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Continuous measurement of suspended-sediment discharge in rivers by use of optical backscatterance sensors

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Abstract Optical sensors have been used to measure turbidity and suspended-sediment concentration by many marine and estuarine studies, and optical sensors can provide automated, continuous time series of suspended-sediment concentration and discharge in rivers. Three potential problems with using optical sensors are biological fouling, particle-size variability, and particle-reflectivity variability. Despite varying particle size, output from an optical backscatterance sensor in the Sacramento River at Freeport, California, was calibrated successfully to discharge-weighted, cross-sectionally averaged suspended-sediment concentration, which was measured with the equal discharge-, or width-increment, methods and an isokinetic sampler. A correction for sensor drift was applied to the 3-year time series. However, the calibration of an optical backscatterance sensor used in the Colorado River at Cisco, Utah, USA, was affected by particle-size variability. The adjusted time series at Freeport was used to calculate hourly suspended-sediment discharge that compared well with daily values from a sediment station at Freeport. The appropriateness of using optical sensors in rivers should be evaluated on a site-specific basis and measurement objectives, potential particle size effects, and potential fouling should be considered.

Key words Colorado River; equal discharge increment method; isokinetic sampling; optical backscatterance sensor; particle size; Sacramento River; suspended sediment; suspended-sediment discharge

INTRODUCTION

Oceanographers began to commonly use optical sensors for measuring turbidity or suspended-sediment concentration (SSC) in the 1970s on the continental shelf, in nearshore waters, and in estuaries (Sternberg, 1989). Optical sensors transmit a pulse of light and measure the intensity of that light at a receiver positioned 0 (transmissometer) to 180 (backscatterance sensor) to the transmitter. The sensor processes the signal so that its output is measured in units of turbidity or is proportional to SSC if the particle size and reflectivity of the sediment remain fairly constant. Calibration of the sensor output voltage to SSC will vary according to particle size and reflectivity; therefore, the sensors must be calibrated in the field or a laboratory using suspended sediment from the field. If the optical window is fouled by biological growth or debris, the sensor output is invalid.

Compared to conventional water sampling, the primary advantage of using optical sensors is that they can provide automated, continuous time series of SSC. This is essential for studies:

(a) at inaccessible locations, such as the continental shelf (Cacchione *et al.* 1995);
(b) during hazardous conditions, such as a tropical storm (Schoellhamer 1995);
(c) of environments with rapidly changing SSC, such as small streams (Lewis 1996), tidally affected water bodies (Christiansen *et al.* 2000, Dyer *et al.* 2000), and nearshore waters (Miles *et al.* 2001);
(d) requiring instantaneous vertical profiles of SSC (Brennan *et al.* 2002);
(e) of intermittent resuspension, such as by trawlers and vessel wakes (Schoellhamer 1996).

The disadvantages of using optical sensors are that varying particle size and reflectivity can confound calibration and fouling by biological growth, and that debris can invalidate data. The slope of the calibration curve, which is approximately equal to the ratio of concentration to output voltage, increases with particle size. Conner & DeVisser (1992) recommended that optical sensors not be used for particle sizes less than 100 micrometers (m) because of the sensors’ increased sensitivity to variability in particle size. Ludwig & Hanes (1990) recommended that optical sensors not be used for sand/mud mixtures. Lighter coloured sediment particles reflect more light than darker particles, affecting sensor calibration (Sutherland *et al.*, 2000). Biological growth on the optical window and biota or debris in front of the optical window can alter sensor output and invalidate data (Schoellhamer, 1993). Other possible sources of error include water and sediment colour, bubbles, plankton, and organic sediment. Despite these potential problems, many marine and estuarine studies have successfully used optical sensors to acquire accurate, continuous SSC data.

Use of optical sensors in rivers for continuous monitoring of suspended sediment is becoming more common in the United States, and a workshop on the topic was held in spring 2002 (Glysson & Gray, 2002). The primary reasons for increased continuous monitoring are regulatory requirements of the US Clean Water Act and improved technology for real-time monitoring for environmental, drinking water, and public health needs.

