary concepts in the discipline of sedimentology 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-data collection for use in managing the world's sedimentary resources.

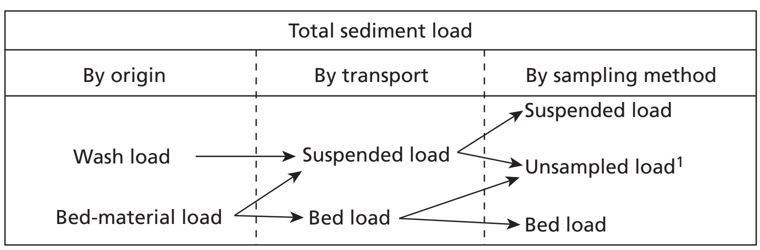
This chapter describes five suspended-sediment-surrogate technologies evaluated in field or laboratory settings by the USGS for monitoring fluvial sediment with varying degrees of potential toward providing continuous, largely automated time-series data used for computing SSLs in rivers. All five of the *in situ* technological applications provide continuous SSC data, and at least two of those may provide PSD data.

The chapter starts with an overview of traditional instruments and techniques for suspended-sediment sampling, against which the surrogate technologies are evaluated. Descriptions of the theory, applications, some advantages, limitations, and costs of each surrogate technology are presented and compared. A subjective evaluation of the efficacy of each technology concludes this chapter. Use of firm, brand, or trade names are for identification purposes only and do not constitute endorsement by the US Government.

1.1.1 Background: traditional suspended-sediment-sampling techniques

Suspended sediment is that part of the total-sediment load (Fig. 1.1) carried in suspension by the turbulent components of the fluid or by Brownian movement (ASTM International 1998). Instruments and methods for collecting suspended-sediment data in the USA have evolved considerably since 1838 when the US Army Corps of Engineers' Captain Andrew Talcott first sampled the Mississippi River (Federal Interagency Sedimentation Project 1940). The earliest suspended-sediment samples were collected by use of instantaneous samplers such as an open container or pail. By 1939, at least nine different types of sediment sampler were being used by US agencies. Most of the samplers had been developed by independent investigators, lacked calibrations, and were deployed using a variety of methods. A 1930s survey of sediment-sampling equipment used in the US indicated that the 30 instantaneous samplers studied had limited usefulness either because of poor intake-velocity characteristics or because of the short filament of water–sediment mixture sampled (Federal Interagency Sedimentation Project 1940; Nelson & Benedict 1950; Glysson 1989).

In 1939, six US Federal agencies and the Iowa Institute of Hydraulic Research organized a committee to consider the development of sediment samplers, sampling techniques, and laboratory procedures, and to coordinate such work among the Federal agencies "actively concerned with the



[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.

Fig. 1.1 Components of total-sediment load considered by origin, by transport, and by sampling method. From Diplas *et al.* (2008).

sedimentation problem" (US Department of Agriculture 1965). This committee has evolved into three entities: the present-day Subcommittee on Sedimentation of the Advisory Committee on Water Information; Technical Committee; and Federal Interagency Sedimentation Project (FISP) (Sedimentation Committee of the Water Resources Council 1976; Skinner 1989; Glysson & Gray 1997; Federal Interagency Sedimentation Project 2008; Subcommittee on Sedimentation 2008). The purpose of the FISP is to study methods and equipment used in measuring the sediment discharge of streams and to improve and standardize equipment and methods where practicable. Through the FISP, an integrated system of sediment samplers, sampling procedures, and analytical methods was developed and is codified in US Federal sediment-monitoring standards (Federal Interagency Sedimentation Project 2008; Edwards & Glysson 1999) and incorporated to a large degree into international standards (ISO 1992a,b, 1997, 2002, 2005). Today, FISP products and techniques form the framework for collection of consistent, reliable, quality-assured fluvial-sediment data in the USA and many other countries.

The bulk of suspended-sediment data collected by US agencies are acquired using manually deployed FISP isokinetic samplers (Davis 2005), and traditional sampling methods described by Edwards & Glysson (1999), Nolan *et al.* (2005), and Gray *et al.* (2008). These include rigid-bottle samplers (bottle samplers), and flexible bag samplers (bag samplers) that fill at a rate determined by the product of the ambient stream velocity at the sampler nozzle and the nozzle's area. These samplers are designed to collect a representative velocity-weighted sample of the water–sediment mixture. FISP isokinetic samplers are designed to ensure that the water velocity entering the intake nozzle is within about 10% of the stream velocity incident on the nozzle throughout the samplers' operable velocity range. If the velocity of water entering the nozzle differs substantially from the ambient velocity, a bias in the SSC and PSD values computed for the sample may result (Federal Interagency Sedimentation Project 1941; Gray *et al.* 2008) (Fig. 1.2). This bias is a result of differing momentums between water and the entrained sediment, and can be particularly pronounced when sand-size material constitutes a substantial fraction of the material in suspension.

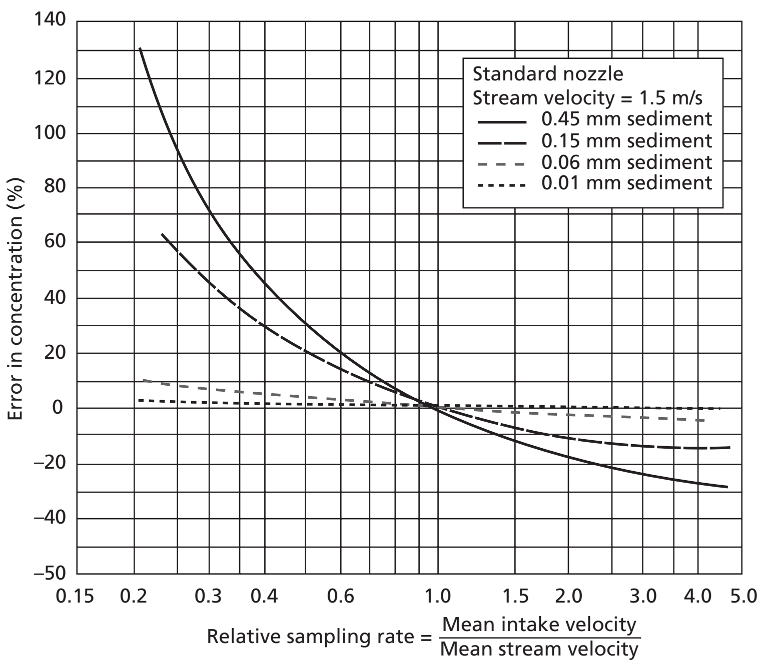


Fig. 1.2 Effect of sampling rates on measured SSCs for four sediment-size distributions.
From Gray *et al.* (2008); adapted from the Federal Interagency Sedimentation Project (1941).

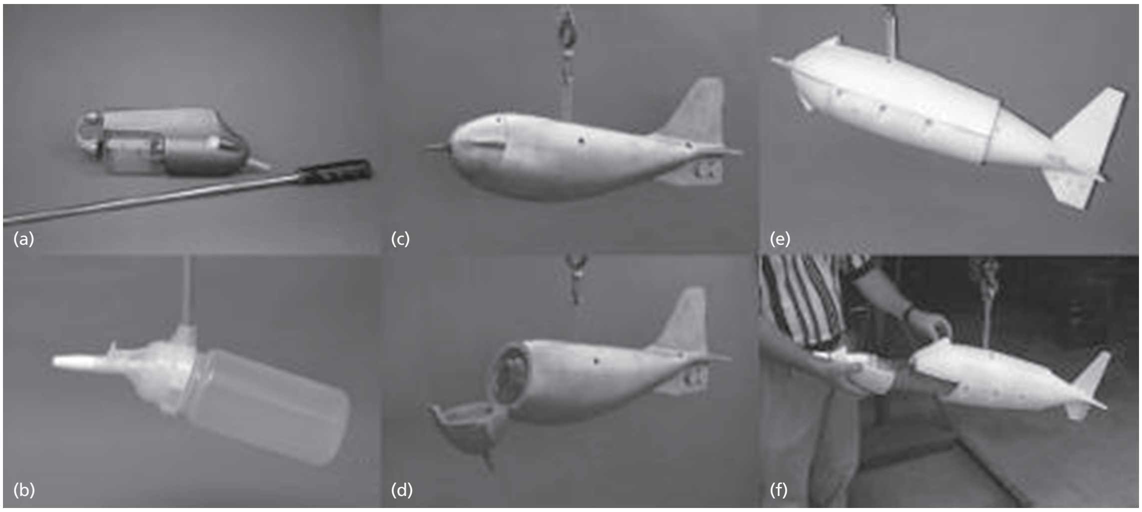


Fig. 1.3 Examples of Federal Interagency Sedimentation Project suspended-sediment samplers. (a) A US DH-48 rigid-bottle sampler; (b) a US DH-81 rigid-bottle sampler; (c) a US D-74 rigid-bottle sampler closed, and (d) open; (e) a US D-96 flexible-bag sampler closed, and (f) open.

A list of FISP suspended-sediment samplers and selected attributes is provided by Davis (2005) and Gray *et al.* (2008). Examples of FISP rigid-bottle- and flexible-bag-type samplers are shown in Fig. 1.3.

A depth-integrating sampler collects and accumulates a velocity- or discharge-weighted sample as it descends and ascends through the water column provided that an appropriate constant transit rate is not exceeded in either transit direction, and the sample container does not overfill. A point-integrating sampler uses an electrically activated valve, enabling the operator to sample points isokinetically either in parts of, or throughout, the water column. Both types of samplers integrate the water column from the water surface to within about 0.1 meters (m) of the bed.

When properly deployed in a single vertical (or, in the case of the point-integrating sampler, at multiple points in a vertical), FISP isokinetic samplers provide representative samples for the parts of the stream sampled. When deployed using either the equal-discharge-increment (EDI) or equal-width-increment (EWI) sampling method (Edwards & Glysson 1999; Nolan *et al.* 2005), an isokinetic sampler integrates a sample proportionally by velocity and area, resulting in a discharge-weighted sample that contains an SSC and PSD representative of the suspended material in transport throughout the cross section at the time that of sample collection.

Although the aforementioned manual samplers have considerable benefits – most notably the acquisition of demonstrably reliable suspended-sediment data from rivers – they have inherent drawbacks. For example, total costs associated with the manual deployment of isokinetic samplers and subsequent sample analytical costs can be substantial or even prohibitive with respect to available resources. Several safety considerations must be addressed any time a hydrographer works in, over, or near a watercourse. The sparse temporal distribution of the derivative data – often but a single observation per day – requires that daily SSL computations be based on estimated SSC values and (or) indexed to another more plentiful if imperfect predictive data source such as river discharge by a sediment-transport curve (Glysson 1987; Gray *et al.* 2008).

1.1.2 Performance criteria for concentrations and particle-size distributions produced by suspended-sediment-surrogate technologies

The reliability and efficacy of data produced by a sediment-surrogate technology are predicated on the adequacy of its calibrations. Two general types of calibration are used: instrument calibrations and cross-section calibrations. Instrument calibration refers in a statistical sense to the precision and variance of data derived from the surrogate measurement in the sampled region (the instrument-measurement realm) to an actual value in the corresponding realm ascertained by independent measurement. Cross-section calibration refers to correlation of the derived data to the mean constituent value occurring in the full stream cross section or stream segment at the time of the measurement, typically using FISP samplers and sampling techniques. Although the instrument-measurement realm generally corresponds to a volume, it is referred to herein in practical terms with respect to the instrument sensor as a point for a local, minute-volume measurement; a water column; or a beam (or average of multiple beams).

Derivations of true mean cross-section constituent values are unlikely from consistently false instrument-measurement-realm values, similar to the axiomatic "garbage in, garbage out" concept in computer science. On the other hand, inferences of false mean cross-section constituent values from true instrument-measurement-realm values can and often do occur. False inferences from true surrogate data can result from heterogeneity typically associated with the occurrence and transport of suspended sediment in the cross section, and is the reason for the need for cross-section calibrations. Therefore, the most meaningful measure of a surrogate technology's reliability is derived from calibrations performed within the instrument-measurement realm. Hence, criteria to evaluate sediment-surrogate technologies should be based solely on instrument calibrations in the instrument-measurement realm, if possible. However, the ultimate measure of the efficacy of a surrogate technology to monitor suspended sediments in rivers is its ability to quantify adequately the sedimentary characteristics of interest over the entire cross section.

Validation of a suspended-sediment-surrogate technology requires evaluation criteria and a well-conceived and -administered testing program (Gray *et al.* 2002; Gray & Glysson 2005). The 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 in some cases, 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;
- the derived data should be relatively simple and straightforward 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 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 PSD and 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 0.002 and 0.5 mm median diameter are required to be ±25% of true median diameters. In the absence of a more rigorous evaluation, this criterion has been applied to all particle sizes in suspension.

SSC acceptance criteria range from ±50% uncertainty at lowest SSCs to ±15% uncertainty for SSC's exceeding 1 gram per liter (g/L). The criteria presented in Table 1.1 are adapted from Gray *et al.* (2002).

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.

Table 1.1 Acceptance criteria for SSC data. The data are considered acceptable when they meet these criteria 95% of the time.

Suspended-sediment concentration		Acceptable uncertainty
Minimum (g/L)	Maximum (g/L)	± Percent
0	<0.01	50
0.01	<0.1	50-25 computed linearly
0.1	<1.0	25-15 computed linearly
1.0	—	15

Adapted from Gray *et al.*(2002).

1.1.3 Ranges in US suspended-sediment concentrations and suspended-sediment discharges

Because of the spatial and temporal variability in river sedimentological regimes, only generalities regarding the expected range of SSCs and PSDs in rivers can be made in the absence of site-specific data. Rainwater (1962) produced an empirically derived map of the 48 conterminous United States showing mean SSC ranges for rivers, generalized over the entire land area, for seven logarithmically based SSC ranges. The SSC ranges were computed and delineated as average annual discharge-weighted mean SSCs, derived from annual measured SSL values divided by their paired annual streamflow values at streamgages. Computed SSC values in the largest range exceeded about 48 g/L.

Meade & Parker (1985) simplified the Rainwater (1962) map into four SSC ranges: less than 0.3 g/L; 0.3–2 g/L; 2–6 g/L; and more than 6 g/L (Fig. 1.4). They also produced a similar-type map for Alaska, USA, using other information sources (Robert Meade, personal communication 1985). These maps (Fig. 1.4) also portray mean annual SSLs from selected river basins to the coastal zone depicted by half circles at river mouths. The area of each half circle is proportional to the average annual sediment mass discharged to the coastal zone. The maps can serve as initial, general indicators of the suitability of a selected sediment-surrogate technology in a river reach of interest.

Additional information on the range of SSCs in US rivers is available from Smith *et al.* (1987), who computed percentile values for SSC data collected at 267 streamgages in medium and large river basins as part of the original USGS National Stream Quality Accounting Network (NASQAN) (USGS 2008c). The 25th, 50th, and 75th SSC percentiles were 0.02, 0.07, and 0.19 g/L, respectively. In 1995, the NASQAN network was redesigned to focus on the nation's largest river basins – the Mississippi (including the Missouri and Ohio), Columbia, and Colorado Rivers, and the Rio Grande. Horowitz (USGS, personal communication 2008) calculated the 10th, 25th, 50th, 75th, and 90th SSC percentiles for the 41 NASQAN streamgages in these large river basins for the period 1994–2006 as 0.01, 0.03, 0.12, 0.32, and 0.74 g/L, respectively.

Many streams transport near-zero SSCs at various times. At the other extreme, SSCs measured during surface runoff from 1989 to 1991 in the Little Colorado River Basin, Arizona and New Mexico, USA, commonly exceeded 100 g/L (Graf *et al.* 1996). SSC values at the Paria River at Lees Ferry streamgage, Arizona, USA, exceeding 1000 g/L have been reported (Beverage & Culbertson 1964).

In general, most of a river's annual sediment budget is transported during infrequent high-flow periods concomitant with relatively large SSCs. Any proposed suspended-sediment surrogate technology deployment should consider not only the statistics quoted above, but also the potential maximum SSC and, where appropriate, maximum particle sizes that might be transported in the period of interest.

1.1.4 Information germane to suspended-sediment-surrogate technology costs

After surrogate-technology efficacy is resolved, cost considerations are often of penultimate interest. The cost of producing reliable, quality-assured suspended-sediment data can be separated into four categories:
- the purchase price of the instrument;
- other capital costs associated with installation, and initial operation of the instrument;
- operational costs to maintain and calibrate the instrument;
- analytical costs to evaluate, reduce, compute, review, store, and disseminate the derived data.

Of these four categories, only the purchase price is straightforward to quantify. The others are dependent on several factors, including site location and physical characteristics, hydrological and

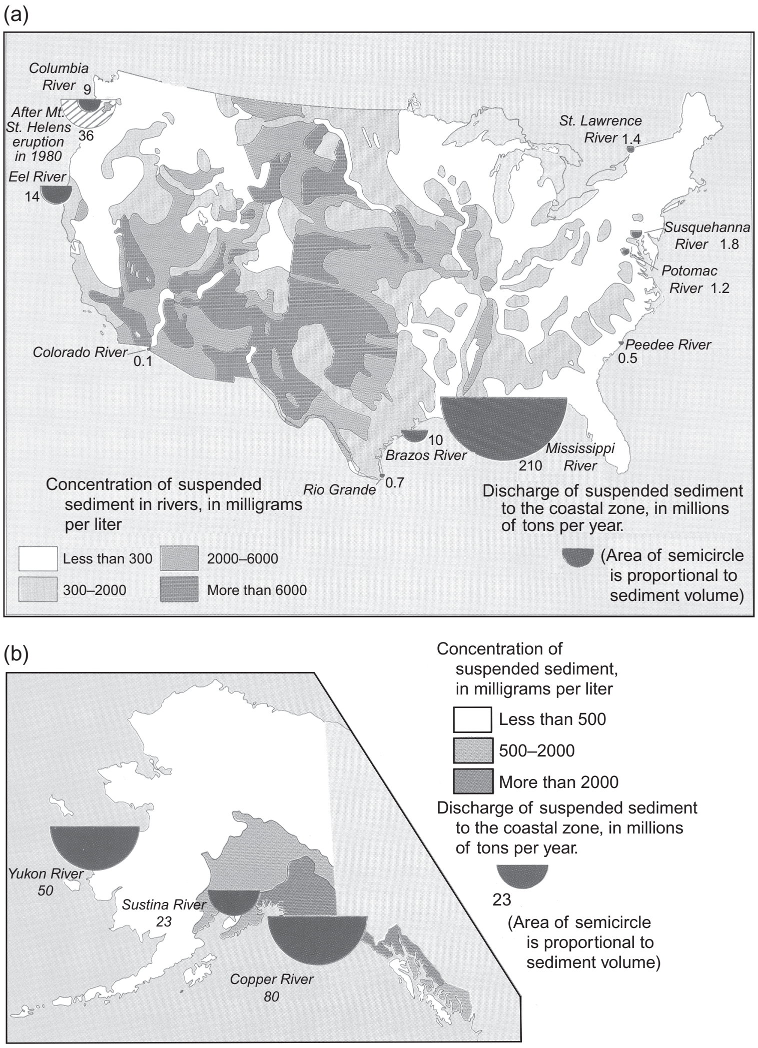


Fig. 1.4 Discharge of suspended sediment to the coastal zone, in millions of metric tonnes per year.

sedimentological regime, availability of electrical power, limitations associated with accessibility, safety considerations, and the time and complexity associated with data analysis. Additionally, any such information inevitably becomes obsolete due, in part, to technological advances, marketing competition, and changes in currency valuation. Hence, relative purchase prices are proffered for the surrogate instruments described herein compared with the actual (summer 2008) purchase price for the most common of the instruments, an *in situ* fully equipped turbidimeter. In some instances, other relevant cost information for a given technology that is considered reliable is provided. That information may be considered in light of the fact that the cost to compute, store, and provide a year's worth of daily SSL data at a USGS streamgaging station in 2001 (adjusted for inflation in 2008 dollars) is estimated to range from US$24,000 to US$78,000 (Gray 2003).

