OVERVIEW OF SELECTED SURROGATE TECHNOLOGIES FOR CONTINUOUS SUSPENDED-SEDIMENT MONITORING

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Abstract: Surrogate technologies for inferring selected characteristics of suspended sediments in surface waters are being tested by the U.S. Geological Survey and several partners with the ultimate goal of augmenting or replacing traditional monitoring methods. Optical properties of water such as turbidity and optical backscatter are the most commonly used surrogates for suspended-sediment concentration, but use of other techniques such as those based on acoustic backscatter, laser diffraction, digital photo-optic, and pressure-difference principles is increasing for concentration and, in some cases, particle-size distribution and flux determinations. The potential benefits of these technologies include acquisition of automated, continuous, quantifiably accurate data obtained with increased safety and at less expense. When suspended-sediment surrogate data meet consensus accuracy criteria and appropriate sediment-record computation techniques are applied, these technologies have the potential to revolutionize the way fluvial-sediment data are collected, analyzed, and disseminated.

INTRODUCTION

The U.S. Geological Survey (USGS) and several partners are evaluating instruments and methods that show promise for providing continuous and reliable—unbiased and quantifiably precise—data on selected fluvial-sediment characteristics in riverine and laboratory settings. Sedimentary phases of interest include characteristics of bed material and bed topography, size distributions and transport rates of sediments in suspension and as bedload, and suspended-sediment concentrations.

This paper describes the operational basis of some of the instruments and techniques being developed or tested (Gartner and Gray, 2003; Gray, 2005), and evaluates initial results of USGS research in bulk-optic, laser-diffraction, digital-optic, acoustic, and pressure-difference technologies (Gray et al., 2003) used to infer selected characteristics of suspended sediments without the need for routine collection and analysis of physical samples (Edwards and Glysson, 1999; Bent et al., 2001). Criteria for the accuracy of data produced by surrogate technologies are suggested, as is a method of using concurrent flow and surrogate data to compute reliable records of suspended-sediment discharge.

SUMMARY OF SURROGATE TECHNOLOGIES IN EVALUATION

Bulk Optics: Measurements of the bulk-optical properties of water are the most common means for determining water clarity and estimating suspended-sediment concentrations (SSC) in United States (U.S.) rivers (Pruitt, 2003). A number of optical instruments are commercially available.

Bulk-optic instruments can be categorized as:

- Transmissometers, which employ a light source beamed directly at the sensor. The instrument measures the light transmission.
- Nephelometers, which measure light scattered by suspended particles (rather than light transmission). Nephelometers generally measure 90° or forward scattering. An optical backscatter (OBS) instrument (Downing et al., 1981; Downing, 1983) is a type of nephelometer designed to measure backscattered infrared radiation in a small (concentration dependent) volume on the order of a few cm^3.

These instruments provide measurements from a single point. Both transmittance and scatterance are functions of the number, size, color, index of refraction, and shape of suspended particles.

These bulk-optical instruments are generally inexpensive, lack moving parts, and provide rapid sampling capability. The instruments rely on empirical calibrations to convert measurements to estimates of SSC. The technology is relatively mature, and has been shown to provide reliable data at a number of USGS streamflow-gaging stations (Schoellhamer and Wright, 2003; Melis et al., 2003; Uhrich, 2003; Rasmussen et al., 2003; Rasmussen, et al. 2005) and other sites (Pratt and Parchure, 2003; Lewis, 2003).

There are several drawbacks associated with use of bulk-optic instruments that include:

- Lack of consistency in instrument measurement characteristics (Ziegler, 2003; Landers, 2003)
- Variable instrument response to grain size, composition, color, shape, and coating,

- Biological fouling or damage to optical windows, and
- Nonlinear responses of sensors to sediment concentration (Downing, 1996).

Maximum concentration limits for these instruments depend in part on particle-size distributions. The OBS has a generally linear response at concentrations 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 very high concentrations up to about 320 g/L (in the non-linear region of the OBS response curve). The upper concentration 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 concentrations but OBS has superior linearity in turbid water. Sensor-output "drift," or the tendency for the output to shift from the calibration curve to spuriously higher values over timescales of days to weeks, remains a problem, particularly in warmer, microbiologically active waters.

Because of the relation between OBS gain and particle size, OBS (like all single-frequency instruments) is best suited for application at sites with relatively stable particle-size distributions. The OBS is minimally affected by changes in particle-size distribution in the range of 200-400µ, moderately affected by changes between 63-125µ, and greatly affected by changes when particles smaller than about 44µ (Conner and De Visser, 1992; Sutherland et al., 2000). Conner and De Visser (1992) caution against using OBS in environments where changes in size distributions occur and particle sizes are less than 100µ. 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 concentrations and ratios of black and white suspended sediment. They found the smallest OBS response for black sediment and the largest for white sediment, with 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 particle-size and –color conditions, unless the instrument is recalibrated for ambient conditions.

