

U.S. GEOLOGICAL SURVEY SUSPENDED-SEDIMENT SURROGATE RESEARCH ON OPTIC, ACOUSTIC AND PRESSURE-DIFFERENCE TECHNOLOGIES

John R. Gray¹, Theodore S. Melis², Eduardo Patiño³, Daniel J. Gooding⁴, David J. Topping⁵, Matthew C. Larsen⁶, and Patrick P. Rasmussen⁷

¹U. S. Geological Survey, Office of Surface Water, Reston, VA (jrgray@usgs.gov)

²U. S. Geological Survey, Grand Canyon Monitoring and Research Center, Flagstaff, AZ (tmelis@usgs.gov)

³U. S. Geological Survey, Ft. Myers, FL (epatino@usgs.gov)

⁴U. S. Geological Survey, Cascades Volcano Observatory, Vancouver, WA (dgooding@usgs.gov)

⁵U. S. Geological Survey, National Research Program, Flagstaff, AZ (dtopping@usgs.gov)

⁶U. S. Geological Survey, National Research Program, Reston, VA (mlarsen@usgs.gov)

⁷U. S. Geological Survey, Lawrence, KS (pras@usgs.gov)

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ABSTRACT

The U.S. Geological Survey is evaluating potentially useful surrogate instruments and methods for inferring the physical characteristics of suspended sediments. Instruments operating on bulk acoustic, bulk and digital optic, laser, and pressure-differential technologies are being tested in riverine and laboratory settings for their usefulness to Federal agencies toward providing quantifiably reliable information on bed-material and bed-topography characteristics, and on concentrations, size distributions and transport rates of sediments in suspension and as bedload. The efficacy of suspended-sediment surrogate technologies based on bulk-optic, digital optic, laser, acoustic, and pressure-difference principles has been evaluated in Arizona, Florida, Kansas, Puerto Rico, and Washington. All but the pressure-difference technology have been shown to provide reliable data under a limited set of riverine and laboratory conditions, and pressure-difference technology tests continue at a new site in Arizona.

INTRODUCTION

A two-thirds decline in the amount of daily sediment data collected by the U.S. Geological Survey (USGS) since 1980 has occurred concomitant with a substantial increase in sediment-data needs and availability of potentially useful but largely untested sediment-surrogate monitoring technologies. Additionally, the Nation lacks nationally accepted standards for the collection or use of data derived from data-collection technologies other than those described by Edwards and Glysson (1999). These factors were instrumental in development of a recommendation by the Federal Interagency Workshop on Turbidity and Other Sediment Surrogates, April 30-May 2, 2002 (Gray and Glysson, 2003) to form a Sediment Monitoring Instrument and Analysis Research Program (SMIARP).

The USGS has, and continues to evaluate instruments that show promise for providing reliable data on selected fluvial-sedimentary characteristics in riverine and laboratory settings on bed-material and bed-topography characteristics, and on concentrations, size distributions and

transport rates of sediments in suspension and as bedload. This paper provides some examples of research in bulk-optic (turbidity), laser, digital optic, acoustic, and pressure-difference technologies used to infer selected characteristics of suspended sediments by the USGS's Water and Biology Disciplines (Gray and others, 2003; Gray and others, 2002).

USGS RESEARCH ON SUSPENDED-SEDIMENT SURROGATE TECHNOLOGIES

Turbidity Data as Suspended-Sediment Surrogates in the Kansas River at DeSoto, Kansas: Sensors that measure the bulk optic properties of water, including turbidity and optical backscatter, have been used to provide automated, continuous time series of suspended-sediment concentrations (SSC) in marine and estuarine studies, and show promise for providing automated continuous time series of SSC and fluxes in rivers (Schoellhamer, 2001). Continuous, in-situ measurements of turbidity to estimate SSC have been made at a stream-monitoring site at the Kansas River at DeSoto, Kansas, since 1999.

Continuous turbidity measurements have been shown to provide reliable estimates SSC with a quantifiable uncertainty. Simple linear regression analysis explained in Christensen and others (2000) was used to develop a site-specific model using turbidity to estimate SSC (Figure 1). The model explains about 93 percent of the variance in SSC. Continuous suspended-sediment discharge estimates from the model are available on-line (U.S. Geological Survey, 2002). The advantages of continuous regression estimates using continuous turbidity measurements over discrete sample collection are that continuous estimates represent all flow conditions regardless of magnitude or duration, and sediment-discharge estimates are obtained essentially continuously at the interval in which water discharges are recorded.

