Evaluation of Sediment-Surrogate Technologies for Computation of Suspended-Sediment Transport

John R. Gray, Eduardo Patiño, Patrick P. Rasmussen, Matthew C. Larsen, Theodore S. Melis, David J. Topping, Michael S. Runner, and Carlos Figueroa Alamo, U.S. Geological Survey

The need for reliable, spatially and temporally consistent fluvial-sediment data has never been greater than at the present time. The traditional use of these data in the United States (U.S.) has been focused on the engineering aspects related to design and management of reservoirs and in-stream hydraulic structures, and on dredging. Over the last two decades, information needs have expanded to include those related to contaminated sediment management, dam decommissioning and removal, environmental quality, stream restoration, geomorphic classification and assessments, physical-biotic interactions, the global carbon budget, and legal requirements such as the U.S. Environmental Protection Agency's Total Maximum Daily Load (TMDL) Program.

Ironically, the recent rise in fluvial-sediment-data needs in the U.S. have coincided with a general decline in the amount of sediment data collected by U.S. Geological Survey (USGS), the primary U.S. agency responsible for acquisition and management of water data in the U.S., including suspended-sediment, bedload, and bottom-material data (Glysson and Gray, 1997). For example, the number of sites where the USGS collected daily suspended-sediment data increased rapidly after 1945, peaking at 360 in 1982 (Glysson, 1989; Osterkamp and Parker, 1991). By 1998, their number had fallen by 65 percent to 125, with an average of 141 sites over the 5-year period ending in September 2002 (U.S. Geological Survey, 2003). This substantial decrease in U.S. sediment monitoring is of particular concern in that the physical, chemical, and biological sediment damages in North America alone were estimated to total about \$16 billion in 1998 (Osterkamp et al., 1998).

Among the factors cited for the decline in the number of USGS daily sediment stations was the need for less expensive and more accurate fluvial sediment data collected using safer, less-manually intensive techniques (Gray, 2002). The annual cost in 2000 for the USGS to collect and publish daily flow and suspended-sediment data at a station was rarely less than \$20 thousand and in some cases was triple that depending on such factors as site location and accessibility, safety issues, types and frequency of data collection, the size distribution of suspended sediments, and hydraulic characteristics of the reach. The standard monitoring procedure requires frequent manual and(or) automated sampling, particularly during higher flows, followed by laboratory processing and subsequent analysis of large data sets (Larsen et al., 2001). Although the manual sampling techniques described by Edwards and Glysson (1999) are safe, automated sampling methods further decrease risks in data collection. Currently, computed sediment loads calculated using either manual or automated field sampling techniques normally lack uncertainty estimates.

In response to cost, safety, and accuracy concerns, the USGS expanded and increased coordination of research on surrogate instruments and methodologies useful for inferring the physical characteristics of fluvial sediments in the river and laboratory. Instruments operating on bulk acoustic, bulk and digital optic, laser, and pressure-differential technologies (Wren et al., 2000; Gray and Schmidt, 1998, 2001; Gray et al., 2002) are being tested in field and laboratory settings for their applicability toward providing quantifiably reliable information (Turcios and Gray, 2001; Turcios et al., 2001) on concentrations and size-distributions of sediment in suspension, as bedload, and as bottom material. This paper focuses on on-going USGS research to characterize suspended-sediment transport using a variety of in-situ sediment-surrogate technologies in concert with traditional techniques described by Edwards and Glysson (1999) at sites in Kansas, Florida, Mississippi, Arizona, and Puerto Rico (figure 1). The USGS welcomes international and domestic collaboration in sediment-surrogate technology research.

Figure 1: Locations of U.S. Geological Survey research sites where fluvial suspended-sediment transport characteristics are being evaluated using a variety of in-situ sediment-surrogate technologies.

