OVERVIEW OF SELECTED SURROGATE TECHNOLOGIES FOR HIGH-TEMPORAL RESOLUTION SUSPENDED-SEDIMENT MONITORING

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Abstract Traditional methods for characterizing selected properties of suspended sediments in rivers are being augmented and in some cases replaced by cost-effective surrogate instruments and methods that produce a temporally dense time series of quantifiably accurate data for use primarily in sediment-flux computations. Turbidity is the most common such surrogate technology, and the first to be sanctioned by the U.S. Geological Survey for use in producing data used in concert with water-discharge data to compute sediment concentrations and fluxes for storage in the National Water Information System. Other technologies, including laser-diffraction, digital photo-optic, acoustic-attenuation and backscatter, and pressure-difference techniques are being evaluated for producing reliable sediment concentration and, in some cases, particle-size distribution data. Each technology addresses a niche for sediment monitoring. Their performances range from compelling to disappointing. Some of these technologies have the potential to revolutionize fluvial-sediment data collection, analysis, and availability.

INTRODUCTION

The U.S. Geological Survey (USGS) is evaluating instruments that have potential for providing continuous and reliable—unbiased and quantifiably precise—data on selected fluvial-sedimentary characteristics in riverine and laboratory settings. The sedimentary phases of interest are suspended sediment (concentrations, size distributions, and transport rates); bed load (size distributions and transport rates); and bed material (size distributions).

This paper describes the operational basis of instruments and techniques for surrogate measurements of suspended sediment being developed and (or) tested (Gartner and Gray, 2003), and summarizes initial results of USGS research in bulk-optic, laser-diffraction, digital-optic, acoustic-attenuation and backscatter, and pressure-difference technologies (Gray and Gartner, 2009; 2010a). These techniques may be used to infer selected characteristics of suspended sediments in lieu of conventional methods, thus largely replacing or supplementing the need for routine collection and analysis of physical samples (Edwards and Glysson, 1999; Nolan et al., 2005; Davis, 2005; Gray et al., 2008) except for calibration and verification purposes.

All of the in-situ instruments described herein require calibration to a mean discharge-weighted constituent value in the cross section. There are two types of such calibrations: local (instrument-specific) calibrations and cross-section calibrations. Local calibrations provide direct and useful information on the performance of the instrument within its realm of measurement. Cross-section calibration equates instrument measurements to a mean discharge-weighted constituent value in the cross section. Thus, cross-section calibrations integrate uncertainties imparted not only by time-variable heterogeneities in suspended-sediment characteristics in the cross section, but also uncertainties associated with instrument measurements. Although instrument-specific calibrations are useful to verify instrument-recorded data, cross-section calibrations are mandatory—and sometimes are the only calibrations performed—when the objective is to monitor suspended-sediment transport in rivers.

In part because turbidity is the most common of the sediment-surrogate technologies—and in spite of notable drawbacks—it is the first of the surrogate technologies formally accepted for operational suspended-sediment monitoring by the USGS. The 2008 purchase price of a fully equipped in-situ turbidimeter with an optical window wiper was about $5,000. Purchase prices for instruments operating on other principles ranged from 1–6 times the turbidimeter's cost.

Additional information on sediment-surrogate technologies is available from Gray and Gartner (2009; 2010a). Those interested in bedload-surrogate technologies may opt to review Gray and Gartner (2010b).

SUMMARY OF SELECTED SUSPENDED-SEDIMENT SURROGATE TECHNOLOGIES

Bulk Optics (Turbidity) Measurement of a bulk-optical property of water—turbidity—is the most common means for determining water clarity and estimating suspended-sediment concentration (SSC) in United States (U.S.) rivers (Pruitt, 2003). A number of bulk-optical instruments—turbidimeters—are commercially available. The technology requires instrument-specific calibrations, and, as with all in-situ instruments, cross-section calibrations to render each measurement representative of the mean cross-section value.

Turbidimeters can be categorized as transmissometers or nephelometers. Transmissometers employ a light source beamed directly at the sensor to measure light transmission. Nephe- lometers measure light scattered by suspended particles rather than light transmission. Nephelometers generally measure 90° or forward scattering. An optical backscatter (OBS) instrument (Downing, 1983) is a type of nephelometer designed to measure backscattered infrared radiation in a small (SSC-dependent) volume on the order of a few cm^3 (essentially a point measurement). Both transmittance and scatterance are functions of the number, size, index of refraction, and shape of suspended particles.