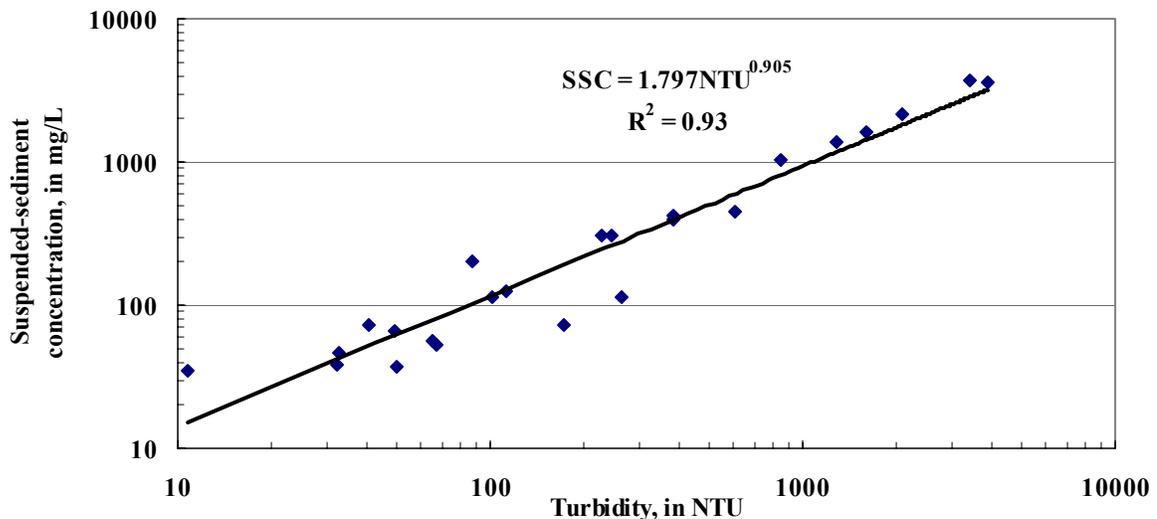


Figure 1. Comparison of field turbidity in nephelometric turbidity units and suspended-sediment concentrations in milligrams per liter (mg/L) for the Kansas River at DeSoto, Kansas, 1999 through 2002.

Laser Data as a Suspended-Sediment Concentration and Particle-Size Distribution

Surrogate in the Colorado River at Grand Canyon, Arizona: Laser diffraction grain-size analysis, a technique pioneered in the 1970's, is predicated on the concept that light impinging on a particle is either absorbed by the particle or is diffracted around the particle. The diffracted rays appear in a small-angle region. The Laser In-Situ Scattering and Transmissometry (LISST) technology measures the small-angle diffraction of a laser and inverts the signal to infer the in-situ particle-size distribution of the material being measured. Summing the volume of sediment in each particle-size class enables calculation of volumetric SSC (Agrawal and Pottsmith, 2001).

Laser sensors are currently being investigated as an alternative monitoring protocol for tracking reach-scale suspended-sediment supply in the Colorado River at Grand Canyon, Arizona, located 164 kilometers downstream from Glen Canyon Dam. This approach provides continuous suspended-sediment transport data that may reduce uncertainty in estimates of the transport of sand and finer material. The LISST data reported here were collected using LISST-100-B manufactured by Sequoia Scientific, Inc.¹ (Agrawal and Pottsmith, 2001; Gartner and others, 2001; Gray and others, 2002). The LISST-100-B is designed to measure suspended particles over a size range of 1.3-250 micrometers. The standard sample path of this device is a cylindrical volume with a diameter of 6 millimeters (mm) and a length of 50 mm.

Initial point data collected at a fixed-depth, near-bank site were obtained averaging 16 measurements at 2-minute intervals during a 24-hour deployment on July 19, 2001. The 720 LISST-100-B point measurements shown in Figure 2 compare favorably with cross-sectional data obtained concurrent with some of the laser measurements by techniques described by Edwards and Glysson (1999). In addition to accurately tracking sand concentrations, the LISST-100-B also recorded the expected increase of variance in the concentration of sand-size particles with increasing flows, with peak values ranging up to 150 mg/L (Figure 2).