The purpose of this paper is to demonstrate that optical backscatterance sensors (Downing *et al.*, 1981) can successfully be used to measure suspended-sediment discharge in rivers if the effects of particle size do not preclude sensor calibration. The issue of the effects of particle size on sensor output is addressed first, followed by an example calculation of suspended-sediment discharge with an optical backscatterance sensor, and measurements of water discharge and discharge-weighted, cross-sectionally averaged SSC. We assume in this paper that sediment particle colour and reflectivity are not significant factors. This paper updates a previous paper on this subject (Schoellhamer, 2001).

STUDY SITES AND METHODS

Optical backscatterance sensors were deployed and water samples were collected in the Sacramento River at Freeport, California, and in the Colorado River at Cisco, Utah, USA. Kendall’s   nonparametric rank correlation coefficient was used to determine if data had a monotonic trend (significance level $P < 0.05$; Helsel & Hirsch, 1992).

Freeport

Flow at Freeport is unidirectional, affected by tidal backwater during low discharge, and is entirely freshwater. Suspended sediment is primarily fine sediment. An optical backscatterance sensor was installed to measure the effects of tidal fluctuations and flood pulses on suspended-sediment discharge and, therefore, sensor output was calibrated to discharge-weighted, cross-sectionally averaged SSC ($\overline{SSC_u}$). Point sensor measurements have been collected continuously near the right bank of the river every 15 min at 0.92 m above the bed since July 1998. The sensor was cleaned every 1–8 weeks.

The output of the sensor was used as an index measurement of suspended sediment that was calibrated to $\overline{SSC_u}$ that usually was measured with the equal discharge increment (EDI) method and sometimes with the equal width increment (EWI) method (Edwards & Glysson, 1999). $\overline{SSC_u}$ is defined as $\int ucdA / \int udA$ where u is a point velocity, c is a point SSC, and the integrals are taken over the cross-sectional area A. The numerator is the suspended-sediment discharge in the cross section and the denominator is the water discharge, so suspended-sediment discharge is the product of water discharge and $\overline{SSC_u}$. The EDI method measures $\overline{SSC_u}$ by using an isokinetic sampler to collect vertically integrated water samples at centroids of equal discharge increments in the cross section (Edwards & Glysson, 1999). For an isokinetic sampler, the nozzle velocity is equal to the water velocity so that coarser (typically sand-sized) particles are not over or under sampled and the sampling rate is proportional to the water velocity. A discharge increment of 20% of the total discharge was used, resulting in samples being collected at lateral locations corresponding to the 10, 30, 50, 70, and 90th percentiles of water discharge. Water discharge was measured hourly with a calibrated ultrasonic velocity meter (Anderson *et al.*, 2001). Velocity distributions in the cross section that were measured with an acoustic Doppler current profiler were used to determine the locations of the discharge centroids. The mean SSC of the five samples is equal to $\overline{SSC_u}$. For most sets of samples, the right bank SSC was close to the average SSC and any discrepancy between the right bank and cross-sectional average would increase the scatter of the calibration. Some $\overline{SSC_u}$ measurements were made with the EWI method, which collects depth-integrated samples at constant lateral spacing in the cross section (Edwards & Glysson, 1999). Some point samples adjacent to the sensor were also collected. Water samples were analysed for percent fines (fraction of mass less than 63 m in diameter). $\overline{SSC_u}$ was measured every 1–2 months and during flood pulses to sample the full range of SSC. The median $\overline{SSC_u}$ was 39 mg l^{-1} and the range was from 10 to 152 mg l^{-1} and the median percent of fine sediment was 85% and the range was from 46 to 98%.