Turbidity Data as a Suspended-Sediment Surrogate in the Kansas River at DeSoto, Kansas

Sensors that measure the bulk optical 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). Use of turbidity measurements to infer the suspended-sediment characteristics of surface waters is the most common of all sediment-surrogate technologies used in the U.S. 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. Samples for analyses of SSC were collected using a US D-77 depth-integrating suspended-sediment (Federal Interagency Sedimentation Project, 2003) and the equal-width-increment method (Edwards and Glysson, 1999). SSC measured in samples ranged from 35 to 3,660 milligrams per liter (mg/L).

A turbidity probe was installed for continuous in-situ measurements and was maintained by methods described by Wilde and Radtke (1998) and Wagner et al. (2000). The sensors measured turbidity values ranging from 0 to 1,000 nephelometric turbidity units (NTU). A portable turbidity sensor was modified to measure up to 4,000 NTU. The turbidity sensors used in this study conform to ISO method 7027 (International Organization for Standardization, 1999). The in-situ sensor is equipped with a wiper that is activated prior to recording a measurement to clear the sensor of accumulated material, thereby improving the optical measurement and also enabling longer intervals between maintenance trips. The sensor is integrated into the USGS streamgaging station's data-collection platform, and the data are available on-line in near-real time (U.S. Geological Survey, 2002).

The turbidity-monitoring site uses a vertical suspension installation from the road bridge deck to the stream, which is the most adaptable and convenient type of installation for maintenance. The installation is made up of a turbidity probe, 3 meters (m) of plastic pipe, a chain, a 12-volt winch, and a radio transmitter. The pipe and turbidity sensor typically are suspended behind a bridge pier to provide protection from blockage, damage, or removal by debris. The winch is used to raise the pipe to the bridge deck for sensor maintenance. An advantage of this type of installation is that it can be installed on any bridge and at almost any vertical bridge support along the bridge. This type of installation can be easily adjusted during high-flow conditions, or changed to a different vertical bridge support over meandering streams.

Continuous turbidity measurements have been shown to reliably estimate SSC with a quantifiable uncertainty. Simple linear regression analysis explained in Christensen et al. (2000) was used to develop a site-specific model using turbidity to estimate SSC (figure 2). 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 is 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.

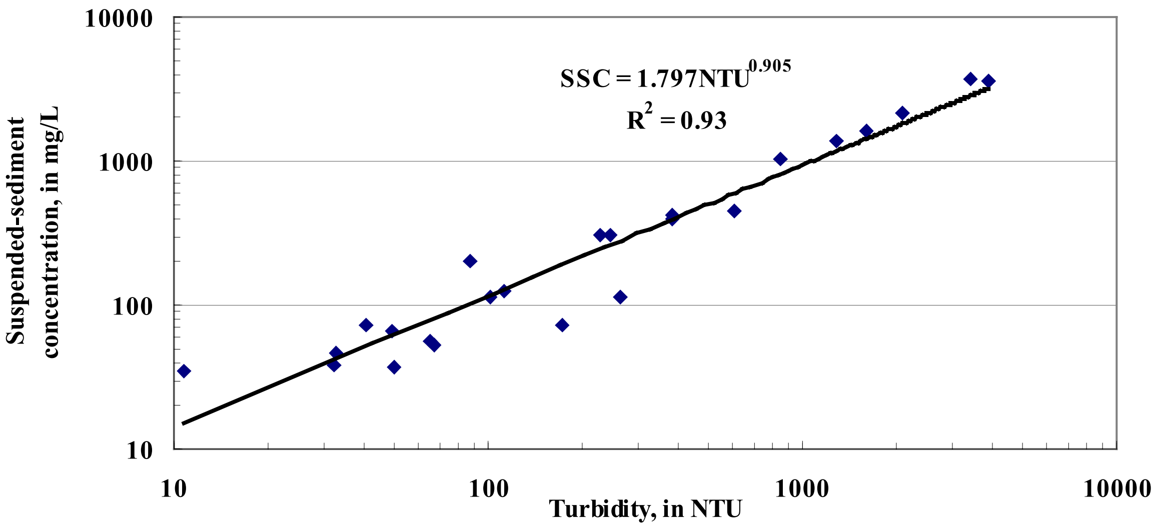

Figure 2: Comparison of field turbidity and suspended-sediment concentrations for the Kansas River at DeSoto, Kansas, 1999 through 2002.