Most commercially available in-situ turbidimeters (Fig. 1) are relatively inexpensive (with respect to other suspended-sediment surrogate technologies), lack moving parts if an optical-window wiper is not part of the instrument, and provide rapid sampling capability. The instruments rely on empirical calibrations to compute SSC from continuous turbidity measurements. The technology is relatively mature, having been used for decades. Turbidimeters and transmissometers have been shown to provide reliable SSC data at a number of USGS streamgages (e.g., Schoellhamer and Wright, 2003; Uhrich, 2003 Rasmussen et al., 2003 Gray and Gartner, 2009; Rasmussen et al., 2010) and other sites (e.g., Pratt and Parchure, 2003 Lewis, 2003).

Figure 5. Photographs showing nephelometry sensors: A) YSI model 6136; B) Hydrolab turbidity sensor; and C) Forrest Technology Systems model DTS-12; D) D & A Instrument Company model OBS 3+; and E) Hach OptiQuant with wiper.

Figure 1 Photographs showing nephelometry sensors: A) YSI model 6136; B) Hydrolab turbidity sensor with wiper; and C) Forrest Technology Systems model DTS-12; D) D & A Instrument Company model OBS 3+; and E) Hach OptiQuant with wiper (from Rasmussen et al., 2010). Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Drawbacks associated with use of turbidimeters include a lack of consistency among different instrument types (Ziegler, 2003; Landers, 2003); variable instrument response to grain size, composition, shape, and coating; nonlinear responses of sensors to SSC (Downing, 1996); and instrument saturation at instrument-specific turbidity values (Gray and Gartner, 2009; Rasmussen et al., 2010). Additionally, the potential for biological fouling or damage to optical windows exists.

Maximum SSC limits for these instruments depend in part on particle-size distribution (PSD). The OBS has a generally linear response at SSC less than about 2 g/L for clay and silt, and 10 g/L for sand (Ludwig and Hanes, 1990), although Kineke and Sternberg (1992) describe the capability to measure SSC values as high as about 320 g/L (in the nonlinear region of the OBS response curve). 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 SSC but OBSs have superior linearity in more turbid water. Sensor-output "drift," or the tendency for the output to shift to spuriously larger values from the calibration curve over timescales of days to weeks, remains a problem particularly in warmer, microbiologically active waters (a mechanical wiper can overcome this problem). Additionally, sensor saturation that may occur at the higher flows that are most influential in sediment transport can limit the usefulness of the derived turbidity data.

Because of the relation between OBS gain and the PSD, an OBS (like single-frequency acoustic instruments) is best suited for application at sites with relatively stable PSDs. It is minimally affected by changes in PSDs in the range of 200–400 µm, but is greatly affected by changes if particles are smaller than about 44µm (Conner and De Visser, 1992). Caution should be exercised in deployments under those conditions, unless the instrument is recalibrated.

Rasmussen et al. (2009) provide guidelines for converting time series of turbidity and water-discharge data to SSC and loads using regression techniques. This technique, based on calibrations with sample data, is the first such surrogate technology to be sanctioned for use by the USGS for producing and storing surrogate sediment-concentration and -load data in the USGS National Water Information System (USGS, 2010).

Laser Diffraction Applications of laser-diffraction instruments to measure SSC and PSD in rivers are a relatively recent undertaking, having been originally developed in the 1990s for use in-situ in marine and estuarine environments. At present, this type of instrument is available from only one manufacturer, Sequoia Scientific, Inc. (2010). Depending on the instrument selected, the technology can cost 2–6 times that of a fully equipped in-situ turbidimeter. The technology may not require routine instrument-specific calibrations. The USGS is testing in-situ and manually deployed versions of this technology at several sites.

Laser-diffraction instruments were originally designed for in-situ and laboratory determinations of PSD and volume SSC, from which mass SSC can be calculated if mean particle density is known. These instruments exploit Mie scattering theory: at small forward-scattering angles, laser diffraction by spherical particles is essentially identical to diffraction by an aperture of equal size (Agrawal and Pottsmith, 1994). The method is mostly insensitive to changes in particle color or composition; however, deviations from spherical shape produces changes to estimated PSD and volume concentration (Agrawal and Pottsmith, 2000; Agrawal et al., 2008).