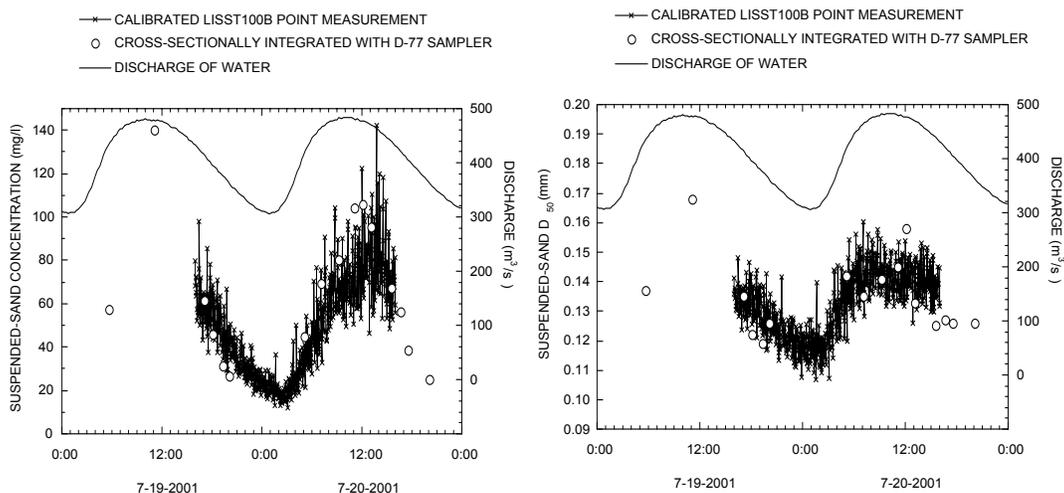


Figure 2. Comparison of sand concentrations and median grain sizes measured in the Colorado River at Grand Canyon, Arizona using a LISST-100-B and a US D-77 bag sampler.

¹ Use of trade or firm names in this report is for identification purposes only and does not constitute endorsement by the U.S. Government.

These initial results, coupled with subsequent testing, suggest that the LISST-100-B is suitable for providing SSC and particle-size data for the Colorado River at Grand Canyon, Arizona. A manually deployable version of the LISST technology is under development (Gray and others, 2002).

Photo-Optic Imaging Data as Laboratory and Stream Suspended-Sediment Surrogates:

Photo-optic imaging of fluids was pioneered by the medical industry in the 1980's for determining red blood cell concentrations. This technology, which is used to delineate, characterize, and enumerate organic particles in blood samples, is being adapted to quantify the concentration and selected size and shape characteristics of suspended sediments in water samples. Research to apply photo-optic imaging for laboratory (Gooding, 2001) and field applications is centered at the U.S. Geological Survey's Cascades Volcano Observatory in Vancouver, Washington (U.S. Geological Survey, 2003).

Photo-optic imaging has the capability to provide in real time suspended-sediment concentrations, and measurements of the size and shape of individual particles in addition to statistics on size and shape for all particles. Laboratory applications include concentration and size-fraction determinations in addition to shape computations. Potential field applications include automatic point measurements and manual measurements as part of a modified depth-integrating sampler (Edwards and Glysson, 1999; Gray and others, 2002).

The technology uses a lens, fiber-optic cable, flow-through cell, and camera with "frame-grabbing" capabilities to obtain a two-dimensional image of suspended solid-phase particles, either in a stream or in a re-suspended sample. The physical viewing area of the flow-through cell has a diameter of 10 millimeters (mm) and an internal depth of 4 mm. The lens and flow-through cell were custom built to match the flow-through cell dimensions. Other parts are commercially available.

A captured high-quality image is automatically converted to a binary image with distinguished particle boundaries using Matrox Inspector with MIL 7.0 Imaging Library software (Matrox Imaging, 2003). This morphologically transformed image usually has fewer details than appear in the original photograph, implying a loss of information. However, its size and shape characteristics remain readily quantifiable.

Once an image has been simplified by morphological transformation, quantitative analysis is conducted on the image. Inherent complexities involved with imaging individual sediment particles in a liquid medium impede extraction of usable information from two-dimensional images. However, as illustrated below, hardware enhancements have improved the quality of the image resulting in more reliable automated computer interpretations.

An unfiltered lens tends to give unreliable results for transparent particles, but polarizing the light used to illuminate the target area eliminates this problem. By combining two in-line polarized filters from 50° to 70° from cross polarization between the illumination source and target area, all particles, become completely darkened but still maintain the requisite contrast with the background as demonstrated in Figure 3.

