Suspended Sediment Profiles in Rivers With LISST-SL2 Laser Diffraction Instrument

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1. ABSTRACT

Measurements of sediment transport in rivers have for long been done laboriously with water samples drawn infrequently, requiring subseqent time-consuming analysis. A new laser diffraction instrument LISST-SL2 has been developed to make these same measurements in real-time, with sediment concentration, grain size distribution, water velocity, and temperature all stored as a function of depth. This capability permits efficient data collection for monitoring agencies, while at the same time, opening new avenues for scientific research. In this paper, we offer a preview of data collected from two rivers on two continents: the Cowlitz river in Washington, US, and the Yangtze river at Wuhan city, China. We discuss similarities, statistics of the data, vertical structure of river columns, time-scales of sediment fluctuation, and derivable flow quantities.

Keywords – River sediments, size distribution, real-time.

2. INTRODUCTION

Sediment transport in rivers has important societal consequences; as such it is a subject of significant scientific research. River meander, sand formations, erosion around bridge pilings, and discharges into estuaries and deltas are all related subjects. The effort in measuring suspended and bedload discharge has a long history (see Orton and Kineke, 2001 for a review; also Kazimierz et al. 2010). Routine monitoring by governments have evolved rigorous procedures and standardized instruments and methods. The present work confirms some old ideas, and advances others.

The simplest study areas on rivers are straight sections which are devoid of secondary motions associated with river meanders, describable, to first order, as a classic flow in a turbulent channel (Schlichting,1968). In these flows, a 'law of the wall' region may exist near the riverbed, where the velocity profile scales as logarithm of the distance from the bed. Such a region exists so long as the channel bed roughness is not a significant portion of the channel depth. Above this logarithmic velocity region, a 'law of the wake' applies where scaling is with channel depth. In these flows, sediment is carried both as suspended load and as bedload. The suspended load carried by rivers can typically be partitioned into a 'wash load' of fine material that is too fine to settle and a resuspended load if the river velocity is sufficient to force resuspension. A vertical gradient in suspended sediment concentration (SSC) exists in the water column. The gradient is established under the competing actions of turbulent diffusion gravitational settling. Since settling velocity depends on grain size and mass density, size principally determines the gradient when flocculation

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is small. The vertical profile was formalized by Rouse (1937). Thus, river channels are expected to exhibit velocity and SSC profiles with scaling laws similar to classic turbulent channels. The SSC profiles are expected to be a composite of component profiles of different size sediments (modified by sediment-induced density stratification when it exists). It is this last item – gradients of different sized grains – that have remained poorly studied, and remain a source of error and disorder in past data because of instrumental limitations to observe size distributions and accurate sediment concentrations. We review these briefly.

Orton and Kineke (2001) measured velocities and sediments in the Hudson River estuary and compared model results with measurements. They used a single calibration of an OBS, which by implication assumes a constant size distribution throughout the water column. With no data on size distribution variability in the water column, they assumed a single settling velocity for their model, 0.22cm/s, which applies to 50 µm sand grains. They reported that the theory-data match was best when a power law relationship was employed between settling velocity and concentration. Even so, data and their models disagreed by orders of magnitude at just short distances above the riverbed. In the end, the use of turbidity type sensors appears to have been unsuitable in this vertically changing PSD environment. It appears to be responsible, at least in part, for the poor match between data and their sophisticated models.

Still other studies have employed physical samples, e.g. Richey et al.(1986). They employed bag samplers and partitioned a vertically integrated sample into fine and coarse sediment with the break at 63 µm. These data are more likely to be accurate, but for sampling errors. Unfortunately, this limits the number of available data points, and vertical structure of PSD was not revealed. The use of bottle samplers is widespread, and it is a de facto standard operating procedure of government agencies. A physical sample promotes confidence in the results. However, as Gitto et al.(2017), using a LISST-SL instrument show, single bottle samples do not represent mean values of SSC. Acoustic backscatter as a surrogate has been an area of promise for a few decades (Guerrero, 2017), but inversion of even the multi-frequency data in a varying situation such as a river column has not been done routinely to date. The laser diffraction method (LD) described in this paper remains the only reliable way to observe river column sediments, although it is a point measurement and requires physical profiling. For completeness, we describe the principle.