1.2 Technological advances in suspended-sediment-surrogate monitoring

The need for more affordable daily and more frequent time-series data, and for data collected with less risk to field personnel, coupled with advanced technological capabilities, is leading to a new era in fluvial-sediment monitoring. The following sections describe theoretical principles (Gray & Gartner 2004), selected examples of field applications, and advantages and limitations of five suspended-sediment-surrogate technologies that cover a range of transport conditions and are considered to be acceptable or promising by the USGS.

1.2.1 Turbidity (bulk optics)

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1.2.1.1 Background and theory

Turbidity is an expression of the optical properties of a sample that cause light rays to be scattered and absorbed rather than transmitted in straight lines through the sample (Ziegler 2003; Anderson 2005). According to the USGS (2004), "Turbidity itself is not an inherent physical property of water (as is, for example, temperature), but rather is a measure of light scattering through a liquid as measured by detectors with known geometry," and hence is operationally defined. Measurements of turbidity are the most common means of determining water clarity and computing SSC in US rivers (Pruitt 2003). The instrument-measurement realm of a turbidimeter is usually a point in a stream (Secchi disk measurements being a notable exception). Both instrument and cross-section calibrations are normally performed.

The configuration of detectors and the source of light are important factors in the response of the turbidity instrument. Although comparisons among instruments with differing designs are often robust, they can also vary according to the character of the sample's matrix and particulates. Results from an interagency workshop held in 2002 demonstrated that turbidity data from different sources and instrumentation can be highly variable and are often in disagreement with each other, even when instrument-calibration methods are similar (Gray & Glysson 2003). In effect, instruments with different detector geometries and light sources often do not make equivalent measurements.

To reduce the variability among instruments measuring identical in-stream turbidity conditions, a USGS protocol (Anderson 2005) requires that turbidity data be reported based on instrument design in one of ten units, comprising eight new reporting units in addition to the two established reporting units, the nephelometric turbidity unit and the formazin nephelometric unit (USGS 2008d). These ten reporting units provide a systematic method by which to characterize the type of turbidimeter used and are intended to improve the comparability of turbidity data.

Commercially available optical instruments operate on one of two bulk-optic principles. Transmissometers use a light source beamed directly at the sensor. The instrument measures the fraction of light from a collimated light source (typically within the visible range at about 660 nm) that reaches a light detector. The fraction of light reaching the detector is converted to a beam attenuation coefficient, which is related to SSC. Few turbidimeters operate on the transmissometry principle. Nephelometers measure visible or infrared (IR) light scattered by suspended particles (rather than light transmitted through particles). They measure scattering in a (SSC-dependent) volume less than a few cubic centimeters. Most turbidimeters measure 90° scattering. Optical backscatterance instruments (OBS) (Downing *et al.* 1981; Downing 1983) are a type of nephelometer designed to measure less than 180° backscattered IR light in a volume on the order of a few cubic centimeters. Figure 1.5 shows examples of nephelometry and optical-backscatter sensors.

Two instruments widely used for *in situ* applications are the YSI Model 6136 turbidimeter (manufactured by YSI, Inc.), which measures IR scatter at 90°, and OBS-3+ (manufactured by Campbell Scientific, Inc.), which measures IR backscattered at about 140–160°. Transmittance and scatterance are functions of the density, size, color, index of refraction, and shape of suspended particles (Conner & De Visser 1992; Sutherland *et al.* 2000).

In summer 2008, the purchase price of an *in situ* nephelometric turbidimeter with sonde, wiper, and controller was about US$5000. The cost of an OBS and cable without a wiper was about equal to the average cost of a fully equipped *in situ* nephelometric turbidimeter.

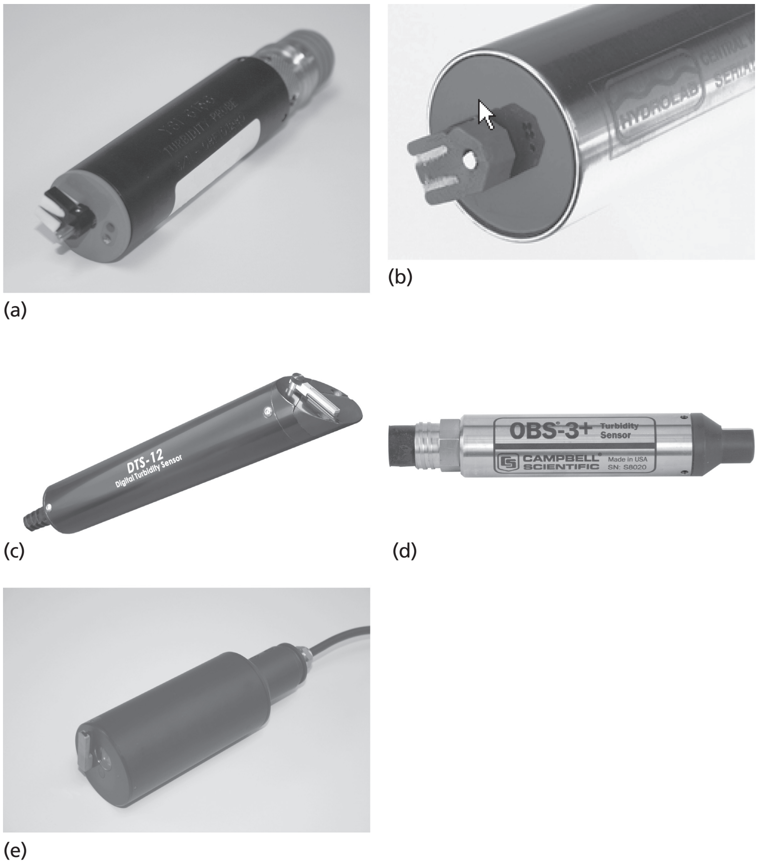


Fig. 1.5 Photographs showing nephelometry sensors. (a) YSI model 6136; (b) Hydrolab turbidity sensor with wiper; (c) Forrest Technology Systems model DTS-12; (d) Campbell Scientific Inc. model OBS 3+; (e) Hach Solitax with wiper. All photographs reproduced with permission.

Bulk-optical instruments lack moving parts (unless outfitted with optical wipers), can be deployed *in situ* to collect time-series data, and provide rapid-sampling capability. The technology is relatively mature, and has been shown to provide reliable data at several USGS streamgages (Uhrich 2002; Melis *et al*. 2003; Schoellhamer & Wright 2003; Uhrich & Bragg 2003; Rasmussen *et al*. 2005) and other sites (Lewis 2002; Pratt & Parchure 2003).

The validity of data produced by bulk-optic instruments can be compromised by at least two in-stream conditions. Biological fouling ("biofouling") of the optical windows of sensors, which results in the tendency for the output to shift from the calibration curve to spuriously larger values over timescales of days or more, remains a problem, particularly in warmer, microbiologically active waters. Commercially available mechanical wiper systems for some sensors may alleviate this problem.

Additionally, turbidity levels exceeding the instrument's maximum measurement limit results in sensor saturation. When saturation occurs, constant values equal to the turbidimeter's upper measurement limit are output, creating a turbidity trace with a "plateau" comprising erroneously low turbidity data. This phenomenon tends to occur at the higher flows and higher SSCs that are most influential in sediment transport. Figure 1.6 shows a hydrograph and turbidity trace for the USGS streamgage on the Kansas River near DeSoto, Kansas, USA, for the period April 12 to May 24, 2002. The turbidity trace for periods encompassing April 22 and May 14 (Fig. 1.6) show the characteristic "saturation plateau" when the in-stream turbidity level exceeded the turbidimeter's maximum recording level.

Maximum SSC limits for turbidimeters depend in part on instrument specifications and the ambient PSD. The OBS instrument has a generally linear

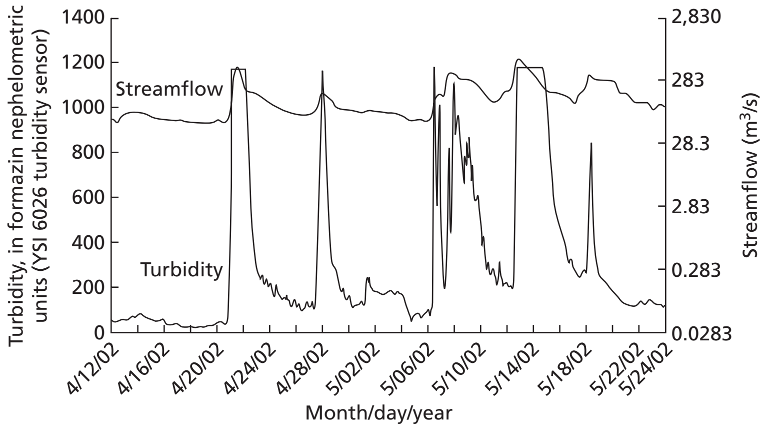


Fig. 1.6 Comparison of continuous measurements of streamflow and turbidity, April 12–May 24, 2002, for USGS streamgage on the Kansas River at DeSoto, Kansas, USA. Turbidimeter saturation occurs around April 22 and May 14.
Adapted from Rasmussen *et al.* (2005).

response at SSCs less than about 2 g/L for clay and silt, and 10 g/L for sand (Ludwig & Hanes 1990), although Kineke & Sternberg (1992) describe the capability to measure SSCs up to about 320 g/L (in the nonlinear region of the OBS response curve). Specifications for an OBS instrument marketed by Campbell Scientific, Inc. (2008) lists an applicable range of 50–500 g/L; however this should be verified by the user for local sediment characteristics. The upper SSC limit for transmissometers depends on optical path length, but may be as low as about 0.05 g/L (D & A Instrument Co. 1991). Thus, transmissometers are more sensitive at low SSCs whereas OBS sensors have superior linearity in highly turbid water (Downing 1996) and are less prone to signal saturation.

Because of the relation between turbidity and PSD, inferences of SSCs from turbidity measurements (like all single-frequency optical and acoustical instruments) are best suited for application at sites with relatively stable PSDs. OBS signal gain is inversely related to grain size (Sutherland *et al.* 2000). Laboratory investigations of Conner & De Visser (1992) indicate OBS signal gain is minimally affected by changes in PSD in the range 200–400 μm but greatly affected by changes when particles are smaller than about 100 μm. They caution against using OBS when changes in the PSD occur and the suspended material is 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 SSCs 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-infrared signal of the OBS, thus modifying its output. Hence, caution should be exercised in deployments under varying PSD and particle-color conditions, unless the instrument is recalibrated for ambient conditions.

Turbidity is often proportional to SSC in the water column within the measuring range of the sensor. Empirical relations between turbidity and SSC have been modeled using linear regression analysis (Walling 1977; Gilvear & Petts 1985; Buchanan & Schoellhamer 1995; Lewis 1996; Christensen *et al.* 2000; Uhrich & Bragg 2003; Lietz & Debiak 2005; Rasmussen *et al.* 2005). If continuously monitored water-discharge and turbidity data are available on the same time interval for a site, the derived unit-value SSCs can be multiplied by their paired water-discharge data to compute continuous SSL without the need for interpolation or estimation. When the turbidity-SSC model is considered adequate as described below, continuous turbidity data calibrated with SSC data from samples collected over a range of flows can provide a more reliable and reproducible SSC time series. When the turbidity-SSC model is considered inadequate, use of water discharge and turbidity may improve model performance sufficiently to justify use of the bivariate model to produce an SSC time series. Upon derivation of an acceptable SSC time series, SSL can be computed from these data and their paired water-discharge time series without the need for interpolation or estimation. Guidelines based on this approach for computing SSC values from continuous turbidity data (or, when appropriate, continuous turbidity and streamflow data) have been produced by Rasmussen *et al.* (2009) and endorsed for collecting and storing SSC and SSL data by the USGS.

The turbidity-based computational scheme has several benefits:

- no subjective interpolation or estimation is required, although the hydrologic judgment and statistical prowess of the analyst may be important in the derivation of the equation used to convert turbidity, or turbidity and water discharge, to SSCs;
- the computational procedure is precisely reproducible;
- the scheme takes full advantage of the available data and computational resources, hence, substantially reduces the time and effort to compute SSL records;
- estimates of uncertainty can be computed for the SSC time series.

An adequate model calibration dataset consists of an appropriate number of instantaneous SSC samples and concurrent turbidity and streamflow measurements made over most of the observed range of hydrologic conditions for the period of record. Another factor that should be considered when determining the adequacy of the number of samples in a calibration dataset is the amount of variability in the relation between turbidity and SSC. The larger the variability in the relation between turbidity and SSC at a site, the greater the need to collect more calibration data.

The key factor for computing time series of SSC data from periodic instantaneous SSC, time series of turbidity, and streamflow data is the type and goodness-of-fit of the regression model used in the computation. A simple linear regression model relating turbidity to SSC is often sufficient for reliable computations of SSC. A multiple linear regression model relating both turbidity and streamflow to SSC may significantly improve the usefulness of the simple turbidity linear regression model. Typically, addition of a streamflow variable is more likely to improve the turbidity-SSC regression if more than about 20% of the suspended-sediment mass is sand-size material (between 62 and 2000 μm median diameter), as inferred from research by Gray *et al.* (2000) on differences between SSCs and total suspended solids measurements.

Prediction intervals are determined to evaluate the uncertainty of SSC regression-computed values (Helsel & Hirsch 2002). Prediction intervals define a range of values for the regression estimate associated with a known level of uncertainty. For a given turbidity value, the 90% prediction interval represents a range of values within which there is a 90% certainty that the true SSC value lies.

Once an acceptable regression model is developed, it can be used to compute SSC within and outside of the period of record used in model development. Maintaining a long-term SSC record requires ongoing collection of turbidity and streamflow time-series data and sample collection for reanalysis and verification of the current SSC regression model. The method for validating the regression model is affected by the frequency of sample collection and the purpose of the study. Regression models can be validated annually (or at some other frequency as needed based on the nature of the monitored hydrologic system and its watershed), after new data have been collected, or on the basis of other valid criteria. Owing to variability in hydrology and other factors, one such period may experience an extreme condition compared with another, such as in floods or droughts, urbanization, wildfire, or implementation of best-management practices. Ergo, a regression model to compute SSC should never be considered static, but rather to represent a set period in a dynamic system in which additional data will help verify changes in the SSC regression relation.

1.2.1.2 Example field evaluations

Continuous turbidity measurements have been shown to provide reliable continuous SSC values with a quantifiable uncertainty at the USGS streamgage on the Little Arkansas River at Sedgwick, Kansas, USA. The adequacy of the calibration dataset was evaluated using duration curves of turbidity and streamflow (Fig. 1.7). The number of samples is often cited as the primary criterion for determining if a dataset is adequate. Although the sample total is important, their broad distribution over the range of

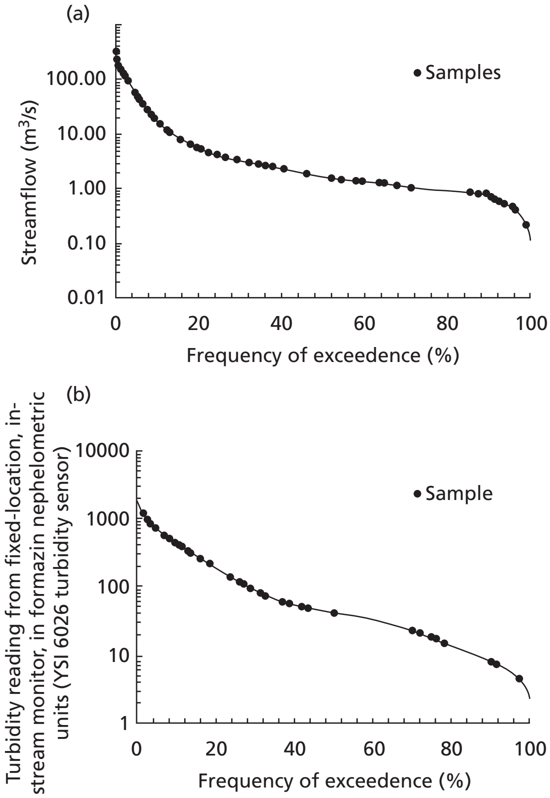


Fig. 1.7 Duration curves for (a) streamflow, and (b) turbidity measured in samples collected in the Little Arkansas River at Sedgwick, Kansas, USA, 1999–2005.

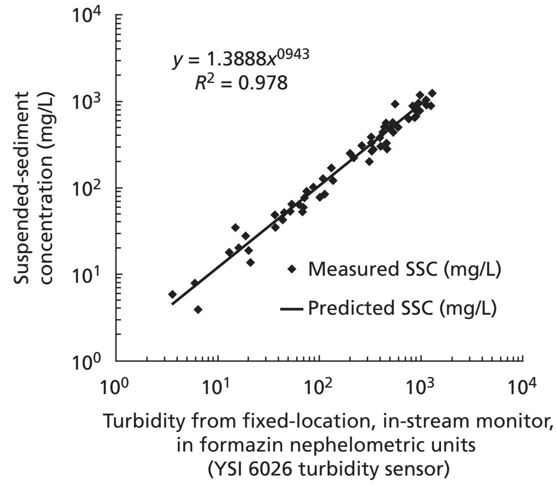


Fig. 1.8 Comparison of field turbidity in formazin nephelometric turbidity units and SSC for the Little Arkansas River at Sedgwick, Kansas, USA, 1999–2006.

observed turbidity, SSC, and streamflow values for the site is paramount in developing a reliable model.

Simple linear regression analysis explained in Rasmussen *et al.* (2009) was used to develop a site-specific univariate model using turbidity to compute time-series SSC (Fig. 1.8). The model explains about 98% of the variance in SSC. Continuous SSLs computed from the model and paired water discharge–SSC time-series datasets are available online (USGS 2005).

Base-10 logarithmic transformation is one of several mathematical functions that can be used to transform datasets to meet the assumptions for linear regression analysis. Other considerations should include the ease of retransforming the results from the model and the bias associated with the retransformation. The computed SSC values must be retransformed to their original units, a step that introduces a bias (usually negative) in computed SSC values (Miller 1951; Koch & Smillie 1986) unless the data are perfectly and positively correlated. To correct for retransformation bias, Duan (1983) introduced a nonparametric bias-correction factor called the "smearing" estimator. Duan's (1983) smearing estimator is insensitive to non-normality in the distribution of regression residuals about a logarithmically transformed model. A method proposed by Cohn *et al.* (1989) assumes normally distributed residuals about the logarithmic model and results in an exact minimum variance unbiased estimator and its variance.

Schoellhamer *et al.* (2002) describe a successful multi-station, multi-year field investigation in California's San Francisco Bay and Delta system. OBS sensors at each station are calibrated with SSC from water samples collected at each site. San Francisco Bay OBS sensors are calibrated to point samples (described in Section 1.1) and San Francisco Delta OBS sensors are calibrated to discharge-weighted, cross-sectionally averaged SSC values. SSL is determined by multiplying the discharge-weighted, cross-sectionally averaged SSC by water discharge, accounting for tide-driven bi-directional flow (Schoellhamer *et al.* 2002).

1.2.1.3 Summary: turbidity (bulk optics) as a suspended-sediment-surrogate technology

Two types of bulk-optic instruments – turbidimeters and optical-backscatter sensors – have been shown to provide reliable data at several field sites at which the limitations of the instrument have not been exceeded. Owing in part to the fact that bulk-optic instruments are the most common and among the most reasonably priced of the suspended-sediment-surrogate technologies, results from a considerable amount of research and evaluation associated with the technology are available to improve and better qualify the derived SSC data. One such outcome was the USGSs development and endorsement of guidelines for converting continuous turbidity time-series data (or continuous turbidity and water-discharge time-series data) to SSC and SSL time-series data (Rasmussen *et al.* 2009).