The in-situ LISST-100 (Laser In-Situ Scattering and Transmissometry) (Fig. 2a) determines particle-size distribution in 32 logarithmically spaced size classes between 1.25–250 µm (LISST-100B), 2.50–500 µm (LISST-100C), or 7.50–1500 µm (LISST-FLOC) (Sequoia Scientific, Inc., 2010). The LISST technology employs a 670-nm wavelength laser over a standard 5-cm path length, although other path lengths can be used depending on typical sediment conditions at the instrument deployment site. 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 (clear-water) 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. The mathematical inversion, details for which are provided in Agrawal and Pottsmith (2000), is done by vendor-supplied software. 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. In addition to PSD, the LISST also includes sensors to measure temperature, pressure, and optical transmission.

The LISST-100, which has been tested in the laboratory and field, has been shown to determine PSD of natural materials and the size of mono-sized particle suspensions within about 10-percent accuracy (Traykovski et al., 1999; Gartner et al., 2001). Unlike single-frequency turbidimeters, these instruments are not subject to potential inaccuracies associated with changes in particle size if the particle sizes fall within the range of instrument sensitivity (Agrawal and Pottsmith, 2000). As is the case with all types of in-situ optical instruments, however, biological fouling may degrade measurements. There is also a measurement limitation (in addition to size range) that is associated with multiple scattering in the presence of high SSC; multiple scattering becomes significant below 30-percent transmission. Limitations associated with high SSC values are based on the laser-path length and SSC, ranging from tenths of a g/L (small particle sizes) to several g/L (large particle sizes).

A. B.

Figure 2 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.).

A simpler and less expensive instrument version, the LISST-25, measures mean volumetric SSC and mean particle size (Sauter mean size). A cable-suspended and streamlined version of the LISST-100, the LISST-SL, has been designed specifically for riverine application. That streamlined isokinetic instrument includes the capability of real-time velocity measurements that are used to control a pump to withdraw a filament of water and route it through the laser beam at the ambient current velocity (Agrawal, and Pottsmith 2006; Gray and Gartner, 2009; Gartner and Gray, 2010). The USGS is conducting laboratory and field tests of the LISST-SL (Broderick Davis, U.S. Geological Survey, oral commun., 2010).

Digital Photo-Optics Digital-imaging acquisition and analysis techniques originated in the 1980s for use in enumerating cells in a blood sample. The technology computes size statistics based on automated measurements of images of individual suspended particles in a flow-through cell. Volumetric SSC is inferred from the size statistics. There are no anticipated routine requirements for instrument-specific calibration of the technology.

Adaptation of digital photo-optic technology for in-situ determination of suspended-sediment size and shape followed in the 1990s (Eisma and Kalf, 1996). The technology, in development and testing at the USGS Cascades Volcano Observatory, Vancouver, Washington, U.S. (Gooding, 2001; Gooding, 2010), 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 suspended-sediment samplers. The cost of off-the-shelf parts for this technology is similar to that for a fully equipped in-situ turbidimeter.

A prototype digital-photo system that employs a lens, fiber-optic cable, exclusively designed flow-through cell, and a camera coupled with a computer and frame grabber capable of obtaining two-dimensional images of suspended particles has been developed for automated use (Gooding, 2010) (Fig. 3). The high-quality image is simplified by pixel level image processing, but retains size and shape characteristics for quantitative analysis with image-processing software. Hardware enhancements have improved image quality for more reliable automated computer interpretations and increased appropriate particle-size range for use. Incorporation of a multi-lens system will permit application in sand-, silt-, and clay-size distributions of suspended material. The upper concentration limit is yet to be established, but tests up to 10 g/L have provided accurate results. The upper limit might be negated in laboratory applications by a dilution system that is being designed to use optically sensed concentration values to automatically add and mix known amounts of de-ionized water to the sample to obtain concentrations within the measurable range.

A number of challenges remain in rendering this laboratory-based technology acceptable for riverine deployment. Partially hidden particles, aggregates, high turbidity levels, and other anomalies can result in the reduction of measurement accuracy. Analytical results are expressed in volume/volume units and not in more commonly used mass/volume units, requiring assumptions about the value of particle density or collection and analysis of samples for SSC and (or) particle density information. Reliable PSD and SSC estimates can be difficult to obtain when the image becomes “noisy” due to 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.

