SUMMARY OF SUSPENDED-SEDIMENT TECHNOLOGIES CONSIDERED AT THE INTERAGENCY WORKSHOP ON TURBIDITY AND OTHER SEDIMENT SURROGATES

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ABSTRACT

Traditional methods for characterizing suspended sediments in surface waters are increasingly being replaced in favor of accurate, continuously collected surrogate data that may be safer, and (or) less expensive to obtain. Bulk optical properties of water such as turbidity and optical backscatterance are the most commonly used surrogates for suspended sediment, but use of other techniques such as acoustic backscatter, laser diffraction, digital photo-optic, and pressure-difference technologies is increasing. The Federal Interagency Workshop on Turbidity and Other Sediment Surrogates (http://water.usgs.gov/osw/techniques/turbidity.html) was held in part to bring focus to the availability and applicability of other sediment-surrogate techniques for fluvial sediment data-collection. In addition to summarizing information about the surrogate techniques for measuring suspended sediment characteristics, workshop participants recommended that the Federal Interagency Subcommittee on Sedimentation establish and foster a group of topical expert advisors; improve communication and technology transfer among individuals and organizations with interests in sediment-surrogate technologies; develop guidelines for calibrating sediment-surrogate sensors; and establish and promulgate criteria for suspended-sediment data accuracy.

INTRODUCTION

Methodologies for characterizing suspended sediments in surface waters that require routine collection and subsequent analysis of water samples are well established (Wilde and Radtke, 1998; Edwards and Glysson, 1999; Yuquin, 1989). However, these traditional methods are increasingly being forsaken in favor of quantifiably accurate, less expensive, and (or) potentially safer continuously recording in situ and laboratory methods for obtaining surrogate[1] data for quantification of suspended-sediment concentrations (SSC) and other selected sedimentary characteristics of surface waters. Monitoring bulk optical properties of water such as turbidity or optical backscatterance is the most common means for obtaining water-clarity data, and for estimating SSC. Other sediment-surrogate measurement techniques including those based on acoustic backscatter, laser diffraction, digital photo-optic, and pressure-difference technologies,

[1]As used herein, a surrogate is an environmental measurement that can be reliably correlated with an in-stream characteristic, such as concentration or particle-size distribution of fluvial sediment. Surrogate data are typically easier, less expensive, and (or) safer to collect than the target variable, and may enable reliable estimates of uncertainty associated with the measurement.

are increasingly being used (Gray et al., 2003). Some of these techniques also measure suspended-sediment size characteristics.

The Federal Interagency Workshop on Turbidity and Other Sediment Surrogates (Gray and Glysson, 2003) was held in Reno, Nevada, April 30 to May 2, 2002, in part to address the potential for applying selected sediment-surrogate technologies to the fluvial sediment data-collection needs of the Nation. The general goals of the workshop related to other sediment-surrogate technologies (as differentiated from goals specific to measurement of water clarity) were to define:

- The state-of-the-art of selected surrogate techniques for the collection of suspended-sediment data and other characteristics of surface water.
- Approximate criteria and (or) conditions under which each technology is a reliable surrogate measurement for SSC and other sedimentary characteristics of surface water.

Participants in workshop breakout sessions examined several techniques for monitoring SSC including bulk optical (turbidity and optical backscatterance), acoustic-backscatter, optic-laser diffraction, digital-photo optic, and pressure-difference methods. Evaluation of each method included consideration for the appropriate conditions (size distribution and/or concentration) under which each technique might be used; important limitations and advantages; potential accuracy, if known; and the priority for potential research for any of the techniques that are not currently widely accepted or used. The majority of the methods were categorized as research techniques, the exception being bulk-optic instruments. A brief summary of the findings about each of the techniques is presented in the following section followed by some general recommendations.

BULK OPTICS (ATTENUATION AND SCATTERANCE)

The amount of suspended material in surface waters has been characterized for decades using optical methods that utilize attenuation (or transmittance) or scatterance. Optical instruments can be generally characterized as one of three types. When the optical light source is shown directly at the sensor the instrument (transmissometer) measures the light transmission, an inherent optical property. In the case of scatterance, the sensor measures the light scattered by suspended particles. Nephelometers generally measure 90° or forward scattering. An optical backscatter instruments such as OBS (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 cubic centimeters. Thus these instruments provide essentially a single point measurement. Both transmittance and scatterance are functions of the number, size, index of refraction, and shape of suspended particles. Optical instruments are generally inexpensive, without moving parts, and provide rapid sampling capability. The instruments rely on empirical calibrations to convert measurements to estimates of SSC.