Acoustic Data as a Suspended-Sediment Surrogate in Florida and Mississippi Streams

The use of acoustic instruments worldwide for the measurement of stream velocities has increased substantially over the last two decades. 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 south Florida streams were used to evaluate the feasibility of estimating time-series data of SSC (Byrne and Patiño, 2001). An AVM was installed in 1993 at the L-4 Canal, a narrow manmade channel in northwestern Broward County used to drain excess runoff from agricultural fields. Water velocities in this freshwater canal, which is no wider than 15 m and averages about 2.5 m deep, range from –0.15 to 0.75 meters per second (m/s). An ADVM was installed in 1997 at the North Fork of the St. Lucie River (in Veterans Park), a tidal channel that discharges into the St. Lucie Estuary along the southeastern coast of Florida. Water velocities in this tidal stream, which is about 85-m wide and averages about 2.5 m deep, range from about –0.5 to 0.5 m/s; salinity varies from 0.2 to about 15 mg/L (fresh to brackish). 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.

Water samples for SSC analyses were collected at the L-4 Canal site using a US DH-59 depth-integrating suspended-sediment sampler (Federal Interagency Sedimentation Project, 2003) and the equal-discharge-increment method (Edwards and Glysson, 1999). Samples at the North Fork site were collected using a horizontal Van Dorn Bottle type sampler at the depth of the ADVM system and about 3 m from the transducer faces. All samples were analyzed for SSC and for organic content. SSC ranged from 22 to 1,060 mg/L at the L-4 Canal site and from 3 to 25 mg/L at the North Fork site. The organic content of samples used in the analysis varied from 30 to 93 percent at the L-4 Canal site and from about 50 to 75 percent at the North Fork site.

Regression analysis techniques were used to develop empirical and site-specific relations between AGC and ABS to SSC at the L-4 Canal and North Fork sites. The general form of the equation used to determine the AGC/ABS to SSC relation at the study sites is:

$$SSC = 10^{\{A * [a + b * \log(salinity) + c * \log(temperature)] + d * \log(velocity) + e\}}$$

where A represents AGC or ABS; a, b, c, and d are regression coefficients; and e is the intercept. The relations obtained using site-specific forms of the above equation produced good results at both sites, with correlation coefficients of 0.91 and 0.87 for the L-4 Canal and North Fork sites, respectively. The L-4 Canal site is a freshwater system and hence the salinity term drops out of the equation (figure 3). Results 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.

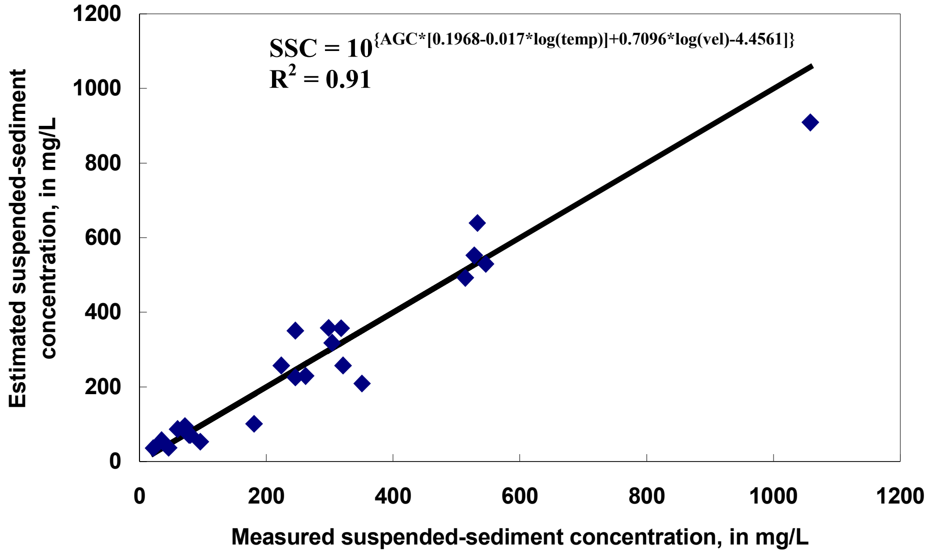

Figure 3: Comparison of estimated and measured suspended-sediment concentrations for the L-4 Canal site, Florida.