The primary advantage of regression-based estimates using continuous turbidity measurements over discrete sample collection is typified by the SSC time series for the Little Arkansas River near Sedgewick, Kansas, USA. Regardless of flow conditions, SSC and SSL values are obtained continuously at the interval in which turbidity and water discharges are recorded (Fig. 1.9).

Turbidity as an SSC surrogate, however, has drawbacks. For example, turbidity time-series data derived from a single point in the stream at the sensor location may not be representative of the sedimentary conditions of the river cross section. Biofouling of optical windows may require frequent site visits to clean and recalibrate the instrument (many sensors offer an integrated wiper, considerably reducing biofouling). A lack of consistency in measurement characteristics among commercially available instruments impinges on the comparability of turbidity measurements (Landers 2003; Ziegler 2003). Instrument response to grain size, composition, color, shape, and coating can be variable, and hence, can reduce the accuracy of derived SSC values. Perhaps most importantly, saturation of the turbidimeter signal can occur, resulting in constant, erroneous SSC values above the saturation limit. Saturation often occurs at high SSCs that tend to occur concomitant with high flows, which are the most influential in suspended-sediment-flux magnitudes. Hence, some knowledge of the turbidimeter measurement range and site sedimentological characteristics is desirable before deploying a continuous turbidimeter for calculating SSC and sediment transport.

1.2.2 Laser diffraction

Jeffrey W. Gartner & John R. Gray

1.2.2.1 Background and theory

Laser diffraction instruments exploit the principle of small-angle forward light scattering to infer PSDs and volume SSCs. These instruments measure scattering over a sufficiently wide range of small forward scattering angles to allow determination of PSD information over a wide range (typically 1 : 100 or

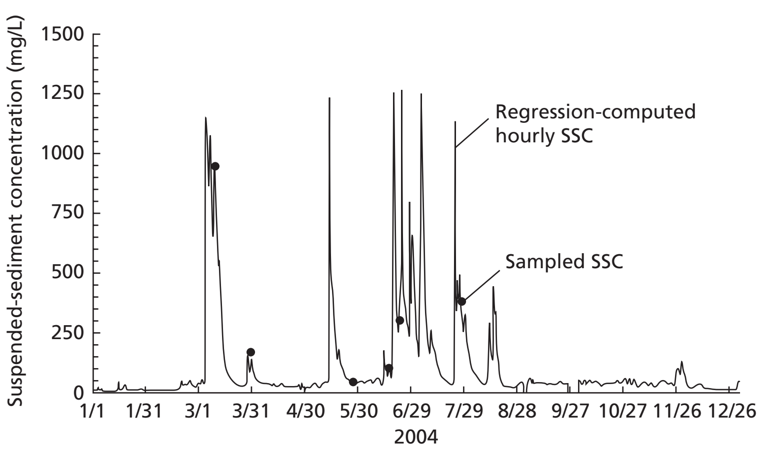


Fig. 1.9 Hourly regression-computed and sampled SSCs, Little Arkansas River near Sedgwick, Kansas, USA, 2004.

(a) (b)

Fig. 1.10 Laser *in situ* scattering and transmissometers. (a) a LISST-100 *in situ* instrument; (b) an in-development LISST-SL (streamlined) manually deployable instrument (photographs courtesy of Sequoia Scientific, Inc.).

1:200) of particle sizes. Scattering by spheres (larger than the wavelength of light) at small angles is equal to diffraction by apertures of the same diameter (Swithenbank *et al*. 1977; Agrawal *et al*. 1991; Agrawal & Pottsmith 1994). In addition, scattering is determined almost completely by light diffracted by the particle; any light transmitted through the particle does not affect the small angle measurement, thus, this method of determining size distributions is mostly insensitive to changes in particle color or composition (Agrawal & Pottsmith 2000). However, departure from spherical shape produces changes in estimated PSDs and SSCs; laser diffraction instruments provide the equivalent sphere-size distribution (Agrawal *et al*. 2008).

Commercially available instruments to measure PSD using laser diffraction have been available for laboratory use since the early 1980s, for example instruments made by Malvern Instruments and Coulter Corporation to name two manufacturers. The first attempt to apply the technology for *in situ* application used a commercial laboratory instrument adapted for ocean use (Bale & Morris 1987). A self-contained version of a laser diffraction instrument that could be deployed in an autonomous mode and determined PSD in eight size classes is described by Agrawal & Pottsmith (1994).

A more advanced and commercially available version of the instrument (Agrawal *et al*. 1996; Agrawal & Pottsmith 2000) capable of providing time series of PSDs and volume SSC values is the Laser In Situ Scattering and Transmissometry (LISST)-100 (Sequoia Scientific, Inc. 2008). The LISST-100 (Fig. 1.10a), with an overall length (minus cable) of 87 cm and diameter of 13 cm, measures optical transmission, water temperature, and hydrostatic pressure in addition to PSD and volume SSC. The LISST uses a 670-nm wavelength solid-state laser. The standard sample path of this device is a cylindrical volume with a diameter of approximately 6 mm and a length of 50 mm, although versions with shorter laser-path lengths are available for highly turbid environments. The instrument uses a 32-ring detector with logarithmically increasing radii to measure scattering intensity at 32 small forward angles that correspond to 1.25–250 μm (LISST-100B), 2.5–500 μm (LISST-100C), or 7.5–1500 μm (LISST_FLOC). The inner radius (smallest-scattering angle) of the ring detector corresponds with the largest measured particles and the outer radius (largest-scattering angle) corresponds with the smallest measured particles. The measured scattering intensity distribution is also referred to as the volume scattering function (VSF) (Pottsmith and Bhogal 1995; Agrawal and Pottsmith 2000). In practice, to determine PSDs and volume SSCs, the measured VSF is first corrected with a background scattering distribution. The corrected VSF is mathematically inverted to determine a PSD that would produce the multi-angle scattering that fits the measured observation in the 32-ring detector. Details of the inversion process can be found in Agrawal & Pottsmith (2000). Volume SSC is calculated from the inverse of the corrected scattering distribution divided by the volume conversion constant, an empirical calibration constant supplied by the manufacturer. Although laboratory versions of laser diffraction instruments are available from several manufacturers, the authors are aware of only one (Sequoia Scientific, Inc. 2008) that produces commercially available instruments designed for *in situ* applications and manual deployment.

The purchase price of one of the laser instruments (*in situ* and manually deployed) described in this section ranges from about two to six times that for a fully equipped turbidimeter, depending on the instrument of interest. The instrument-measurement realm of the *in situ* instruments described herein is a point in a stream. When used for measurement of PSD or volume SSC, they do not require routine instrument calibrations.

The LISST-100, which has been field and laboratory tested, has been shown to successfully determine PSDs of natural materials and the size of mono-sized particle suspensions within about a 10% accuracy (Traykovski *et al.* 1999; Gartner *et al.* 2001; Meral 2008). It can also be used to determine mass SSC from volume SSC if particle density is known (Traykovski *et al.* 1999; Gartner *et al.* 2001; Melis *et al.* 2003). Unlike single-frequency optical backscatter instruments, these instruments are not subject to potential inaccuracies associated with changes in PSDs if the particle sizes fall within the range of instrument sensitivity (Agrawal & Pottsmith 2000). Onboard memory and power allow high temporal resolution sampling at intervals up to 5 Hz during field studies that range in time scales from days (or tidal cycles) to months. In addition to analysis of PSDs and concentrations of inorganic material, LISST instruments are now being used increasingly for analysis of size distribution and population concentration and mixing dynamics of organic material such as phytoplankton (see, for example, Serra *et al.* 2001, 2003; Karp-Boss *et al.* 2007).

There are limitations associated with the use of LISST instruments for determining size distribution of suspended sediment. The scattering model (Mie theory) requires absence of multiple light scattering; thus, there is an upper SSC limit because of the presence of multiple scattering from particles at high SSC. Agrawal & Pottsmith (2000) found multiple scattering effects occurred when optical transmission was less than 30%. The limiting SSC is a function of particle-size distribution, laser-path length, and SSC; it ranges from tenths of a gram per liter (for small particle sizes) to a few grams per liter (for larger particle sizes). In addition, as is the case with all types of *in situ* optical instruments, biofouling can degrade measurements.

These problems can be addressed with anti-fouling shutters or optical blocks that reduce the laser path length (Sequoia Scientific, Inc. 2008). For example, reducing the optical path in water from the standard 5 cm to 3 mm has been effective in extending measurement limits to 2–3 g/L of fine material. For still higher SSCs, a LISST-Infinite was developed as part of a research-and-development project with the USGS. The LISST-Infinite, a prototype of which was tested by the USGS (Konrad *et al.* 2006), pumps a water–sediment sample to the instrument, and then uses automated multi-stage dilution (as necessary) before measuring PSDs and SSCs with a built-in LISST-100. Thus, the measurable SSC limit is, in theory, extended to the highest SSCs of material that can be pumped to the LISST-100 (Yogesh Agrawal, Sequoia Scientific, Inc., personal communication 2008). However, the process of pumping the water-sediment sample from a point in the channel may alter the original size distribution. Still another version of the LISST-100, the LISST-FLOC, is designed to measure larger particles such as flocculated estuarine marine particles.

As previously presented, laser diffraction techniques historically have interpreted the light scattered by natural particles as 'equivalent spheres', i.e. an ensemble of spheres with identical angular scattering properties. However, spherical particles are rarities in nature. Angular scattering from irregularly shaped particles is different to that from spheres. An irregular particle scatters light similarly to that of a spherical particle that is ¼- to ½-phi larger than the irregular particle's median diameter (Agrawal *et al.* 2008). For example, a natural particle of diameter 10 μm may be inferred as a 12- to 14-μm particle using laser diffraction. Agrawal *et al.* (2008) quantified the multi-angle laser scattering characteristics of natural particles. They interpreted the measured laser light scattering as random shaped particles rather than spheres, an interpretation that produced results consistent with sieved samples.

An instrument somewhat similar to the LISST-100, the LISST-25, measures mean SSC and Sauter mean particle size (the diameter of a sphere that has the same volume/surface area ratio as the particle of interest) in two size classes (2.5–63 µm and 63–500 µm) (Sequoia Scientific, Inc. 2008). The LISST-25 is based on the same principles as the LISST-100, but, unlike the LISST-100, it determines SSC through a weighted summation of the output of ring detectors rather than the inversion of intensity distribution to obtain size distribution. The weighted sum can be affected by use of comet-like shaped focal plane detectors (Yogesh Agrawal, Sequoia Scientific, Inc., personal communication 2008).

A cable-suspended, streamlined, isokinetic version of the LISST-100, the LISST-SL (Fig. 1.10b), is being developed for manual river deployment. The LISST-SL is designed to address the potential problem of flow disturbance associated with the size and shape of the conventional LISST-100 instruments. The LISST-SL features the capability of real-time velocity measurement that 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*. 2004; Agrawal & Pottsmith 2006). This isokinetic flow-through capability is a prerequisite for reliably ascertaining the suspended-sediment properties in all but the shallowest or most sluggish rivers. The performance of the LISST-SL is being evaluated by the FISP (2008).

1.2.2.2 Example field evaluation

Laser diffraction sensors are being investigated as an alternative monitoring protocol for tracking reach-scale suspended-sediment supply at a USGS streamgage on the Colorado River at Grand Canyon, Arizona, USA, located 164 km downstream from Glen Canyon Dam (Melis *et al*. 2003; Topping *et al*. 2004). A canyon wall-mounted LISST-100 provides continuous PSD and SSC data for computing suspended-sediment transport that may reduce uncertainty in estimates of the transport of sand and finer material.

An example of data collected by the LISST-100B at the Colorado River at the Grand Canyon streamgage is shown in Fig. 1.11. Data were obtained by averaging 16 measurements at 2-minute intervals during a 24-hour deployment in July 2001. The time series of 720 LISST-100B measurements obtained from a single point in the river compare favorably with cross-sectional data obtained concurrent with some of the LISST-100B measurements using an isokinetic bag sampler and techniques described by Nolan *et al.* (2005). In addition, the LISST-100B also recorded the increase of variance in the SSC of sand-size particles expected with increasing flows (Melis *et al*. 2003); peak SSC values ranged between 0.06 and 0.14 g/L (60–140 mg/L).

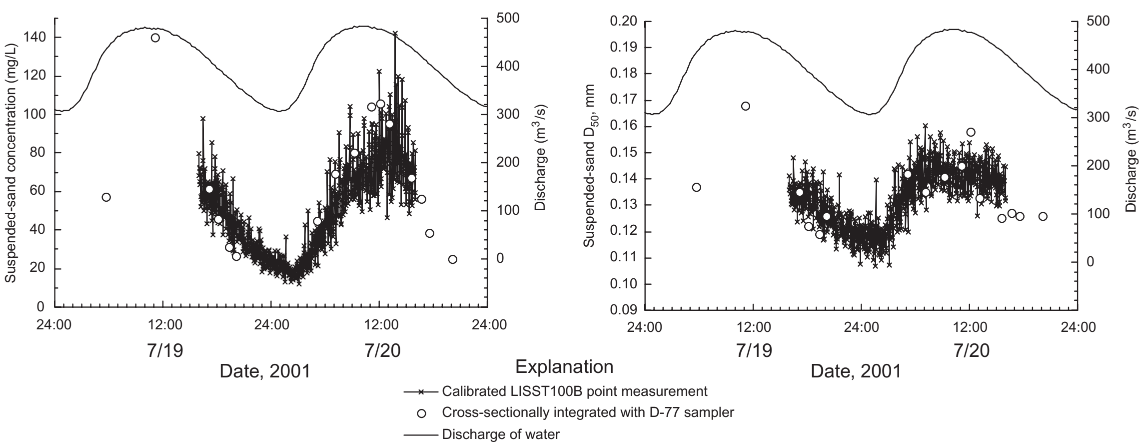


Fig. 1.11 Comparison of SSC (left) and median grain sizes (right) measured at the USGS streamgage, Colorado River at Grand Canyon, Arizona, USA, using a LISST-100-B and a US D-77 bag sampler.
From Topping *et al*. (2004).

1.2.2.3 Summary: laser diffraction as a suspended-sediment surrogate technology

A major advantage of the LISST technology is real-time measurement of PSD in 32 ¼-phi-diameter size classes, a capability shared by no other currently available sediment-surrogate monitoring instrument. LISST instruments do not require instrument calibration when used for PSD or volume SSC.

Nevertheless, the technology has some limitations. The measurement is a point sample. In addition, SSC measurements are in volume units, thus requiring estimates or measurements of sediment density to convert to mass SSC units. When deployed *in situ*, the LISST is susceptible to biofouling unless anti-fouling shutters are used. Reductions in data accuracy due to the presence of non-spherical particles and loss of data from signal saturation can occur. Finally, the cost of a LISST instrument is two to six times that of a fully equipped *in situ* turbidimeter. However, for applications that require long-term repetitions of at-a-point or spatially dense measurements, especially if PSD data are required, the LISST suite of instruments may represent the most cost-effective approach for suspended-sediment data acquisition.

1.2.3 Digital Optical Imaging

Daniel J. Gooding

1.2.3.1 Background and theory

A digital optic-image analysis and pattern recognition system that does not require routine calibration has been developed and is being adapted to quantifying SSCs and selected size and shape characteristics of suspended sediment in water samples. The technology, commercially promoted by the medical industry in the 1990s to quantify cells in a blood sample, computes size statistics based on automated measurements of individual particles. Volumetric SSC is inferred from the size statistics.

The technology, in development and testing at the USGS Cascades Volcano Observatory, Vancouver, Washington, USA, was conceptualized for application in the laboratory. However, a field version is planned for testing as part of a stream-side pumping system. The technology may eventually be adapted for use in manually deployed isokinetic sediment samplers. The cost for a complete unit without environmental packaging is similar to that for a fully equipped turbidimeter. The instrument-measurement realm of a digital-optic measurement is a point. Like the LISST technology, routine instrument calibrations are unnecessary.

The principal components of the system are up to three charged-coupled-device progressive scan cameras (each with a selected lens) and a multi-port flow-through cell. Each lens is affixed to the flow-through cell using extension tubes, keeping a precise optical alignment between the cameras, lenses, targeted area, and backlighting (Fig. 1.12a). All components other than the flow-through cell, for which a patent is pending, and extension tubes are commercially available.

The key component of the system, and the only part developed explicitly for this application, is the multi-port flow-through cell (Fig. 1.12b). The flow-through cell serves two purposes: to separate particles into fractions smaller and larger than 75 µm, thus enabling a relatively unobstructed analysis of the smaller particles; and to disjoin and isolate particles to create a more robust digital image of each particle. If imaged particles are separated, or can be digitally separated, they easily can be identified, measured, and counted by the software.

Computing SSC is based on four attributes derived from the images: particle population, particle shape, grayscale relation to turbidity, and the amount of light passing through the entire image. The amount of light (average image brightness) and average image grayscale are measured over a sequence of several images from the flow-through cell taken within 2–6 seconds. The net changes for brightness and grayscale are relative to a reference image using clear water contrast against the sample images. Particle volumes are estimated by calculating a "z" axis length (the third unmeasured axis in the two-dimensional image) based on the particle shape, texture, chord length, and the particle center of gravity from the two-dimensional image.

A multi-camera configuration measures PSDs in the range of 4–4000 µm. This three-order-of-magnitude range cannot be accomplished using a single magnification, hence the use of multiple cameras and lenses is required. The software is designed to integrate images from up to three cameras depending on the particle-size range required by the

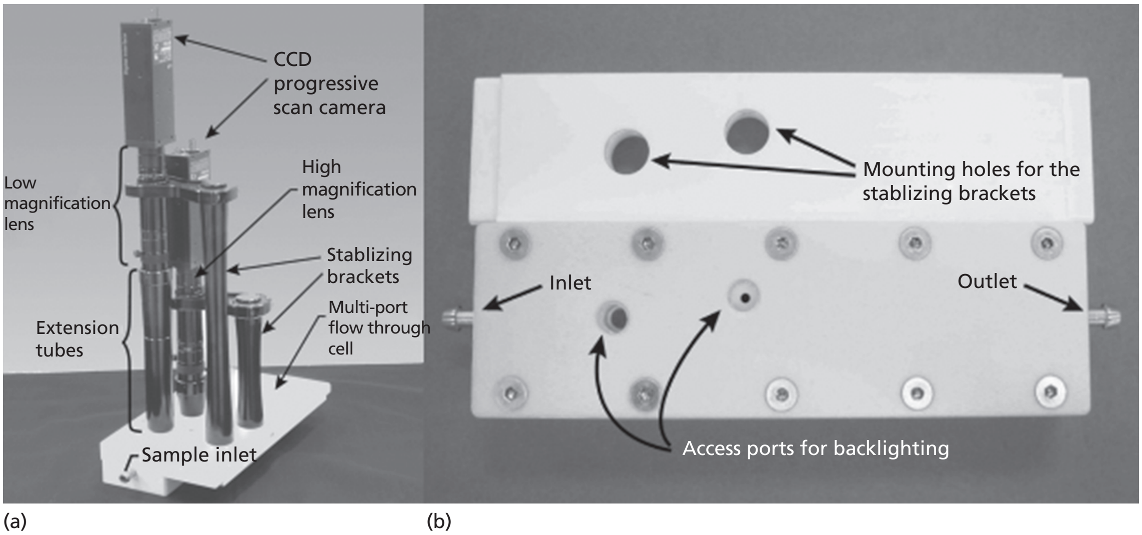


Fig. 1.12 Suspended-sediment digital optic-imaging components. (a) Cameras atop encased lenses with extension tubes and encased flow-through cell (fiber-optic cable not shown). (b) Multi-port flow-through cell (patent pending).