There are several difficulties associated with use of optical instruments that include: 1) limited standard for design; 2) instrument response varies with grain size, composition, shape, and coating; 3) biological fouling or damage to optical windows; and 4) nonlinear response of sensors (Downing, 1996). High concentration limits for these instruments depend in part on particle-size distribution. The OBS has a generally linear response below about 2 grams/liter (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 concentration up to about 320 g/L (in the non-linear region of the OBS response curve). The upper concentration limit for the transmissometer depends on optical path length but may be as low as about 0.05 g/L (D & A Instrument Co., 1991). Thus the transmissometer is more sensitive at low concentrations but the OBS has superior linearity in turbid water. Because of the relation between OBS gain and particle size, the OBS (like other single frequency instruments) is best suited for conditions of constant particle-size distribution unless recalibrated. It is minimally affected by changes in particle-size distribution in the range of 200-400 microns (μ) but is greatly affected when particles are generally below 100μ (Conner and De Visser, 1992). Caution should be exercised under those conditions unless the instrument is recalibrated.

ACOUSTIC BACKSCATTER

The process of estimating mass concentration of suspended material from acoustic backscatter is based on the sonar equation (Urick, 1975; Reichel and Nachtnebel, 1994). Applications of the technique have been tested since the 1980's (Gartner, 2003) although, at present, the method has seen only limited use. Post-processing algorithms are complex requiring compensations for hydrologic properties of ambient water such as temperature, salinity, and pressure as well as instrument characteristics such as frequency, power, and transducer design (Thorne and others, 1991; Downing and others, 1995). Researchers generally develop their own software although a commercial product is available (Land and Jones, 2001) but not widely tested as yet. Results with single frequency instruments can provide estimates of SSC but lack information about size distribution. The method appears appropriate in concentration up to several g/L; higher concentrations are problematic especially when using high acoustic frequencies that are more subject to attenuation from sediment. The result is non-linear (backscatter intensity) response at high concentrations (Hamilton and others, 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 and others, 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 generally immune to biological fouling, non-intrusive, and providing a time series of SSC profiles when an acoustic Doppler velocity profiler is employed for measurements (Downing, 1996; Hamilton and others, 1998). However the relation between acoustic frequency and particle size limits the size range for which the method is appropriate (Hanes and others, 1988; Schaafsma and others, 1997). For example, with a 1200 kilohertz acoustic Doppler current profiler (ADCP) the upper size limit is less than about 400μ. In addition, variations in size distribution increase errors associated with the acoustic backscatter method, similar to all single frequency instruments, thus careful calibrations are critical. Estimates of SSC with accuracy similar to optical instruments are possible under some conditions (Thevenot and Kraus, 1993); comparisons with analyzed water samples have been found to agree within about 10-20 percent (Thevenot and others, 1992; Thorne and others, 1991; and Hay and Sheng, 1992). This technique is yet to be routinely applied; additional testing under various conditions is desirable.

LASER DIFFRACTION

Commercially available instruments for both laboratory and in-situ measurements using laser diffraction are available for determining size distribution of suspended material. These instruments exploit Mie scattering theory that states that at small forward scattering angles, laser light diffraction by spherical particles is essentially identical to diffraction by an aperture of equal size (Agrawal and Pottsmith, 1994). An in-situ version, the LISST-100 (Laser In Situ Scattering and Transmissometry), uses 32 ring detectors to determine particle size distribution between 5-500 or 1.25–250µ. (Sequoia Scientific, Inc[2] manufactures the LISST family of products.) The LISST-100 has been tested in laboratory and field; it has been shown to successfully determine natural particle size distributions and the size of mono-sized particle suspensions within about 10 percent accuracy (Traykovski and others, 1999; Gartner and others, 2001). The LISST-100 can be used to determine volume concentration or SSC if particle density is known or can be reliably inferred (Gartner and others, 2001). Unlike single frequency optical backscatter instruments such as OBS, these instruments are not subject to potential inaccuracies associated with changes in particle size of suspended materials (Agrawal and Pottsmith, 2000). However, as is the case with all types of in-situ optical instruments, biological fouling may degrade measurements (Agrawal and Pottsmith, 2000). In situ versions of laser diffraction instruments may be deployed unattended to provide a time series of particle-size distribution. However there are measurement limitations (in addition to size range) that are associated with multiple scattering in the presence of high particle concentration. Limitations associated with high SSC are based on the laser-path length and particle-size distribution 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 and others, 1999). New instrument options and versions are being developed to address these problems and increase range of applications. The LISST-25 provides a Sauter mean size of suspended material; the LISST-FLOC covers the size range of 7.5-1500µ; and the Isokinetic LISST (under development) is a streamlined version of LISST designed for real-time, wire-lowered, flow-through isokinetic sampling.

DIGITAL PHOTO-OPTIC IMAGING

Digital photo-optic imaging techniques originated in the 1980's for use in analysis of blood characteristics. Adaptation of the technology for in-situ determination of suspended-sediment size and shape followed in the 1990's (Eisma and Kalf, 1996). 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 2-dimensional image of suspended particles has been developed for automated use (Gooding, 2001). The high quality image is simplified by morphological transformation but retains size and shape characteristics for quantitative analysis with imaging software. Hardware enhancements have improved image quality for more reliable automated computer interpretations (Gray and others, 2003) and increased appropriate 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 has not currently been established but tested levels to 10 g/L have provided

[2] Use of trade, product, or firm name is for descriptive purposes only and does not imply endorsement by the U.S. Geological Survey.

accurate results. Efforts are now focused on refining and testing computer software to determine particle concentration, size, and shape in real or near-real time. Present equipment is designed for laboratory use, although the technology is also intended for in-situ applications. The system is presently designed for determining size distributions and turbidity measurements, however future plans are to add ability 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.