On the Yazoo River below Steele Bayou near Long Lake, Mississippi, near the confluence of the Yazoo and Mississippi Rivers at Vicksburg, acoustic Doppler current profiler (ADCP) measurements have been made since January 1996. Flow at this site is affected by the stage of the Mississippi River and the Yazoo River has been shown to exhibit bidirectional and full upstream flow, as well as full downstream flow. Since data collection began in 1996, more than 250 discharge measurements have been made using the ADCP, with concurrent depth-integrated, equal-discharge increment, sediment samples collected during more than half of these measurements. Measured discharges ranged from approximately –106 to 2,010 cubic meters per second (m^3/s). Stream velocity ranges from very slow in the upstream direction to more than 1.8 m/s in the downstream direction. SSC measured by techniques described by Edwards and Glysson (1999) are generally between 50 and 400 mg/L. ABS data from discharge measurements, along with average velocity and water temperature, are being used to develop equations to estimate suspended sediment from these properties. The equation will be applied to the ADCP measurements to estimate SSC for the measurements with no concurrent suspended-sediment sample.

A side-looking ADVM with the capability to measure the velocity and backscatter in five bins across the stream was installed at the Yazoo River in 2002. Suspended-sediment samples are being collected at the center of each bin at the depth of the ADVM using a US P-72 point-integrating suspended-sediment sampler (Federal Interagency Sedimentation Project, 2003) or a pumping sampler, depending on the velocity of the stream at the time of sample collection (Edwards and Glysson, 1999). Velocity and backscatter data are recorded for each of the ADVM's five acoustic bins, as well as an average value. Water temperatures at the ADVM are also measured and recorded. Data are transmitted via a data-collection platform to the USGS in Pearl, Mississippi. When sufficient data are collected they will be analyzed using techniques similar to those used by the USGS in Florida to develop an equation or equations that will estimate instantaneous SSC using ABS, velocity, and temperature data.

Laser Data as a Suspended-Sediment Concentration and Particle-Size Distribution Surrogate in the Colorado River at Grand Canyon, Arizona

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 Laser In-Situ Scattering and Transmissometry (LISST) data reported here were collected using LISST-100-B manufactured by Sequoia Scientific, Inc.[1] (Agrawal and Pottsmith, 2001, 2002; Gartner et al., 2001).

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 LISST-100 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 the volumetric SSC (Agrawal and Pottsmith, 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 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 4).