Laser Diffraction: Applications of laser diffraction in rivers is a relatively recent undertaking, having been originally developed in the 1990's for use in marine and estuarine environments. The USGS is testing in-situ and manually deployed versions of this technology in field and laboratory settings (Topping et al., 2006; Mark N. Landers, USGS, oral commun., 2005; Lawrence Freeman, USGS, oral commun., 2005). At present, this type of in-situ instrument is commercially available from a single manufacturer.

The instruments are designed for in-situ and laboratory determinations of suspended material particle-size distributions from which concentrations can be calculated. 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). Thus, this method of estimating concentration and size distribution is mostly insensitive to changes in particle color or composition. Departure from sphericity does produce as yet unknown changes in calibration, and in most cases distorts the fine particle end of the retrieved size distribution. New research is addressing this question empirically (Yogesh Agrawal, Sequoia Scientific, Inc., 2005, written comm.)

The in-situ LISST-100 (Laser In Situ Scattering and Transmissometry) (use of trade, product, or firm name is for descriptive purposes only and does not imply endorsement by the USGS) uses 32 ring detectors to determine particle-size distributions between 2.5-500µ or 1.25–250µ (Sequoia Scientific, Inc., 2004). The LISST-100, which has been field and laboratory tested, has been shown to successfully determine particle-size distributions of natural materials and the size of mono-sized particle suspensions within about a 10-percent accuracy (Traykovski et al., 1999; Gartner et al., 2001). The LISST-100 can also be used to determine SSC from volume concentration if particle density is known (Gartner et al., 2001). Unlike single-frequency optical backscatter instruments, these instruments are not subject to potential inaccuracies associated with changes in particle size if the particles 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 can degrade measurements. This problem can be addressed with anti-fouling shutters that are now available for the LISST-100 (Yogesh Agrawal, Sequoia Scientific, Inc., 2005, written comm.).

In-situ versions of laser diffraction instruments may be deployed unattended to provide a time series of particle-size distributions. There are measurement limitations (in addition to size range), however, that are associated with multiple scattering in the presence of high SSC. 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). For suspensions of typical marine sediments, appropriate concentration levels range between about 0.15-5 g/L (Traykovski et al., 1999).

New instrument options and versions are being developed to address these problems and increase the range of applications. For example, reducing the optical path in water from the standard 5 cm to 3 mm has been effected to extend measurement limits to 2-3 g/l of fine material. For still higher concentrations, a LISST-Infinite was developed by Sequoia Scientific, Inc., as part of a research-and-development project with the USGS. The LISST-Infinite, a prototype of which is being tested by the USGS (Konrad et al. 2006), employs a pump to bring a water-sediment sample to the instrument, and then uses automated multi-stage dilution (as necessary) before measuring particle-size distributions and concentrations with a built-in LISST-100. Thus, the measurable concentration limit is, in theory, extended to the highest concentrations of material that can be pumped to the LISST-100 (Yogesh Agrawal, Sequoia Scientific, Inc., 2005, written comm.).

A simpler instrument—the LISST-25—has been developed for measuring a mean concentration and a mean particle size (Sauter mean size). Another instrument, the LISST-FLOC covers the size range from 7.5-1500µ.

A manually deployable cable-suspended streamlined version of the LISST-100 developed for riverine application—the LISST-SL—is in development and testing (Federal Interagency Sedimentation Project, 2005). The LISST-SL is designed to measure real-time velocities that in turn are used to control a pump to withdraw a filament of water and route it through the laser beam at a rate approximately equal to the ambient current velocity (Gray et al, 2002; Gray and Agrawal, 2004). Achieving isokinetic flow-through capability by the LISST-SL—considered by the Federal Interagency Sedimentation Project to be +/- 10 percent of the ambient stream velocity, although the actual sedimentological efficiency of any device that relies on the isokinetic-flow principle may also vary with changes in ambient particle-size distributions (Federal Interagency Sedimentation Project, 1941)—is a prerequisite for reliably ascertaining the suspended-sediment properties in all but the shallowest or most sluggish rivers (Edwards and Glysson, 1999; Agrawal and Pottsmith, 2006).

Digital Photo-Optics: Digital-imaging acquisition and analysis techniques pioneered by industry in the late 1970's became relatively sophisticated in the later 1980's following the advent of high-speed computers with ample storage capabilities. The initial focus of the technology's application included biomedical image processing (such as for enumerating blood cells), machine vision for manufacturing, and computer vision for use in robotics. Adaptation of the technology for in-situ determination of suspended-sediment size and shape followed in the 1990's (Eisma and Kalf, 1996). This technology is in development at the USGS Cascades Volcano Observatory (CVO) fluvial-sediment laboratory (U.S. Geological Survey, 2005; Gooding, 2001). Present equipment is designed for laboratory use, although the technology also is intended for in-situ applications.