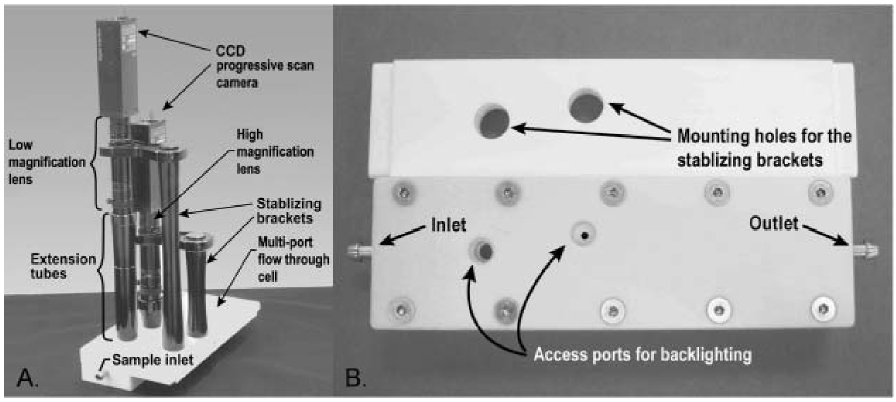

Figure 3 Suspended-sediment digital optic-imaging components: A) Cameras atop encased lenses with extension tubes and encased flow-through cell (fiber optic cable not shown).
B) Multi-port flow-through cell (patent pending). From Gooding, 2010.

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 laboratory and riverine environments.

Acoustic Backscatter Use of acoustic attenuation and backscatter (AABS) intensity to compute SSC has increased in recent years. The method can be broadly classified into two approaches. The first approach may use specially designed instruments, often employing multiple frequencies over generally short ranges (a few meters), and requires instrument calibration that is frequently accomplished in a laboratory. The theory and application are well documented (e.g., Hanes et al., 1988; Sheng and Hay, 1988; Hay, 1991; Thorne et al., 1991; Hay and Sheng, 1992; Thorne and Campbell, 1992; Crawford and Hay, 1993; Thorne et al., 1993; Thorne et al., 1995; Richards et al., 1996; Thorne et al., 1996; Schaafsma and Hay, 1997; Thorne and Hardcastle, 1997; Thorne and Buckingham, 2004; and Thorne and Meral, 2008). Thorne and Hanes (2002) provide an extensive overview and review of the technique.

The second approach employs commercially available acoustic Doppler current profilers (ADCPs). The underlying theory, based on the sonar equation [which relates reverberation level to the intensity of emitted signal, transmission losses, and target strength (Urick, 1975; Reichel and Nachtnebel, 1994)], is the same for both approaches which utilize the strength of the signal backscattered from suspended particles. However, the first approach utilizes the linear form of the equations evaluated in terms of pressure or voltage. In the ADCP approach, the equations are formulated in logarithmic form (in decibels). Theoretical aspects of the ADCP approach are well documented (e.g., Thevenot et al., 1992; Reichel and Nachtnebel, 1994; Deines, 1999; and Gartner, 2004), and applications have been described for a wide range of environments (e.g., Schott and Johns, 1987; Thevenot et al., 1992; Thevenot and Kraus, 1993; Jay et al., 1999; Klein, 2003; Gartner, 2004; Topping et al., 2004, 2006, 2007; Hoitink and Hoekstra, 2005; Hortness, 2006; Wall et al., 2006; Tessier et al., 2008; and Gartner and Wright, 2010, among many others). Of the technologies described herein, AABS perhaps is the most likely to be calibrated using only cross-section sampling techniques owing to the difficulty associated with instrument-specific calibrations in the area ensonified by the acoustic beam(s).

Applications of this technology require empirical calibrations to convert AABS measurements to estimates of SSC. Post-processing algorithms are complex, requiring compensations for hydrologic properties of ambient water such as temperature, salinity, pressure, and suspended materials as well as instrument characteristics such as frequency, power, and transducer design (Thorne et al., 1991; Downing et al., 1995). Researchers generally develop their own software although at least some commercial products are available (Land and Jones, 2001; Mol, 2003) but not yet widely tested. However, progress is being made toward developing guidelines for reducing the data (David Topping, U.S. Geological Survey, oral commun., 2010).