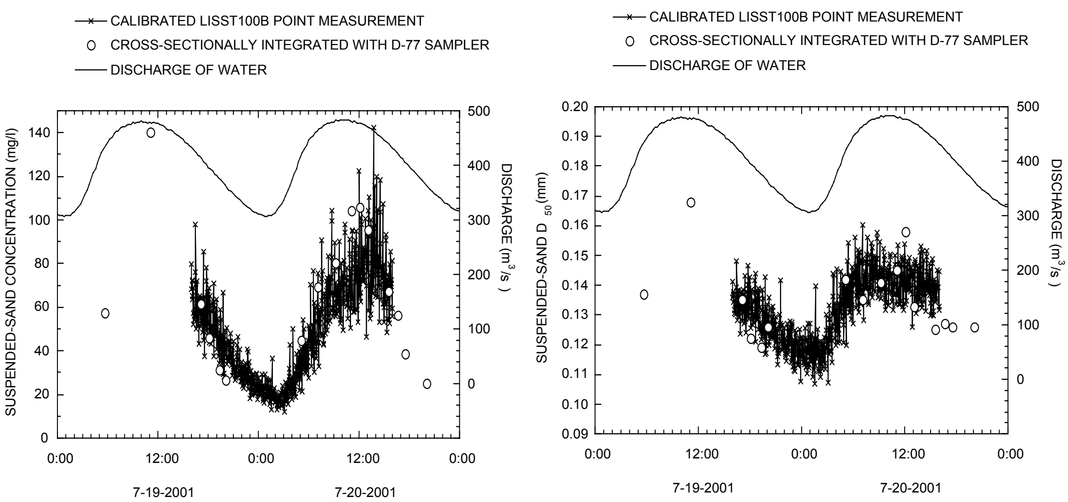

Figure 4: Comparison of sand concentrations and median grain sizes measured in the Colorado River at Grand Canyon using a LISST-100-B and a US D-77 bag sampler.

[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 et al., 2002).

Pressure Differential Data as a Suspended-Sediment Concentration Surrogate in the Río Caguitas, Puerto Rico

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 Puerto Rico from October-December, 1999 (Larsen et al., 2001). The double bubbler, which was originally developed by Design Analysis Associates, Logan, Utah, to measure crude oil density, measures the weight of the water by means of two immersed pressure-transducer orifices vertically separated by 304.8 mm. A constant mass flow of gas (dry air or nitrogen) to the two orifices submerged in the measurement fluid (water) is provided by a gas supply system. Two solenoid valves feeding the differential unit are used to obtain offset and atmospheric correction for the actual pressure-sensing element. The pressure-sensing element produces a voltage value directly proportional to the pressure difference sensed at the orifices. A temperature probe near the bubble discharge orifices provides the requisite data to correct for the effect of water temperature on the density of pure water. By subtracting the density of water from the value measured for the density of the water-sediment mixture, the SSC can be estimated and used as a relatively inexpensive and continuously measured surrogate for data obtained from analyses of water samples.

Continuous double bubbler instrument data collected during October-December 1999 at a streamgaging station on the Río Caguitas, Puerto Rico. Mean annual runoff for the period 1990-99 at this site was 1,080 mm and the flood of record had a peak discharge of 708 m^3/s (Diaz et al., 1999). Mean annual suspended-sediment discharge for the period 1992-99 was 1,340 tonnes per square kilometer. Most of the annual sediment discharge occurs in runoff from a few storms when SSC exceed about 500 mg/L. As of 2000, the maximum SSC measured at the site using techniques described by Edwards and Glysson (1999) was 17,700 mg/L.

The data collected during October-December 1999 contained a large amount of signal noise, making interpretation difficult. The data collected at 5-minute intervals were smoothed by stepwise averaging six data points using a 30-minute moving mean. This increased the serial correlation somewhat, requiring a more sophisticated method for data analysis, including determination of minimum and maximum thresholds so that outliers could be discarded from the data set. To calculate the weight density of suspended sediment and dissolved solids (the latter insignificant in the calculation of sediment discharges during storm runoff), the weight density of pure water at 27 degrees Celsius (ºC), equal to 996.516 kilograms per cubic meter, was subtracted from the smoothed data value.

The tests of the double bubbler instrument at this site showed relatively poor agreement between discharge, SSC, and water density (figure 5). The 1999 tests indicate that the double bubbler instrument values generally track substantial variations in SSC, but a large amount of signal noise remains.