The presence of turbidity caused by organic and colloidal material also can hinder obtaining a useable image for analysis. Using a near-ultraviolet wavelength of 450 – 500 nanometers to

illuminate the target area results in a decrease in reflectance and refraction, as seen when using visible-wavelength spectrum lighting. Images of particles—“blobs”—suspended within turbid water are shown in Figure 4. The water-sediment mixture in this image has a concentration of 10,000 mg/L of material finer than 0.062 mm. Even though the contrasting software has caused the blobs to lose some textural details, the imaging software can still select the blobs and edge detection can be performed. In some cases, the region of interrogation may still be obscured by turbidity depending on the nature of the factors causing the turbidity. If the spatial correlation of the background cannot be automatically determined, automatic detection of particle boundaries becomes less precise or impossible. More testing and development is required in this regard.

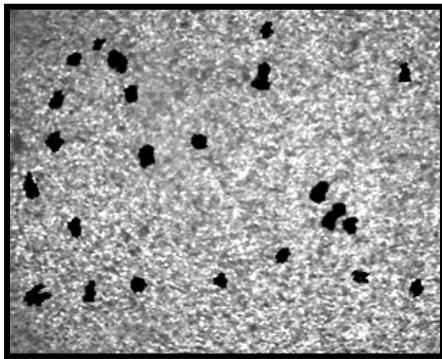


Figure 4. A morphologically transformed image of a water-sediment mixture comprised of 10,000 mg/L of material finer than 0.062 mm.

Perhaps the most difficult task of imaging the blobs deals with connected, aggregated, and (or)

overlapping particles that appear as single blobs. The software dissection of multiple interlocking particles can be difficult, requires the most comprehensive part of the analysis software, and may contribute to longer processing times. With this and other possible hindrances, it may be desirable to analyze several images to average out any biases caused by poor-quality images. The basic design of the software is to analyze selected layers of the image starting with well-delineated and easily identifiable particles, leaving characterization of particles that are obscured or that otherwise present definitional problems for the final and most computationally intensive analyses.

Research on the photo-optic imaging technology now focuses on refining the software to maximize automatic interpretation of aggregates. As shown in Figure 5, the most recent version of the software is able to distinguish a blob as two discrete particles, labeled as 100 and 102. The blob labeled as 99 may be two connected or overlapping particles, but the software interpreted it as a single particle. The sample material used in this image consists of very fine sand. Some of the sand grains are made up of two minerals fused together, which give the barbell-shaped appearance.

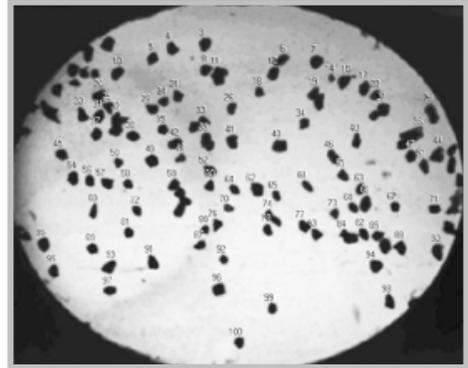


Figure 3. A morphologically transformed image of a water-sediment mixture illuminated by cross polarization. Each sediment particle or those appearing as groups are numbered.

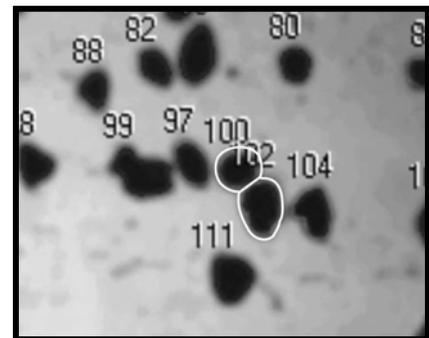


Figure 5. A morphologically transformed image of a water-sediment mixture comprised of material 0.062-0.125 mm showing potentially inconsistent interpretation of overlapping or connected particles.

Acoustic Data as Suspended-Sediment Surrogates in Two South Florida Streams: Use of acoustic instruments worldwide for the measurement of stream velocities has increased substantially since the 1980's. These instruments are capable of providing information on acoustic return signal strength, which in turn has been shown in some settings to be useful as a surrogate parameter for estimating SSC and fluxes (Gartner and Cheng, 2001). Two main types of acoustic instruments have been used extensively in the U.S.: The acoustic velocity meter (AVM), and the newer acoustic Doppler velocity meter (ADVM). The AVM system provides information on automatic gain control (AGC), an index of the acoustic signal strength recorded by the instrument as the acoustic pulse travels across a stream. The ADVM system provides information on acoustic backscatter strength (ABS), an index of the strength of return acoustic signals recorded by the instrument. Both AGC and ABS values increase with corresponding increases in the concentration of suspended material. SSC is then computed based on site-specific relations established between measured SSC values and information provided by the acoustic instrument.

