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HIGH-RESOLUTION MONITORING OF SUSPENDED-SEDIMENT CONCENTRATION AND GRAIN SIZE IN THE COLORADO RIVER IN GRAND CANYON USING A LASER-ACOUSTIC SYSTEM

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Abstract: To monitor sediment transport in the Colorado River in Grand Canyon, Arizona, USA, we have designed and are evaluating a laser-acoustic system for measuring the concentration and grain size of suspended sediment every 15 min. This system consists of (1) a subaqueously deployed laser-diffraction instrument (either a LISST 100 or a LISST 25X) connected to an automatic pump sampler, and (2) an EZQ acoustic-doppler current meter. When laser transmission drops below a user-defined threshold (as a result of increased suspended-sediment concentrations), the LISST triggers the automatic pump sampler to collect samples at a user-defined rate. This allows samples to be collected when the suspended-sediment concentrations exceed the upper limit for the LISST and the EZQ acoustic-Doppler current meter (around 2,000 $mg \cdot l^{-1}$-3,000 $mg \cdot l^{-1}$). Beginning in August 2002, we began testing this system on the Colorado River in Grand Canyon, and have developed stable coefficients relating the pump, laser-diffraction, and acoustic-backscatter measurements to cross-sectionally integrated measurements of suspended-sediment concentration and grain size. Variability between either sequential laser-diffraction or acoustic-backscatter measurements is substantially less than the variability between sequential cross-sectionally integrated measurements of concentration and grain size (collected with standard U.S. Geological Survey samplers and methods). Furthermore, the variability between either the laser-diffraction or acoustic-backscatter point measurements and the cross-sectionally integrated measurements is typically less than the variability between paired cross-sectionally integrated measurements of concentration and grain size. These observations suggest that more error may be introduced during the computation of suspended-sediment loads based on conventional sampling methods than is introduced during the computation of suspended-sediment loads using the laser-acoustic system.

Keywords: Suspended sediment, Grain size, Laser-diffraction, Acoustic-backscatter

1 INTRODUCTION

Sandbars and other sandy deposits in and along the Colorado River in Grand Canyon National Park (GCNP) were an integral part of the pre-dam riverscape, and are important for habitat, protection of archeological sites, and recreation (Rubin *et al.*, 2002). Recent work has shown that these sandbars are dynamic landforms and represent the bulk of the ecosystem's sand reserves. These deposits have eroded substantially following the 1963 closure of Glen Canyon Dam that reduced the supply of sand at the upstream boundary of GCNP by about 94%; sandbars in the upstream part of Grand Canyon have decreased in size by about 25% during the last 15 years (Schmidt *et al.*, 2002). Recent work has shown that sand transport in the post-dam river is supply limited (Topping *et al.*, 2000a, 2000b), and is equally regulated by the discharge of water and short-term changes in the grain size of sand available for transport (Rubin and Topping, 2001). These short-term changes in grain size are driven by changes in the upstream supply of sand caused by either tributary flooding or by moderate to high dam releases (Rubin *et al.*, 1998; Topping *et al.*, 1999, 2000b). During and following

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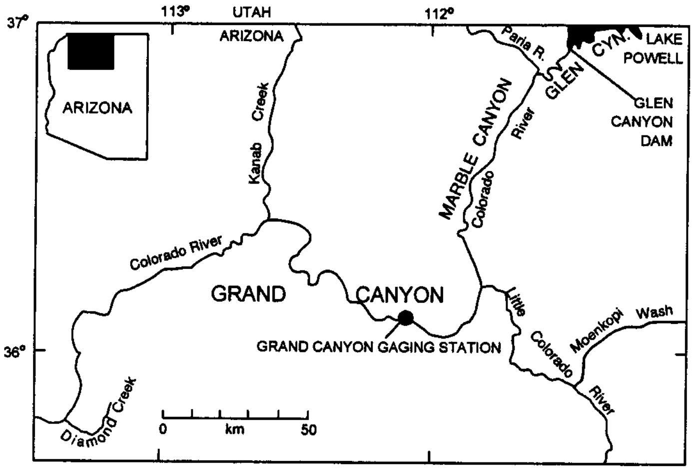


Fig. 1 Map of the Study Area showing the Location of the Colorado River near Grand Canyon, Arizona gaging Station (USGS station number 09402500)