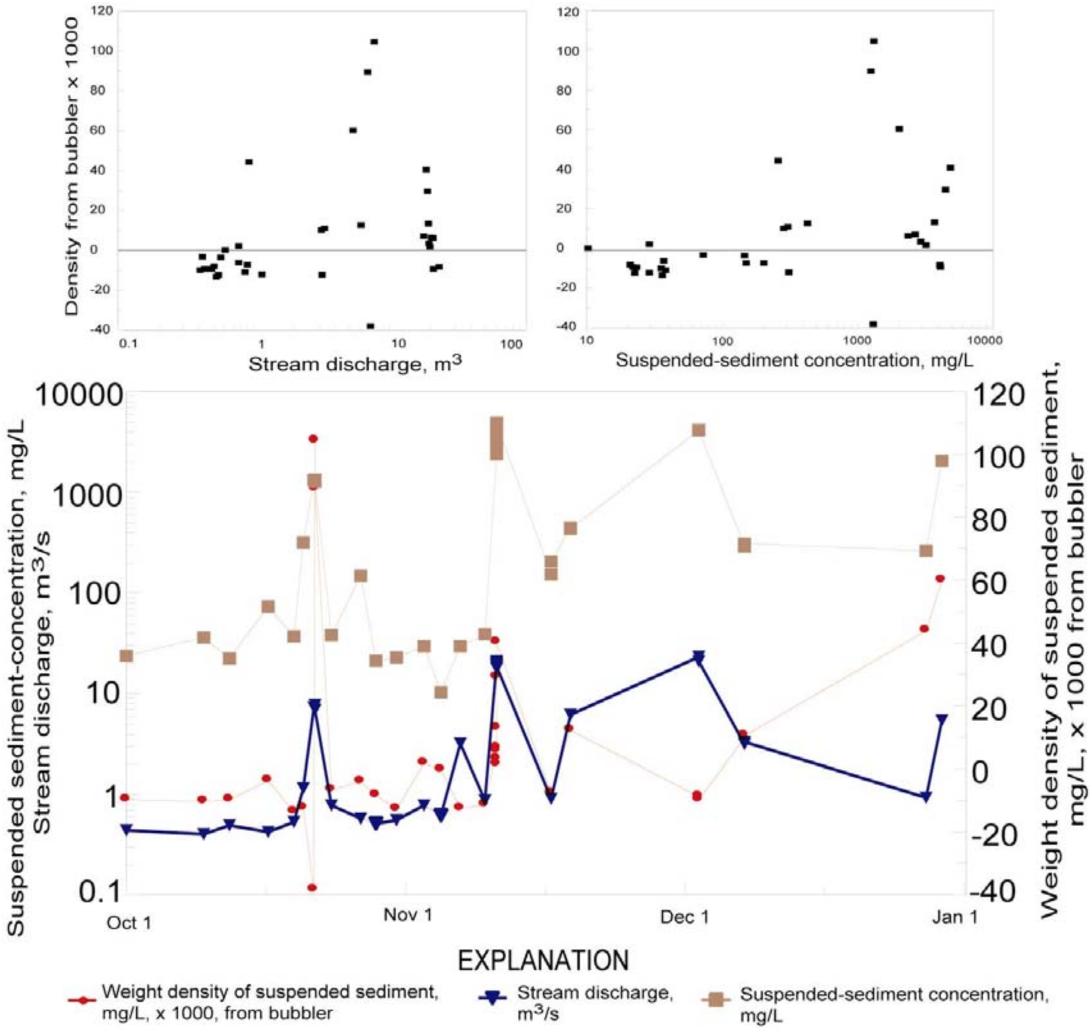

Figure 5: Scatter plots and time series of stream discharges, suspended-sediment concentrations, and weight density of suspended sediments and dissolved solids measured with a double bubbler, October 1, 1999, to January 1, 2000. Discharge and sediment data are instantaneous samples, and the double bubbler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

A complicating factor for this method is turbulence in the water column, which introduces noise about equal to the signal of interest, particularly during high discharges when the largest SSC occur. Additionally, diurnal and storm-related fluctuations in water temperature must be accounted for by using a continuously logging temperature sensor. The daily range in water temperatures at the Río Caguitas test site are as much as 10 ºC. The high relative humidity characteristic of this humid-tropical site may also complicate the use of the double bubbler because of the sensitivity of the narrow diameter bubbler gas lines to moisture, unless the gas lines are equipped with dryer tubes.