The LD method is an international standard, ISO-13320:2009. The LISST-SL is a submersible LD instrument, developed in a Cooperative Research and Development Agreement (CRADA) between Sequoia Scientific, Inc. of Bellevue, Washington and the United States Geological Survey[3] (USGS). This instrument measures PSD, SSC, velocity, temperature, optical transmission, and depth, all at 1Hz. Czube et al.(2015) published an instrument evaluation. The data presented in this paper are from 2 rivers, one in Washington State,US and another in Yangtze river at Wuhan, China.

INSTRUMENTATION

The measurements were made with the LISST-SL instrument, and more recently with its successor the LISST-SL2. The instrument is a complete package that includes sensors for flow

[3] The CRADA does not imply an endorsement of the instrument by USGS.

velocity, depth, water temperature, iso-kinetic intake control, laser diffraction optics, and sensors for engineering parameters. Power is provided via a 2-conductor wire (USGS standard B-reel), and data is

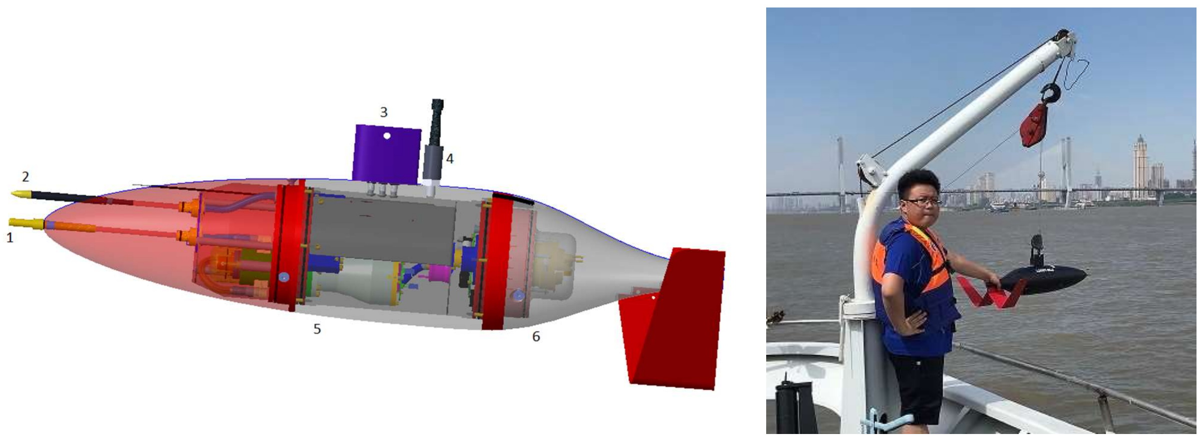

Figure - 1: LISST-SL2 with transparent colors, and use from a boat in Wuhan, China.

transmitted from the instrument to a surface Topside Box (TB) which contains battery and data relay electronics. The TB delivers data to a laptop computer where data are processed for immediate display and storage. The data from LISST-SL2 are processed every second and all parameters (PSD, depth, temp., velocity) are displayed. Upon saving a datafile, a menu option on LISST-SL2 software computes and displays averaged quantities over selected depths and depth ranges. Details are at https://www.sequoiasci.com/product/lisst-sl/ . The instrument can be used from bridges following USGS procedures as used for samplers, or from a boat, Fig. 1.

3. DATA

Cowlitz River, Washington, USA: Data acquired during a field test of the original LISST-SL by USGS personnel were plotted as vertical profiles. The LISST-SL and -SL2 record optical transmission across a 3mm path, which is a single-parameter measure that acts as indicator of turbidity. Transmission, velocity, SSC and PSD are shown below plotted as functions of depth.

These data show the difficulty of SSC measurement with turbidity sensors. Whereas the turbidity appears nearly constant through the water column, the concentration shows an increase with depth. Similarly, the particle size distribution shows a sand mode that is absent at the surface but grows to become prominent with depth. The SSC profile shows a distinct minimum at each depth, except the lowest. This corresponds to the vertically constant wash load at a ϕ value of 6 throughout the water column, as clearly seen in the PSD data. This structure fits the classical channel flow. The apparently constant turbidity misses this profile view due to the poor responsivity of turbidity to increasing grain size. These detailed data contain lot more information that we shall discuss later.

