REAL-TIME ANALYSIS OF CONCENTRATED FLUVIAL SUSPENDED SEDIMENTS

Chris Konrad, Research Hydrologist, U.S. Geological Survey, Tacoma, WA, cpkonrad@usgs.gov
Chuck Pottsmith, Vice President, Sequoia Scientific Inc., Bellevue, WA, pottsmith@sequoiasci.com
Ted Melis, Integrated Science Program Manager, U.S. Geological Survey, Flagstaff, AZ, tmelis@usgs.gov
Dave Rubin, Research Geologist, U.S. Geological Survey, Santa Cruz, CA, drubin@usgs.gov

INTRODUCTION

Anthropogenic changes in sediment transport and deposition in rivers, lakes, and coastal waters is a global concern [Baca and others, 1982; Walling and Webb, 1996; Koebel and others, 1999; Wang and others, 2003; Langland and others, 2004]. In the United States, over 5000 water bodies are listed as water-quality impaired due to sedimentation [U.S. EPA, 2005a]. Human structures (for example, roads, dams, levees, revetments, and drainage networks) and activities (forestry, agriculture, urban development, water management) can either increase or decrease the amount and size of sediment delivered to and transported by rivers depending on the type of change and the location of interest in a river basin [Anderson, 1954; Guy and Ferguson, 1963; Brown and Krygier, 1971; Trimble, 1983; Williams and Wolman, 1984; Thoms, 1987; Syvitski and others, 2005]. Changes in sediment loads affect management of water resources in many ways. For example, water supplies may require additional treatment before water can be used for out-of-stream municipal and industrial uses. Reservoirs may have to be dredged to restore their storage capacity. Increased sediment loads also impair in-stream uses of water, such as when physiological functions of aquatic organisms are affected by high sediment concentrations in the water column or when sediment deposits render the streambed inhabitable and reduce the available volume of low-velocity aquatic habitat. Conversely, anthropogenic reduction in the amount or size of sediment transported in a river may also impair in-stream uses where aquatic organisms are adapted to higher levels of turbidity and aquatic habitats are created by deposition of fluvial sediment.

THE NEED FOR SUSPENDED SEDIMENT DATA FROM STREAMFLOWS WITH HIGH CONCENTRATIONS

Sediment data are needed for informed management decisions to address the concerns about the effect of changing sediment loads on water resources [Pennisi, 2004; U.S. EPA, 2005b]. Efforts to manage sediment loads in many rivers must proceed on the basis of few – if any - direct measurements of fluvial sediment in transport and, instead, use regional estimates of sediment yields or surrogates such as bank erosion [Tetra Tech, U.S. Environmental Protection Agency, and Tennessee Department of Environment and Conservation, 2002; Oregon Department of Environmental Quality, 2004; Thompson, 2005]. In these cases, suspended sediment data for periods when streamflow and concentrations are high, would increase the precision of the estimated loads defining the problem and the precision of monitoring efforts to assess when the problem has been addressed.

In rivers, suspended sediment data are typically collected by periodic sampling at a point with a manual or automatic pump sampler and occasional manual collection of water samples over a cross-section. The cross-sectional samples are used to develop a coefficient to relate the concentration of point samples to the mean sediment concentration across the river. This approach, however, cannot resolve changes in suspended-sediment concentration and particle-size distributions at time-scales shorter than the point sampling interval. For example, storm-scale hysteresis cannot be defined by daily samples in many rivers, so it must be inferred by analyzing data from individual storm events or from long time periods that include samples from both the rising and falling limbs of the hydrograph. Moreover, it is uncertain that interpolation of sediment concentrations between samples collected with a pump sampler accurately represents the changing sediment concentration during high flow events, particularly if the samples fail to capture peak concentrations during those events.