In performing the calibration between backscatter and $\overline{SSC_u}$, it became apparent that the response of the sensor had consistently drifted during the 3-year deployment. That is, for the same $\overline{SSC_u}$, the voltage returned by the sensor had been increasing with time, causing the ratio of SSC to sensor voltage (C/V), which is the slope of the calibration line, to decrease with time ($P < 0.001$). There was no temporal trend in percent fines ($P = 0.18$), so a change in particle size did not cause the sensor drift.

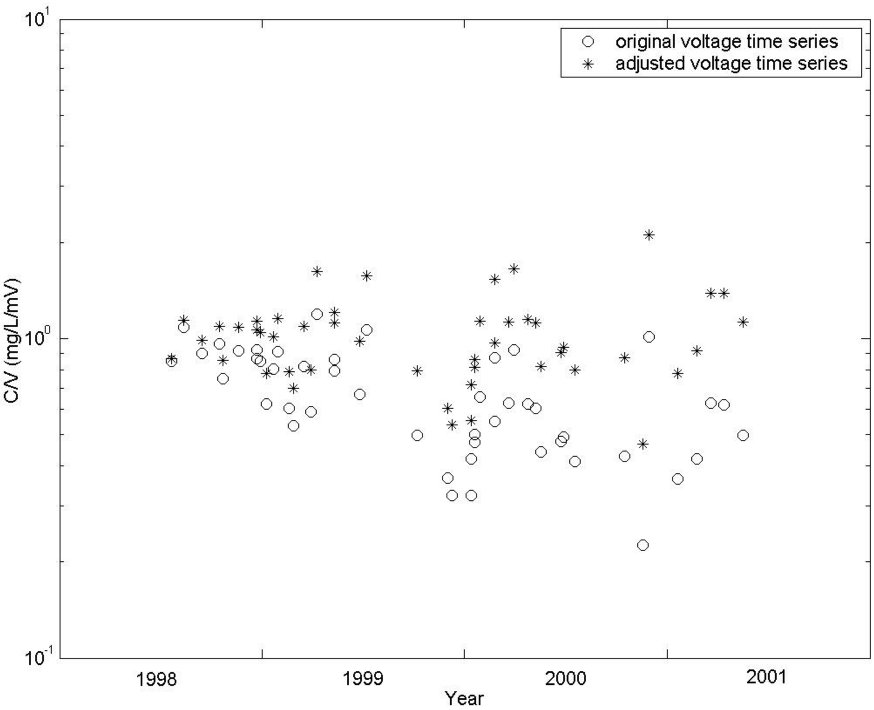

Fig. 1 Ratio of suspended-sediment concentration to sensor voltage (C/V) as a function of time in the Sacramento River at Freeport, California. Drift of the sensor is indicated by the decrease in C/V with time for the original voltage time series. The adjusted voltage time series did not drift with time.

Possible causes of the drift are changes in the performance of the instrument or a systematic change in another water quality parameter that may affect optical backscatter, such as water colour or the organic content of the sediment. To account for this drift, an inverse power regression was used to estimate the relationship between C/V and time. The ratio at initial deployment was estimated from this fit, and used to adjust the sensor voltage time series so that C/V did not drift with time. Figure 1 shows C/V *vs* time for the original time series, illustrating the sensor drift, and for the adjusted voltage time series.

Cisco

Vertical profiles of optical backscatterance sensor measurements and suspended sediment were collected from the Colorado River near Cisco, Utah, from 10–12 May 1995. The objective was to evaluate the performance of OBS in the Colorado River, a sand channel with suspended bed material load and fine sediment wash load. While measuring vertical profiles at three stations, 118 pairs of point sensor measurements and suspended-sediment samples were collected from near the bed to near the water surface with a sensor attached to the side of a US P61 suspended-sediment sampler (Edwards & Glysson, 1999) close behind the nozzle. Almost all of the suspended sediment near the bed was sand and very little suspended sand was near the surface. SSC ranged from 480 to 40 000 mg l^{-1}. Concentration of fine sediment varied from 400 to 620 mg l^{-1} during the 3 days of data collection. $\overline{SSC_u}$ was not measured.