2 THE LASER-ACOUSTIC SYSTEM

At the Grand Canyon gaging station test site, the laser-acoustic system consists of: (1) a Sequoia Scientific LISST (Laser In-Situ Scattering and Transmissometry)-25X(Use of brand and firm names in this paper does not constitute endorsement by the USGS.) type C laser-diffraction instrument and a Sequoia Scientific LISST-100 type C laser-diffraction instrument (http://www.sequoiasci.com/products/LISST_Inst.aspx), (2) an ISCO 6712 automatic pump sampler (http://www.isco.com/aspscripts/products3.asp?PDG=201101010), and (3) a Nortek EZQ acoustic-Doppler current meter (http://www.nortek-as.com/brochures/EZQ.pdf). The ISCO pump sampler is triggered by the LISST instruments when laser transmission drops below a user-defined threshold (due to higher suspended-sediment concentrations) and then samples at a user-defined rate.

The two LISST instruments are suspended in the river from a steel cable on pulleys attached to a vertical cliff. The sampling path lengths of the two LISST instruments are 1 cm. The LISST-25X averages 1,000 samples collected over 110 s out of every 15 min; output is concentration of total suspended sediment, concentration of suspended sand, Sauter mean sizes of total suspended sediment and suspended sand, and laser transmission. The LISST-100 averages 100 samples collected over 30 s out of every 15 m; output is concentration of suspended sediment in 32 log-spaced size classes from 2.5 μm to 500 μm, water temperature, pressure, and laser transmission.

The ISCO 6712 automatic pump sampler has a capacity of 24 one-liter bottles. We designed the LISST-ISCO pump-sampler control circuit to allow data collection during periods when the Colorado River is so greatly enriched with suspended sediment that the LISST instruments overestimate suspended-sediment concentration owing to multiple scattering or provide no usable data owing to extremely low laser transmission. The protocol is as follows: when the measured laser transmission is less than the user-defined threshold, the LISST instrument electronically enables the automated program of the ISCO pump sampler. Once the pump sampler is activated, samples are collected from a fixed intake located near the LISST instruments at pre-defined intervals until either the measured laser transmission exceeds the user-defined threshold, or the supply of 24 one-liter sample bottles is exhausted.

The 1-MHz EZQ acoustic-Doppler current meter is rigid-mounted subaqueously on a pipe attached to a vertical wall. It has two horizontal acoustic beams spaced 50 degrees apart for measuring 2-D-planform velocity using the Doppler effect, a vertical acoustic beam and pressure transducer for measuring stage, and a 45 degree downward-looking acoustic beam for measuring bed scour and fill. The beam width is 3.4 degrees. We have deployed the horizontal beams of the EZQ to measure particle counts starting 8 m from the instrument in three 5-m long cells. The EZQ averages 78,000 sampling bursts over 13 min out of every 15-minute interval. The 1 MHz EZQ is acoustically sensitive to particles with diameters ranging from about 30 μm to about 600 μm (Lohrmann, 2001). Over this range of particle sizes, particle counts and sediment concentration are positively correlated. Particles smaller than about 30 μm are perceived by the EZQ to be part of the fluid. No correlation exists between particle counts and sediment concentration for particles larger than about 600 μm.

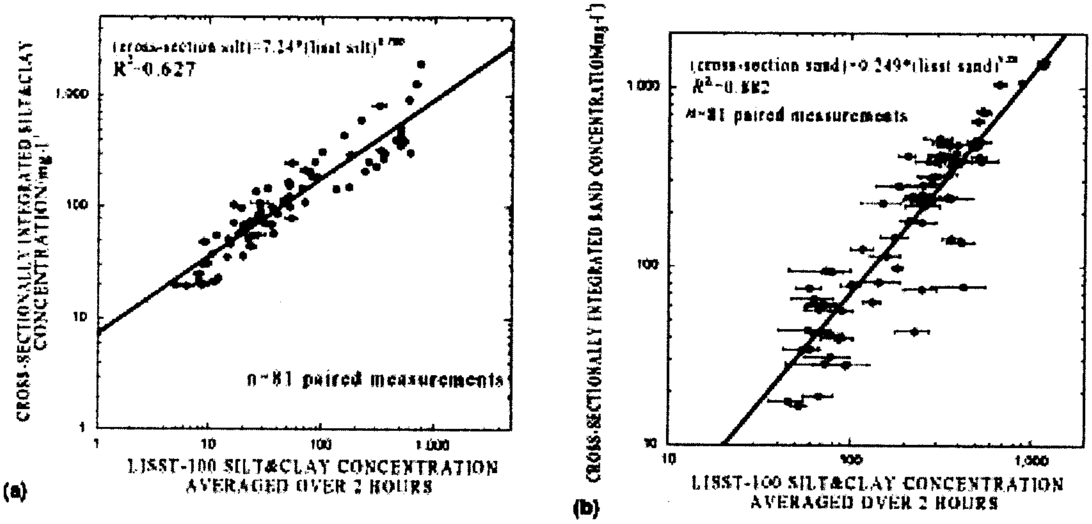
3 VARIABILITY BETWEEN SEQUENTIAL CONVENTIONAL CROSS-SECTIONALLY INTEGRATED SAMPLES