The paucity of sediment data, particularly when sediment concentrations are high, is not a trivial issue when calculating sediment loads. In many rivers, much of the long-term (years) sediment load is transported during only a few days or weeks of high flows [Leopold et al., 1964]. The cumulative distribution of a river's sediment load can also be viewed in terms of the sediment concentration of flows transporting the load. The sediment load in 26 rivers in the U.S. with daily suspended-sediment records of at least 10 years [U.S. Geological Survey, 2005] was analyzed with respect to the sediment concentration. Flows with concentrations above 2000 mg/L carried a median value of 32 percent of the long-term load in these rivers (fig. 1). Although the distribution of the load depends on climate and basin physiography, suspended sediment data from flows with sediment concentrations on the order of 10^3 mg/L and higher are critical to accurate estimates of sediment loads in many rivers.

Monitoring of fluvial suspended sediment has advanced in recent years through the development of many different technologies that may be able to provide a continuous record of suspended sediment concentrations [Reichel and Nachtnebel, 1994; Lewis and Rasmussen, 1999]. Optical technologies based on measurements of light scattering and diffraction are widely employed to provide a measure of macroscopic material suspended in water [van Wijngaarden and Roberti, 2002; Lewis, 2003; Thonon and van der Perk, 2003; Schoellhamer and Wright, 2003; Topping et al., 2005]. Despite the advances in optical technologies, none currently are sufficient for continuous monitoring of high concentrations of suspended sediment ($> 10^3$ mg/L) for a number of reasons. For example, some turbidity meters can be used in flow with high suspended sediment concentrations, but they require calibration of the output to measured sediment concentrations [Urhich and Bragg, 2003]. The operational range of laser diffraction is limited to concentrations around 3,000 mg/L because high concentrations of suspended sediment reduce the transmission of light or produce multiple scattering that obscures the relationship between sediment concentration and the signal from the instrument [Topping et al., 2005]. As an alternative, optical technologies can be used to trigger pump sampling during periods when sediment concentration are out of range of the optical sensor [e.g., Lewis, 2003; Topping et al., 2005], but this approach still is limited by the pump sampling interval and may require frequent visits to collect samples that must be analyzed.