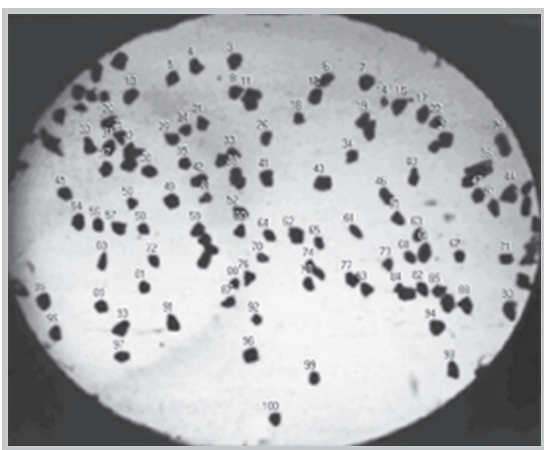


Fig. 1.13 A morphologically transformed image of a water-sediment mixture illuminated by cross-polarization. Each sediment particle and a possible aggregate appearing as a single particle are numbered.

application. Once an image of the water–sediment mixture in the flow-through cell is captured, morphological transformations (successions of pixel-level image processing) are conducted. The final image is used to extract discrete particle information such as maximum and minimum lengths, shape and area (Kindratenko 1997) (Fig. 1.13). Although there may be an upper SSC-measurement limit, any such value is still to be determined.

Inherent complexities involved with imaging individual particles in a liquid medium can create impediments to extracting usable information from the binary images, which usually contain fewer textural details than appear in the original image. Despite some loss of detail in the image, the derived solid-phase images, referred to as “blobs,” are better suited for analysis by the imaging software – particularly for conducting discrete analyses such as particle-edge detection and for computing the size and shape characteristics of individual sediment particles in the final analysis.

The flow-through cell design results in effective dispersion of most particles to render most particle boundaries distinguishable. In the event of incomplete particle dispersion and (or) large SSCs that increase the incidence of imaged-particle overlap, the software uses interpretations based on image normalization, segmentation, and other imaging analysis tools to aid in identifying individual particles.

Balance in contrast is essential for obtaining useful images of sediment particles. As part of the prototype lens assembly, two in-line polarized filters are oriented 50–70° from cross-polarization between the illumination source and target area. This assembly helps darken bright areas created by translucent particles and reduces scattered light caused by refraction and reflectance of the material being imaged. A suitable diffuser is needed for the backlighting to assure balanced lighting throughout the image.

Turbidity, caused by organic and colloidal material, is another hindering factor in obtaining an assessable particle image for analysis. The use of a near-ultraviolet wavelength of 0.45–0.5 µm produces a sharper image of particles. Also, with the shorter wavelength, there is less light scatter due to reflectance and refraction as occurs when using the full visible light spectrum. Figure 1.14 shows suspended material finer than 62 µm at an SSC of 10 g/L (10,000 mg/L) in a sample that was seeded with a small number of 125- to 250-µm particles that were digitally enhanced by the software.

In some cases, the binary image could still be degraded by turbidity, depending on the nature of the factors causing the turbidity. If the spatial correlation of the background cannot be automatically resolved, automatic detection of particle boundaries becomes less precise or unattainable. More analysis and development is required in this regard.

Perhaps the most difficult task in the automatic calculation of size characteristics of imaged blobs deals with connected, aggregated, and overlapping particles that appear as a single blob on the image. The software's segmentation algorithm works well in identifying discrete particles within aggregates by detecting disparities within clusters. Because of this and other possible hindering factors, it is desirable to analyze several images from the same water–sediment sample to better characterize the actual volume SSC computed from poor-quality images. The software is designed to analyze selected layers of the image starting with well-delineated and easily identifiable particles, leaving characterization of those particles that are obscured or that otherwise present definitional problems for the final and most computationally intensive analyses. Research on the photo-imaging technology continues to focus on refining the software to maximize automatic interpretation of aggregates.

For example, the software is able to distinguish a blob as two discrete particles, labeled as 100 and 102 (numbers appear above respective blobs) (Fig. 1.15). Although the blob labeled as 99 may be two connected or overlapping particles, the software interpreted the blob as a single particle. Very fine sand composes the sample material used in this image. Using a microscope, it was observed that some of the sand grains are indeed made up of two naturally fused minerals that gave some of the single particles a barbell-shape appearance.

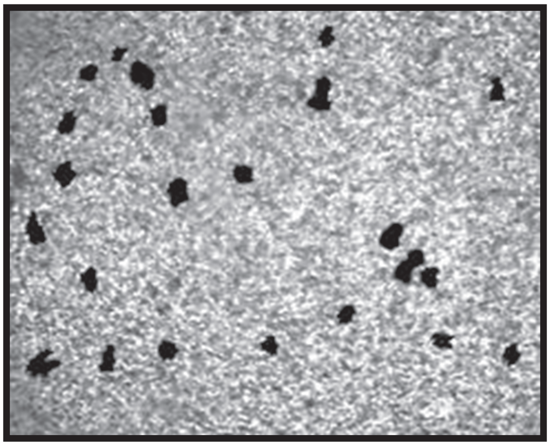


Fig. 1.14 A morphologically transformed image of a water-sediment mixture composed of 10 g/L of material finer than 62 µm, seeded with 125- to 250-µm particles that appear as dark blobs.

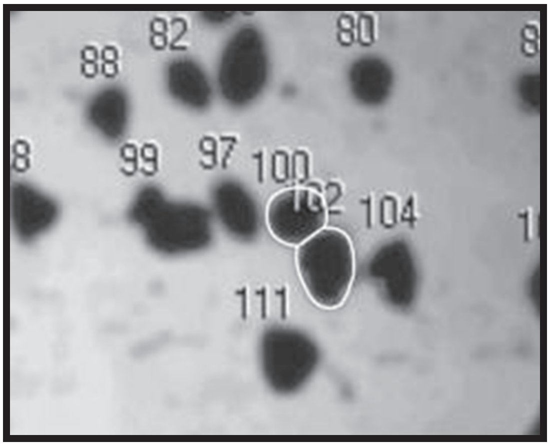


Fig. 1.15 A morphologically transformed image of a water–sediment mixture composed of 62–125 µm particles showing potentially inconsistent interpretation of overlapping or connected particles.

1.2.3.2 Status of laboratory evaluation

Research in quantitative digital-optic analysis for suspended-sediment particles has so far been limited to laboratory conditions at the USGS Cascades Volcano Observatory, Vancouver, Washington, USA. The technology calculates, enumerates, and sums volumes of individual moving particles photographed in a flow-through cell. There are no routine requirements for validation of the technology, although cross-section calibrations will be required if deployed in the field in the future.

Several challenges remain in rendering this laboratory-based technology acceptable for laboratory or riverine deployment. Partly hidden particles, aggregates, and other anomalies can result in less-accurate measurements, as can higher turbidity levels. The multi-port flow-through cell design reduces these problems; however, imaging bias can still occur, such as at very large SSC of clay-size particles. Analytical results are expressed in volume/volume units and not in more commonly used mass/volume units, requiring assumptions on the value of particle density or collection and analysis of samples for SSC and (or) particle density. Reliable PSD and SSC estimates can be difficult to obtain when the image becomes "noisy" because of several factors. Aggregates, organics, air bubbles, and stagnant material within the viewing area can cause the image to become corrupted and numerically unstable. Special safeguards incorporated into the software help overcome these obstacles.

If the source of the imaging problems is identified, then there may be geometric and statistical solutions to the problem. For example, image-to-image comparisons can be used to check for stationary particles that have adhered to the flow-through cell windows viewing area. This particular group of pixels becomes useless for analytical purposes until the area has cleared. The software recognizes the recurring blob and will not use the occupied pixels in sequential calculations until the area clears or changes. Air bubbles could be counted as particles, but with their distinctive geometric attributes the software can easily identify them as such and remove them from subsequent SSC calculations.

There are inherent difficulties for digital-imaging systems to perform well in real-world environments. However, if the problems can be identified and quantified and the number of complicating environmental variables minimized, it may be feasible to achieve practical quantitative results for measuring SSC and PSDs in riverine environments.

1.2.3.3 Summary: digital optical imaging as a suspended sediment surrogate technology

Digital-optic imaging technology remains in the research and development phase and has yet to be deployed for testing beyond the laboratory. Other than the flow-through cell and lens extensions, the technology is composed of off-the-shelf parts available at a cost similar to that of a fully equipped turbidimeter. Routine instrument calibrations are unnecessary.

Pending completion of testing and development, several inferences on limitations based on its attributes can be made:

- The technology can be affected by some of the same drawbacks as those for the bulk-optic and laser technologies. These drawbacks include issues associated with samples drawn from a single point, biofouling of the optic lenses, and upper measurement limits;
- Assumptions or measurements of mean particle density are required to convert volume SSC values to mass SSC values;
- Because the flow-through cell system is designed to separate aggregated sediments, it is not suitable for ascertaining SSCs of flocculents.

1.2.4 Pressure difference

John R. Gray, Nancy J. Hornewer, Matthew C. Larsen, Gregory G. Fisk, & Jamie P. Macy

1.2.4.1 Background and theory

The pressure-difference technique for monitoring SSC relies on measurements from two precision pressure-transducer sensors arrayed at different, fixed elevations in a water column. The difference in pressure readings is converted to a fluid-density value, from which SSC is inferred after correcting for water temperature (dissolved-solids concentrations in fresh-water systems are rarely large enough to be of consequence in the density computation). One of the first uses of the pressure-difference technique for measuring fluid density was applied to crude oil in pipes (William Fletcher, Design Analysis Associates, Inc., personal communication 1999).

The specific weight of the water–sediment mixture from measured pressure differences in a water column between two pressure-transducer orifices anchored at different depths can be calculated by the following equation:

$$\gamma = (p_1 - p_2)/(z_2 - z_1) \qquad (1)$$

where: γ is the specific weight of the fluid; p_1 and p_2 are the simultaneous pressure measurements at orifices 1 and 2, respectively; and z_1 and z_2 are the simultaneous measurements of the distances to the water surface from orifices 1 and 2, respectively.

The difference in the distances from the fixed orifices to the water surface is a constant value. SSC is calculated as the difference in the specific weights of the water–sediment mixture and that of pure water at the same temperature as the ambient streamflow. Implicit assumptions in the method are that the simultaneous pressure measurements represent the same water surface, and that the density of the water–sediment mixture above the lower sensor is more or less equal to that above the higher sensor. Exceptionally sensitive pressure transducers are required. The technology has both laboratory and field applications (Lewis & Rasmussen 1999). The purchase price of the technology is similar to that for a fully equipped turbidimeter. In theory, the installation should require a minimum of maintenance other than removal of debris from the in-stream sensor assembly. The instrument-measurement realm is a water column. Instrument calibrations can be accomplished by sampling in or near the instrumented water column with a suspended-sediment sampler, although they are often supplanted by cross-section calibrations.

The technique has been applied in the laboratory with promising results of better than 3% accuracy (0.543 ± 0.014 g/L) for determining mass concentration of suspensions of glass microspheres (Lewis & Rasmussen 1999). However, application of this technique in the field can be complicated by a low signal-to-noise ratio associated with low-to-moderate SSC, turbulence, large dissolved-solids concentrations, and large water-temperature variations. Additionally, analyses may be complicated by density variations in the suspended material. William Fletcher (Design Analysis Associates, Inc., personal communication 2005) indicated that calculations based on a moving average of the pressure-difference data tended to provide a smoother time series of SSC that was more comparable to SSC data derived from water–sediment samples obtained by methods described by Nolan *et al.* (2005).

1.2.4.2 Example field evaluations

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) and near the mouth of the Paria River in Arizona, USA. Continuous pressure-difference data were collected during October–December 1999 at the Río Caguitas streamgage using a Double Bubbler Pressure Differential instrument developed by Design Analysis Associates, Inc. (2008) (Figs 1.16 and 1.17). Most of the annual sediment discharge in the lower Río Caguitas occurs in runoff from a few storms when SSC exceeds about 0.5 g/L. The maximum SSC measured at the streamgage during the Double Bubbler tests based on water samples collected by an automatic pumping sampler was 17.7 g/L.

The analytical procedure 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, this test of the Double Bubbler instrument in Puerto Rico showed relatively poor agreement among discharge, SSC, and the manipulated water-density data measured by the Double Bubbler (Fig. 1.18). 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) concomitant with in-stream measured SSC values of 0.01–0.1 g/L (10–100 mg/L). However, all but two of the samples collected during seven high-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

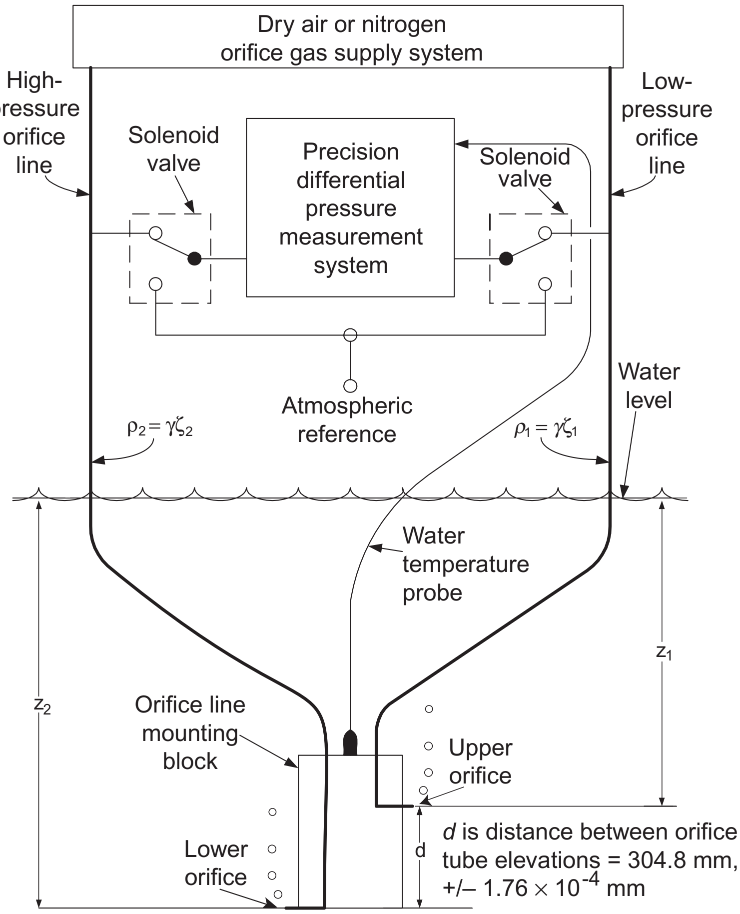
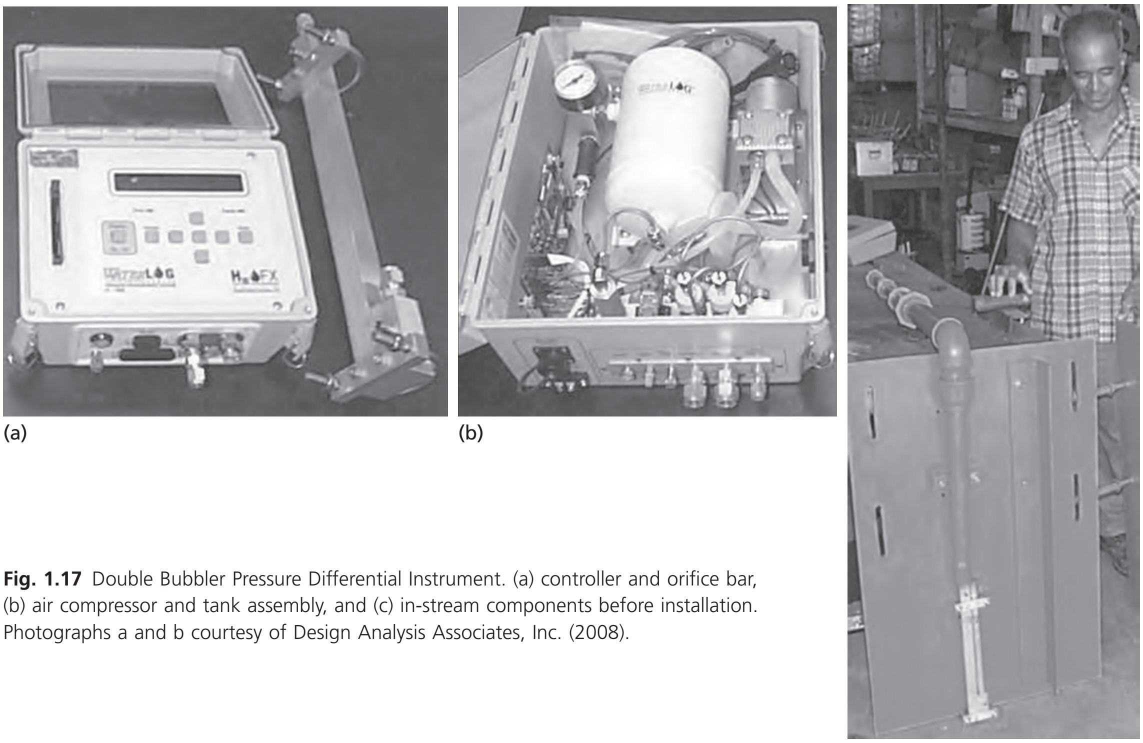


Fig. 1.16 Schematic of the Double Bubbler Pressure Differential instrument. Adapted from Larsen *et al.* (2001).

interest, particularly during high discharges that occur more or less concomitant with the largest SSC levels. Additionally, diel and storm-related fluctuations in water temperatures must be accounted for by using a continuously logging temperature sensor (the daily range in water temperatures at the Río Caguitas streamgage is as much as 10 °C). The high relative humidity characteristic of this humid-tropical site can 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 weight densities of higher flows might be substantially larger than those measured at the Río Caguitas streamgage during the Double Bubbler tests.

In 2004, the Puerto Rico Double Bubbler system was transferred to the USGS streamgage on the Paria River at Lees Ferry, Arizona, USA, and augmented with a continuous water-temperature sensor. SSCs near 10^3 g/L have been measured during storm runoff at this streamgage. Deployment of the Double



(a) (b) (c)

Fig. 1.17 Double Bubbler Pressure Differential Instrument. (a) controller and orifice bar, (b) air compressor and tank assembly, and (c) in-stream components before installation. Photographs a and b courtesy of Design Analysis Associates, Inc. (2008).

Bubbler in the Paria River was predicated on the hypothesis that the expected large weight densities, ranging up to about double that of pure water under hyperconcentrated streamflow conditions (Beverage & Culbertson 1964), would prove to be within the Double Bubbler's operating range.

Double Bubbler data were collected, at 5-minute intervals, during periods of elevated flow at the Paria River streamgage from July 2004 through September 2006. Data collected from 14 periods of storm runoff were examined and compared with results from suspended-sediment samples collected during the storm runoff. The samples were collected using a combination of automated-pump samplers, depth-integrating samplers in a single vertical and deployed in the cross section, and dip samples (Nolan *et al.* 2005; Edwards & Glysson 1999). The elevated flows had peaks ranging from about 7–90 m^3/s; the maximum SSC measured was 382 g/L in water from an automated-pump sampler. A total of 261 suspended-sediment samples were collected during the 14 storm-runoff periods, and 86% of those samples had SSC values larger than 50 g/L. Double-Bubbler data were collected only during periods when water levels immersed both pressure sensors (the instrument was not fully submerged during normal shallow flows).

Double Bubbler data were filtered to remove outliers but not smoothed, because smoothing appeared to have little effect on reducing signal noise for data collected at this site. Water-temperature data were continuously recorded near the Double-Bubbler orifices. The weight density of suspended sediment and dissolved solids was calculated by subtracting the weight density of pure water, corrected for temperature, from the filtered data.