Prior to developing cross-section coefficients (Edwards and Glysson, 1999) relating the pump, LISST, and EZQ measurements to analytical results from conventional cross-sectionally integrated samples at the Grand Canyon gaging station, we collected paired sequential cross-sectionally integrated samples using conventional D-77 and D-96 bag samplers (Federal Interagency Sedimentation Project, 2004). This was necessary to help place constraints on whether more error may be introduced in sediment loads computed using these cross-section coefficients than is introduced in sediment loads computed using only the conventional cross-sectionally integrated samples. The results of this test indicate that, regardless of sampler type, the variability between conventional cross-sectionally integrated samples is high for sand concentration (with R^2 between paired samples < 0.7) and extremely high for sand grain size (with R^2 between paired samples < 0.1).

4 DEVELOPMENT OF CROSS-SECTION-COEFFICIENT RELATIONS

Following evaluation of the variability inherent in conventional cross-sectionally integrated suspended-sediment measurements, we developed cross-section-coefficient relations calibrating the ISCO pump-sampler measurements, and the LISST-25X and the LISST-100 laser-diffraction measurements (Fig. 2) to the cross-sectionally integrated measurements of suspended-sediment concentration and grain size. We found that the variability around these cross-section-coefficient relations to be typically much less than that between the paired conventional cross-sectionally integrated samples (especially for suspended-sand concentration and grain size).

Calibration of the EZQ acoustic-backscatter measurements to the conventional cross-sectionally integrated sediment-transport measurements was slightly more complicated. To compute both silt and clay concentrations and sand concentrations using the single frequency EZQ, we used the fact that, for the 1MHz EZQ, increases in the concentration of particles smaller than about 30 μm lead to an increase in the absorption and dissipation of the acoustic



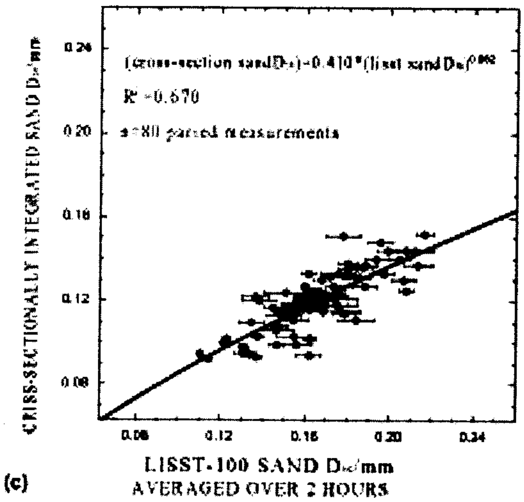


Fig. 2 Cross-section-coefficient relations between: **(a)** the suspended-silt and clay concentration measured by the LISST-100 and the cross-sectionally integrated suspended-silt and clay concentration, **(b)** the suspended-sand concentration measured by the LISST-100 and the cross-sectionally integrated suspended-sand concentration **(c)** the median size of the suspended sand measured by the LISST-100 and the cross-sectionally integrated median size of the suspended sand (note linear scale).

energy by the fluid (relative to under clear-water conditions), and do not result in increases in the backscatter of acoustic energy. LISST-100 measurements indicate that, at higher concentrations of silt and clay, the grain size of the suspended silt and clay in the Colorado River is, in fact, predominantly finer than 30 μm; thus, changes in the concentration of particles smaller than 30 μm can be used as a proxy for changes in the concentration of all of the silt and clay (i.e., all particles finer than 63 μm). Because the near-surface concentration of suspended sediment is approximately equal over the portion of the river sampled by the EZQ (in the region about 8m to 23 m from the instrument), we evaluated the effect of temporal changes in the concentration of particles finer than 30 μm on the fluid absorption of the acoustic energy by assuming that the range-normalized echo level was equal in cells 1 and 3. Based on Lohrmann (2001), the range-normalized echo level, E, (in dB) in any one cell is evaluated as:

$$E = 0.43A + 20\log_{10}(R) + 2\alpha_f R + 20R\int \alpha_p \mathrm{d}r \quad , \tag{1}$$

where A is the amplitude of the backscattered acoustic signal strength (in counts), R is the distance along the beam from the instrument (in m), α_f is the fluid absorption of the acoustic energy (in dB·m^{-1}), and α_p is the attenuation of the acoustic energy by particles sensed by the EZQ (in dB·m^{-1}). For the 1 MHz EZQ, if no particles finer than 30 μm are present, then α_f is due to only the molecular transfer of acoustic energy to heat in water (and depends only on the salinity of the water). Since the last term in equation 1 describes the absorption and scattering of the acoustic energy by particles in the size range sensed by the 1 MHz EZQ (30μm -600 μm), we excluded this last term from this analysis. Thus, Eq. 1 was rearranged to solve for α_f by setting the range-normalized echo level in cells 1 and 3 to be equal. Fig. 3(a) shows the relation between α_f computed by this approach and silt and clay concentration. A simpler method to capture the effect of silt and clay-concentration-driven changes in α_f was to use the ratio of the amplitude of the backscattered acoustic signal strength in cell 3 to that

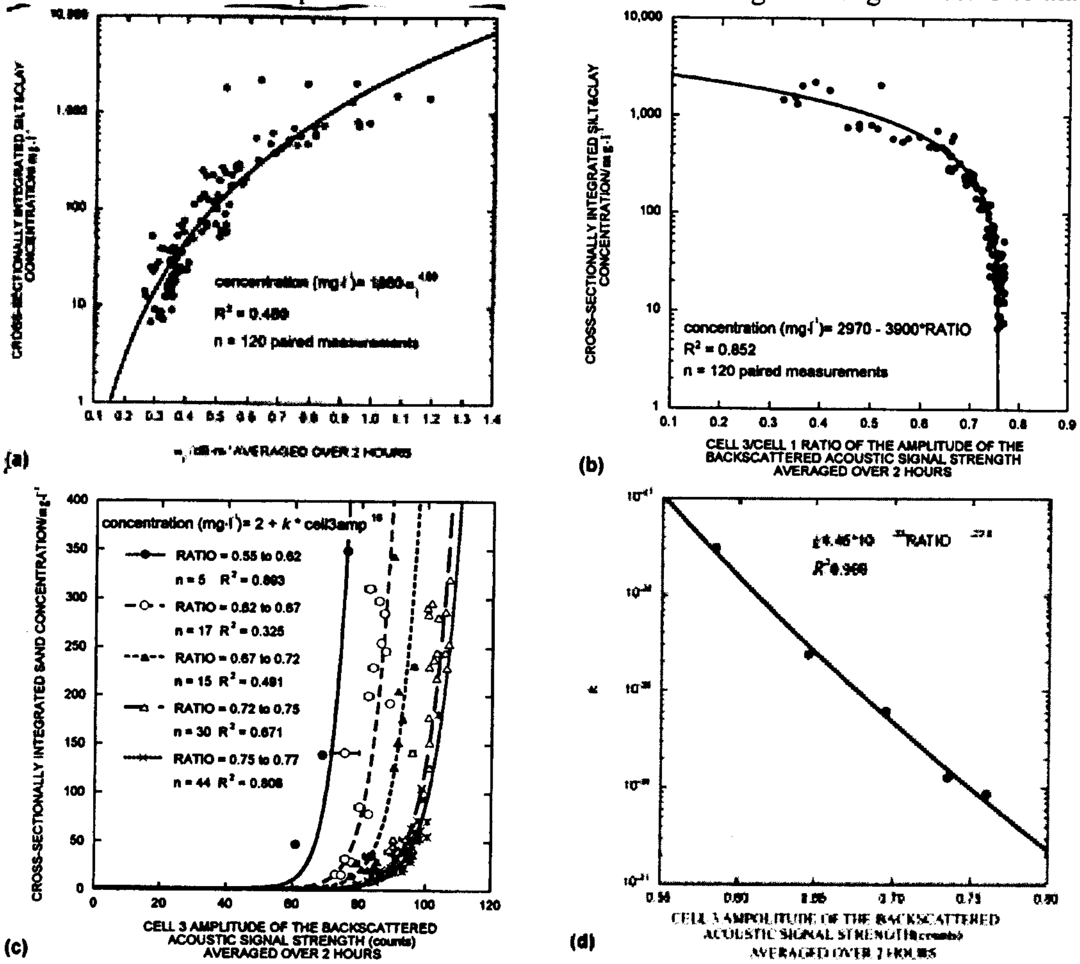
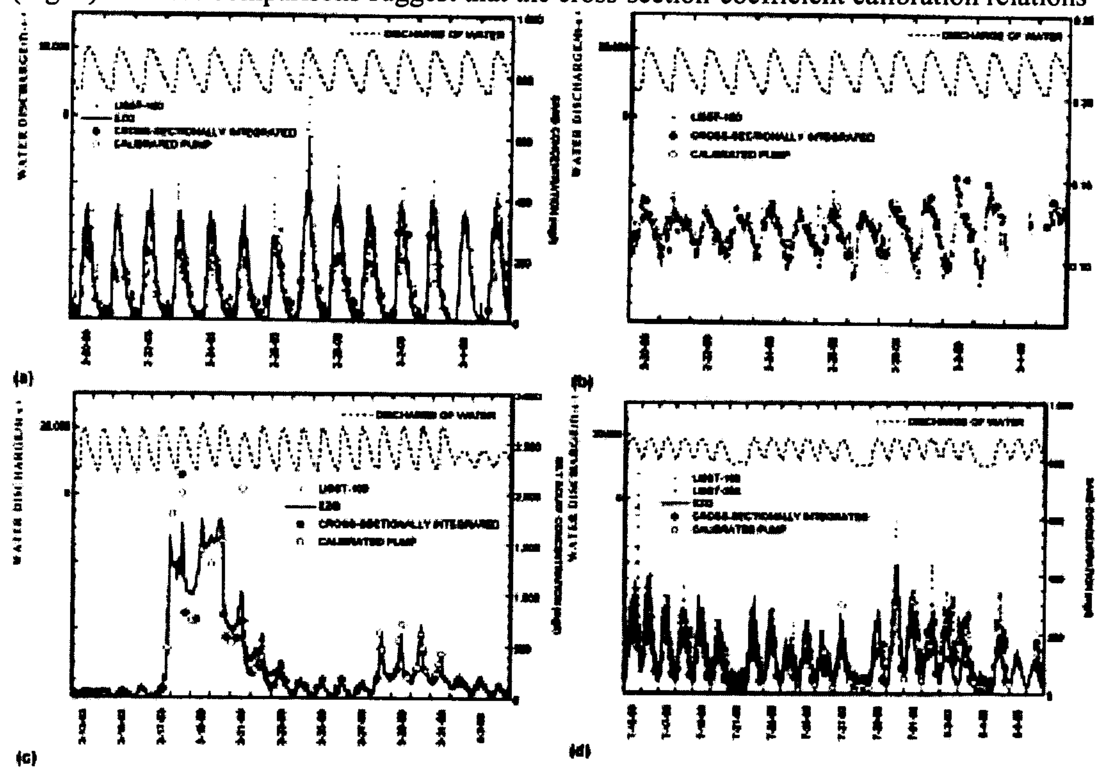


Fig. 3 (a) Power-law relation between the coefficient of fluid absorption and the cross-sectionally integrated concentration of suspended silt and clay. (b) Linear relation between the ratio of the amplitude of the backscattered acoustic signal strength in cell 3 to that in cell 1 and the cross-sectionally integrated concentration of suspended silt and clay. (c) Power-law relations between the amplitude of the backscattered acoustic signal strength in cell 3 and the cross-sectionally integrated concentration of suspended sand for small ranges of the ratio in b. (d) Power-law relation between the ratio in b and the constant k in c

in cell 1 as a proxy for suspended silt and clay concentration (Fig. 3(b)). Then, for small ranges in this ratio (i.e., for small ranges in the suspended-silt and clay concentration), power-law cross-section-coefficient relations were developed to relate the amplitude of the backscattered acoustic signal strength in cell 3 to the cross-sectionally integrated measurements of suspended-sand concentration (Figs. 3(c)-3(d)).