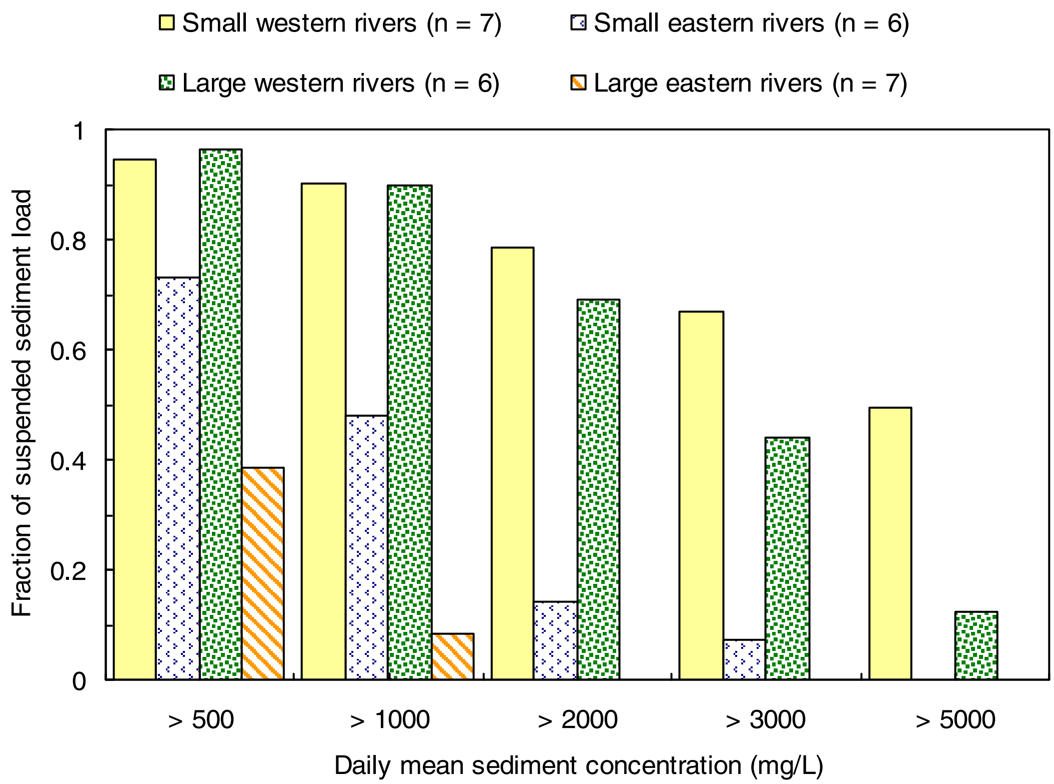

Figure 1. The fraction of suspended sediment load in 26 U.S. rivers carried by streamflow with high-concentrations of sediment. Minimum period of record is 11 years. Regional division is made at the Missippi River. Data source: U.S. Geological Survey, 2005.

A SYSTEM FOR REAL-TIME, CONTINUOUS ANALYSIS OF HIGH CONCENTRATIONS OF SUSPENDED SEDIMENT

A partnership of USGS scientists and Sequoia Scientific engineers has developed a suspended-sediment monitoring system (LISST-Infinite) with the goal of real-time analysis of highly concentrated suspended sediment. (Note that the use of a business or product name does not represent an endorsement by USGS.) The LISST-Infinite system integrates a laser diffraction sediment analyzer (LISST-25x) with an external pump, a dilution chamber and internal pump, and a digital controller that operates the pumps and eight valves. The LISST-25x is a self-contained, submersible instrument designed for in-situ measurements of the concentration and mean particle-size of suspended sediment (2.5 to 500 µm) and the concentration and mean particle-size of material greater than 62 µm. With the LISST-Infinite, the LISST-25X has been modified with an external pump and a dilution system for out-of-water deployment. Water passes through an optical cell, located in the laser path of the LISST-25x and connected to the external pump and dilution system with tubing (fig. 2).

