CROSS-STREAM VARIATIONS IN SUSPENDED SEDIMENT TRANSPORT OVER DUNES, IMPLICATIONS FOR SAMPLING

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ABSTRACT

The magnitude of the lateral variations in the concentration of suspended sediment over dunes in an alluvial sand-bed channel are poorly known. Characterizing the lateral distributions of suspended sediment is important for understanding its causes and for accurate measurement of the rate of sediment transport. A series of laboratory experiments were conducted in a laboratory flume to characterize the lateral variations of suspended sediment over dunes. Twenty experimental runs were made using a flow depth of 0.13 m in a 1.2 m wide flume channel (Fr = 0.5, D_{50} =0.52 mm). Suspended sediment concentrations were simultaneously sampled at two points located at the same depth but spaced laterally at intervals of 0.40, 0.20, 0.10 and 0.05 m. Also, acoustic instruments were used to obtain high-resolution bed profiles and depth-integrated suspended sediment concentration for the lower region of the flow. Mean absolute differences between paired suspended sediment concentrations were shown to increase and then level off to values between 25 and 40 percent of the mean concentration as the lateral spacing between samples was increased. An analysis of the sediment concentration distributions indicated that 16 sample positions across the channel would be required to define the mean suspended sediment concentration with a confidence interval of less than 5% of the mean concentration with a probability of 0.95. This study provides new information for understanding lateral variations in the concentration of suspended sand over dunes and new information for devising effective strategies for sediment sampling.

INTRODUCTION

Human impacts on watersheds in many cases lead to increased loads of sediment in fluvial systems. These increased loads may impair designated uses and aquatic habitats. Changes in the amount of sediment carried by a stream or river have been identified as the single largest reason for the listing of a stream or river as impaired on the 1996 National Water Quality Inventory (Section 305(b) Report to Congress). Accurate sediment loads can be used to identify unstable stream corridors and degrading landscapes, to assess best management and stream stabilization techniques, and to evaluate stream rehabilitation techniques. Accurate determinations of suspended sediment concentrations are essential to assess the impact of sediment on the watershed. To improve measurement and prediction technologies for suspended sediment, more information on the sources of temporal and spatial variations are needed.

For unidirectional flows with bed shear stresses greater than the initiation of motion of the bed material sediment, most sand-sized sediment will form the following series of bed form types as flow strength increases: ripples, dunes, antidunes, and chutes and pools (Simons and Richardson, 1961). These irregularities of the bed have long been known to significantly influence characteristics of the flow and transport of the bed material sediment (Gilbert, 1914). Dunes are arguably the most important bed form on sand-bed streams.

Transport of sand on a dune covered bed is a highly variable process (Carey, 1985; Hubbell et al., 1981, 1987; Gomez et al., 1989, 1990). Samples of suspended sand collected at a point over dunes have been shown to exhibit variations with time from a fraction to several times the mean concentration in time as well as laterally (Wren et al., 2000). Knowledge of lateral variations and its causes is critical information for improving the measurement and prediction of suspended sediment transport rates. This information also has important implications for the collection of representative suspended sediment samples over dunes and for the side-by-side testing of new measurement devices as compared to conventional suspended sediment measurement devices. The purpose of this study was to document the magnitude of the lateral variation in the transport of sand in suspension over dunes for a range of length scales.

Experiments

All experiments were conducted in an adjustable-slope flume (30 m long, 1.2 m wide, 0.6 m deep) located in the hydraulic laboratory at the National Sedimentation Laboratory, Oxford, Mississippi. Flow rate in the flume was measured using pressure readings from a Venturi meter in the return pipe. Flow depth was determined by subtracting the mean bed elevation from the water surface elevation in a 12-m-long approach section to the measurement region. Bed and water surface transects were collected with in-air and underwater acoustic distance measurement devices that operated at 6 and 15 Hz, respectively. The bottom of the flume was covered with a 0.15 m deep layer of sand with a median diameter of 0.52 mm ($[D_{84}/D_{16}]^{1/2} = 1.54$).