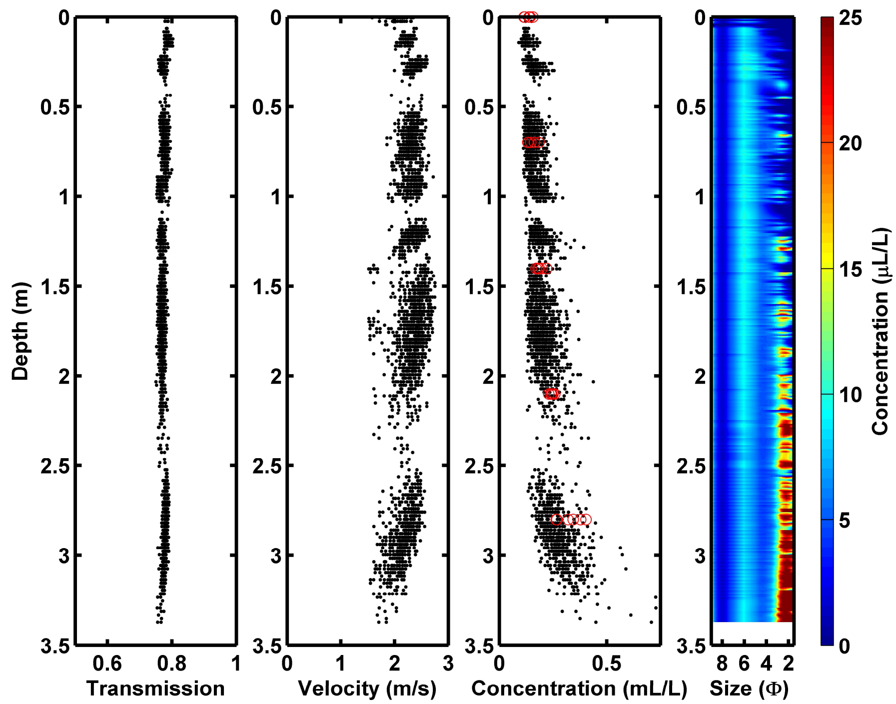

Figure - 2. Vertical profiles of transmission, velocity, SSC, and particle size distribution from Cowlitz River, Washington, USA. Data were obtained on 15 March 2011 by USGS personnel. Red circles in concentration profiles (3rd panel) are physical samples obtained by USGS personnel.