This test of the double bubbler instrument showed the need for temperature compensation, and possibly the need to deploy the instrument at a site where the signal-to-noise ratio is substantially larger than 1.01. The double bubbler is being tested in Arizona's Paria River, where SSC in excess of a 1 x 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 surrogate technologies for estimating SSC and fluxes in the U.S and Puerto Rico. Those based on optics, acoustics, and laser principles have been shown to be successful in a limited number of test sites. The approach using the pressure-differential principle shows promise for use in highly concentrated streamflows. The USGS welcomes international and domestic collaboration in sediment-surrogate technology research.

References

Agrawal, Y.C., and Pottsmith, H.C., 2001, Laser sensors for monitoring sediments: capabilities and limitations, A Survey. Proceedings of the 7th Federal Interagency Sedimentation Conference, Reno, Nevada, March 25-29, Vol. I, III-144 to III-151.

Agrawal, Y.C., and Pottsmith, H.C., 2002, New isokinetic version of LISST technology targets needs of the Federal Subcommittee on Sedimentation: Proceedings of the Turbidity and Other Sediment Surrogates Workshop, April 30 - May 2, 2002, Silver Legacy Hotel, Reno, Nevada, 4 p., on-line at: http://water.usgs.gov/osw/techniques/TSS/listofabstracts.htm .

Byrne, M.J., and Patino, Eduardo, 2001, Feasibility of using acoustic and optical backscatter instruments for estimating total suspenced solids concentrations in estuarine environments: Proceedings of the 7th Federal Interagency Sedimentation Conference, Reno, Nevada, March 25-29, Vol. I, III-135 to III-138.

Christensen, V.G., Jian, Xiaodong, Ziegler, A.C., 2000, Regression analysis and real-time water-quality monitoring to estimate constituent concentrations, loads, and yields in the Little Arkansas River, South-Central Kansas, 1995-99. U.S. Geological Survey Water-Resources Investigations Report 00-4126, 36 p.

Diaz, Pedro L., Aquino, Zaida, Figueroa-Alamo, Carlos, Vachier, R.J., and Sanchez, A.V., 1999, Water resources data, Puerto Rico and the U.S. Virgin Islands, Water Year 1999: U.S. Geological Survey Water-Data Report PR 99-1, 599 p.

Edwards, T.K., and Glysson, G.D., 1999, Field methods for measurement of fluvial sediment: U.S. Geological Survey Techniques of Water-Resources Investigations Bk 3, Ch. C2, 89 p.; also available at http://water.usgs.gov/osw/techniques/sedimentpubs.html .

Federal Interagency Sedimentation Project, 2003: Accessed January 31, 2003, at http://fisp.wes.army.mil/ .

Gartner, J.W., Cheng, R.T., Wang, P. and Richter, K., 2001, Laboratory and field evaluations of the LISST-100 instrument for suspended particle size determinations. Journal of Marine Geology, Vol. 175, pp.199-219.

Gartner, J.W., and Cheng, R.T., 2001, The promises and pitfalls of estimating suspended solids based on backscatter intensity from acoustic Doppler current profiler: Proceedings of the 7th Federal Interagency Sedimentation Conference, March 25-29, 2001, Reno, Nevada, Vol. 1, III-119 to III-126.

Glysson, G.D., 1989, 100 years of sedimentation study by the USGS, in, Proceedings of the International Symposium, Sediment Transport Modeling, Sam S.Y. Wang, ed.: American Society of Civil Engineers, New Orleans, August 14-18, 1989, pp. 260-265.

Glysson, G.D., and Gray, J.R., 1997, Coordination and standardization of Federal sedimentation activities: Proceedings of the U.S. Geological Survey Sediment Workshop, February 4-7, 1997, accessed July 19, 2001, at http://water.usgs.gov/osw/techniques/workshop/glysson.html.

Gray, J.R., Glysson, G.D., and Mueller, D.S., 2002, Comparability and accuracy of fluvial-sediment data: A view from the U.S. Geological Survey: Proceedings of the American Society of Civil Engineers, Hydraulic Measurements and Methods Symposium, July-August, 2002, Estes Park, CO, 6 p.