Suspended sediment samples and bed elevation data were collected 23.5 m downstream of the inlet tank. Suspended sediment samples were collected at the same time from two identical "L" shaped samplers (Fig. 1) (inside diameter = 4.4 mm, outside diameter = 6.4 mm) at lateral spacings of 0.40, 0.20, 0.10 and 0.05 m. The paired sample locations were symmetrical to the longitudinal centerline of the channel. All samples were collected isokinetically to avoid bias (Report no. 5, 1941; Nelson and Benedict, 1950). Paired samples of the sediment water mixtures were collected for 40 seconds at 2-minute intervals over 2-hr periods. At each of the four lateral spacings, samples were collected at five different heights above the mean bed elevation. A continuous record of the bed height was collected at the two sampling sites (Fig. 1) with an underwater acoustic distance measuring device (BASIS-bed form and sediment imaging system) at 30 Hz. The BASIS system was also used in four experiments (21, 25, 29, 33) to measure the suspended sediment concentration from 50 mm below the transducer face to the sediment bed using acoustic backscatter information. The acoustic device allowed concentration measurements to be examined at 1-second intervals rather than the 40 second intervals for pump samples.

The region encompassed by the BASIS measurements was on average the lower 43% of the flow depth. Thirty samples of backscatter data were averaged to yield suspended sediment concentrations at a net frequency of 1 Hz. This number of measurements was recommended by Thorne et al. (1991), who found that from 20 to 30 backscatter samples were required to obtain reasonable values for the suspended sediment concentration. A total of 20 experimental runs

were considered for this study (Table 1).

RESULTS

Mean suspended sediment concentrations for each of the five relative depths used in point sampling are shown in Figure 2. There was no consistent bias between samples collected at the same relative depth for different sampler spacings. Mean suspended sediment concentrations were observed to decrease with distance above the bed. Suspended-sediment concentration was considerable even at the greatest values of y/d (0.8), where y is the vertical position above the bed and d is the average flow depth (Fig. 2). Samples were not collected at y/d values below about 0.4, because of the likelihood that the sampler intake would be buried during the two-hour period.

Comparison of Paired Samples

The mean absolute difference (M_{ad}, mg/l) was used to compare the differences between the paired suspended sediment samples:

$$M_{ad} = \frac{\Sigma abs(C_1 - C_2)}{N} \tag{1}$$

where C_1 and C_2 are the concentrations (mg/l) of sediment simultaneously collected from samplers 1 and 2, respectively, *abs* represents the absolute value, and N is the number of paired samples collected. The value of the M_{ad} decreases with decreasing distance between the sampler probes. The ratios of M_{ad} to the mean concentration of suspended sediment ranged from approximately 22 to 42 % (Fig. 3).

Differences in Suspended Sediment Concentration Near the Bed

The differences in suspended sediment concentration near the bed of the channel were investigated in four of the experiments using acoustic backscatter data. This information was stored in 5 mm range bins and was found to be positively correlated with suspended sediment concentration from a distance of 50 mm from the transducer face to the sediment bed. This meant that detailed suspended sediment concentration data were available over the bottom 43 percent of the flow depth. The point samples overlapped with the upper range of the acoustic backscattering data in four of the experiments. The correlation between the measured sediment concentration from the isokinetic point sampler and mean voltage from backscattering is shown in Figure 4 for the two sensors during experiments 21, 25, 29, 33. No significant differences among the four experiments were found between the relation of sediment concentration to backscatter voltage (Fig. 4). These two relations were used to calculate suspended sediment concentration for each 5 mm bin during the measurement periods of experiments 21, 25, 29, and 33. The mean percent error (%error=|100*(meas.-pred)/meas.|) for each of the 4 experimental runs was calculated as 36%, 28%, 20%, and 51% for runs 21, 25, 29, and 33, respectively (see Wren et al., 2003).

The suspended sediment concentration from the 2 sensors (run 21, sampler spacing = 0.4 m) for the bottom 43% of the flow depth are contoured and shown in Figure 5. The contours in Figure 5 show evidence of coherent structures that begin near the bed and protrude to varying heights into the flow. These structures undoubtedly contribute to variations in sediment concentration laterally and with time. The time variations of the depth-averaged mean

concentration for the bottom 43% of the flow depth are shown for experiment 21 in Figure 6. As expected, there is a lack of correlation between the sediment concentrations at the two locations. The ratio of the mean absolute difference to the mean sediment concentration is seen to be about 14% for the 0.05 m sampler spacing and to level off to about 25% as the spacing between the samplers increases (Fig. 7). The mean absolute difference of the mean sediment concentrations for the upper 57% of the flow derived from point samples are seen to be greater in magnitude (maximum 36%) than for the lower 43% of the flow (Fig. 7).