Similar to data collected at the Río Caguitas in Puerto Rico, the Double Bubbler data collected at the USGS streamgage on the Paria River at Lees Ferry, Arizona, USA, had a large amount of signal noise, also making interpretation difficult. Relations between measured SSC and SSC calculated from

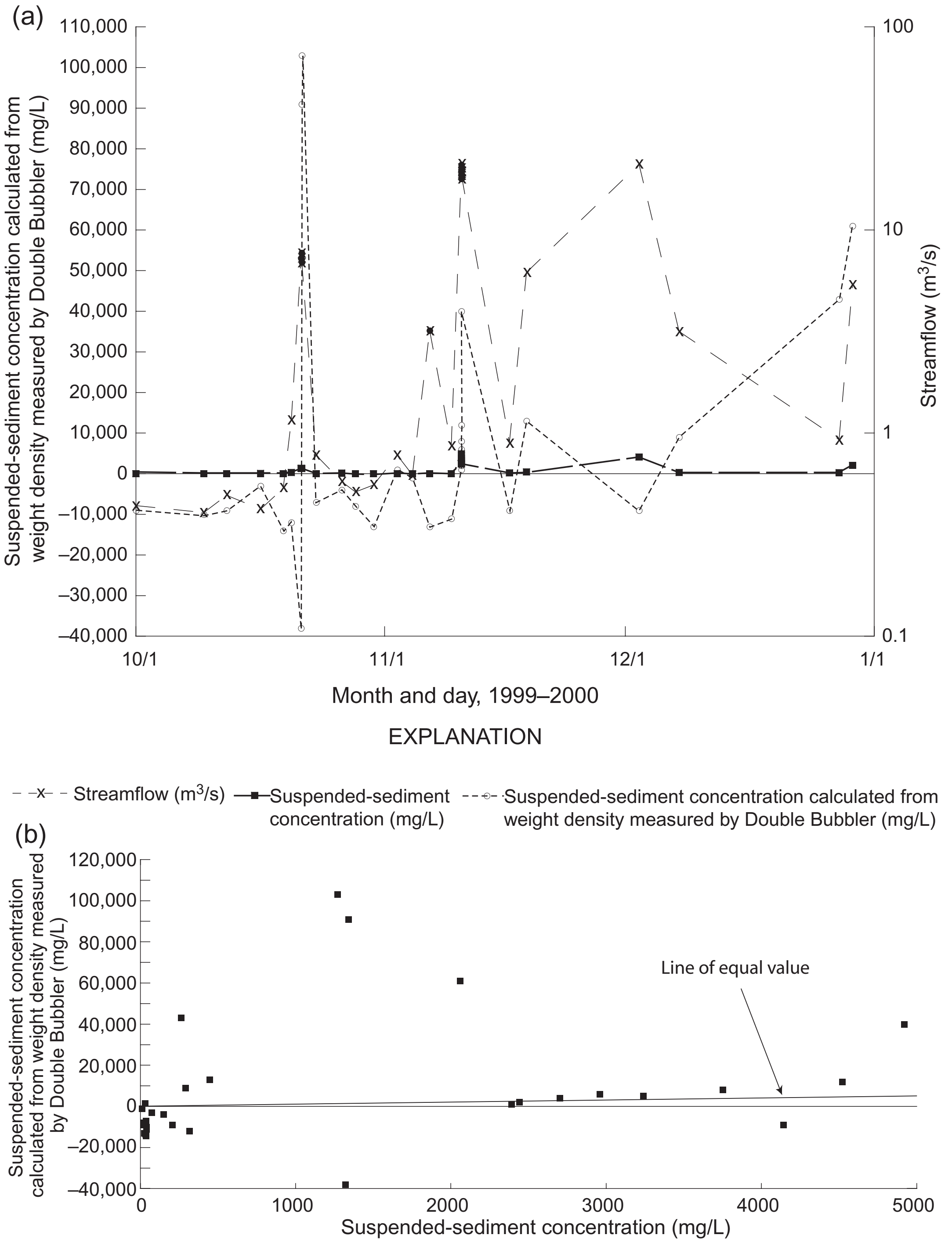


Fig. 1.18 Data for the USGS streamgage on the Rio Caguitas, Puerto Rico, October 1999 to January 2000. (a) Time series of streamflow, SSCs from samples, and SSCs calculated from weight densities of suspended sediments and dissolved solids measured using the Double Bubbler; symbols denote measured values, dashed interpolation lines are included for viewing purposes only; (b) scatter plot of measured SSCs from samples and those calculated from the Double Bubbler. Streamflow and sediment data are instantaneous samples, and each Double Bubbler SSC value, calculated from weight density, is a 30-minute mean of measurements made at 5-minute intervals.

Double Bubbler data lacked consistency, as illustrated by Fig. 1.19. Although parts of the record more or less show agreement between Double Bubbler-derived SSC data and those from analyses of physical samples, none of the sampled SSC values on January 10–12, 2005, was among the dozens of Double Bubbler values exceeding about 220 g/L. However, the veracity of the larger Double Bubbler measurements cannot be dismissed out-of-hand as measurement artifacts; essentially all of the physical-sample SSC values plot among Double Bubbler data, and all but the largest Double Bubbler SSC value are less than the historical maximum SSC of 1,080 g/L reported by Beverage & Culbertson (1964) for the Paria River streamgage.

It has been surmised that bed movement during Paria River Double Bubbler tests caused the lower orifice to become partly or fully blocked at times, contributing to erroneous data. In their tests of an *in situ* densimeter (pressure-difference monitoring system), Tollner *et al*. (2005) identified the passage of bed forms between the densimeter's orifices and fluid turbulence as potential complicating factors in SSC computations. They conclude that densimeter measurements, although feasible under laboratory conditions, are unreliable in general field conditions.

The USGS experience with the Double Bubbler cannot unequivocally support or refute Tollner *et al*.'s (2005) conclusion. However, because of its strong theoretical underpinnings, continuous monitoring capability, and – not unimportantly – a lack of any other proven surrogate technology for providing SSC time-series data in highly concentrated and hyperconcentrated streamflow conditions, the pressure-difference technique continues to be evaluated.

1.2.4.3 Summary: pressure difference as a suspended sediment surrogate technology

The pressure-difference technology was tested to ascertain if it could fulfill what may be a unique niche in suspended-sediment monitoring because, at least in theory, its performance improves as SSCs increase. The technology is relatively robust, being prone to neither signal drift nor biofouling, and is comparatively inexpensive. The technology doubles as a redundant stage sensor for the site. The theoretical underpinnings of the technology are relatively simple and straightforward. Given a valid set of temperature-compensated measurements at higher SSC values that are adequately filtered and smoothed to reduce the effects of turbulence, the technology may provide a time series of SSC that is ultimately superior to the periodic datasets obtained by traditional methods. The instrument can be calibrated using single-vertical samples. The water-column measurements are theoretically more representative of the mean cross-section SSC than point measurements.

In spite of its sound theoretical underpinnings, the field performance of the Double Bubbler in Puerto Rico and northern Arizona, USA, has yet to be fully resolved. Research is continuing into whether development and use of empirical relations from calibration data in lieu of the theoretical considerations are warranted. The required computational scheme presupposes that the SSC in the vertical profile between the sensors is more or less equal to that above the higher sensor. This assumption is difficult to verify and may not be valid. The technology is unreliable for measuring SSC at less than about 10 g/L, and the actual lower measurement threshold may be at a somewhat larger SSC. The technology is incapable of measuring SSC when the top orifice is out of water. Spurious data are numerous and are believed to be associated with flow turbulence or orifice blockage by bedforms. Continuous pressure-difference measurements may be useful in developing a continuous SSC trace under some circumstances but are not yet considered sufficiently reliable to replace traditional suspended-sediment-monitoring techniques.

1.2.5 Acoustic backscatter

Jeffrey W. Gartner & Scott A. Wright

1.2.5.1 Background and theory

Attempts to characterize SSC from *in situ* acoustic backscatter sensors (ABS) have increased in recent years. In contrast to traditional methods using analyses of water samples utilizing gravimetric or other techniques, use of ABS to estimate SSC is non-intrusive, far less labor intensive for the derived data density, more or less unaffected by biofouling, and results in a continuous time series of SSC. Use of ABS is appealing because SSC profiles can be obtained in

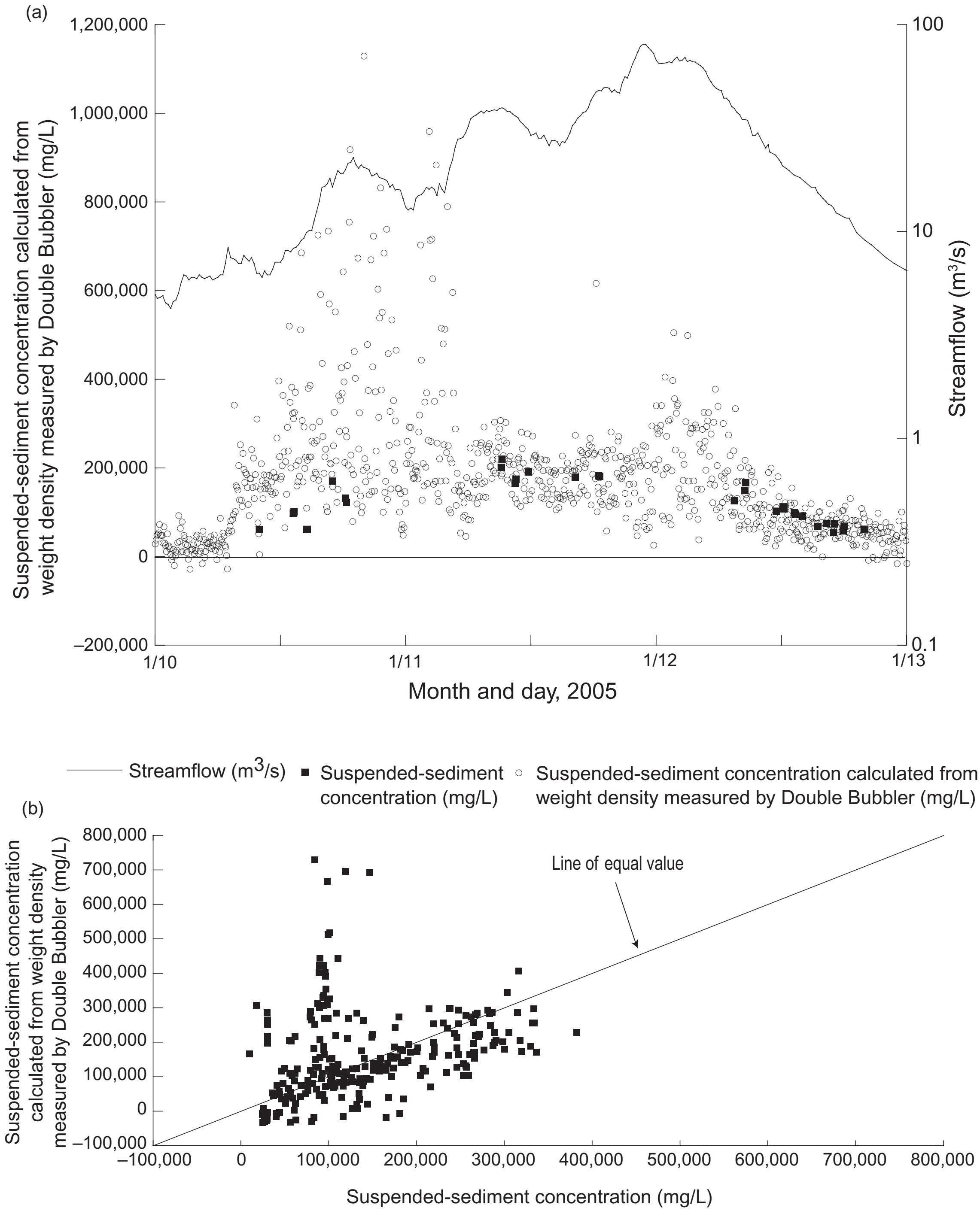


Fig. 1.19 Data for the USGS streamgage on the Paria River at Lees Ferry, Arizona, USA, July 2004 through September 2006. (a) Time series of streamflow, SSCs from samples, and SSCs calculated from weight densities of suspended sediments and dissolved solids measured using the Double Bubbler for a storm in January 2005; (b) scatter plot of measured SSCs from samples and those calculated from the Double Bubbler. Streamflow and sediment data are instantaneous samples, and the Double Bubbler SSC values, calculated from weight densities, are from measurements made at 5-minute intervals.

the acoustic beam, which typically characterize the sedimentary content of multiple orders of magnitude more water than point samplers. Like bulk-optic techniques, empirical calibrations are required to convert the ABS measurements to SSC. Complex post-processing requires compensations for physical properties of ambient water such as temperature, salinity, and pressure, and, in some cases, suspended materials. Additional compensations are needed for instrument characteristics such as frequency, power, and transducer design.

The purchase price of a commercially available single-frequency Doppler *in situ* instrument is about two to four times that of a fully equipped turbidimeter. Because biofouling has little if any effect on the performance of the sensor, field-maintenance costs are probably less than that for a turbidimeter. The instrument-measurement realm is multiple conic beams. Instrument calibrations can be performed using physical samples collected within the volume of the beam; however, they are often supplanted by cross-section calibrations.

The development and application of the ABS technology can be broadly grouped into two approaches, based primarily on the instrumentation type and target application (the underlying theory is equivalent for the two approaches). The first approach uses specially designed acoustic instrumentation often using multiple frequencies to compute SSCs and grain sizes over relatively short ranges (1–2 m). This approach has primarily been applied using fixed deployments to study near-bed sediment transport processes in the marine environment. There are ample publications describing the development and application of this approach (see, for example, Hanes *et al.* 1988; Sheng & Hay 1988; Hay 1991; Thorne *et al.* 1991, 1993, 1995, 1996; Hay & Sheng 1992; Thorne & Campbell 1992; Crawford & Hay 1993; Richards *et al.* 1996; Schaafsma & Hay 1997; Thorne & Hardcastle 1997; Thorne & Buckingham 2004; Thorne & Meral 2008). A review paper by Thorne & Hanes (2002) provides a good overview of the technique. This approach requires calibration of a "system constant" for each instrument, which is typically accomplished in the laboratory (Thorne & Hanes 2002). At least one commercially available instrument that uses this technique but lacks Doppler capability is available (Aquatec Group 2008).

The second approach uses commercially available *in situ* acoustic Doppler current profiles (ADCPs; the term ADCP is used generically and does not imply a particular manufacturer unless specified.) This approach is particularly suited to monitoring suspended-sediment flux because ADCPs provide three-dimensional velocity profiles as well as acoustic backscatter information. As stated above, the underlying theory is the same, though for the ADCP approach the sonar equations are typically formulated in logarithmic form (i.e. in decibels (dB); see next section) whereas for the first approach the linear form of the equations are used (i.e. in terms of pressure or voltage). The increasing popularity of ADCPs for characterizing hydrodynamics in fluvial, estuarine, and coastal environments has facilitated the concurrent estimation of suspended-sediment properties in these environments as well.

Theoretical aspects of the ADCP approach have been well documented (see, for example, Thevenot *et al.* 1992; Reichel & Nachtnebel 1994; Deines 1999; Gartner 2004). Applications have been documented for a wide range of environments (see, for example, Schott & Johns 1987; Thevenot *et al.* 1992; Thevenot & Kraus 1993; Jay *et al.* 1999; Klein 2003; Gartner 2004; Topping *et al.* 2004, 2006, 2007; Hoitink & Hoestra 2005; Hortness 2006; Wall *et al.* 2006; Tessier *et al.* 2008; among many others). At least one commercial software product is available to convert backscatter to SSC (Land & Jones 2001). Comparisons of SSC computed from acoustic backscatter with SSC values determined from water samples have been found to agree within about 10–20% (Thevenot *et al.* 1992; Thorne *et al.* 1991; Hay & Sheng 1992).

The theoretical development presented below is constructed in terms of the logarithmic form of the sonar equations, which is the typical form used for the ADCP approach. This form is particularly suited to this approach because commercially available ADCPs typically provide the conversion factor from raw backscatter counts to decibels (see below), which facilitates accounting for transmission losses and empirical calibration of backscatter to SSC. The logarithmic form of the sonar equations can be inverted to obtain an expression for SSC:

$$SSC_{computed} = 10^{(A+(B*RB))} \quad (2)$$

The exponent of eqn. 2 contains a term for the relative acoustic backscatter, *RB*, measured by an instrument such as an ADCP as well as terms for an intercept, *A*, and slope, *B*, determined by regression of concurrent ABS with known mass SSC measurements ($SSC_{measured}$) on a semi-log plane in the form of $\log(SSC_{measured}) = A + (B*RB)$. The relative backscatter is the sum of the echo level measured at the transducer plus the two-way transmission losses (Thevenot *et al.* 1992) as defined below.

In its simplified form, the sonar equation (Urick 1975) can be written as:

$$RL = SL - 2TL + TS \quad (3)$$

where: *RL* is the reverberation level; *SL* is the source level, which is the intensity of emitted signal that is known or measurable; *2TL* is the two-way transmission loss; and *TS* is the target strength, which is dependent on the ratio of wavelength to particle diameter.

All variables in eqn. 3 are measured in decibels. In terms of ADCP parameters, $RL = K_c(E - Er)$, where *E* is ADCP echo intensity recorded in counts, *Er* is ADCP received signal strength indicator (RSSI) reference level (the echo baseline when no signal is present), in counts, and K_c is the RSSI scale factor used to convert counts to decibels. K_c varies among instruments and transducers and has a value of 0.35–0.55 (Deines 1999). The two-way transmission loss is defined as:

$$2TL = 2(\alpha_w + \alpha_s)R + 20\log R \quad (4)$$

where: *R* is the range to the ensonified volume, in meters; α_w is an absorption coefficient for water; α_s is an attenuation coefficient accounting for viscous and scattering losses due to suspended sediment (see below), both in decibels per meter; $2(\alpha_w+\alpha_s)R$ is the combined transmission loss due to water absorption and sediment attenuation; and $20\log R$ is the loss due to spreading.

The absorption coefficient for water is a function of acoustic frequency, salinity, temperature, and pressure (Schulkin & Marsh 1962). Because of nonspherical spreading in the transducer near field, the spreading loss is different in near and far transducer fields. The transition between near and far transducer fields is called the critical range, $R_{critical}$. $R_{critical} = \pi a_t/\lambda$ where a_t is the transducer radius, in centimeters, and λ is acoustic wavelength. The near-field correction, ψ, for spreading loss can be calculated from the formula in Downing *et al.* (1995) as:

$$\psi = \left[1 + 1.35Z + (2.5Z)^{3.2}\right] \Big/ \left[1.35Z + (2.5Z)^{3.2}\right] \quad (5)$$

where: Z is $R/R_{critical}$.

As an example, $R_{critical}$ is 167 cm for a 1200-kHz ADCP with a 5.1-cm diameter transducer.