Data from the AVM and ADVM systems collected in the L-4 Canal in Broward County, Florida, and the North Fork of the St. Lucie River at Stuart, Florida (Byrne and Patiño, 2001). In addition to the acoustic instruments, water-quality sensors were installed at both sites to record specific conductance (or salinity) and temperature data. These data were used to monitor the potential effects that density changes could have on the AGC/ABS to SSC relations.

Results shown in Figure 6 suggest that this technique is feasible for estimating SSC in South Florida streams and other streams with similar flow and sediment-transport characteristics. Additional research is progressing on the effects of changes in the physical composition of suspended sediments, including the percent organic material, and the effect that a varying particle-size distribution may have on the established acoustic-SSC relations.

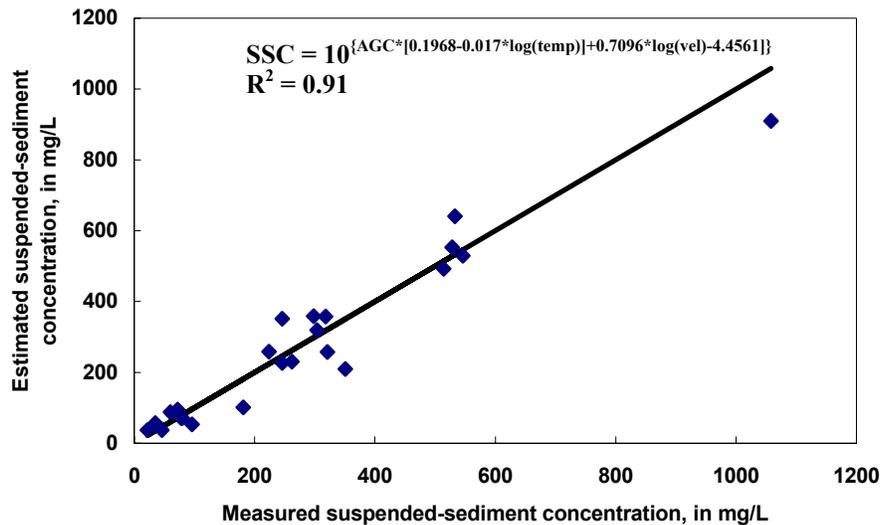


Figure 6. Comparison of estimated and measured suspended-sediment concentrations for the L-4 Canal site, Broward County, Florida.

Pressure-Differential Data as a Suspended-Sediment Concentration Surrogate in the Río Caguitas, Puerto Rico: Estimation of suspended-sediment concentrations from fluid density computed from pressure measurements shows promise for monitoring highly sediment-laden streamflows. Precision pressure-transducer measurements from vertically imposed orifices at different elevations are converted to density data by use of simultaneous equations. When corrected for water temperature, the density data are used to estimate sediment concentrations from a density-concentration relation (U.S. Geological Survey, 1993). Thus, the device provides continuous (typically on 15-minute interval) sediment data that can be transmitted by satellite as stage and other data are transmitted. The cost savings and improved data quality can be substantial over those for traditional techniques sediment-data acquisition techniques.

An instrument for continuously and automatically measuring the density of a water-sediment mixture as a surrogate for SSC, referred to as a double bubbler precision differential pressure measurement system by the manufacturer, was tested in at the Río Caguitas streamgaging station in Puerto Rico from October-December, 1999 (Larsen and others, 2001) (Figure 7).