Implications for Sampling and Discussion

The fraction of suspended sediment carried in the lower 43% of the flow was determined from a weighted average to be 80% of the total carried by the channel. This indicates that although the variations in the upper part of the channel were large, they were only of secondary importance for the movement of suspended sand through the channel in these experiments. The variations of suspended sediment transport in the lower 43% collected using acoustic backscattering data will be explored further in this section.

The number of lateral sample positions (verticals) required to adequately define the mean cross-section suspended sediment concentration was explored using the data from this study. Depth-averaged suspended sediment concentrations across 1.067 m of the channel were calculated from a series of backscatter data collected using the BASIS system. Two transducers of the BASIS system were mounted on a stepper-motor powered rail table which traversed across the flume channel in 13.7 s. Acoustic data were collected at 30 Hz and each set of suspended sediment concentration values were derived from the mean of ten backscatter measurements yielding data sets of 41 discrete mean concentrations spaced 0.026 m apart over the lower 43% of the flow depth. A total of 53 transects were collected across of the flow width using the same flow conditions as for experiments 21- 40 (Table 1).

A computer program was written to simulate sampling from 41, 32,16, 8, 4,and 2 equally spaced positions across 1.067 m of the channel. The mean (m), standard deviation (s), standard error ($s_e = s/n^{1/2}$), and 95% confidence interval were then calculated for each of the six sampling positions for the 53 transects. The 95% confidence interval (I_{95})was defined as:

$$I_{95} = m \pm \frac{t_{\alpha/2} s}{\sqrt{n}} \qquad (2)$$

where t is the tabulated value of the student's t distribution, and ∀ is one minus the probability (Mendenhall, 1975).

The results for sensor 1 (Fig. 8) illustrate that for up to 16 positions, both the standard error and width of the 95% confidence interval decrease dramatically with an increasing number of sampling locations. For the conditions present in the flume channel, 41 positions yielded the best result in terms of standard deviation, standard error and width of the 95% confidence interval. The use of 41, 16, 4, and 2 sampling positions yielded confidence intervals of ∀ 1.47%, ∀ 2.86%, ∀12.9%, and ∀102% of the mean concentration, respectively. This study documents the advantage of collecting representative depth-integrated samples of suspended sediment over dune beds. Mean absolute differences for the depth-integrated samples were 25%

as compared to 42% for the point samples (see above).

The determination of 16 sample locations across the flume compares closely with the sampling guidance for suspended sediment sampling given by Edwards and Glysson (1999). Their sampling guidance consists of a minimum of 4 sample positions and a maximum of 9 for the equal discharge increment method (Edwards and Glysson, 1999, p. 43), and a minimum of 10 positions and a maximum of 20 for the equal width increment method for channels over 1.5 m wide (Hubbell, D.W., et al., 1956). As many samples as possible are recommended for channels less than 1.5 m wide with a minimum of 0.076 m between sample locations. Their equal width increment guidelines for channels less than 1.5 m in width, would indicate a maximum of 16 sampling positions for the channel used in this study. These guidelines yield a similar number of positions as was determined for this study.

This study showed that side by side samples would be expected to have mean absolute differences of about 14% of the mean for depth integrated samples, and 18% for point samples. While the bed forms in the channel resemble closely those from large rivers (see Abraham and Pratt, 2002), similar side-by-side experiments need to be conducted with identical samples in streams and rivers. A series of side-by-side tests with identical samplers should be included for investigations in which new samplers are compared to established ones.