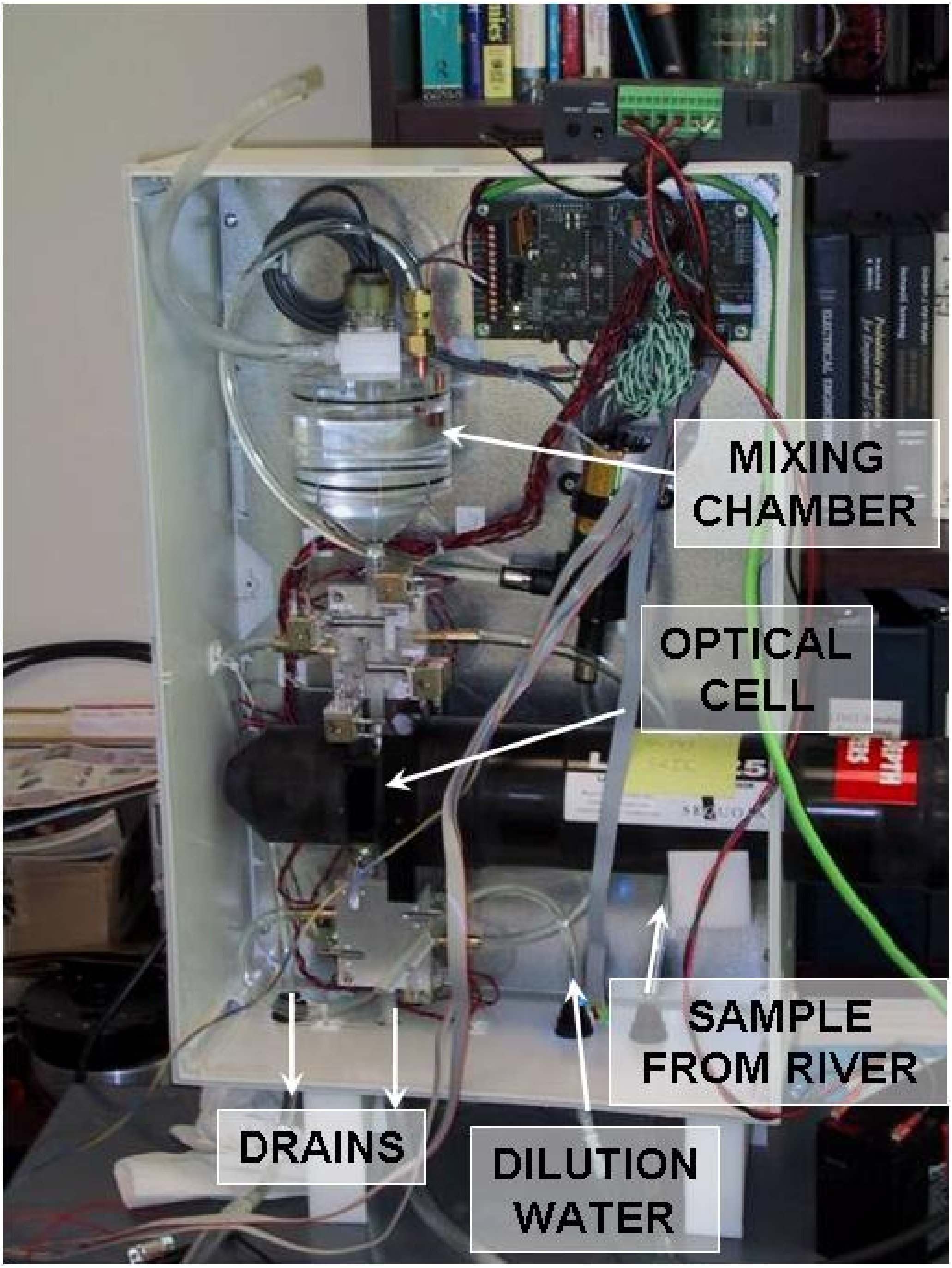

Figure 2. LISST-Infinite. Photo credit: Chuck Pottsmith.

At the beginning of each measurement cycle, filtered water from an external source (e.g., a water tank) drains into a dilution chamber with a volume of about 400 ml. Once the dilution chamber is filled, filtered water flows through the optical cell and the LISST-25x makes a background reading on the clear water. Once the background reading has been obtained, about 2,000 ml of water is pumped from the river through the cell in the LISST, purging any river water remaining in the intake line from the previous measurement cycle. After the intake line is purged, the

LISST-25x obtains concentration and particle-size data while river water is circulated through the cell. If the laser transmission is less than 30%, the LISST-25x notifies the controller, which then initiates a dilution cycle: pumping is stopped and an 8 ml sample is retained in the analyzer while the rest of the river water is drained. The filtered water in the dilution chamber is mixed with the retained sample and the resulting diluted sample is analyzed. The dilution step may be repeated until transmission is greater than 30%. Once the sample has been analyzed, the whole system drains, the dilution chamber is refilled with clean water, and the system is ready to pump the next sample from the river.

In addition to the limits imposed by high concentrations of suspended sediment, biological growth on the transmission or detection components of optical sediment sensors can also degrade their in-situ performance and necessitate frequent cleaning or recalibration of optical instruments. The LISST compensates for biofouling of its optics by using the background reading. Moreover, biofouling of the LISST-Infinite should be limited by light availability because the instrument will be housed in a closed instrument box (fig. 2).

The system is currently being tested in a laboratory setting. Initial tests have been conducted to assess the variability of the analysis of undiluted sediment-water mixtures. The variability of the analysis is critical to the validity of dilution of sub-samples at higher concentrations. For these tests, a churn-splitter was filled with sediment-laden water and churned while the LISST-Infinite pumps and analyzes the mixture. The mixture drained back into the churn-splitter creating a closed loop. The concentration and particle-size of the mixture was analyzed 10 times. Mixtures with concentrations ranging from 49 to 525 mg/L were tested. The median coefficient of variation of concentration was 0.07 (range 0.06 to 0.10). The median coefficient of variation of the mean particle-size was 0.04 (range 0.02 to 0.10). The variation of the results reflects both the heterogeneity of the sediment in the water and potential errors from analyzing sub-samples of the sediment-water mixture. Nonetheless, the variation does not appear to be substantial relative to other potential sources of error such as the effect of point sampling.