For the particle-size range and acoustic frequencies of interest here, attenuation from suspended sediment consists of a viscous loss component and a scattering loss component (Flammer 1962; Richards *et al.* 1996). In the presence of suspended sediments that are generally less than 100–200 µm, the viscous and scattering components of attenuation change in opposing ways to changes in size (for typical ADCP transducer frequencies). Attenuation from viscous losses increases inversely with sediment size. Attenuation from scattering losses increases directly with sediment size. Scattering characteristics are a function of λ to particle circumference $2\pi a_p$, where a_p is particle radius. When $\lambda \gg 2\pi a_p$, most of the scattering pattern propagates backward; however, as λ approaches $2\pi a_p$, the scattering pattern increases in complexity, and when $\lambda \ll 2\pi a_p$ half the scattered pattern propagates forward and the remainder is scattered through all directions (Flammer 1962). In the case of 1200-kHz acoustic sources, $\lambda = 2\pi a_p$ for 400-µm diameter particle size. Taken together, scattering- and viscous-loss terms account for little attenuation with 1200-kHz frequency unless particle size is very small or SSCs are very high, in which case corrections for attenuation are needed. However, in the case of higher frequencies, total attenuation may need to be accounted for even at lower SSC if particles are very small (viscous losses) or larger than about 100- to 150-µm diameter (scattering losses). The result is a nonlinear (backscatter intensity) response at high SSC (Hamilton *et al.* 1998). Although a function of frequency, attenuation from sediment may need to be accounted for in the presence of as little as 0.1 g/L (Libicki *et al.* 1989; Thorne *et al.* 1991); multiple scattering produces nonlinear response when SSC is on the order of 10 g/L (Sheng & Hay 1988; Hay 1991). Thorne *et al.* (1991) found that, in the case of 3.0- and 5.65-MHz acoustic frequencies, attenuation from fine sands may become significant at ranges on the order of a meter when

SSC levels approach 0.1 g/L. Attenuation due to presence of sediment can be accounted for following Flammer (1962). A coefficient, ζ, is defined as:

$$\zeta = K(\gamma - 1)^2 \{S/[S^2 + (\gamma + \tau)^2]\} + (K^4 a_p^3)/6 \quad (6)$$

where: $K = 2\pi/\lambda$; γ is the particle or aggregate wet density divided by the fluid density; $\tau = 0.5 + 9/(4\beta a_p)$; $S = [9/(4\beta a_p)][1 + 1/(\beta a_p)]$; $\beta = [\omega/2\nu)]^{0.5}$; $\omega = 2\pi f$, f is frequency in Hz; and ν is the kinematic viscosity of water, in stokes. The two-way attenuation from suspended particles, $2\alpha_s$ in decibels per centimeter, is equal to (8.68)(ζ)(SSC), where SSC is dimensionless (1000 ppm = 0.001) and 8.68 is the conversion from nepers to decibels. The first term in eqn. 6 is the attenuation from viscous losses and the second term is the attenuation from scattering losses. An alternative form for the scattering loss component can be found in Richards *et al.* (1996).

From a practical standpoint, it is not necessary to know the source level, nor is it typically feasible to measure all the characteristics of suspended material required to directly model target strength (Thevenot *et al.* 1992; Reichel & Nachtnebel 1994). Therefore, following the derivation of Thevenot *et al.* (1992), eqn. 3 is cast in terms of relative backscatter, $RB = RL + 2TL$. After appropriate substitutions, the sonar equation can be written in the desired form in terms of SSC and relative backscatter as:

$$\mathrm{SSC} = 10^{(-0.1K_2 + 0.1RB)} \quad (7)$$

where: K_2 is a parameter that includes terms for source level, target strength, ensonified volume, and mass of suspended material.

The theoretical parameters $A = -0.1K_2$ and $B = 0.1$ are appropriate for an SSC of uniform particles of the same mass and other properties. For a distribution of particles in the field, agreement with the theoretical values is experimentally checked by regression of RB with measured estimate of SSCs at the same location. Thevenot *et al.* (1992) determined the coefficient $-0.1K_2$ to be equal to 0.97 and 1.43 for laboratory and field calibrations, respectively. They determined values for the coefficient multiplying RB to be 0.077 (laboratory) and 0.042 (field). Thus eqn. 7 can be used to compute a time series of SSC from ADCP ABS at any distance from the acoustic transducer where valid backscatter data are available once appropriate transmission losses and slope and intercept values are determined. An alternative approach is to assume the theoretical value for the slope, B, equal to 0.1 and determine an appropriate value of intercept, $A = \log_{10}(\mathrm{SSC}_{\mathrm{measured}}) - 0.1RB$.

Limitations of the acoustic technique are well described in the literature (e.g. Reichel & Nachtnebel 1994; Hamilton *et al.* 1998). One critical limitation is the fact that it is not possible to differentiate between concurrent changes in SSC and PSD (without sufficient calibrations) when using a single-frequency instrument, as changes in both SSCs and PSDs can result in a change in the backscatter signal strength. In addition, there is an appropriate acoustic frequency for a given PSD. Errors in estimates of SSC will increase if a substantial fraction of the suspended material includes particles that are too large or too small for a response by a given frequency. For these reasons, techniques or instruments that utilize more than one acoustic frequency are preferable to single frequency methods. Several applications of multi-frequency instrumentation have successfully characterized both SSC and mean particle size (Hay & Sheng 1992; Crawford & Hay 1993; Thorne *et al.* 1996; Topping *et al.* 2007).

Finally, an alternative approach for segregating size fractions using a single acoustic frequency has been developed by Topping *et al.* (2006, 2007) on the Colorado River at Grand Canyon, Arizona, USA. This approach segregates the silt-clay and sand components of the suspension by taking advantage of the fact that silt-clay tends to dominate acoustic attenuation whereas sand tends to dominate backscatter. Side-looking ADCPs are mounted on the river bank that profile across the river width; after removing the two-way transmission losses, the slope of the backscatter profile yields the attenuation coefficient, which is strongly correlated with silt-clay SSC, while the acoustic backscatter is strongly correlated with sand SSC. The potential to segregate "wash load" from "bed material suspended load" in sand-bedded rivers warrants future testing of this methodology in a wider range of environments.

1.2.5.2 Example field application

A multi-instrument, multi-frequency system has been established at the USGS streamgage on the Colorado River at Grand Canyon, Arizona, USA, to produce data from which continuous SSCs and SSLs can be computed (Topping *et al.* 2007). The system uses

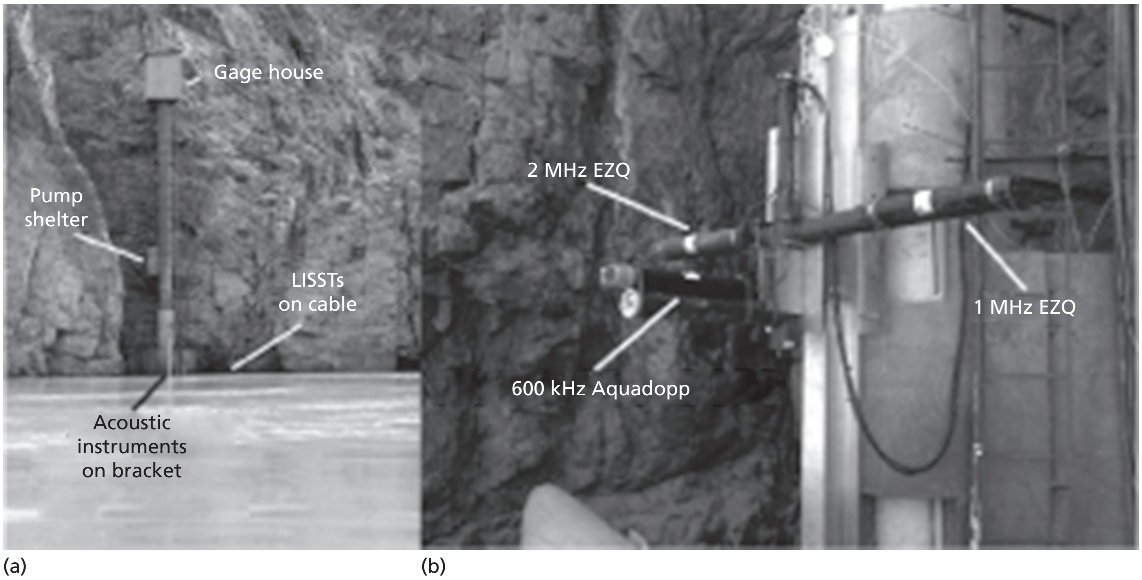


Fig. 1.20 Photograph of an array of the three acoustic Doppler current profilers used to estimate SSCs and PSDs in the Colorado River in Grand Canyon, Arizona, USA.
From: Topping *et al.* (2007).

three single-frequency (1.0 and 2.0 MHz, and 600 kHz) side-looking ADCPs (Fig. 1.20). A post-processing technique is applied to analyze (1) acoustic attenuation to compute the suspended silt-clay size fraction, and (2) acoustic backscatter to compute the suspended-sand fraction in a size range applicable for each frequency. Topping *et al*. (2007) indicate that the approach is applicable for monitoring SSC over the ranges of 0.01–20 g/L (silt-clay) and 0.01–3 g/L (sand); results are within 5% of those computed by conventional methods. In addition, the method calculates median grain size within 10% of that measured by conventional means. Topping *et al*. (2007) infer a greater accuracy with this technique than with a conventional sampling regime largely due to the substantially greater sample frequency and volume. Figure 1.21 shows comparisons of SSC from three-frequency acoustic backscatter, calibrated pump, and LISST measurements.

1.2.5.3 Summary: acoustic backscatter as suspended sediment surrogate technology

As a surrogate for SSC, acoustic backscatter holds several advantages over other suspended-sediment-surrogate technologies. Unlike point measurements, profiles of acoustic backscatter measurements from Doppler velocity instruments can cover a substantial part of the water depth or river cross section; they can integrate orders of magnitude more flow than other methods that rely on at-a-point or single-vertical measurements. Sediment fluxes in the beam can be computed and empirically indexed to the mean cross-sectional SSC value. These data in turn can be used with continuous water-discharge data to compute unit- and daily-value sediment fluxes at the monitoring site. Unlike optic-based surrogate instruments, biological fouling is not a problem.

In addition to some major advantages over other surrogate techniques, the acoustic backscatter method has some limitations. Similar to optical surrogate techniques, a single-frequency source cannot differentiate between change in PSD and change in SSC without calibration and there is an appropriate frequency for a given particle size and a somewhat narrow frequency range for which the method is appropriate for a given size distribution. A series of calculations are required for the reduction and analysis of the acoustic signals; thus until standard operating procedures are developed and adopted for this

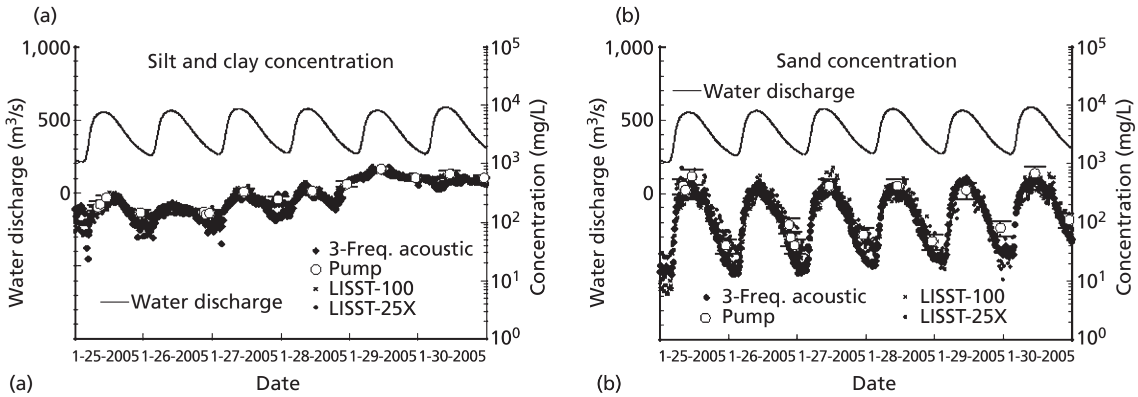


Fig. 1.21 Comparisons of SSCs from three-frequency acoustic backscatter, calibrated pump, and LISST measurements (a) suspended-silt and -clay concentration and (b) suspended-sand concentration.
From Topping *et al.* (2007).

technique, considerable time and effort for a user to compute a time series of SSC from ABS may be required. The cost of a single-frequency *in situ* instrument is about double that for a fully equipped turbidimeter, but the field maintenance cost is expected to be less than that for a turbidimeter.

1.3 Summary and conclusions

Five surrogate technologies for monitoring suspended-sediment-transport characteristics have been or are being tested and evaluated by the USGS toward deployment in operational sediment-transport monitoring programs. The five technologies are bulk optics (turbidity), laser optics, digital optics, pressure difference, and acoustic backscatter. None of the *in situ* technologies measures the surrogate constituent of interest over the entire cross section. Hence, most if not all of the technologies require cross-section calibration. Although most of the *in situ* instruments are routinely calibrated, this step is sometimes bypassed in favor of cross-section calibration.

Table 1.2 summarizes selected attributes of the five suspended-sediment-surrogate technologies presented herein. All of the technologies, with suitable calibration, provide time series of computed SSC at sub-daily sampling frequencies at-a-point (three optical technologies), in a single vertical (pressure-difference technology), or along one more cone-shaped beams (acoustic technology) in streamflow. The capability for providing computed time series of SSC is a major advantage over the relatively sparse data produced by traditional methods for collecting and computing records by conventional methods described by Porterfield (1972), Edwards & Glysson (1999), and Nolan *et al.* (2005). The routine need to estimate SSC values for periods lacking sample data and to interpolate between known or estimated SSC values interjects an unquantifiable degree of uncertainty in traditionally derived sediment-discharge values. The reduction in uncertainty associated with the availability of continuous surrogate data likely will result in a more accurate computation of sediment discharges even considering uncertainties associated with instrument-measurement realm or cross-section calibration of surrogate measurements.

Spatial correlations between any surrogate measurement and its respective mean value in the cross section are still required. However, because of the relatively large ensonified volume associated with acoustic surrogate techniques, correlations associated with the acoustic-backscatter technology are at least theoretically less variable than those for the single-vertical pressure-difference technology, which in turn are theoretically less variable than those for the at-a-point measurements obtained by bulk, laser, or digital-optics technologies.

The most common surrogate technology is turbidity (bulk-optics). Turbidity has been shown to provide sufficiently reliable data for computing SSC

Table 1.2 Summary of selected attributes of five suspended-sediment surrogate technologies.

Technology	Turbidity (bulk optics)		Laser		Digital optic imaging	Pressure difference	Hydroacoustic	
Instrument or type	*In situ* turbidimeter	*In situ* OBS	*In situ* LISST-100	Manually deployed LISST-SL	Multi-camera stream-side pumping system	*In situ* Double Bubbler	*In situ* single-frequency acoustic Doppler profiler	*In situ* multiple-frequency acoustic Doppler profiler
Price relative to *in situ* turbidimeter	*ca*. $5,000 (summer 2008)	About 1×	About 5×	About 6×	About 1×–2×	About 1×	About 2×–4×	Unknown
Approximate concentration measurement range	Standard 0–2 g/L. Available at larger ranges	Standard 0–5 g/L. Available at larger ranges	Depending on versions: 0–2 g/L (particle size dependent)	About 0–2 g/L (particle size dependent)	0–10 g/l; future testing may elucidate a larger upper limit	Larger than about 10 g/L, but needs more research; theoretically no upper limit	Signal attenuation limited as function of PSD and frequency	Signal attenuation limited as function of PSD and frequency
Approximate measurement range, PSD (mm)	Does not measure PSD	Does not measure PSD	0.0025–0.5 or 0.00125–0.25	0.0025–0.5 or 0.00125–0.25	0.004 – 4.0	Does not measure PSD	Does not measure PSD Particle size dependent. Ratio circumference to wavelength <1	May measure sand versus silt/clay content. Particle size dependent. Ratio circumference to wavelength <1

Table 1.2 *Continued*

Technology	Turbidity (bulk optics)		Laser		Digital optic imaging	Pressure difference	Hydroacoustic	
Measurement metric basis to routinely compute mean cross-sectional values	Calibrated to SSC from physical samples in mass units	Calibrated to SSC from physical samples in mass units	Calibrated to SSC from physical samples in mass units; PSD in 32 size classes; volume SSC, converted to mass SSC if density known	Calibration may be unnecessary; PSD in 32 size classes; volume SSC, converted to mass SSC if density known	Calibrated to SSC from physical samples in mass units	Calibrated to SSC from physical samples in mass units	Calibrated to SSC from physical samples in mass units	Calibrated to SSC from physical samples in mass units. If PSD, by variable response to selected frequencies
Ancillary measurements	None	None	Depth and water temperature	Depth, ambient velocity, water temperature	None	Stage	Index velocity. Depth if oriented down	Index velocity. Depth if oriented down
Reliability and robustness	Optical window may foul, causing signal to drift with time. Sensor may saturate at larger SSC	Optical window may foul, causing signal to drift with time. Sensor may saturate at larger SSC	Requires anti-fouling device or bioblock. Sensor may saturate at larger SSC; PSD larger than 0.5 mm not included in calculations.	PSD larger than 0.5 mm not included in calculations.	Accuracy may decrease with window fouling; software will correct for this within yet-undefined limits	Low SSC data unreliable; veracity of higher SSCs unresolved	More or less unaffected by fouling. Responds almost solely to entrained sediment	More or less unaffected by fouling. Responds almost solely to entrained sediment

Region of measurement	Fixed point	Fixed point	Fixed point; device may be used in profiling mode by cable suspension	Point, vertical, or multiple verticals by cable suspension	Fixed point	Single fixed vertical, mean SSC 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	Lab sedimento-logical tests completed 2008; field sedimento-logical and isokinetic tests in 2009	Unresolved. Preliminary tests show accurate PSD results for silt and fine sand, additional testing is planned	Unresolved based on two field tests; additional evaluation required	Shown useful in field applications where PSD does not change dramatically	Shown to provide accurate silt-clay versus sand-size fractions in one field deployment
Potential for meeting U.S. Geological Survey accuracy criteria	High for mass SSC depending on nature of the turbidity-SSC relation	High for mass SSC depending on nature of the turbidity-SSC relation	High for volume SSC and for PSD	High for volume SSC and for PSD	High for PSD; accuracy is still not determined for SSC	Low for mass SSC	Moderate for mass SSC	High for mass SSC; moderate for silt-clay versus sand-size fractions
Potential for application in suspended-sediment monitoring programs	Endorsed by the USGS, given appropriate in-stream sedimentological conditions, calibrations, and ability to maintain instruments	Endorsed by the USGS, given appropriate in-stream sedimentological conditions, calibrations, and ability to maintain instruments	High (given appropriate in-stream sedimentological conditions, known density, and ability to maintain instruments)	High (among potential uses, perform calibrations for *in situ* instruments)	High for laboratory SSC and PSD; moderate for field applications	Unknown pending additional testing using modifications of the physical system and algorithms	Moderate (given appropriate in-stream sediment-ological conditions, and calibration)	High for SSC; moderate for silt-clay versus sand-size fractions

in several varied field settings so as to warrant USGS endorsement for use in operational sediment-monitoring programs. However, instrument-sensor saturation can result in failure to record usable data during periods of high SSCs associated with higher streamflows, which tend to be the most influential in sediment-transport calculations. SSC 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. The presence of biofouling can cause bias in signal accuracy or render the data unusable if the optical surface is not kept clean manually or by using a mechanical wiper. Two fully equipped turbidimeters and one optical backscatterance meter purchased in the summer 2008 each cost about US$5000. This cost can be a small fraction of the annual cost associated with monitoring suspended-sediment transport using traditional techniques. However, the potential for additional site visits for maintenance, cleaning, or the collection of calibration samples can result in increased operating costs.

Similar to bulk-optical sensors, laser-optic instruments also are prone to biofouling and signal saturation at high SSC. However, these instruments have the major advantage in providing continuous PSDs from which volumetric SSC can be calculated, as well as mass SSC if particle density is known or can be confidently estimated. The cost of the LISST suite of instruments (the only commercially available *in situ* instruments using forward (multi-angle) laser light scattering measurements) ranges from two to six times that of a fully equipped turbidimeter.

The digital-optic surrogate technique determines volume SSC by enumerating and summing the volumetric characteristics of individual sediment particles from a digital image of a filament of sample in a flow-through cell. Real-time measurements of particles between 4 and 4000 μm are possible and the system requires no routine calibration. The technology's performance is currently limited to laboratory analyses, although it may have applications for bank-operated pumping systems or for manual deployment in rivers. Similar to the LISST instrument, results are expressed in volume/volume relations and not the more common mass/volume units. Indistinct particle boundaries can reduce measurement accuracy, as can high turbidity from organic or colloidal material. The cost of off-the-shelf instrument parts is one to two times that for a fully equipped turbidimeter.