CONCLUSIONS

Lateral variations in the concentration of suspended sand over dune bed forms in a laboratory channel, expressed as mean absolute differences, ranged from 20 to 42% of the mean concentration for point samples collected at lateral spacings of 0.05 to 0.40 m (0.2 to 3 times the flow depth). Sediment concentrations integrated over the lower 43% of the flow depth had mean absolute differences ranging from 14 to 25% for lateral spacings of 0.05 0.40 m. For the conditions characterized in this study, 8-16 measurements of the mean sediment concentration in the lower 43% of the flow depth (representing 80% of the suspended sediment) collected across the cross-section yielded an estimate of the mean suspended sediment concentration with a confidence interval of from ∀3 to 5%. Depth integrated samples showed significantly lower mean absolute differences than point samples (25 versus 36%) for paired samples, underscoring the importance of collecting representative depth-integrated samples to accurately characterize suspended sediment concentration. Comparative studies of different types of suspended sediment samplers should include a series of tests of side-by-side samples collected with identical samples to serve as baseline data.

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REFERENCES

Abraham, D. D., Pratt, T. (2002). "Quatification of bed-load transport on the Upper Mississippi River using multibeam survey data and traditional methods." ERDC/CHL CHETN-VII-4, U.S. Army Engineer Research and Development Center, Vicksburg, MS, 9 p.

Carey, W. P. (1985). "Variability in measured bedload-transport rates." Water Resources Bulletin, 21(1), 39-48.

Edwards, T. K, Glysson, G. D. (1999). "Field methods for measurement of fluvial sediment. " U. S. Geological Survey Techniques of Water-Resources Investigations, Book 3, Chapter C2, 89 p.

Gilbert, G. K. (1914). "The transportation of debris by running water." U. S. Geological Survey Professional Paper 86.

Gomez, B., Naff, R. L., Hubbell, D. W. (1989). "Temporal variations in bedload transport rates associated with the migration of bedforms." Earth Surface Processes and Landforms, 14, 135-156.

Gomez, B., Hubbell, D. W., Stevens, H. H., Jr. (1990). "At-a-point bed load sampling in the presence of dunes." Water Resources Research, 26(11): 2717-2731.

Hubbell, D. W., and others (1956). Investigations of some sedimentation characteristics of a sand-bed stream, Progress Report no. 1, U.S. Geological Survey Open File Report, 78 p.

Hubbell, D. W., Stevens, H. H., Jr., Skinner, J. V., Beverage, J. P. (1981). "Recent refinements in calibrating bedload samplers." Proceedings of Water Forum 1981, v. I, p. 128-141.

Hubbell, D. W., Stevens, H. H., Jr., Skinner, J. V., Beverage, J. P. (1987). "Laboratory data on coarse sediment transport for bedload-sampler calibrations." U. S. Geological Survey Water Supply Paper 2299, 313 p.

Mendenhall, W. (1975). Introduction to Probability and Statistics, 4th Edition. Duxbury Press, North Scituate, Massachusetts, U.S. A., 460 p.

Nelson, M.E., Benedict, P. C. (1950). "Measurement and analysis of suspended-sediment loads in streams." Trans ASCE, 116, 891-918.

Report No. 5, (1941). "Laboratory investigation of suspended sediment samplers." Report No. 5, St. Paul U. S. Engineer District Sub-Office Hydraulic Laboratory, University of Iowa, Iowa City, Iowa, 97 p.

Simons, D. B., Richardson, E. V. (1961). "Forms of bed roughness in alluvial channels." Journal Hydraulics Division, 87(3): 87-105.

Thorne, P. D., Vincent, C. E., Hardcastle, P. J., Rehman, S., Pearson, N. (1991). "Measuring suspended sediment concentrations using acoustic backscatter devices." Marine Geology, 98:7-16.

Wren, D. G., Bennett, S .J., Barkdoll, B. D., Kuhnle, R. A. (2000). " The effect of spatial and temporal separation on suspended-sediment concentration measurements." International Conference on Hydroinformatics, International Association of Hydraulic Research, Iowa City, Iowa.

Wren, D. G., Kuhnle, R. A. Chambers, J. (2003). "Progress in acoustic suspended-sediment measurement in laboratory flumes." A.S.C.E. World Water & Environmental Resources Congress, 10 p..

Table 1. Summary of Experimental Conditions.