5 COMPARISON TO CROSS-SECTIONALLY INTEGRATED CONVENTIONAL SEDIMENT-TRANSPORT DATA

After application of the cross-section-coefficient relations in section 4, the pump, LISST, and EZQ sediment-transport measurements were compared to conventional cross-sectionally integrated sediment-transport measurements, both during the period used for calibration in section 4 (through June 2003) and during the post-calibration period beginning in July 2003 (Fig. 4). These comparisons suggest that the cross-section-coefficient calibration relations



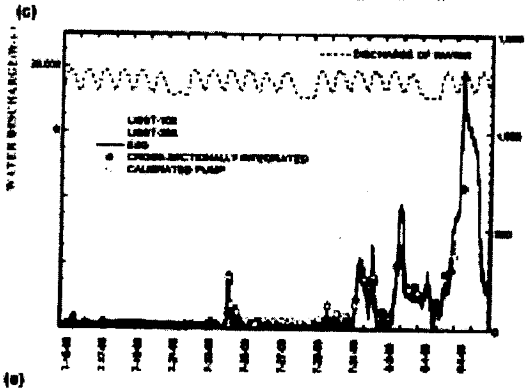


Fig. 4 **(a)** Comparison of measured suspended-sand concentrations during February 20-March 5, 2003. **(b)** Comparison of measured suspended-sand median grain size during February 20-March 5, 2003. **(c)** Comparison of measured suspended-silt and clay concentrations during the tributary-flooding period of March 13-April 3, 2003. **(d)** Comparison of measured suspended-sand concentrations during the post-calibration period of July 15-August 7, 2003. **(e)** Comparison of measured suspended-silt and clay concentrations during the post-calibration period of July 15-August 7, 2003

developed prior to July 2003 are stable. Thus, once calibrated, the laser-acoustic system can be used to provide continuous measurements of suspended-sediment concentration and grain size, with fewer required conventional samples for future verification of the laser-acoustic measurements.

Orders of magnitude more sediment-transport measurements can be made each day by the laser-acoustic system than is possible using conventional sampling methods. Furthermore, most of the data collected by the laser-acoustic system do not have to be processed in a laboratory, as do the data collected by conventional suspended-sediment samplers. Only samples collected by the ISCO pump sampler (at higher suspended-sediment concentrations) have to be processed in a laboratory before they can be used. Thus, the laser-acoustic system allows for real-time computation of suspended-sediment concentration and grain size. For comparison, it takes approximately 2-3 days to process a suspended-sediment sample through a laboratory for concentration and grain size and, depending on laboratory workload, might result in delays on the order of months in producing the data.

6 VARIABILITY BETWEEN SEQUENTIAL EZQ AND LISST MEASUREMENTS: HOW REPRESENTATIVE OF THE SEDIMENT CONDITIONS IN THE RIVER ARE THE LASER-ACOUSTIC MEASUREMENTS?

Analyses indicate that the variability between sequential EZQ and LISST measurements is considerably less than that between sequential conventional cross-sectionally integrated samples. This result suggests that once calibrated, the laser-acoustic system may provide more accurate measurements of suspended-sediment concentration and grain size than do conventional sampling methods. Because the volume of water sampled in the cross-section by conventional sampling methods is comparable to or smaller than the volume of water effectively sampled by the laser-acoustic system, once calibrated the laser-acoustic system may provide data that are not only more accurate, but are also more representative of temporal changes in the sediment-transport conditions in the river. Cross-sectionally integrated samples collected with conventional samplers sample 10^0 l to 10^1 l of water over 30 min. As deployed, the LISST instruments effectively sample 10^0 l of water over 100 seconds. Thus, over 30 min, the LISST instruments sample 10^1 l of water. As deployed, the EZQ effectively samples 10^7 l of water over 13 min. Thus, over 30 min, the EZQ samples 10^8 liters of water.

7 CONCLUSIONS

The results presented in this paper indicate that LISST laser-diffraction and EZQ acoustic-backscatter data are suitable for monitoring suspended-sediment transport in the Colorado River and suggest that these data may be used to monitor suspended-sediment transport in other settings (given that deployments are carefully designed and maintained, and that sufficient calibration/verification data are collected). The laser-acoustic sediment-transport data provide a minimum of 1 order of magnitude tighter temporal resolution of sediment-transport than can be collected using conventional sampling methods. Furthermore, no laboratory analyses are required before using the laser-acoustic sediment-transport data. This allows for real-time computation of suspended-sediment concentration and grain size. Laboratory analyses of conventionally collected suspended-sediment samples take days to complete. Finally, once calibrated, the LISST laser-diffraction and EZQ acoustic-backscatter data may provide a more accurate measure of sediment transport than can be obtained using conventional samplers.

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