PARTICLE-SIZE EFFECTS

The relationship between SSC and sensor output is dependent on particle size, which can confound calibration of a sensor. In estuaries like San Francisco Bay, particle size is fairly constant and sensor calibrations are remarkably invariant with time and depth (Buchanan & Ganju, 2002). However, in channels with a variable suspended particle size, sensor output depends on particle size and SSC. Finer sediment has more reflective surfaces per unit mass, so, for constant SSC, sensor output increases as the suspended sediment becomes finer. Particle-size effects were negligible in the Sacramento River at Freeport, California, but were more pronounced in the Colorado River at Cisco, Utah.

Freeport

The linear equation for $\overline{SSC_u}$, as a function of sensor output (Fig. 2), was determined using the robust, nonparametric, repeated median method (Buchanan & Ganju, 2002). Optical sensor calibration data typically do not have residuals with constant variance, which is required when using the ordinary least-squares method to obtain the best linear, unbiased estimator of SSC. Robust regression also minimizes the influence of high leverage points. Scatter of the calibration data is caused by comparing a point sensor measurement with a cross-sectionally averaged SSC, particle-size effects, and any other source of error including possible effects of water and sediment colour, bubbles, plankton, and organic sediment.

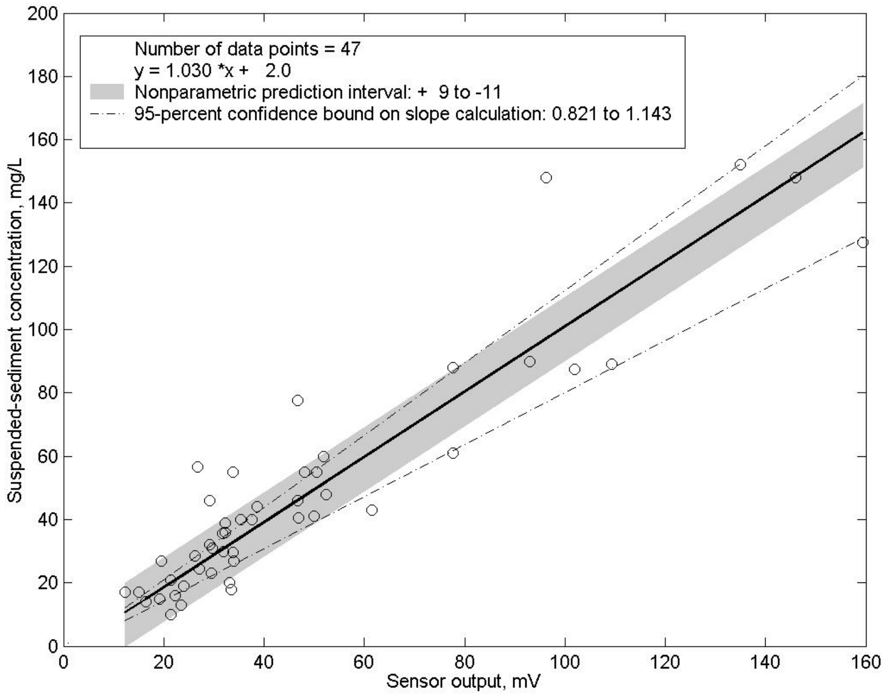

Fig. 2 Calibration of an optical backscatterance sensor in the Sacramento River at Freeport, California. Sensor output drift has been corrected.