Gray, J.R., and Schmidt, L., 1998, Sediment technology for the 21'st Century: Proceedings of the Federal Interagency Workshop, St. Petersburg, Florida, February 17-19, 1998, accessed May 21, 2001, at http://water.usgs.gov/osw/techniques/sedtech21/index.html .

Gray, J.R., and Schmidt, L., 2001, Sediment-data quality, availability, and emerging technologies – A discussion, M. Paul Moseley, ed.: Gravel Bed Rivers V, New Zealand Hydrological Society, pp. 369-373.

Gray, J.R., 2002, The need for sediment surrogate technologies to monitor fluvial-sediment transport: Proceedings of the Turbidity and Other Sediment Surrogates Workshop, April 30 - May 2, 2002, Silver Legacy Hotel, Reno, Nevada, 4 p., on-line at: http://water.usgs.gov/osw/techniques/TSS/listofabstracts.htm.

International Organization for Standardization (ISO), 1999, Water-quality-determination of turbidity, method 7027. 18 p.

Larsen, M.C., Figueroa-Alamo, C., Gray, J.R., and Fletcher, William, 2001, Continuous automated sensing of streamflow density as a surrogate for suspended-sediment concentration sampling: Proceedings of the 7th Federal Interagency Sedimentation Conference, Reno, Nevada, March 25-29, Vol. I, III-102 to III-109.

Osterkamp, W.R., Heilman, P., and Lane, L.J., 1998, Economic considerations of a continental sediment-monitoring program: International Journal of Sediment Research, Vol. 13, No. 4, pp. 12-24.

Osterkamp, W.R., and Parker, R.S., 1991, Sediment monitoring in the United States: Proceedings of the Fifth Federal Interagency Conference, Last Vegas, Nevada, March 18-21, 1991, Vol. I, pp. 1-15 to 1-23.

Schoellhamer, D. H., 2001, Continuous monitoring of suspended sediment in rivers by use of optical sensors: Proceedings of the 7th Federal Interagency Sedimentation Conference, March 25-29, 2001, Reno, Nevada, Vol. 1, III-160 to III-167.

Turcios, L.M., and Gray, J.R., 2001, U.S. Geological Survey sediment and ancillary data on the World Wide Web: Proceedings of the 7th Federal Interagency Sedimentation Conference, March 25-29, 2001, Reno, Nevada, Poster 31-36.

Turcios, L.M., Gray, J.R., and Ledford, A.L., 2001, Summary of U.S. Geological Survey on-line instantaneous fluvial sediment and ancillary data: Accessed June 26, 2001, at http://water.usgs.gov/osw/sediment .

U.S. Geological Survey 2002, Real-time water-quality concentrations and loads estimated using regression analysis: Accessed December 30, 2002 at http://ks.water.usgs.gov/Kansas/rtqw/sites/DES/htmls/2001_P61028.shtml .

U.S. Geological Survey, 2003, Statistics on Hydrologic Data-Collection Stations Operated by the USGS: Accessed January 31, 2003 at http://144.47.61.11/StationCounts/ .

Wagner, R.J., Mattraw, H.C., Ritz, G.F., Smith, B.A., 2000, Guidelines and standard procedures for continuous water-quality monitors-site selection, field operation, calibration, record computation, and reporting. U.S. Geological Survey Water-Resources Investigations Report 00-4252, 53 p.

Wilde, F.D., Radtke, D.B., eds., 1998, Field measurements, *in* National Field Manual for the Collection of Water-Quality Data. U.S. Geological Survey Techniques of Water-Resources Investigations, Bk. 9, Ch. A6, pp. 3-20.

Wren, D.G., Barkdoll, B.D., Kuhnle, R.A., and Derrow, R.W., 2000, Field techniques for suspended-sediment measurement: American Society of Civil Engineers, Journal of Hydraulic Engineering, Vol. 126, No. 2, pp. 97-104.