Research on the pressure-difference technology (Double Bubbler) implies that its use should be limited to SSCs exceeding at least 10 g/L, which is generally larger than the suitable SSC range for the other surrogate techniques examined herein (with the exception of the LISST-Infinity laser instrument). This relatively robust technology, the cost of which is similar to that of a fully equipped turbidimeter, measures SSC in a fixed water column. The theoretical underpinnings of this technology are straightforward and its field application is relatively simple. However, performance of the pressure-difference technology has been marginal at best in field tests in Puerto Rico (maximum SSCs approaching 20 g/L) and Arizona, USA (maximum SSCs 10^2–10^3 g/L). Nevertheless, potential remains for use of this technology because it may provide time series of very high SSC that cannot be resolved using other surrogate techniques.

The acoustic backscatter technology shows the most promise for meeting the needs of suspended-sediment monitoring programs. Mounted *in situ* in a side-looking (or, less often, upward-looking) orientation, the technology is relatively robust and can integrate several orders of magnitude more flow than those technologies that make point measurements. Results using a three-frequency instrument array at the USGS streamgage on the Colorado River at Grand Canyon, Arizona, USA, have compared well with manually collected calibration data for sand-size material in the range 0.01–3 g/L and for finer material in the range 0.01–20 g/L. At present, the cost of using a three-frequency Doppler array (three separate instruments such as used at the USGS streamgage on the Colorado River at Grand Canyon) is about sixfold that for a fully equipped turbidimeter. Although at least one multi-frequency ABS is commercially available, it lacks Doppler (velocity) capability. Research and development efforts toward production of a reasonably priced multi-frequency hydroacoustic instrument are underway.

1.4 Prospects for operational surrogate monitoring of suspended-sediment transport in rivers

This chapter has described five surrogate technologies for monitoring characteristics important to understanding properties of sediment transport in rivers. Some characteristics common to these five technologies include the following:

• all address measurement of fluvial-sediment characteristics that are difficult, expensive, and (or) dangerous to directly measure with sufficient frequency to adequately define their spatial and temporal variability;

• all are generally affordable – ranging from about the cost of a fully equipped turbidimeter (about US$5000 in 2008) to about sixfold that cost for the more expensive laser-diffraction technologies;

• all (with the possible exception of the laser-diffraction and digital-optic technologies) require site-specific calibrations, although the need for calibration is expected to diminish over time;

• all require derivation of coefficients equating values recorded by the surrogate instrument to the mean cross-section constituent value;

• all but turbidity, which is endorsed by the USGS for use in operational sediment-monitoring programs, require additional testing and evaluation.

The USGS endorsement of SSC and SSL computations from turbidity measurements notwithstanding, none of the technologies is suitable for monitoring all the suspended-sediment characteristics in all rivers under all flow and sediment-transport conditions. Nevertheless, if care is exercised in matching surrogate technologies to appropriate river and sediment conditions, it is becoming possible to monitor SSC and SSL remotely and continuously in a variety of rivers over a range of flow and sedimentary conditions within generally acceptable accuracy limits. Endorsement and broad-scale deployment of certifiably reliable sediment-surrogate technologies supported by operational and analytical protocols are revolutionary concepts in fluvial sedimentology. The benefits 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 resources.

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References

Agrawal, Y. C. & Pottsmith, H. C. (1994) Laser diffraction particle sizing in STRESS. *Continental Shelf Research*, **14**, 1101–21.

Agrawal, Y. C. & Pottsmith, H. C. (2000) Instruments for particle size and settling velocity observations in sediment transport. *Marine Geology* **168**(1–4), 89–114.

Agrawal, Y. C. & Pottsmith, H. C. (2006) The isokinetic streamlined suspended-sediment profiling LISST-SL – status and field results. In: Proceedings of the 8th Federal Interagency Sedimentation Conference, Reno, Nevada, April 2–6 2006, 288–295, http://pubs.usgs.gov/misc_reports/FISC_1947-2006/pdf/1st-7thFISCs-CD/8thFISC/Session%202C-1_Agrawal.pdf.

Agrawal, Y. C., McCave, I. N. & Riley, J. B. (1991) Laser diffraction size analysis. In *Principles, Methods, and Application of Particle Size Analysis*, J. P. M. Syvitski (ed.), 119–28. New York: Cambridge University Press.

Agrawal, Y. C., Pottsmith, H. C., Lynch, J. & Irish, J. (1996) Laser instruments for particle size and settling velocity measurements in the coastal zone. In Proceedings Oceans 1996, Institute of Electrical and Electronic Engineers, Fort Lauderdale, Florida, 23–26 September, 1135–42.

Agrawal, Y. C., Whitemore, A., Mikkelsen, O. A. & Pottsmith, H. C. (2008) Light scattering by random shaped particles and consequences on measuring suspended sediments by laser diffraction. *Journal of Geophysical Research* **113**, C04023, 11pp.

Anderson, C. W. (2005) Turbidity (version 2). US Geological Survey Techniques of Water Resources Investigations Book 9, chapter A6, section 6.7, http://water.usgs.gov/owq/FieldManual/Chapter6/6.7_contents.html.

Aquatec Group. (2008) http://www.aquatecgroup.com/aquascat.html.

ASTM International. (1998) Terminology for fluvial sediment. Designation D 4410-98, 6p.

Bale, A. J. & Morris, A. W. (1987). In-situ measurements of particle size in estuarine waters. *Estuarine, Coastal and Shelf Science* **24**, 253–63.

Bent, G. C., Gray, J. R., Smith, K. P. & Glysson, G. D. (2003) A synopsis of technical issues for monitoring sediments in highway and urban runoff. In *The National*

Highway Runoff Data and Methodology Synthesis, G. E. Granato, C. Zenone, & P. E. Cazenas (eds), 113–63. US Department of Transportation Publication No. FHWA-EP-03-054, 1, http://ma.water.usgs.gov/fhwa/products/ofr00497.pdf.

Beverage J. P. & Culbertson, J. K. (1964) Hyperconcentrations of suspended sediment. *Journal of the Hydraulics Division*, Proceedings of the American Society of Civil Engineers, **90**, 117–28.

Bogen, J., Fergus, T. & Walling, D. E. (2003) Erosion and sediment transport in rivers, technological and methodological advances. International Association of Hydrological Sciences, Publication 283, 238pp.

Buchanan, P. A. & Schoellhamer, D. H. (1995). Summary of suspended-solids concentration data, Central and South San Francisco Bays, California, water years 1992 and 1993. US Geological Survey Open-File Report 94-543, 15pp.

Campbell Scientific, Inc. (2008) http://www.d-a-instruments.com/.

Christensen, V. G., Xiaodong, J. & Ziegler, A. C. (2000) Regression analysis and real-time water-quality monitoring to estimate constituent concentrations, loads, and yields in the Little Arkansas River, South-Central Kansas 1995–99. US Geological Survey Water-Resources Investigations Report 00-4126, 36pp., http://ks.water.usgs.gov/Kansas/pubs/reports/wrir.00-4126.html.

Cohn, T. A., DeLong, L. L., Gilroy, E. J., Hirsch, R. M. & Wells, D. K. (1989). Estimating constituent loads. *Water Resources Research*, **25**(5), 937–42.

Conner, C. S. & De Visser, A. M. (1992) A laboratory investigation of particle size effects on optical backscatterance sensor. *Marine Geology* **108**, 151–59.

Crawford, A. M. & Hay, A. E. (1993) Determining suspended sand size and concentration from multifrequency acoustic backscatter. *Journal of the Acoustical Society of America* **94**(6), 3312–24.

D & A Instrument Company. (1991) OBS-1 & 3 Instruction manual. D & A Instrument Company, Port Townsend, Washington, 41pp.

Davis, B. E. (2005) A guide to the proper selection and use of federally approved sediment and water-quality samplers: US Geological Survey Open-File Report 2005-1087, 20pp., http://pubs.usgs.gov/of/2005/1087/.

Deines, K. L. (1999) Backscatter estimation using broadband acoustic Doppler current profilers. Proceedings of the IEEE Sixth Working Conference on Current Measurement, San Diego, CA, March 11–13 1999, 249–253.

Design Analysis Associates. (2008) http://www.waterlog.com/.

Diplas, P., Kuhnle, R. A., Gray, J. R., Glysson, G. D. & Edwards, T. E. (2008) Sediment transport measurements. In *Sedimentation Engineering*, M. H. García (ed.), *American Society of Civil Engineering Manuals and Reports on Engineering Practice*, no.110, 307–53.

Downing, J. P. (1983). An optical instrument for monitoring suspended particles in ocean and laboratory. In *OCEANS 1983, San Francisco, California, August 29-September 1 1983, Proceedings: 199–202*.

Downing, J. P. (1996) Suspended sediment and turbidity measurements in streams – What they do and do not mean. In *Automatic Water Quality Monitoring Workshop*, Richmond, B.C., February 12–13 1996.

Downing, J. P., Sternberg, R. W. & Lister, C. R. B. (1981) New instrumentation for the investigation of sediment suspension processes in the shallow marine environment. *Marine Geology* **42**, 19–34.

Downing, A., Thorne, P. D. & Vincent, C. E. (1995) Backscattering from a suspension in the near field of a piston transducer. *Journal of the Acoustical Society of America*, **97**(3), 1614–20.

Duan, N. (1983) Smearing estimate – a nonparametric retransformation method. *Journal of the American Statistical Association*, **78**(383), 605–10.

Edwards, T. E. & Glysson, G. D. (1999) Field methods for collection of fluvial sediment. US Geological Survey Techniques of Water-Resources Investigations Book 3, Chapter C2, 89p. http://water.usgs.gov/osw/techniques/Edwards-TWRI.pdf.

Federal Interagency Sedimentation Project. (1940) *Field practice and equipment used in sampling suspended sediment*. Iowa City, Iowa University Hydraulics Laboratory, Interagency Report no.1, 175pp., http://fisp.wes.army.mil/Report%201.pdf.

Federal Interagency Sedimentation Project. (1941) *Laboratory investigation of suspended sediment samplers*. Iowa City, Iowa University Hydraulics Laboratory, Interagency Report no.5, 99pp., http://fisp.wes.army.mil/Report%205.pdf.

Federal Interagency Sedimentation Project. (2008) http://fisp.wes.army.mil/.

Flammer, G. H. (1962) Ultrasonic measurement of suspended sediment. US Geological Survey Bulletin 1141-A. Government Printing Office, Washington, DC, 48pp.

Gartner, J. W. (2004) Estimating suspended solids concentrations from backscatter intensity measured by acoustic Doppler current profiler in San Francisco Bay, California. *Marine Geology* **211**, 169–87.

Gartner, J. W., Cheng, R. T., Wang, P. F. & Richter, K. (2001) Laboratory and field evaluations of LISST-100 instrument for suspended particle size determinations. *Marine Geology* **175**(1–4), 199–219.

Gartner, J. W., Mueller, D. S., Wall, G. R. & Gray, J. R. (2003) Breakout session 4: other fluvial-sediment surrogates. In *Proceedings of the Federal Interagency Workshop on Turbidity and Other Sediment Surrogates, April 30–May 2 2002, Reno, Nevada, 21–27*. http://pubs.usgs.gov/circ/2003/circ1250/.

Gilvear, D. J. & Petts, G. E. (1985) Turbidity and suspended solids variations downstream of a regulating reservoir. *Earth Surface Processes Landforms*, **10**(4), 363–73.

Glysson, G. D. (1987). Sediment-transport curves. US Geological Survey Open-File Report 87-218, 47pp., http://pubs.er.usgs.gov/usgspubs/ofr/ofr87218.

Glysson, G. D. (1989). 100 years of sedimentation study by the USGS. In Proceedings of the International Symposium, Sediment Transport Modeling, Sam S.Y. Wang, ed. American Society of Civil Engineers, New Orleans, August 14–18 1989, 260–65.

Glysson, G. D. & Gray, J. R. (1997). Coordination and standardization of Federal sedimentation activities. Expanding Sediment Research Capabilities in Today's US Geological Survey. February 4–7, 1997, 2pp., http://water.usgs.gov/osw/techniques/workshop/.

Graf, J. B., Wirt, L., Swanson, E. K., Fisk, G. G. & Gray, J. R. (1996) Streamflow transport of radionuclides and other chemical constituents in the Puerco and the Little Colorado River Basins, Arizona and New Mexico: US Geological Survey Water-Supply Paper 2459, 89pp., http://pubs.er.usgs.gov/usgspubs/wsp/wsp2459.

Gray, J. R. (2003) US Geological Survey suspended-sediment surrogate research, Part I: Call for a sediment monitoring instrument and analysis research program. In Proceedings of the Virginia Water Research Symposium 2003, Water Resource Management for the Commonwealth, Virginia Polytechnic Institute and State University, Blacksburg, October 8-10 2003, 53–57.

Gray, J. R. (ed.). (2005) Proceedings of the Federal Interagency Sediment Monitoring Instrument and Analysis. Workshop, September 9–11 2003, Flagstaff, Arizona: US Geological Survey Circular 1276, 46pp., http://water.usgs.gov/pubs/circ/2005/circ1276/. Appendix 4 is available only online at: http://water.usgs.gov/osw/techniques/sediment/sedsurrogate2003workshop/listofpapers.html.

Gray, J. R., Agrawal, Y. C. & Pottsmith, H. C. (2004) The LISST-SL streamlined isokinetic suspended-sediment profiler. In *Proceedings of the 9th International Symposium on River Sedimentation, Yichang, China, October 18-21 2004*, vol. **IV**, Cheng Liu (ed.), 2549–555. Tsinghua University Press, http://water.usgs.gov/osw/techniques/Lisst_Gray_Agrawal_Pottsmith.pdf.

Gray, J. R. & Gartner, J. W. (2004) Surrogate technologies for continuous suspended-sediment monitoring in the United States. In Proceedings of the 9th International Symposium on River Sedimentation, October 18-21 2004, Yichang, China, vol. IV, 2515–22. Tsinghua University Press,.

Gray, J. R. & Gartner, J. W. (2009) Technological advances in suspended-sediment surrogate monitoring. *Water Resources Research*, **45**, W00D29, doi: 10.1029/2008WR007063, 20pp.

Gray, J. R. & Glysson, G. D. (eds) (2003) Proceedings of the Federal Interagency Workshop on Turbidity and Other Sediment Surrogates, April 30–May 2 2002, Reno, Nevada, US Geological Survey Circular 1250, 56pp., http://pubs.er.usgs.gov/usgspubs/cir/cir1250.

Gray, J. R. & Glysson, G. D. (2005) Attributes of a sediment monitoring instrument and analysis research program. In Proceedings of the Federal Interagency Sediment Monitoring Instrument and Analysis Research Workshop, September 9–11 2003, Flagstaff, Arizona, 6pp., http://water.usgs.gov/osw/techniques/sediment/sedsurrogate2003workshop/gray_glysson.pdf.

Gray, J. R., Glysson, G. D. & Edwards, T. E. (2008) Suspended-sediment samplers and sampling methods. In *Sediment Transport Measurements*, M. Garcia (ed.), Sedimentation Engineering – Processes, Measurements, Modeling, and Practice, American Society of Civil Engineers, Manual 110, Chapter 5.**3**, 320–39.

Gray, J. R., Glysson, G. D. & Mueller, D. S. (2002) Comparability and accuracy of fluvial-sediment data – a view from the US Geological Survey. In Proceedings of the ASCE Specialty Conference, Hydraulic Measurements & Experimental Methods Conference, Estes Park, Colorado, July 28-August 1 2002, 6pp. http://water.usgs.gov/osw/techniques/asce.pdf.

Gray, J. R., Glysson, G. D., Turcios, L. M. & Schwarz, G. E. (2000) Comparability of suspended-sediment concentration and total suspended solids data. US Geological Survey Water-Resources Investigations Report 00-4191, 14pp., http://water.usgs.gov/osw/techniques/sedimentpubs.html.

Gray, J. R., Gooding, M. T. S., Topping, D. J. & Rasmussen, P. P. (2003a) US Geological Survey suspended-sediment surrogate research, Part II: Optic technologies. In Proceedings of the Virginia Water Research Symposium 2003, Water Resource Management for the Commonwealth, Virginia Polytechnic Institute and State University, Blacksburg, October 8–10 2003, 58–64.

Gray, J. R. & Osterkamp, W. R. (2007) A vision for a worldwide fluvial-sediment information network. Keynote Paper, In Proceedings of the 10th International Symposium on River Sedimentation, Moscow, Russia, August 1-4 2007, Vol. I, 43–54, http://www.irtces.org/zt/10isrs/lunwen/Session%200/Symposium_0_5.htm.

Gray, J. R., Patiño, E. & Larsen, M. C. (2003b). US Geological Survey suspended-sediment surrogate research, Part III: Acoustic and pressure-differential technologies. In *Proceedings of the Virginia Water Research Symposium 2003, Water Resource Management for the Commonwealth, Virginia Polytechnic Institute and State University, Blacksburg, October 8–10 2003*, 65–69.

Gray, J. R. & Simões, F. J. M. (2008) Estimating sediment discharge. In M. Garcia (ed.), *Sedimentation Engineering – Processes, Measurements, Modeling, and Practice*, American Society of Civil Engineers, Manual 110, Appendix D, 1067–88.

Hamilton, L. J., Shi, Z. & Zhang, S. Y. (1998) Acoustic backscatter measurements of estuarine suspended cohesive sediment concentration profiles. *Journal of Coastal Research* **14**(4), 1213–24.

Hanes, D. M., Vincent, C. E., Huntley, D. A. & Clarke, T. L. (1988) Acoustic measurements of suspended sand concentration in the C2S2 experiment at Stanhope Lane, Prince Edward Island. *Marine Geology* Elsevier Science Publishers, Amsterdam, 185–96.

Hay, A. E. (1991) Sound scattering from a particle-laden, turbulent jet. *Journal of the Acoustical Society of America*, **90**(4) pt 1, 2055–74.

Hay, A. E. & Sheng, J. (1992) Vertical profiles of suspended sand concentration and size from multi-frequency acoustic backscatter. *Journal of Geophysical Research*, **97**(C10), **15**,661–77.

Helsel D. R. & Hirsch, R. M. (2002) Statistical methods in water resources – Hydrologic analysis and interpretation. US Geological Survey Techniques of Water-Resources Investigations, book 4, chap. A3, 510pp., http://pubs.usgs.gov/twri/twri4a3/

Hoitink, A. J. F. & Hoekstra, P. (2005) Observations of suspended sediment from ADCP and OBS measurements in a mud-dominated environment. *Coastal Engineering*, **52**(2), 103–18.

Hortness, J. E. (2006) Using acoustic backscatter technology to measure suspended sediment concentrations in Idaho streams. In Proceedings, 8th Federal Interagency Sedimentation Conference, April 2-6 2006, Reno, NV, CD-ROM, ISBN 0-9779007-1-1.

ISO. (1992a) Measurement of liquid flow in open channels – method for measurement of bedload discharge. Technical report 92-9212, 20pp.

ISO. (1992b) Liquid flow measurement in open channels – sampling and analysis of gravel-bed material. International Standard ISO 9195, 9pp.

ISO. (1997) Measurement of liquid flow in open channels –bed-material sampling. International Standard ISO 4364, 39pp.

ISO. (2002) Measurement of liquid flow in open channels –methods for measurement of characteristics of suspended sediment. International Standard ISO 4363, 27pp.

ISO. (2005) Liquid flow in open channels – sediment in streams and canals – Determination of concentration, particle size distribution and relative density. International Standard ISO 4365, 47pp.

Jay, D. A., Orton, P., Kay, D. J., Fain, A. & Baptisa, A. M. (1999) Acoustic determination of sediment concentrations, settling velocities, horizontal transports and vertical fluxes in estuaries. In Proceedings: 6th Working Conference on Current Measurement, 3/11–3/13 1999, San Diego, CA, 258–63.

Karp-Boss, L., Azevedo, L. & Boss, E. (2007) LISST-100 measurements of phytoplankton size distribution: evaluation of the effects of cell shape. *Limnology and Oceanography: Methods* **5**, 396–406.