Experimental run numbers	Flow rate ($m^3 s^{-1}$)	Flow depth (m)	Water surface slope	Water Temp. (^{O}C)
21-40	0.0816	0.1273	0.00301	26-27

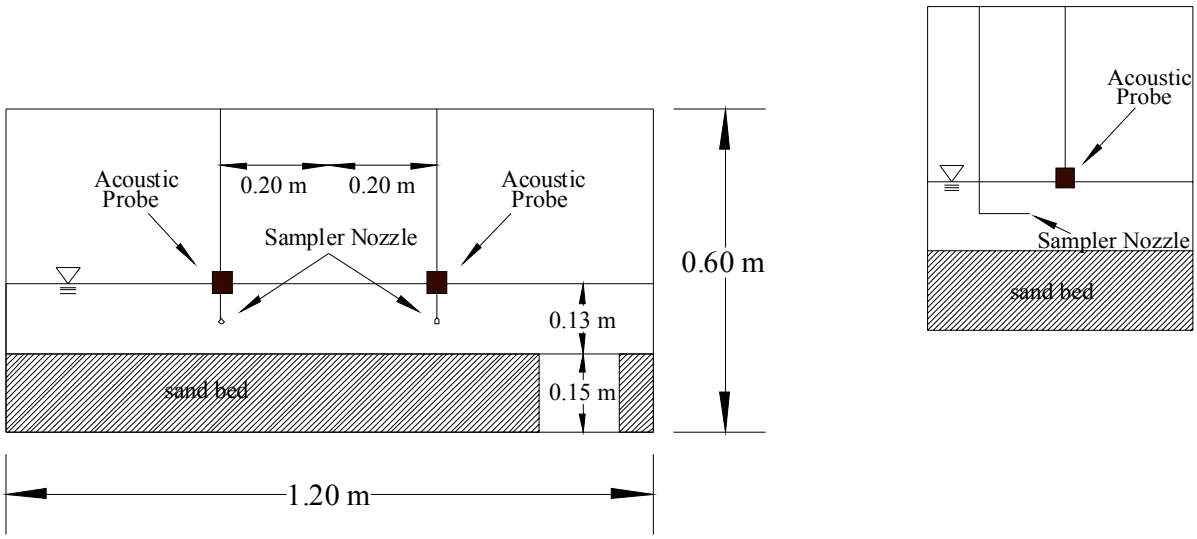


Figure 1. Sketch of measurement equipment set-up: left- view upstream, right-side view.

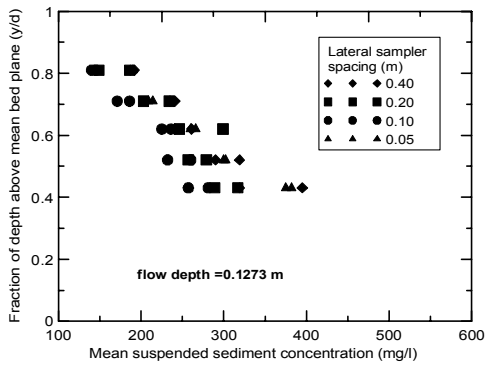


Fig. 2. Suspended sediment concentration with depth for point samples.

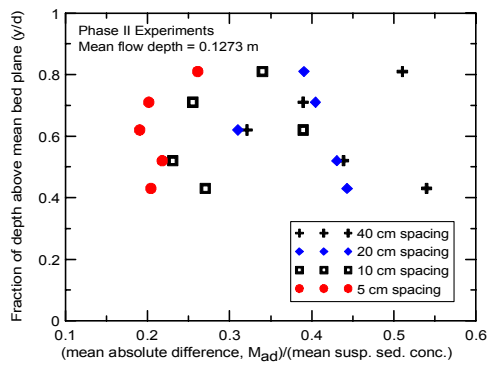
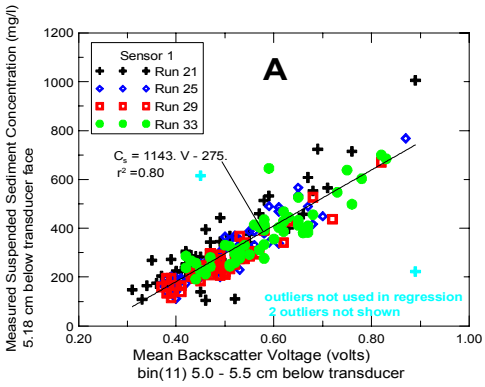


Fig.3. Ratio mean absolute difference to mean concentration.