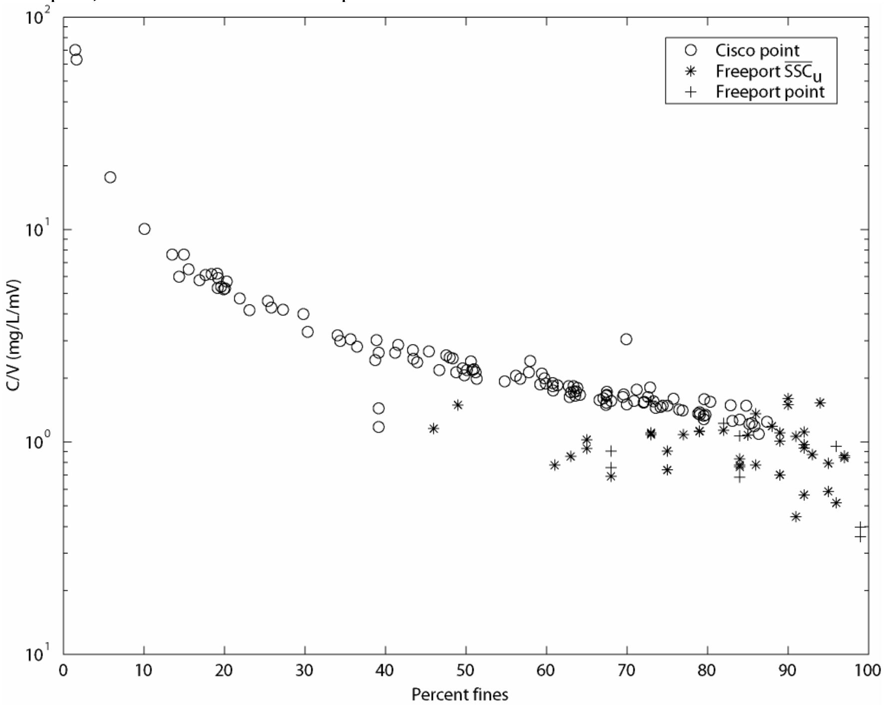

Fig. 3 Ratio of suspended-sediment concentration to sensor voltage (C/V) as a function of the fraction of fine sediment in the Sacramento River at Freeport, California, and in the Colorado River at Cisco, Utah. C/V for any data point is approximately equal to the slope of a calibration line through that point. A different sensor was used at each site and each sensor has slightly different optical characteristics, so the difference in the trend of C/V, not the absolute value of C/V, should be compared between the sites.

Particle-size variations had a negligible effect on the calibration of the sensor at Freeport. Sensor output is virtually zero when SSC is zero, so C/V for any data point is approximately equal to the slope of a calibration line through that point. At Freeport, the fraction of fine sediment ranged from 46 to 98% and C/V from the $\overline{SSC_u}$ samples (barely) did not have a statistically significant monotonic trend with percent fines (Fig. 3, Kendall's $P = 0.07$). C/V calculated using point samples collected adjacent to the sensor is similar to C/V calculated with $\overline{SSC_u}$ samples (Fig. 3).

Cisco

Particle-size variation precluded successful calibration of the sensor at Cisco (Fig. 3). Sensor output correlated poorly with SSC (Fig. 4(a)) but well with fine sediment concentration (Fig. 4(b)), indicating that fine sediment determined sensor output and suspended sand had little effect. As the fraction of fine sediment increased from 1 to 87%, C/V decreased exponentially by almost two orders of magnitude (Fig. 3, $P < 0.001$). C/V variability is particularly large when the fine sediment is less than 30%, a level never reached at Freeport. The output of a continuously deployed sensor would be more sensitive to variations in fine sediment concentration (wash load) than variations in suspended sand (bed material load). Thus, a sensor could be calibrated to