The initial test results provide only a limited assessment of the accuracy of sediment concentration and particle-size information provided by the LISST-Infinitie because the LISST reports the concentration and mean particle-size of sediment ranging from 2.5 to 500 microns and 63 to 500 microns, while laboratory analyses provides results in terms of the cumulative concentration of sediment <0.001 mm, < 0.002 mm, < 0.004 mm, < 0.008 mm, ... , < 1.0 mm. The median concentrations reported by the LISST for ¾ of the initial samples were within the expected range of concentrations based on laboratory analysis. For two samples with greater than 1 mg/L of sand, the LISST reported concentrations were 3.1 mg/L compared to 2.9 mg/L for the laboratory analysis and 36 mg/L compared to 38 mg/L. Future testing will evaluate the accuracy of the concentration and particle-size of diluted samples as determined by the LISST-Infinite.

Continuous suspended-sediment data is most difficult to collect at remote sites because of the limited capacity of automatic pump samplers. The LISST-Infinite will be deployed initially in the Elwha River in the Olympic Peninsula, Washington, where the Department of Interior is planning removal of two high dams. A modified version of the system that will provide the concentration of individual size-classes of suspended sediment has been proposed for use in the main channel of the Colorado River and in its major tributaries below Glen Canyon Dam in support of adaptive management of the Colorado River ecosystem. Currently, the only other alternative would be frequent trips into these remote sites to retrieve water samples and replace sample bottles.

SUMMARY

Continuous, real-time suspended-sediment monitoring is vitally important for managing water resources but remains an elusive goal that will be achieved only with new technologies. Information on suspended sediment, particularly during periods of high sediment concentration, is needed for accurate calculation of sediment loads. The LISST-Infinite, which integrates laser-diffraction technology for sediment analysis with a dilution cycle, has been developed to analyze high concentrations of suspended sediments. It is being tested under both laboratory and field conditions. If successful, this approach could be used to collect continuous information on fluvial sediment transport, even at remote sites without the need for frequent maintenance.

REFERENCES

Anderson, H. W. (1954). “Suspended sediment discharge as related to streamflow, topography, soil, and land use,” Eos, 35, pp. 268-281.

Baca, E., Bedient, P B, and Olsen, R. (1982). “Urban impacts of water supply reservoir,” Journal of Environmental Engineering, 108, pp. 73-87. 1982.

Brown, G. W. and Kreygier, J. T. (1971). “Clear-cut logging and sediment production in the Oregon Coast Range,” Water Resources Research, 7, pp. 1189-1198.

Guy, H. P. and Ferguson, G. E. (1963). “Sediment in small reservoirs due to urbanization,” American Society of Civil Engineers Transactions, 128, pp. 982-992.

Koebel, J. W., Jones, B. L., and Arrington, D.A. (1999). “Restoration of the Kissimmee River, Florida: Water quality impacts from canal backfilling,” Environmental Monitoring and Assessment, 57, pp. 85-107.

Langland, M. J., Phillips, S. W., Raffensperger, J. P., and Moyer, D. L. (2004). “Changes in Streamflow and Water Quality in Selected Nontidal Sites in the Chesapeake Bay Basin, 1985-2003,” U.S. Geological Survey Scientific Investigations Report 2004-5259.

Lewis, A. J., and Rasmussen, T. C. (1999). “Determination of suspended sediment concentrations and particle size distributions using pressure measurements,” Journal of Environmental Quality, 28, pp.1490-1496.

Lewis, J. (2003). “Turbidity-controlled sampling for suspended sediment load estimation,” Erosion and Sediment Transport Measurement in Rivers: Technological and Methodological Advances, IAHS Publication. 283, pp. 13–20.

Leopold, L. B., M. G. Wolman, and J. P. Miller (1964). Fluvial processes in geomorphology, Dover Publications, New York.

Oregon Department of Environmental Quality, Applegate Subbasin Total Maximum Daily Load HUC #17100309, 83 p.

Pennisi, E. (2004). “The Grand (Canyon) Experiment,” Science, 306, pp. 1884-1886.