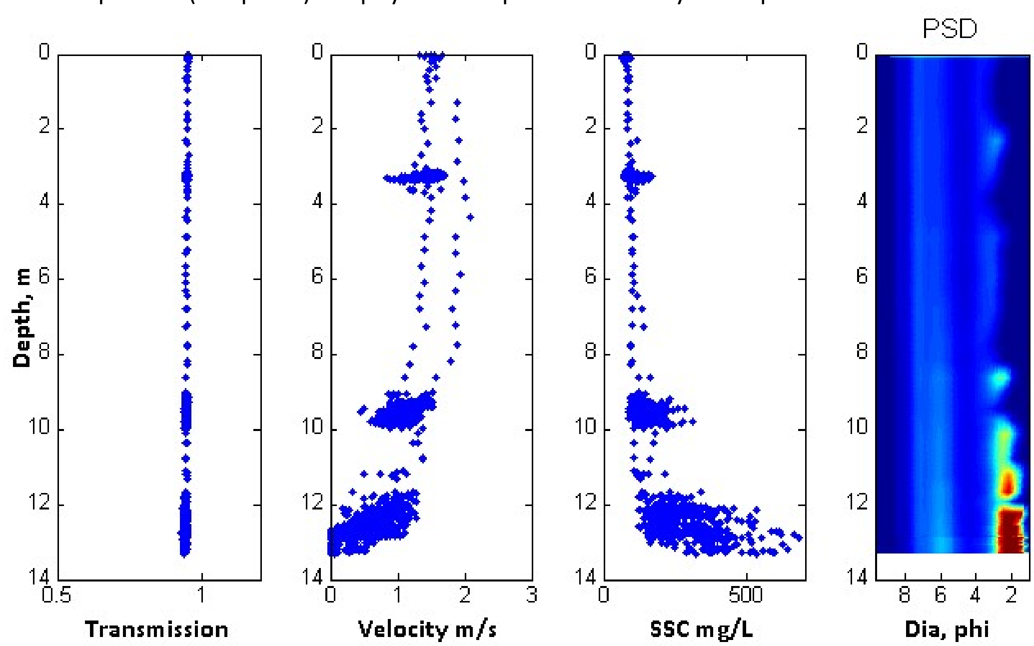

Figure - 3: A single profile at the eastern station in Yangtze river shows 1,272 samples collected over 20 minutes. LISST-SL2 was held at 3.5, 10 and 12.5m depth. Sparse data are obtained during change of instrument depth.

Yangtze River, Hebei Province, China: The more advanced LISST-SL2 was used in the Yangtze river at 3 stations across the river channel, on 27 June, 2018. Data were collected by local river personnel, principally at a few discrete depths selected as 60% of nominal depth and deepest. Figure 3 shows the results, qualitatively similar to Figure 2.

4. DISCUSSION

In both rivers, the turbidity-like optical transmission is vertically uniform, left panels, Figs. 2 and 3. Thus turbidity measurements misrepresent the true structure, as revealed in the concentration profiles, panels 3, Figs.2 and 3 . This is a well-known behavior of turbidity sensors, whose response (V/concentration) varies as 1/*d, d* being grain diameter of sediment. Consequently, the larger grains of suspended sand do not significantly affect turbidity. Regarding the velocity data, we note only that they are relatively constant until the reduction near-bottom.

Returning to measurements of sediment concentrations and particle size distributions, we briefly discuss the statistics of concentrations, time-scales of fluctuations of different size fractions, vertical variation of particle size distribution averaged over small depths (compared to river depth), the vertical gradients of different size classes in the context of Rouse profiles, and the direct estimate of turbulent flux.

Concentration statistics: A close look at the concentration profiles of Figs.2-3 (3rd panels) reveals that for any depth, there exists a sharp minimum, to which an apparently random scatter of concentrations is observed. The size distributions in the 4th panel on each figure explain this behavior – the minimum is defined by the vertically uniform wash-load, on which fluctuating suspended load is superposed. An examination of the histograms of data of Fig.2 clearly displays the

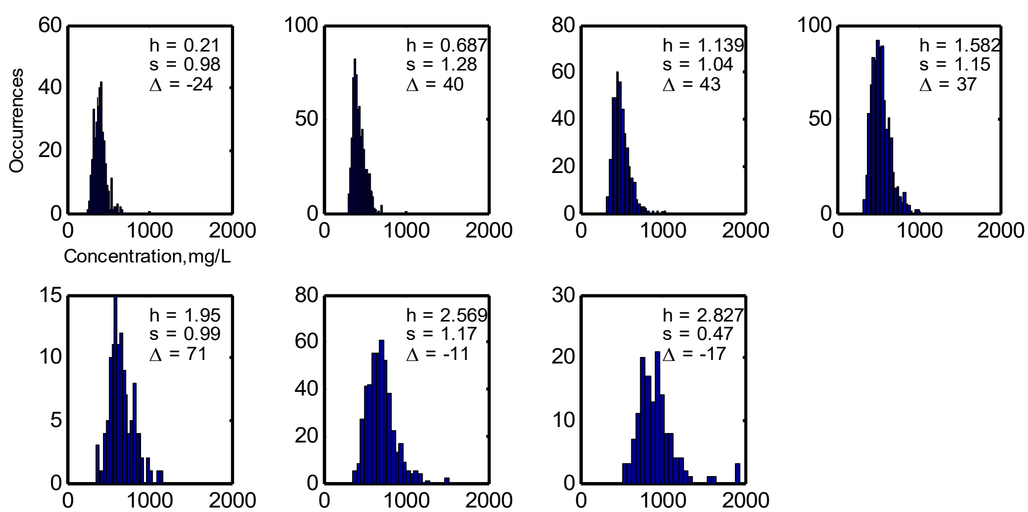

Figure - 4: Statistics of concentration measurements at different depth below river surface, Cowlitz river.