Instruments operating at a single acoustic frequency can, with proper calibration, provide estimates of SSC but at least theoretically lack information about PSD. The method appears appropriate for use in SSC up to several g/L. Quantification of higher SSC may be problematic, especially when using higher acoustic frequencies that are more prone to attenuation by suspended sediments. The result is a nonlinear (backscatter-intensity) response at high SSC (Hamilton et al., 1998). Acoustic attention from silt- and clay-size sediment must be accounted for in any system where these sediments vary substantially over time. Acoustic attenuation from sand-size sediments at SSC values less than about 2 g/L (using AABS frequencies in the 0.6–2 MHz range with typical power outputs) generally can be ignored in the analysis (David Topping, U.S. Geological Survey, written commun, 2010). However, Libicki et al. (1989) and Thorne et al. (1991) note that – although a function of acoustic frequency – attenuation by suspended sediments should be accounted for in the presence of as little as 0.1 g/L. Additionally, Sheng and Hay (1988) and Hay (1991) observe that multiple scattering produces nonlinear response when SSC is on the order of 10 g/L. The relation between acoustic frequency and particle-size limits the size range for which the method is appropriate (Hanes et al., 1988; Schaafsma et al., 1997). For example, with a 1,200 kilohertz ADCP, the upper size limit is less than about 400 µm. In addition, similar to all single frequency instruments, variations in PSD increase errors associated with the AABS method. Thus, careful calibrations are critical.

The method is usually deployed in-situ in side-looking orientation, but has been used in upward orientation (Wall et al., 2006). AABS is essentially non-intrusive and has the advantage of being much less susceptible to biological fouling than optical techniques. AABS also holds a distinct advantage over most other surrogate technologies in that, if an ADCP is used, it measures in beams that may extend tens of meters in the channel. Additionally, when AABS measurements by ADCP are calibrated to compute SSC, concurrent measurements of velocity profile allow for estimates of suspended-sediment transport. Estimates of SSC at accuracies similar to those for optical instruments are possible under some conditions (Thevenot and Kraus, 1993); comparisons with SSC values from water samples have been found to agree within about 10–20 percent (Thevenot et al., 1992; Thorne et al., 1991; and Hay and Sheng, 1992). Topping et al. (2007) report even better accuracies with this technique.

Single-frequency instruments cost as little as double that of a fully equipped turbidimeter. Although maintenance requirements associated with an AABS system are expected to be less than for a turbidimeter, until standard methods for operating and analyzing the derivative data are produced and validated, the added analytical complexity of processing AABS data may offset or even exceed time savings associated with reduced field maintenance.

The approach using AABS measured by ADCPs is the focus of research at a number of USGS streamgages. Results of initial tests of single-frequency AABS are encouraging (Byrne and Patiño, 2001; Gartner, 2004; Topping et al., 2006, 2007; Gartner and Wright, 2010). Research is expanding into use of multi-frequency AABS to characterize PSD in addition to SSC. An approach for segregating size fractions using a multiple-instrument, multiple-frequency system has been developed by Topping et al. (2006, 2007) on the Colorado River at Grand Canyon, Arizona, U.S. (Fig. 4). The approach utilizes a post-processing technique to analyze acoustic attenuation to compute the suspended silt-clay size fraction, and acoustic backscatter to compute the suspended-sand fraction in a size range applicable for each frequency. Side-looking ADCPs are mounted on the river bank that profile across the river width; after digitally removing the two-way transmission losses, the slope of the backscatter profile yields the attenuation coefficient, which is strongly correlated with silt-clay SSC, whereas the acoustic backscatter is strongly correlated with sand SSC.

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); when averaged over long time periods, results are within 5 percent of those computed by conventional methods, and the method calculates median grain size within 10 percent of that measured by conventional means. Topping et al. (2007) infer that acoustic data are comparable in accuracy to data collected by conventional methods, and that due to the high-temporal resolution of the data, sediment records computed from acoustic data may be more accurate than those computed using conventional techniques.

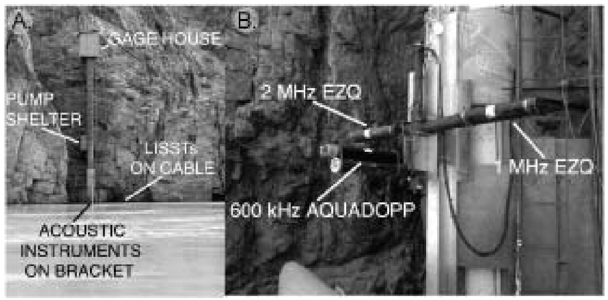

Figure 4 Photograph of an array of the three acoustic Doppler current profilers used to estimate SSCs and PSDs in the Colorado River in Grand Canyon, Arizona, U.S.
From: Topping et al. (2007).