PRESSURE DIFFERENCE

The pressure-difference technique employs dual pressure transducers to infer SSC from density of sediment bearing water at two locations in the water column. The pressure difference is converted to a water density value. Implicit assumptions in the method are that density of water and sediment are known and very sensitive pressure transducers are used. The technique has been applied in 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). For field applications, laboratory analysis of water samples is used to convert the density values to determine average SSC between the two pressure transducer inlets at known distance apart. The method has been field tested at a US Geological Survey (USGS) streamflow-gaging station in Puerto Rico with mixed results. Application of this technique in the field is complicated by low signal to noise ratio, turbulence, dissolved solids concentration, and temperature variations (Larsen and others, 2001). Additionally, analysis may be complicated by density variations of suspended material. The differential pressure method has been generally successful in the field at concentrations above 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.

GENERAL RECOMMENDATIONS

In addition to summarizing information about the techniques, participants in workshop breakout sessions provided the following general recommendations to improve ability to estimate SSC. It is well understood that to implement these recommendations might require additional funding; however, it is believed that the potential benefits of implementing these recommendations outweigh their cost. If necessary, additional source(s) of funding should be sought. Those recommendations include the following four categories:

***Sediment Monitoring Instrumentation and Analysis Research Program*:** The active support of a sediment monitoring instrument and research program (SMIARP) is recommended. Subsequent to the workshop, Gray (2003) suggested attributes of a SMIARP. This would include expanding capabilities at several sites and at least one laboratory for testing, and evaluating existing and future instruments and techniques (optical, acoustic, laser, etc) as tools to address problems of determining mass concentration and other selected characteristics. The SMIARP concept is being applied at a growing number of existing streamgages in the United States. SMIARP sites are based on the premise that the benefits of the whole is greater than the sum of parts. That is, more progress might be made by concentrating efforts with new instruments and new techniques so that necessary tools are available for instrument intercomparisons, obtaining ground truth data applicable to all technologies, and understanding complex sediment processes.

Topical Expert Advisors: Establishment and fostering of group(s) of topical expert advisors or steering committees modeled after the U.S. Geological Survey Hydroacoustics Work Group (U.S. Geological Survey, 2003) is recommended. These advisors (private, Federal, State, and academic) could be called on to provide guidance, training, and recommendations to the Subcommittee on Sedimentation as well as researchers and others applying new techniques and technology in the field. Such experts might be called on to review potential success of efforts to determine SSC using various techniques.

Improved Communication: Improved communications and technology transfer to distribute information about emerging technologies applicable to determination of SSC by establishing mechanisms such as a users group, newsletter, list server or web site is recommended. Useful information that might be distributed would include successes, failures, field experiences, and general problems encountered using various techniques to estimate characteristics of suspended sediment. In addition, non-technical data users should be informed about issues involved in producing data including assumptions, limitations, methods, and applicability.

Calibration Guidelines: Where appropriate, guidelines for calibrating sensors should be provided or updated to reflect recent advances in turbidity- or surrogate-data collection. Turbidity standards that meet quality standards should be available through a central clearinghouse and calibration methodologies of users should be documented (Schoellhamer, 2003).

Data Accuracy: Establishment and promulgation of criteria for suspended-sediment data accuracy is recommended.

SUMMARY

Participants in the Federal Interagency Turbidity and Other Sediment Surrogates workshop found that, in general, all of the sediment-surrogate techniques considered showed promise, although some have limited application. They determined that no single technique or instrument is capable of estimating SSC under all conditions. Variations in hydrologic conditions, as well as particle compositions, mass concentrations, and size distributions of suspended material, among other factors, may require use of multiple frequency instruments or even multiple instrument types to determine mass concentrations to a reasonable degree of accuracy. In all cases other than direct measurement through use of isokinetic water samplers, some method of instrument calibration is required to determine mass concentration.

Additional testing is required to determine if, and under what conditions, the specific techniques examined might be suitable for use in determining SSC, as ascertaining the success or failure of a given technology was considered to be more desirable than doing nothing. These tests should include side-by-side evaluations of various instruments and techniques as described above in concert with ground-truth measurements as part of the recommended Sediment Monitoring Instrument and Analysis Research Program.

While the goal of addressing accuracy requirements for SSC estimates went unfulfilled, participants in one breakout session stated that, in understanding sediment transport processes, less accurate data with higher temporal and/or spatial resolution are sometimes better than a limited number of more accurate measurements. However, it is necessary to define the uncertainty associated with the resulting answer and determine what is an acceptable reduction in accuracy for increased temporal and/or spatial resolution. Subsequent to the workshop, accuracy guidelines were developed (Gray and others, 2003) for SSC measurements for a laser-diffraction instrument, and endorsed by the Technical Committee, Federal Interagency Sedimentation Project (Federal Interagency Sedimentation Project, written commun. 2003).

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