resulting skewness, Fig. 4. Here, we show the histograms of concentrations at depths h, with skewness s, and a shift between mean and mode Δ. The skewness decreases with increasing importance of suspended load. The implication is that single samples (bottles) are likely to see the modal concentration, which would be offset from the true mean by Δ. This underscores the conclusion of Gitto et al.(2017) regarding the need for 16 bottle samples to obtain a stable mean.

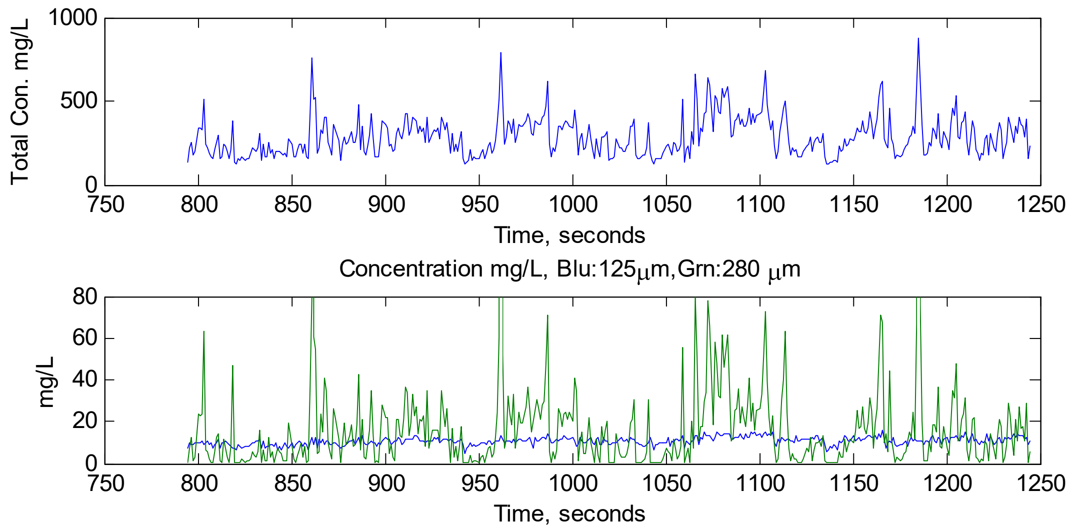

Figure -5: Time scales of fluctuations of total concentration (top) and of two distinct size classes – 125 and 280μm; Yangtze river data.

Integral Time Scales: A look at the time series of total concentration reveals long period fluctuations, showin in Fig. 5 (top). When the time-series of distinct sizes is plotted, the differing

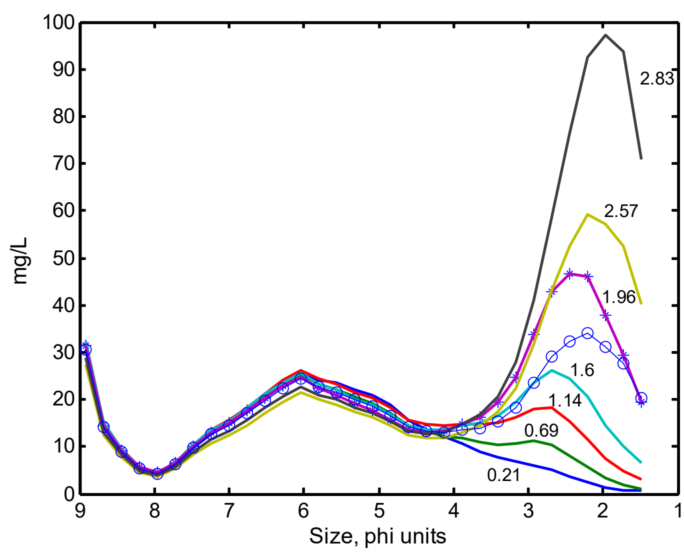

Figure - 6: Mean PSD at depths marked on each curve, Cowlitz river data.

time scales for sands that are quite close in size, 125 and 280µm are distinct. This clearly points to resuspension of fine sand and coarse sand in uncorrelated events. One can qualitatively infer that concentration fluctuations near this riverbed had time scales of order 50 seconds, so that, again it follows that to obtain good averages, several minutes of the time series are necessary.