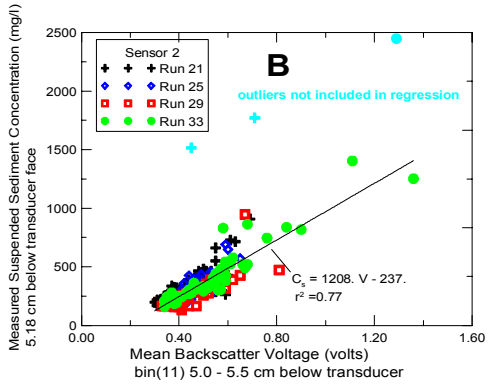


Fig. 4. Measured suspended sediment concentration; point samples versus mean backscatter voltage for experiments 21,25,29,33. A)sensor 1 -right viewed downstream, B) sensor 2 -left viewed downstream.

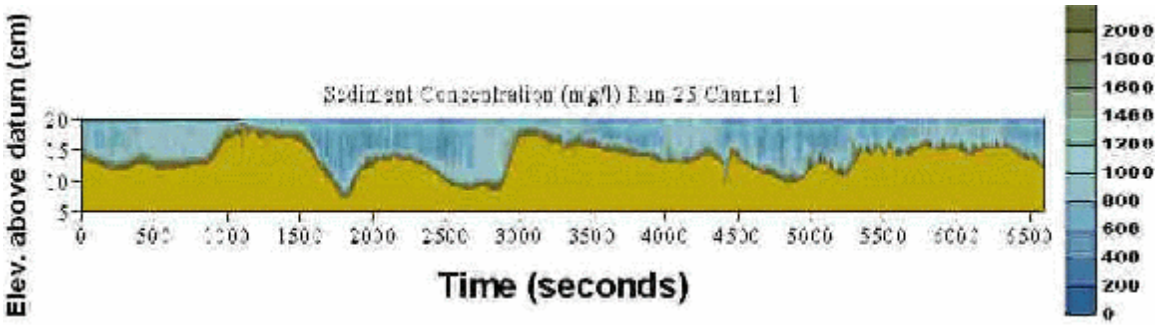


Fig. 5. Contours of suspended sediment concentration for lower 43% of flow depth with time for experiment 25, sequence 5.

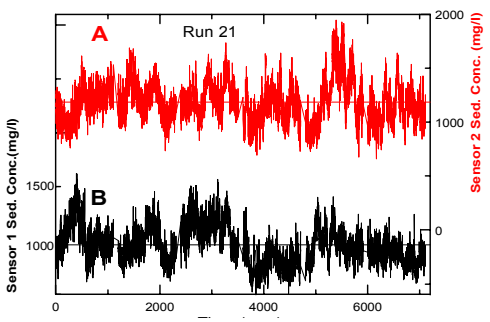


Fig. 6. Mean suspended sediment conc. for lower 43% of flow depth with time, (exp. 21) A) sensor 2, B) sensor 1.

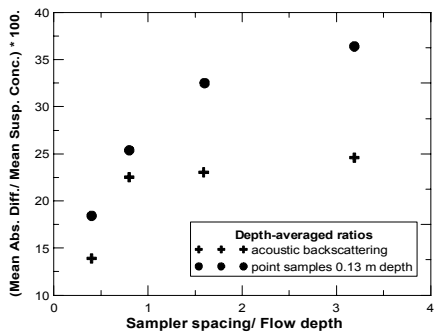


Fig. 7. Ratio M_{ad} to mean suspended sediment concentration vs. ratio of sampler spacing to flow depth for concentration data from point samples and acoustic backscattering.

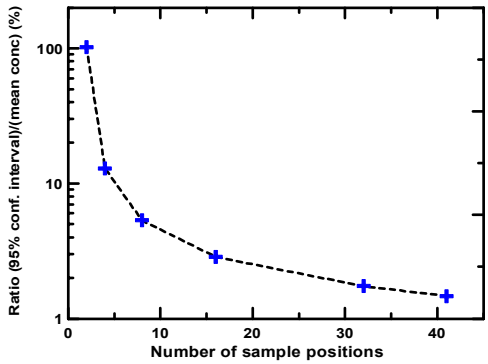


Fig. 8. The width of 95% confidence interval versus the number of sampling locations across the channel.