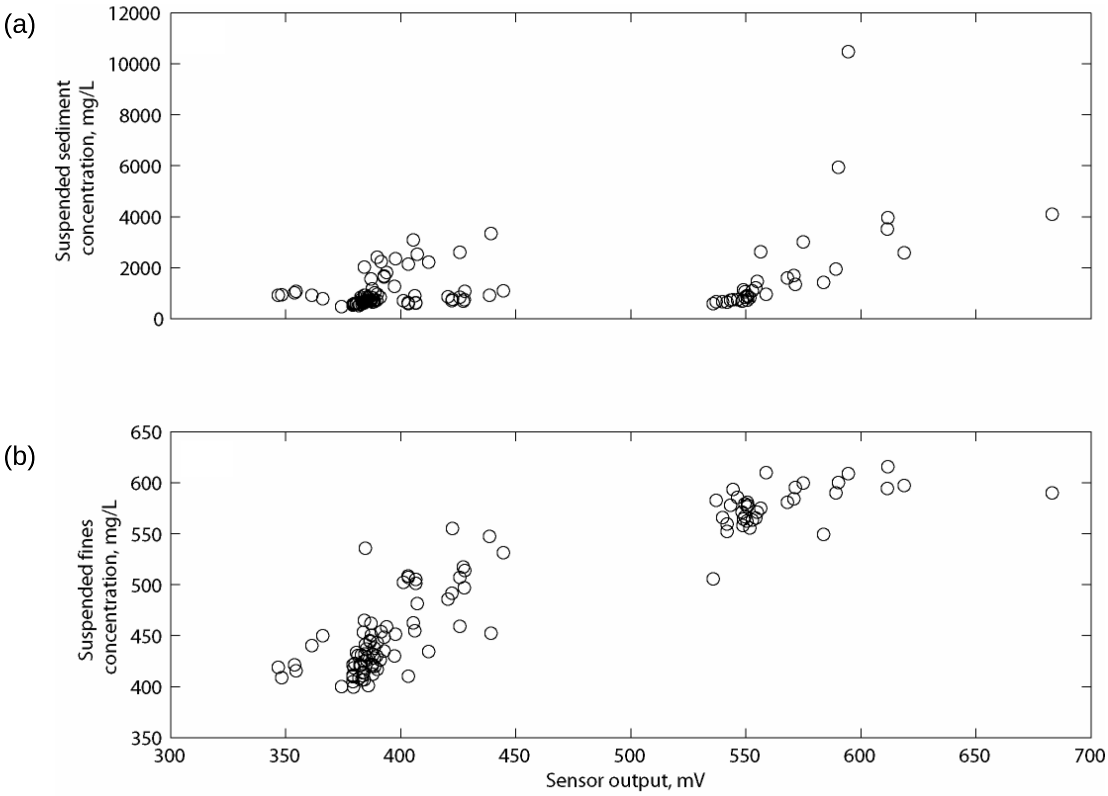

Fig. 4 Calibration of an optical backscatterance sensor in the Colorado River at Cisco, Utah. Sensor output correlates poorly with suspended sediment concentration (a) but correlates well with the suspended fine sediment concentration (b). Five data points with large concentration or sensor output are not included for clarity.

wash load but not SSC, and it could not be used to calculate suspended-sediment discharge.

CALCULATION OF SUSPENDED-SEDIMENT DISCHARGE

After correcting for sensor drift, output from the sensor at Freeport was converted to a time series of $\overline{SSC_u}$ using the calibration line shown in Fig. 2. Suspended-sediment discharge then was computed as the product of water discharge and $\overline{SSC_u}$. The hourly suspended-sediment discharge from the sensor compared well with daily suspended-sediment discharge from a sediment station operated by the US Geological Survey (USGS) at Freeport (Fig. 5; Anderson *et al.*, 2001).

Advantages and disadvantages of an optical sensor are demonstrated in this time series. The sensor provides excellent temporal resolution and allows identification of two peaks in SSC during a typical flow pulse: an immediate rise to peak, in response to local resuspension, and a smaller, broader peak 4–5 days later (Schoellhamer & Dinehart 2000). As flow increases, resuspension decreases the supply of erodible sediment on the bed; therefore, the first peak begins to diminish in 1–2 days. Because particle-size variations did not adversely affect the sensor calibration, the primary disadvantage of optical sensors is fouling, as only 44% of the Freeport data were valid