Particle Size Distribution: Due to the rich depth profile of the Cowlitz river data, we choose to display the vertical variation of PSD in it. Fig. 6 shows the PSD at depths marked on each curve, and the half-depth profile is identified with circles.

In the final figure we show the vertical profile of concentraton of various size grains (left) and the vertical profile of flux of sediments, separated into washload and suspended load at size 63µm. The flux is computed as the product of means, velocity and concentration. The decomposition into mean and turbulent, correlated flux <U’C’> is omitted for the present.

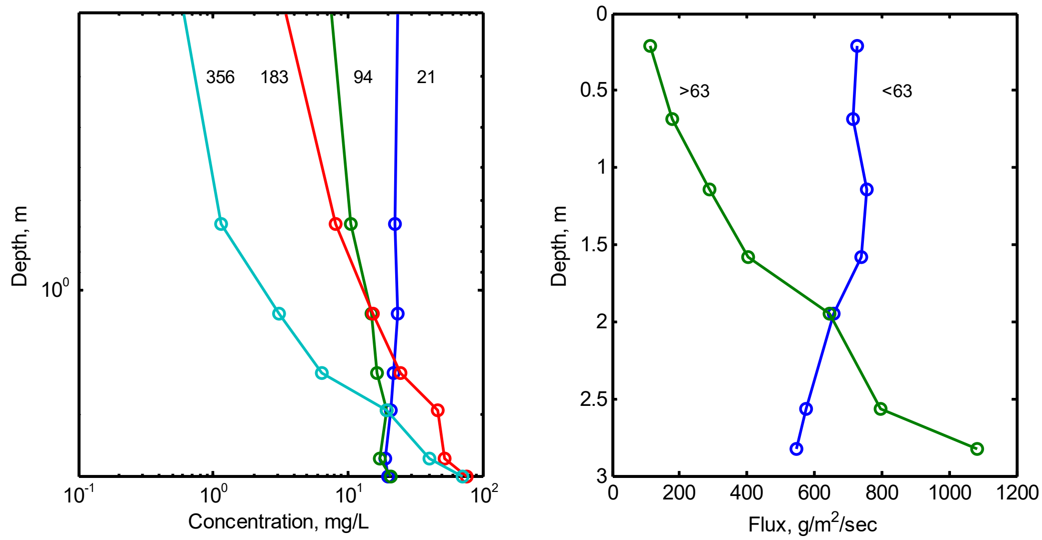

Figure - 7: Vertical profiles of concentration of a few selected size grains (left), and flux of washload and suspended load. Note. the ordinate on left is logarithmic/

The vertical profiles of concentration of various grain sizes reflect the Rouse-like increase in gradient with increasing grain size. We have used these profiles of various size grains, along with the Rouse formulation to estimates the bottom friction velocity. To estimate u_*, we equate the slope of logarithmic profiles to $-w_{f,n}/k u_*$, where $w_{f,n}$ is the fall velocity of size *n* and *k* is von Karman’s constant. These estimates are reproduced in Table 1, they fall in a narrow range. These estimates can be compared with direct estimates, but we leave that to a later report. There appears to be a consistent increase in estimated value u_* with increasing grain size. We do not have an explanation for this increase. Also, since the location of the riverbed or bed profile is not known exactly, there are unknown errors in these estimates.

Table I: u_* estimates from profiles of different sized grains.

Size *microns*	171	202	238	281	332	391	462
Dia. μm	131	155	183	216	255	302	352
u_* cm/sec	5.2	5.2	5.3	5.6	6.1	6.9	8.3

5. SUMMARY

New instruments provide river column data on sediments and velocity in conformity with iso-kinetic principles. Classical forms of sediment distributions are seen to occur in two rivers. The data permit examination of established theories and conventions on sampling river sediments.

ACKNOWLEDGEMENTS

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