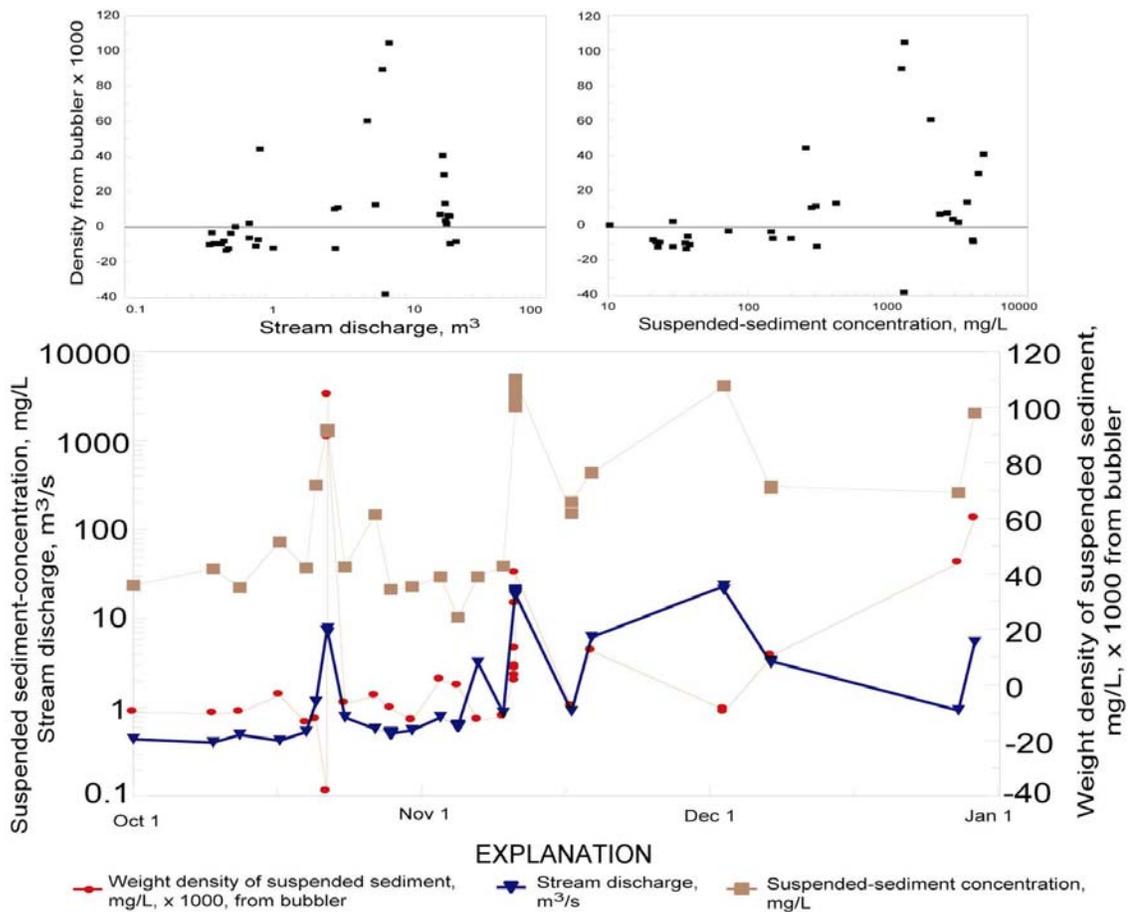


Figure 7. Scatter plots and time series of stream discharges, suspended-sediment concentrations, and weight density of sediments and dissolved solids measured with a double bubbler, October 1, 1999, to January 1, 2000, Río Caguitas, Puerto Rico. Discharge and sediment data are instantaneous samples, and the double bubbler weight density value is a 30-minute mean of measurements made at 5-minute intervals.

The data collected during October-December 1999 at this site showed relatively poor agreement between discharge, SSC, and water density (Figure 2). The 1999 tests indicate that the double bubbler instrument values generally track substantial variations in SSC, but a large amount of signal noise remains. The maximum SSC measured at the site as of 2000 – 17,700 mg/L – corresponds to a signal-to-noise ratio of about 1.02.

This test of the double bubbler instrument showed the need for temperature compensation, and possibly the need to deploy the instrument at a site where the signal-to-noise ratio is substantially larger than 1.02 for the bulk of the runoff hydrograph. The double bubbler is being tested in Arizona's Paria River, where SSC in excess of a 1×10^6 mg/L have been measured, yielding a signal-to-noise ratio of about 2.0. If adequate results can be achieved, increases in data accuracy and substantial reductions in costs of sediment monitoring programs for rivers carrying moderate-to-large SSC can be realized.

SUMMARY

The USGS is evaluating the efficacy of suspended-sediment surrogate technologies based on bulk-optic, digital optic, laser, acoustic, and pressure-difference principles in Arizona, Florida, Kansas, Puerto Rico, and Washington. All provide concentration data, and those based on digital optic and laser principles also provide size-distribution data. All but the pressure-difference technology has been shown to provide reliable data under a limited set of riverine and laboratory conditions. Tests on all technologies continue, with those for the pressure-difference technology taking place at a different venue in Arizona.

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