Reichel, G., and Nachtnebel, H. P. (1994). “Suspended sediment monitoring in a fluvial environment: advantages and limitations applying on Acoustic Doppler Current Profiler,” Water Research, 28, pp. 751-761.

Schoellhamer, D. H. and S. A. Wright (2003). “Continuous measurement of suspended-sediment discharge in rivers by use of optical backscatterance sensors,” Erosion and Sediment Transport Measurement in Rivers: Technological and Methodological Advances, IAHS Publication 283, pp. 28–36.

Syvitski, J. P. M., Voeroesmarty, C J., Kettner, A. J., and Green, P. (2005). “Impact of Humans on the Flux of Terrestrial Sediment to the Global Coastal Ocean,” Science, 308, pp. 376-380.

Tetra Tech, U.S. Environmental Protection Agency, and Tennessee Department of Environment and Conservation (2002). Total maximum daily load (TMDL) for Siltation & Habitat Alteration in the Harpeth River Watershed (HUC 05130204) Cheatham, Davidson, Dickson, Hickman, Rutherford, & Williamson County, Tennessee, 30 p.

Thompson, M. (2005). Beaver-Camas Subbasin Assessment and TMDLs, Idaho Department of Environmental Quality, 153 p.

Thoms, M. C. (1987). “Channel sedimentation within the urbanized River Thame, UK,” Regulated Rivers, 1, pp. 229-246.

Thonon, I. and van der Perk, M. (2003). “Measuring suspended sediment characteristics using a LISST-ST in an embanked flood plain of the River Rhine,” Erosion and Sediment Transport Measurement in Rivers: Technological and Methodological Advances, IAHS Publication 283, pp. 37–44.

Topping, D. J., Melis, T. S., Rubin, D. M., and Wright, S. A. (2005). “High-resolution monitoring of suspended-sediment concentration and grain size in the Colorado River in Grand Canyon using a laser-acoustic systems,” Proceedings of the Ninth International Symposium on River Sedimentation, October 18-21, 2004, Yichang, China, pp. 2507-2514.

Trimble, S. W. (1983). “A sediment budget for Coon Creek basin in the Driftless Area, Wisconsin, 1985-1977,” American Journal of Science, 283, pp. 454-474.

Walling, D. E. and Webb, B.W. (eds.) (1996). Erosion and Sediment Yield: Global and Regional Perspectives, IAHS Publication no. 236, 586 pp.

Wang, K. H., Jin, K. R., Tehrani, M. (2003). "Field measurement of flow velocities, suspended solids concentrations, and temperatures in Lake Okeechobee," Journal of the American Water Resources Association, 39, pp. 441-456.

Williams, G. P. and Wolman, M. G. (1984). "Downstream effects of dams on alluvial rivers," U.S. Geological Survey Professional Paper, 1286, 83 p.

Urhich, M. A. and Bragg, H. M. (2003). "Monitoring instream turbidity to estimate continuous suspended-sediment loads and yields and clay-water volumes in the upper North Santiam River basin, Oregon, 1998-2000, U. S. Geological Survey Water-Resources Investigations Report 03-4098, 43 p.

U. S. EPA (2005a). "National Section 303(d) List Fact Sheet," http://oaspub.epa.gov/waters/national_rept.contr, accessed on September 15, 2005.

U. S. EPA (2005b). "Sediment Concentration Drastically Reduced in Las Vegas Wash," EPA 841-F-05-004G, http://www.epa.gov/owow/nps/Success319/state/pdf/nv_lvwash.pdf, accessed at on September 4, 2005.

U. S. Geological Survey (2005). "Suspended-Sediment Database Daily Values of Suspended Sediment and Ancillary Data," http://co.water.usgs.gov/sediment/seddatabase.cfm accessed on September 15, 2005

van Wijngaarden, M. and Roberti, J. R. (2002). "In situ measurements of settling velocity and particle size distribution with the LISST-ST," in Winterwerp, J. C. and Kranenburg, C. (eds.), Fine Sediment Dynamics in the Marine Environment, pp. 295-311.