A prototype for digital imaging acquisition and classification for suspended sediment analysis that utilizes an exclusively designed flow-cell enables discrete identification of particle attributes such as size and shape. Using software developed at CVO, a high-quality digital image of suspended-sediment particles is simplified by morphological transformation. The transformation retains the size and shape characteristics of the discretely imaged particles for quantitative analysis. Hardware enhancements have improved image quality for more reliable automated computer interpretations and extended the size range that can be resolved. Use of a multi-lens system will permit applications with sand-, silt-, and (or) clay-size distributions of suspended material.

There is no lower concentration limit. The upper limit is yet to be established, but tests up to 10 g/L have provided accurate results. The upper limit might be obviated 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 (Daniel Gooding, USGS, 2005, written commun.).

Efforts are now focused on refining and testing computer software to determine particle concentration, size, and shape in real or near-real time. The system is presently designed for determining size distributions and turbidity; however future plans are to add capability to determine SSC from size-distribution information. Nevertheless, digital photo-optic systems requiring little or no calibration may ultimately replace visual accumulation tube and pipette laboratory techniques for analysis of particle-size distributions.

Acoustic Backscatter: The technique of using acoustic backscatter (ABS) intensity to estimate mass concentration of suspended material, first tested in the 1980's (Gartner, 2003), is the focus of research at about a dozen USGS streamflow-gaging stations (Gray et al., 2003). Results of some initial tests of single-frequency ABS are encouraging (Byrne and Patiño, 2001). Research has expanded into use of multi-frequency ABS that may provide continuous information on particle-size distributions in addition to concentrations (Topping et al., 2006; Mark N. Landers, USGS, oral commun., 2005).

The method, which utilizes the strength of the signal backscattered from suspended-sediment particles, is based on the sonar equation (Urick, 1975; Reichel and Nachtnebel, 1994). ABS applications require empirical calibrations to convert 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, for example Jay et al., 1999 or Gartner, 2004, although at least one commercial product is available (Land and Jones, 2001) but not yet widely used.

Instruments operating at a single acoustic frequency can provide estimates of SSC but lack information about particle-size distributions. The method appears appropriate for use in concentrations up to several grams per liter. Quantification of higher concentrations may be problematic, especially when using high acoustic frequencies that are more prone to attenuation from sediment. The result is a non-linear (backscatter intensity) response at high concentrations (Hamilton et al., 1998). Although a function of frequency, attenuation from sediment should be accounted for in the presence of as little as 0.1 g/L (Libicki et al., 1989; Thorne et al., 1991) and multiple scattering produces non-linear response when SSC is on the order of 10 g/L (Sheng and Hay, 1988; Hay, 1991).

The method has the advantage of being less susceptible to biological fouling than optical techniques and is non-intrusive. ABS also holds a distinct advantage over most other surrogate technologies in that, if an acoustic Doppler velocity profiler (ADCP) is used, it measures in a beam that may extend tens of meters laterally or vertically in the channel, thus integrating the sedimentary characteristics over an area. Additionally, when calibrated, the estimated SSC values enable calculations of suspended-sediment transport when coupled with river-discharge values, for example Topping et al., 2006 or Wall et al., 2006. The relation between acoustic frequency and particle size, however, limits the size range for which the method is appropriate (Hanes et al., 1988; Schaafsma et al., 1997). For example, with a 1200 kilohertz ADCP, the method is appropriate for particle-size distributions in which there is no significant concentration of particles larger than about 400µ. The method is increasingly less accurate as the percentage of particles approaching or larger than this limit increases. In addition, variations in size distribution increase errors associated with the ABS method, similar to all single frequency instruments, thus careful calibrations are critical. 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).

<u>Pressure Difference:</u> 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, 1999, oral commun.). The technology has laboratory and field applications (Lewis and Rasmussen, 1999). Information on the field performance of the technology is available from USGS streamflow-gaging stations in Puerto Rico, Georgia, and Arizona. Initial tests at concentrations ranging up to about 1.5 g/L at a USGS streamflow gaging station in Puerto Rico were encouraging, but were not unequivocally successful (Larsen et al., 2001). Results from subsequent tests at the Paria River at Lees Ferry, Arizona, streamflow-gaging station at concentrations of hundreds of g/L are encouraging (Gregory G. Fisk, USGS, oral commun., 2005).