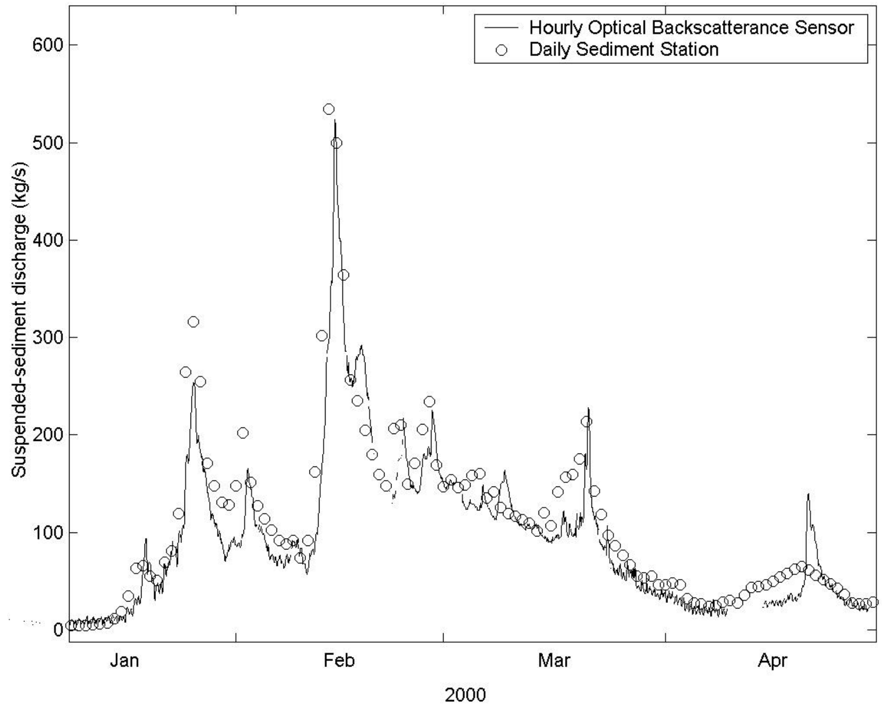

Fig. 5 Suspended-sediment discharge in the Sacramento River at Freeport, California, January–April 2000. Sediment station data are from Anderson *et al.* (2001).

due to fouling. More frequent cleaning and self-cleaning sensors can reduce the effect of fouling. Despite fouling, the sensor made about 42 times more successful measurements than the daily station, providing the ability to monitor sediment pulses on the order of hours rather than days.

CONCLUSIONS

Optical backscatterance sensors successfully can monitor suspended sediment in rivers if the effects of particle size and reflectivity do not preclude sensor calibration. If no such preclusion exists, optical sensors can be used in conjunction with water-discharge measurements and cross-sectional water sampling to measure the suspended-sediment discharge of rivers. The appropriateness of using optical sensors in rivers should be evaluated on a site-specific basis and measurement objectives, potential particle size effects, and potential fouling should be considered.

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REFERENCES

Anderson, S. W., Rockwell, G. L., Smithson, J. R., Friebel, M. F. & Webster, M. D. (2001) Water resources data, California, water year 2000. US Geol. Survey Water-Data Report CA-00-4, vol. 4, Sacramento, California, USA. http://ca.water.wr.usgs.gov/data/

Brennan, M. L., Schoellhamer, D. H., Burau, J. R., & Monismith, S. G. (2002) Tidal asymmetry and variability of bed shear stress and sediment bed flux at a site in San Francisco Bay, USA. In *Fine Sediment Dynamics in the Marine Environment* (ed. by J. C. Winterwerp and C. Kranenburg), 93–108. Elsevier Science B.V., Amsterdam, The Netherlands.

Buchanan, P. A. & Ganju, N. K. (2002) Summary of suspended-sediment concentration data, San Francisco Bay, California, water year 2000. US Geol. Survey Open File Report 02-146, Sacramento, California, USA. http://water.usgs.gov/pubs/of/ofr02146/

Cacchione, D. A., Drake, D. E., Kayen, R. W., Sternberg, R. W., Kineke, G. C., & Tate, G. B. (1995) Measurements in the bottom boundary layer on the Amazon subaqueous delta. *Mar. Geol.* **125**, 235–257.