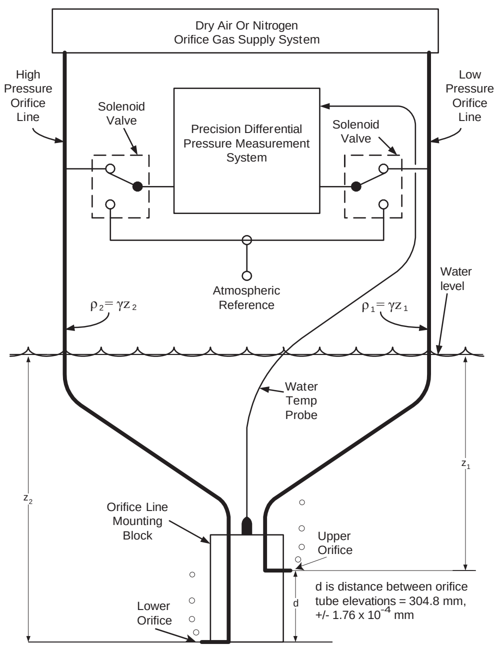

Figure 5 Schematic of the Double Bubbler Pressure Differential instrument.
Adapted from: Larsen et al. (2001).

Pressure Difference One of the first uses of the pressure-difference technique for measuring fluid density was applied to crude oil in pipes (William Fletcher, D&A Associates, oral commun., 1999). The technology has laboratory and field applications (Lewis and Rasmussen, 1999). Information on the field performance of the technology is available from USGS streamgages in Puerto Rico and Arizona, U.S. (Larsen et al., 2001; Gray et al., 2010). As of 2009, the instrument deployed sequentially at the USGS streamgages is no longer marketed, but its essential parts—two precision pressure sensors—are available from a number of vendors. The cost of the parts of a pressure-difference instrument is similar or marginally larger than that for a fully equipped turbidimeter. Figure 5 shows a schematic of a pressure-differential system (adapted from Larsen et al., 2001).

The pressure-difference technique relies on simultaneous measurements from two precision pressure-transducer sensors arrayed at different fixed elevations in a water column. The difference in pressure readings are converted to a water-density value, from which SSC is inferred after correcting for water temperature (dissolved-solids concentrations in these fresh-water systems are inconsequential in the density computation). Implicit assumptions in the method are that density of water and sediment are known, and high-resolution pressure transducers are used. The technique has been applied in the laboratory with promising results of better than 3-percent accuracy (0.543 ± 0.014 g/L) for determining mass concentration of suspensions of glass microspheres (Lewis and Rasmussen, 1999).

Application of this technique in the field can be complicated by low signal-to-noise ratio, turbulence, large dissolved solids concentrations, and temperature variations. Additionally, analysis may be complicated by density variations in the suspended material.

The performance of the pressure-difference instrument at USGS streamgages in Puerto Rico (maximum sampled SSC values of about 1.7 g/L) and Arizona (maximum sampled SSC values of about 380 g/L) was mixed at best. Measurements at both sites were characterized by a large signal-to-noise ratio, making interpretation difficult. Both datasets contained negative SSC (an impossibility) at lower, mostly clear-water flows. Both datasets were characterized by periods of poor and good correlations to sampled values during periods of storm runoff, and with unreliable data at very low SSC characteristic of base-flow periods. To date, the USGS experience with this technology supports neither acceptance nor rejection of this technology for operational monitoring. Testing of the pressure-difference technology by the USGS has been suspended (Nancy Hornewer, U.S. Geological Survey, written commun., 2010).

SUMMARY

New river monitoring technologies being studied by the USGS show considerable promise for providing continuous and quantifiably accurate suspended-sediment data. It is unlikely that any one technology will suffice for all monitoring needs of the USGS. An understanding of the sedimentary conditions in a given river coupled with knowledge of data requirements and the attributes of these technologies is needed to select an appropriate surrogate technology. Instruments that meet data-accuracy criteria can be deployed operationally and used to produce quantifiably accurate suspended-sediment records.

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