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 is 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 exceptionally sensitive 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, significantly large dissolved solids concentrations, and temperature variations. Additionally, analysis may be complicated by density variations in the suspended material. The differential pressure method generally has been successful in the field at concentrations greater than about 50 g/L but needs additional evaluation in the range of 10-50 g/L. The technique may not be reliable at lower concentrations. William Fletcher (D&A Associates, 2005, oral commun.) indicated that calculations based on a moving average of the pressure-difference data tended to provide a smoother concentration time series and render them more comparable to available concentration data derived from water-sediment samples obtained by methods described by Edwards and Glysson (1999).

RANGE AND ACCURACY CRITERIA

All of the preceding sediment-surrogate technologies are capable of providing a signal that can be empirically converted to a concentration value (in the case of laser-diffraction technology, LISST, concentration is inferred from summation of the measured particle-size distribution). However, a fundamental question remains: Can the technology provide reliable measurements over the full range of the sedimentary parameter of interest? Thus, it is important for a user to recognize the sensitivity of these systems to particles outside their measurement range.

A measurement range normally is confined by the expected extremes for the parameter of interest within the context of the monitoring program's objectives. For example, if the objective is to quantify mass transport, the instrument should be able to measure the concentration values that can occur at the site during the monitoring period, with particular emphasis on the larger concentrations and higher flows. If information on transport by size class is sought, then a sufficient number of particle-size distributions are needed; ergo, the instrument must be capable of characterizing the full range of particle sizes expected at the site.

Among the benefits of sediment-surrogate technologies—aside from not requiring routine collection of a physical sample for subsequent analysis—is the capability to compute estimates of uncertainty associated with the derived unit- and daily-value data. The subject of uncertainty estimates in concentration or particle-size distribution measurements, and particularly in flux measurements, is complex given that each measurement variable – the surrogate signal and the calibration, streamflow, and ancillary data – have non-zero variances. Until research provides a reliable means for such computations, uncertainties computed for sediment-surrogate measurements will be referenced to analytical results from periodically collected, representative water samples (Edwards and Glysson, 1999) which are widely considered to be the best such data available describing the sedimentary conditions of the Nation's rivers and streams.

Gray et al. (2002) developed accuracy criteria specifically for development of the LISST-SL. An updated version of those concentration and particle-size distribution criteria suggested for general use follows:

- Particle-Size Distributions: The instrument should be capable of measuring suspended-sediment particles ranging from 2-2,000µ median diameter within 25 percent of the actual size for 90 percent of the measured values.
- Suspended-Sediment Concentrations: The instrument should provide SSC from zero to the maximum expected concentration value for 90 percent of measured values to within:
  (a) 50 percent of actual SSC for SSC less than 0.01 g/L,
  (b) from 50 percent of actual SSC of 0.01 g/L to 25 percent of SSC of 0.1 g/L, computed linearly,
  (c) from 25 percent of actual SSC of 0.1 g/L to 15 percent of SSC of 1 g/L, computed linearly,
  (d) from 15 percent of actual SSC of 1 g/L to 10 percent of SSC of 10 g/L, computed linearly, and
  (e) 10 percent of actual SSC for SSC greater than 10 g/L.

Deviations from these criteria should not be skewed within a single size-distribution or in a concentration range, rather, they should be more or less evenly distributed throughout the measuring ranges.

SEDIMENT-RECORD COMPUTATION

Use of a reliable unit-value time series of SSC with paired discharge values represents the most accurate means for computing suspended-sediment loads on a sub-daily and daily basis. Record computation based on this technique was developed in the middle 20th century (Porterfield, 1972) and is used by the USGS today. In the late 1990's, the USGS developed the Graphical Constituent Loading Analysis System (GCLAS), a software package for computing daily discharge (load) records of suspended sediment and other water-quality constituents, to facilitate and enhance those computational techniques (Mckallip et al., 2001).

GCLAS features an interactive graphical user interface that permits easy entry of estimated constituent-concentration values and provides new tools to aid in making those estimates. It uses a water-discharge time series, and suspended-sediment values to determine daily suspended-sediment discharges and associated daily mean SSC. The program also is capable of computing discharges of any constituent expressed in terms of mass per volume.

GCLAS includes tools to aid in making estimates of constituent concentrations for periods when concentration data are missing or under-sampled. In addition, GCLAS facilitates analysis and application of cross-section coefficients, which are multipliers used to adjust concentration values obtained from samples collected at a fixed point or vertical so that the concentration values are more representative of the discharge-weighted mean concentration at the cross-section and time of interest.

CONCLUSIONS

New river monitoring technologies being studied by the USGS and several partners show considerable promise for providing continuous and quantifiably accurate data describing selected characteristics of suspended-sediment. 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 will be deployed operationally, and new software will use the derivative data to compute quantifiably accurate records of suspended-sediment discharge.

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