Kindratenko, V. (1997). Development and application of image analysis techniques for identification and classification of microscopic particles. PhD thesis, University of Antwerp, Belgium 1997, Part 2, Shape Analysis.

Kineke, G. C. & Sternberg, R. W. (1992) Measurements of high concentration suspended sediments using the optical backscatterance sensor. *Marine Geology* **108**, 253–58.

Koch, R. W. & Smillie, G. M. (1986). Bias in hydrologic prediction using log-transformed regression models. *Water Resources Bulletin*, **22**(5), 717–32.

Klein, H. (2003) Investigating sediment re-mobilisation due to wave action by means of ADCP echo intensity data: field data from the Tromper Wiek, western Baltic Sea. *Estuarine, Coastal and Shelf Science*, **58**(3), 467–74.

Koltun, G. F., Eberle, M., Gray, J. R. & Glysson, G. D. (2006) User's manual for the Graphical Constituent Loading Analysis System (GCLAS). US Geological Survey Techniques and Methods Book 4, Chap. C1, 50pp. http://pubs.er.usgs.gov/usgspubs/tm/tm4C1.

Konrad, C. H., Pottsmith, H. C., Melis, T. S. & Rubin, D. M. (2006) Real-time analysis of concentrated fluvial suspended sediments. In Proceedings of the 8th Federal Interagency Sedimentation Conference, Reno, Nevada, April 2-6 2006, 585–91. http://pubs.usgs.gov/misc_reports/FISC_1947-2006/pdf/1st-7thFISCs-CD/8thFISC/Session%208C-2_Konrad.pdf.

Land, J. M. & Jones, P. D. (2001) Acoustic measurement of sediment flux in rivers and near-shore waters. In Proceedings of the 7th Federal Interagency Sedimentation Conference, March 25-29 2001, Reno, Nevada, III 127–34., http://pubs.usgs.gov/misc_reports/FISC_1947-2006/pdf/1st-7thFISCs-CD/7thFISC/7Fisc-V1/7FISC1-3.pdf.

Landers, M. N. (2003) Summary of blind sediment reference sample measurement session. In *Proceedings of the Federal Interagency Workshop on Turbidity and Other Sediment Surrogates, April 30-May 2 2002, Reno, Nevada*, J. R. Gray & G. D. Glysson (eds), 29–30. US Geological Survey Circular 1250, http://water.usgs.gov/osw/techniques/turbidity.html.

Larsen, M. C., Figueroa-Alamo, C., Gray, J. R. & Fletcher, W. (2001) Continuous automated sensing of streamflow density as a surrogate for suspended-sediment concentration sampling. In Proceedings of the 7th Federal Interagency Sedimentation Conference, Reno, Nevada, March 25–29, vol. I, III-102 to III-109, http://pubs.usgs.gov/misc_reports/FISC_1947-2006/pdf/1st-7thFISCs-CD/7thFISC/7Fisc-V1/7FISC1-3.pdf.

Lewis, J. (1996) Turbidity-controlled suspended sediment sampling for runoff-event load estimation. *Water Resources Research*, **32**(7), 2299–310.

Lewis, J. (2002) Estimation of suspended sediment flux in streams using continuous turbidity and flow data coupled with laboratory concentrations. In Proceedings of the Federal Interagency Workshop on Turbidity and Other Sediment Surrogates, April 30-May 2 2002, Reno, Nevada, J. R. Gray & G. Douglas Glysson (eds). US Geological Survey Circular 1250, 3pp., http://water.usgs.gov/osw/techniques/TSS/LewisTSS.pdf.

Lewis, A. J. & Rasmussen, T. C. (1999) Determination of suspended sediment concentrations and particle size distributions using pressure measurements. *Journal of Environmental Quality*, **28**, 1490–96.

Libicki, C., Bedford, K. W. & Lynch, J. F. (1989). The interpretation and evaluation of a 3-MHz acoustic backscatter device for measuring benthic boundary layer sediment dynamics. *Journal of the Acoustical Society of America* **85**(4), 1501–11.

Lietz, A. C. & Debiak, E. A. (2005) Development of rating curve estimators for suspended-sediment concentration and transport in the C-51 canal based on surrogate technology, Palm Beach County, Florida 2004-05. US Geological Survey Open-File Report 2005-1394 19pp., accessed March 2008, at http://pubs.usgs.gov/of/2005/1394/.

Ludwig, K. A., Hanes, D. M. (1990). A laboratory evaluation of optical backscatterance suspended solids sensors exposed to sand-mud mixtures. *Marine Geology* **94**, 173–79.

Meade, R. H. & Parker, R. S. (1985). Sediment in rivers of the United States. US Geological Survey Water-Supply, Paper 2275, 49–60.

Melis, T. S., Topping, D. J. & Rubin, D. M. (2003) Testing laser-based sensors for continuous in situ monitoring of suspended sediment in the Colorado River, Arizona. In *Erosion and Sediment Transport Measurement in Rivers, Technological and Methodological Advances* J. Bogen, T. Fergus & D. E. Walling (eds), 21–27. International Association of Hydrological Sciences Publication 283.

Meral, R. (2008) Laboratory evaluation of acoustic backscatter and LISST methods for measurements of suspended sediments. *Sensors*, **8**, 979–93.

Miller, C. R. (1951) Analysis of flow-duration sediment rating curve method of computing sediment yield: US Bureau of Reclamation, 55pp.

Nelson, M. E. & Benedict, P. C. (1950) Measurement and analysis of suspended sediment loads in streams. Transactions of the American Society of Civil Engineers, paper no. 2450, 891–918.

Nolan, K. M., Gray, J. R. & Glysson, G. D. (2005) Introduction to suspended-sediment sampling. US Geological Survey Scientific Investigations Report 2005-5077, http://pubs.er.usgs.gov/pubs/sir/sir20055077.

Osterkamp, W. R., Heilman, P., Gray, J. R., and 33 others. (2004) An invitation to participate in a North American sediment-monitoring network. American Geophysical Union, EOS, 84, no.40, October 5 2004, 386–89.

Osterkamp, W. R., Heilman, P. & Lane, L. J. (1998) Economic considerations of a continental sediment-monitoring program. *International Journal of Sediment Research* **13**(4), 12–24, http://water.usgs.gov/osw/techniques/Osterkamp.html.

Pimentel, D., Harvey, C., Resosudarmao, P., *et al*.. (1995) Environmental and economic costs of soil erosion and conservation benefits. *Science*, **267**, 1117–23.

Porterfield, G. (1972) Computation of fluvial-sediment discharge. US Geological Survey Techniques of Water-Resource Investigations Book 3, Chapter C3, 66pp., http://water.usgs.gov/pubs/twri/twri3-c3/.

Pottsmith, H. C. & Bhogal, V. K. (1995) In-situ particle size distribution in the aquatic environment. In *14th World Dredging Congress, Amsterdam, The Netherlands, Nov. 19, 1995*.

Pratt, T. & Parchure, T. (2003) OBS calibration and field measurements. In *Proceedings of the Federal Interagency Workshop on Turbidity and Other Sediment Surrogates, April 30-May 2 2002, Reno, Nevada*, J. R. Gray & G. D. Glysson (eds). US Geological Survey Circular 1250, 3pp., http://water.usgs.gov/pubs/circ/2003/circ1250/.

Pruitt, B. A. (2003) Uses of turbidity by states and tribes. In Proceedings of the Federal Interagency Workshop on Turbidity and Other Sediment Surrogates, April 30-May 2 2002, Reno, Nevada, J. R. Gray & G. D. Glysson (eds), 31–46. US Geological Survey Circular 1250, http://pubs.usgs.gov/circ/2003/circ1250/.

Rainwater, F. H. (1962). Stream composition of the conterminous United States: US Geological Survey Hydrologic Atlas 61, 3 maps, http://pubs.er.usgs.gov/usgspubs/ha/ha61.

Rasmussen, P. P., Gray, J, R., Glysson, G. D. & Ziegler, A. C. (2009) Guidelines and procedures for computing time-series suspended-sediment concentrations and loads from in-stream turbidity-sensor and streamflow data. US Geological Survey Techniques and Methods Report 3 C4, http://pubs.usgs.gov/tm/tm3c4/.

Rasmussen, T. J., Ziegler, A. C. & Rasmussen, P. P. (2005) Estimation of constituent concentrations, densities, loads, and yields on Lower Kansas River, Northeast Kansas, using regression models and continuous water-quality modeling, January 2000 through December 2003: US Geological Survey Scientific Investigations Report 2005-5165, 117pp., http://pubs.usgs.gov/sir/2005/5165/.

Reichel, G. & Nachtnebel, H. P. (1994) Suspended sediment monitoring in a fluvial environment: Advantages and limitations applying an acoustic Doppler current profiler. *Water Research*, **28**(4), 751–61.

Richards, S. D., Heathershaw, A. D. & Thorne, P. D. (1996) The effect of suspended particulate matter on sound attenuation in seawater. *Journal of the Acoustical Society of America* **100**(3), 1447–50.

Schaafsma, A. S. & Hay, A. E. (1997) Attenuation in suspensions of irregularly shaped sediment particles: A two-parameter equivalent spherical scatterer model. *Journal of the Acoustical Society of America* **102**(3), 1485–502.

Schoellhamer, D. H., Buchanan, P. A. & Ganju, N. K. (2002) Ten years of continuous suspended sediment concentration monitoring in San Francisco Bay and Delta. In Proceedings: Turbidity and Other Sediment Surrogates Workshop, April 30 – May 2 2002, Reno, Nevada, http://water.usgs.gov/osw/techniques/TSS/schoelhamer.pdf.

Schoellhamer, D. H. & Wright, S. A. (2003) Continuous measurement of suspended-sediment discharge in rivers by use of optical backscatterance sensors. In, J. Bogen, T. Fergus & D. E. Walling (eds), 28–36. International Association of Hydrological Sciences Publication 283.

Schott, F. & Johns, W. (1987) Half-year-long measurements with a buoy-mounted acoustic Doppler current profiler in the Somali Current. *Journal of Geophysical Research*, **92**(C5), 5169–76.

Schulkin, M. & Marsh, H. W. (1962) Sound absorption in sea water. *Journal of the Acoustical Society of America*, **34**(6), 864–65.

Sedimentation Committee of the Water Resources Council. (1976) Proceedings of the Third Federal Inter-Agency Sedimentation Conference: March 22-25 1976, Denver, Colorado, 7 chapters, variously paged, http://pubs.usgs.gov/misc_reports/FISC_1947-2006/pdf/1st-7thFISCs-CD/3rdFISC/3FiscTOC.PDF.

Sequoia Scientific, Inc. (2008) http://www.sequoiasci.com/default.aspx?SectionName=home.

Serra, T., Colomer, J., Cristina, X. P., Vila, X., Arellato, J. B. & Casamitjana, X. (2001) Evaluation of laser in situ scattering instrument for measuring concentration of phytoplankton, purple sulfur bacteria, and suspended inorganic sediments in lakes. *Journal of Environmental Engineering*, November, 1023–30.

Serra, T., Granata, T., Colomer, J., Stips, A., Mohlenberg, F. & Casamitjana, X. (2003) The role of advection and turbulent mixing in the vertical distribution of phytoplankton. *Estuarine, Coastal and Shelf Science*, **56**, 53–62.

Sheng, J. & Hay, A. E. (1988) An examination of the spherical scatter approximation in aqueous suspensions of sand. *Journal of the Acoustical Society of America* **83**(2), 598–610.

Skinner, J. V. (1989) History of the Federal Interagency Sedimentation Project. In Proceedings of the International Symposium, Sediment Transport Modeling, American Society of Civil Engineers, New Orleans, August 14–18 1989, S. S. Y. Wang (ed), 266–71.

Smith, R. A., Alexander, R. B. & Wolman, M. G. (1987) Water-quality trends in the nation's rivers: *Science*, **235**, 1607–15.

Subcommittee on Sedimentation. (2008) http://acwi.gov/sos/, accessed September 30, 2008.

Sutherland, T. F., Lane, P. M., Amos, C. L. & Downing, J. (2000) The calibration of optical backscatter sensors for suspended sediment of varying darkness levels: *Marine Geology* **162**, 587–97.

Swithenbank, J., Beer, J. M., Taylor, D. S., Abbot, D. & McCreath, C. C. (1977) A laser diagnostic technique for the measurement of droplet and particle size distribution. In *Experimental Diagnostics in Gas Phase Combustion Systems: Progress in Astronautics and Aeronautics*, vol. **53**, B. J. Zinn (ed.), 421–47.

Tessier, C., Le Hir, P., Lurton, X. & Castaing, P. (2008) Estimation of suspended sediment concentration from backscatter intensity of Acoustic Doppler Current Profiler. *Comptes Rendus – Geoscience*, **340**(1), 57.

Thevenot, M. M., Prickett, T. L. & Kraus, N. C. (1992). Tylers Beach, Virginia, dredged material plume monitoring project 27 September to 4 October 1991: Dredging Research Program Technical Report DRP-92-7, US Army Corps of Engineers, Washington, D.C, 204pp.

Thevenot, M. M. & Kraus, N. C. (1993) Comparison of acoustical and optical measurements of suspended material in the Chesapeake Estuary. *Journal of Marine Environmental Engineering*, **1**, 65–79.

Thorne, P. D. & Buckingham, M. J. (2004) Measurements of scattering by suspensions of irregularly shaped sand particles and comparison with a single parameter modified sphere model, *Journal of the Acoustical Society of America* **116**(5), 2876–89.

Thorne, P. D. & Campbell, S. C. (1992) Backscattering by a suspension of spheres. *Journal of the Acoustical Society of America* **92**(2), 978–86.

Thorne, P. D. & Hanes, D. M. (2002) A review of acoustic measurements of small-scale sediment processes. *Continental Shelf Research* **22**, 603–32.

Thorne, P. D. & Hardcastle, P. J. (1997) Acoustic measurement of suspended sediments in turbulent currents and comparison with in-situ samples. *Journal of the Acoustical Society of America* **101**(5), 2603–14.

Thorne, P. D., Hardcastle, P. J. & Hogg, A. (1996) Observations of near-bed suspended sediment turbulence structures using multifrequency acoustic backscatter. In *Coherent Flow Structures in Open Channels*, P. J. Ashworth, S. J. Bennet, J. L. Best & S. J. McLelland (eds). John Wiley & Sons Ltd.

Thorne, P. D., Hardcastle, P. J. & Souslby, R. L. (1993). Analysis of acoustic measurements of suspended sediment. *Journal of Geophysics Research* **98**(C1) 899–910.

Thorne, P. D., Vincent, C. E., Harcastle P. J., Rehman, S. & Pearson, N. (1991) Measuring suspended sediment concentrations using acoustic backscatter devices. *Marine Geology*, **98**, 7–16.

Thorne, P. D., Waters, K. R. & Brudner, T. J. (1995) Acoustic measurements of scattering by objects of irregular shape. *Journal of the Acoustical Society of America* **97**(1), 242–51.

Thorne, P. D. & Meral, R. (2008) Formulations for the scattering properties of suspended sandy sediments for use in the application of acoustics to sediment transport. *Continental Shelf Research*, **28**(2), 309–17.

Tollner, E. W., Rasmussen, T. C., Upchurch, B. & Sikes, J. (2005) Simulated moving bed form effects on real-time in-stream sediment concentration measurement with denitometry. *ASCE Journal of Hydraulic Engineering*, **132**(12), 1141–44.

Topping, D. J., Melis, T. S., Rubin, D. M. & Wright, S. A. (2004) High-resolution monitoring of suspended-sediment concentration and grain size in the Colorado River in Grand Canyon using a laser acoustic system. In Proceedings of the 9th International Symposium on River Sedimentation, Yichang, China, 2507–14.

Topping, D. J., Wright, S. A., Melis, T. S. & Rubin, D. M. (2006) High-resolution monitoring of suspended-sediment concentration and grain size in the Colorado River using laser-diffraction instruments and a three-frequency acoustic system. In Proceedings, 8th Federal Interagency Sedimentation Conference, April 2–6 2006, Reno, Nevada, CD-ROM, ISBN 0-9779007-1-1.

Topping, D. J., Wright, S. A., Melis, T. S. & Rubin, D. M. (2007) High-resolution measurement of suspended-sediment concentrations and grain size in the Colorado River in Grand Canyon using a multi-frequency acoustic system. In Proceedings of the 10th International Symposium on River Sedimentation, Moscow, Russia, vol. 3, 330–39.

Traykovski, P., Latter, R. & Irish, J. D. (1999) A laboratory evaluation of the LISST instrument using natural sediments: *Marine Geology* **159**, 355–67.

Uhrich, M. A. (2002) Determination of total and clay suspended-sediment loads from instream turbidity data in the North Santiam River Basin, Oregon 1998–2002. In Proceedings of the Federal Interagency Workshop on Turbidity and Other Sediment Surrogates, April 30-May 2 2002, Reno, Nevada, J. R. Gray & G. Douglas Glysson (eds). US Geological Survey Circular 1250, 3pp., http://water.usgs.gov/pubs/circ/2003/circ1250/.

Uhrich, M. A. & Bragg, H. M. (2003) Monitoring instream turbidity to estimate continuous suspended-sediment loads and yields and clay-water volumes in the Upper North Santiam River Basin, Oregon 1998–2000. US Geological Survey Water-Resources Investigations Report 03-4098, 44pp., http://pubs.usgs.gov/wri/WRI03-4098/.

Urick, R. J. (1975) *Principles of Underwater Sound*, 2nd edn. New York: McGraw Hill, 384pp.

US Department of Agriculture. (1965) Proceedings of the Federal Inter-Agency Sedimentation Conference: Miscellaneous Publication No. 970, 933pp.

US Environmental Protection Agency. (2008) National section 303-d list fact sheet, causes of impairments: total maximum daily loads. http://iaspub.epa.gov/waters10/attains_nation_cy.control?p_report_type=T#causes_303d

US Geological Survey. (2004) Revision of NFM Chapter 6, Section 6.7 – Turbidity: Office of Water Quality Technical Memorandum 2004.03, http://water.usgs.gov/admin/memo/QW/qw04.03.html.

US Geological Survey. (2005) Real-time water-quality concentrations and loads estimated using regression analysis, http://nrtwq.usgs.gov/explore/plot?site_no=07144100&pcode=80154&period=ytd_all&timestep=uv.

US Geological Survey. (2008a) National Streamflow Information Program: Home Page, http://water.usgs.gov/nsip/.

US Geological Survey. (2008b) USGS water data for the nation: National Water Information System Home Page, http://waterdata.usgs.gov/nwis.

US Geological Survey. (2008c) USGS water data for the nation: National Stream Quality Accounting Network Home Page, http://water.usgs.gov/nasqan/.

US Geological Survey. (2008d) US Geological Survey implements new turbidity data-reporting procedures, in, US Geological Survey National Field Manual for the collection of water-quality data: US Geological Survey Techniques of Water-Resources Investigations, Book 9, Ch. 6.7, http://water.usgs.gov/owq/turbidity/TurbidityInfoSheet.pdf.

Wall, G. R., Nystrom, E. A. & Litten, S. (2006) Use of an ADCP to computer suspended-sediment discharge in the tidal Hudson River, New York, US Geological Survey, Scientific Investigations Report 2006-5055, 16pp.

Walling, D. E. (1977) Assessing the accuracy of suspended sediment rating curves for a small basin, *Water Resources Research*, **13**, 531–38.

Ziegler, A. C. (2003) Breakout session 1 – Definition of optical methods for turbidity and data reporting. In Proceedings of the Federal Interagency Workshop on Turbidity and Other Sediment Surrogates, April 30–May 2 2002, Reno, Nevada, J. R. Gray & G. Douglas Glysson (eds), 9–13. US Geological Survey Circular 1250, http://water.usgs.gov/pubs/circ/2003/circ1250/.