Christiansen, T., Wiberg, P. L., & Milligan, T. G. (2000) Flow and sediment transport on a tidal salt marsh surface. *Estuarine, Coastal Shelf Sci.* **50**, 315–331.

Conner, C. S., & DeVisser, A. M. (1992) A laboratory investigation of particle size effects on an optical backscatterance sensors. *Mar. Geol.* **108**, 151–159.

Downing, J. P., Sternberg, R. W. & Lister, C. R. B. (1981) New instrumentation for the investigation of sediment suspension processes in the shallow marine environment. *Mar. Geol.* **42**, 19–34.

Dyer, K. R., Christie, M. C., Feates, N., Fennessy, M. J., Perjup, M., & van der Lee, W. (2000) An investigation into processes influencing the morphodynamics of an intertidal mudflat, the Dollard Estuary, The Netherlands: I. Hydrodynamics and suspended sediment. *Estuarine, Coastal Shelf Sci.* **50**, 607–625.

Edwards, T. K. & Glysson, G. D. (1999) Field methods for measurement of fluvial sediment. *Techniques of Water-Resources Investigations of the US Geological Survey*, book 3, chap. A2, Reston, Virginia, USA.

Glysson, G. D. & Gray, J. R. (2002) Turbidity and Other Sediment Surrogates Workshop: Reno, Nevada, April 30–May 2, 2002. http://water.usgs.gov/osw/techniques/turbidity.html

Helsel, D. R. & Hirsch, R. M. (1992*) Statistical Methods in Water Resources: Studies in Environmental Science*, **49**, Elsevier, New York, USA.

Lewis, J. (1996) Turbidity-controlled suspended sediment sampling for runoff-event load estimation. *Water Resour. Res.* **32,** 2299–2310.

Ludwig, K. A. & Hanes, D. M. (1990) A laboratory evaluation of optical backscatterance suspended solids sensors exposed to sand-mud mixtures. *Mar. Geol.* **94**, 173–179.

Miles, J. R., Russell, P. E., & Huntley, D. A. (2001) Field measurements of sediment dynamics in front of a seawall. *J. Coastal Res*. **17**, 195–206.

Schoellhamer, D. H. (1993) Biological interference of optical backscatterance sensors in Tampa Bay, Florida. *Mar. Geol.* **110**, 303–313.

Schoellhamer, D. H. (1995) Sediment resuspension mechanisms in Old Tampa Bay, Florida. *Estuarine, Coastal Shelf Sci.* **40**, 603–620.

Schoellhamer, D. H. (1996) Anthropogenic sediment resuspension mechanisms in a shallow microtidal estuary. *Estuarine, Coastal Shelf Sci.* **43**, 533–548.

Schoellhamer, D. H. (2001) Continuous monitoring of suspended sediment in rivers by use of optical sensors. (Proc. of the Seventh Federal Interagency Sedimentation Conf., Reno, Nevada, USA, March 25–29, 2001), III-160–III-167. http://ca.water.usgs.gov/abstract/sfbay/Schoellhamer.pdf

Schoellhamer, D. H., & Dinehart, R. L. (2000) Suspended-sediment supply to the Delta from the Sacramento River. (Proc. of the CALFED Bay-Delta Program Science Conf., Sacramento, California, USA, October 3-5, 2000). http://ca.water.usgs.gov/program/sfbay/calfedsed/SedimentSupply.html

Sternberg, R. W. (1989) Instrumentation for estuarine research. *J. Geophys. Res.* **94**(C10), 14289–14301.

Sutherland, T. F., Lane, P. M., Amos, C. L., & Downing, J. (2000) The calibration of optical backscatter sensors for suspended sediment of varying darkness levels. *Mar. Geol.* **162**, 587–597.