CONTINUOUS MONITORING OF SUSPENDED SEDIMENT IN RIVERS BY USE OF OPTICAL SENSORS

David H. Schoellhamer, Research Hydrologist, U.S. Geological Survey, Sacramento, California

Placer Hall, 6000 J Street, Sacramento, California 95819, dschoell@usgs.gov

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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. Two potential problems are adverse particle size effects and biological fouling. Output from an optical sensor at Freeport on the Sacramento River was successfully calibrated to discharge-weighted cross-sectionally averaged suspended-sediment concentration despite varying particle size whereas the calibration of an optical sensor used at Cisco on the Colorado River was affected by particle size variability. The optical sensor time series at Freeport was used to calculate hourly suspended-sediment discharge that compared well with daily values from a sediment station at Freeport.

INTRODUCTION

Marine and estuarine studies of sediment transport have benefited from the use of optical sensors to measure turbidity and suspended-sediment concentration (SSC). Optical sensors transmit a pulse of infrared light through an optical window (Downing and others, 1981). The light is scattered, or reflected, by particles in front of the window to a distance of about 4 to 8 inches at angles up to 165°. Some of this scattered, or reflected, light is returned to the optical window where a receiver converts the backscattered light to a voltage output. The voltage output is proportional to SSC if the particle size and optical properties of the sediment remain fairly constant. Calibration of the sensor output voltage to SSC will vary according to the size and optical properties of the suspended sediment; therefore, the sensors must be calibrated either in the field or a laboratory using suspended material from the field. If the optical window is fouled by biological growth or debris, sensor output is invalid.

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

- at inaccessible locations such as the continental shelf (Cacchione and others 1995),
- during hazardous conditions such as a tropical storm (Schoellhamer 1995),
- of environments with rapidly changing SSC such as tidally-affected water bodies (Christiansen and others 2000, Dyer and others 2000, Schoellhamer 1996a, Uncles and others 1994),
- requiring instantaneous vertical profiles of SSC (Edmunds and others 1997),

- of irregular resuspension such as by trawlers and vessel wakes (Schoellhamer 1996b).

The disadvantages of optical sensors are that changing particle size can confound calibration and fouling by biological growth and debris can invalidate data. The slope of the calibration curve, which is approximately equal to the ratio of concentration to output voltage, increases as the particle size increases. Conner and DeVisser (1992) recommended that optical sensors not be used for particle sizes less than 100 _m because of increased sensitivity to changes in particle size. Ludwig and Hanes (1990) recommended that optical sensors not be used for combined sand/mud mixtures. Biological growth on the optical window and biota or debris in front of the optical window can increase sensor output and invalidate data (Schoellhamer 1993). Despite these potential problems, many marine and estuarine studies have successfully used optical sensors to acquire accurate continuous SSC data.

The purpose of this paper is to demonstrate that optical sensors can successfully monitor suspended sediment in rivers. The issue of particle size effects is addressed first and then an example calculation of suspended-sediment discharge with on optical sensor is presented.

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 (Buchanan and Ruhl 2000). In channels with a variable suspended particle size, however, sensor output depends on particle size and SSC. Finer sediment has more reflective surfaces per unit mass, so sensor output increases as the suspended sediment becomes finer and SSC is constant. Particle size effects on optical sensors were absent in the Sacramento River at Freeport, California, but were present in the Colorado River at Cisco, Utah.

Freeport: Flow at Freeport is unidirectional but is affected by tidal backwater during low discharge. An optical sensor was installed to measure the effect of tidal fluctuations and flood pulses on suspended-sediment discharge and therefore sensor output was calibrated to discharge-weighted cross-sectionally averaged SSC. Optical sensor measurements were continuously collected near the right bank of the river every 15 minutes 3 feet above the bed beginning in July 1998. The sensor was cleaned every 1-2 months. Twenty concurrent suspended-sediment samples and optical sensor measurements are available from July 1998 to September 1999. The discharge-weighted cross-sectionally averaged samples were analyzed for SSC and percent fines (fraction of mass less than 63 _m in diameter). The median SSC was 44 mg/L and the range was 14 to 148 mg/L. For most sets of samples the right bank SSC is close to the average SSC and any discrepancy between the right bank and cross-sectional average would increase the scatter of the calibration.

The linear equation for SSC as a function of sensor output (fig. 1) was determined using the robust, nonparametric, repeated median method (Buchanan and Ruhl 2000). Optical sensor calibration data typically do not have residuals with constant variance, which is required when using ordinary least squares to obtain the best linear unbiased estimator of SSC. Robust regression also minimizes the influence of high leverage points.

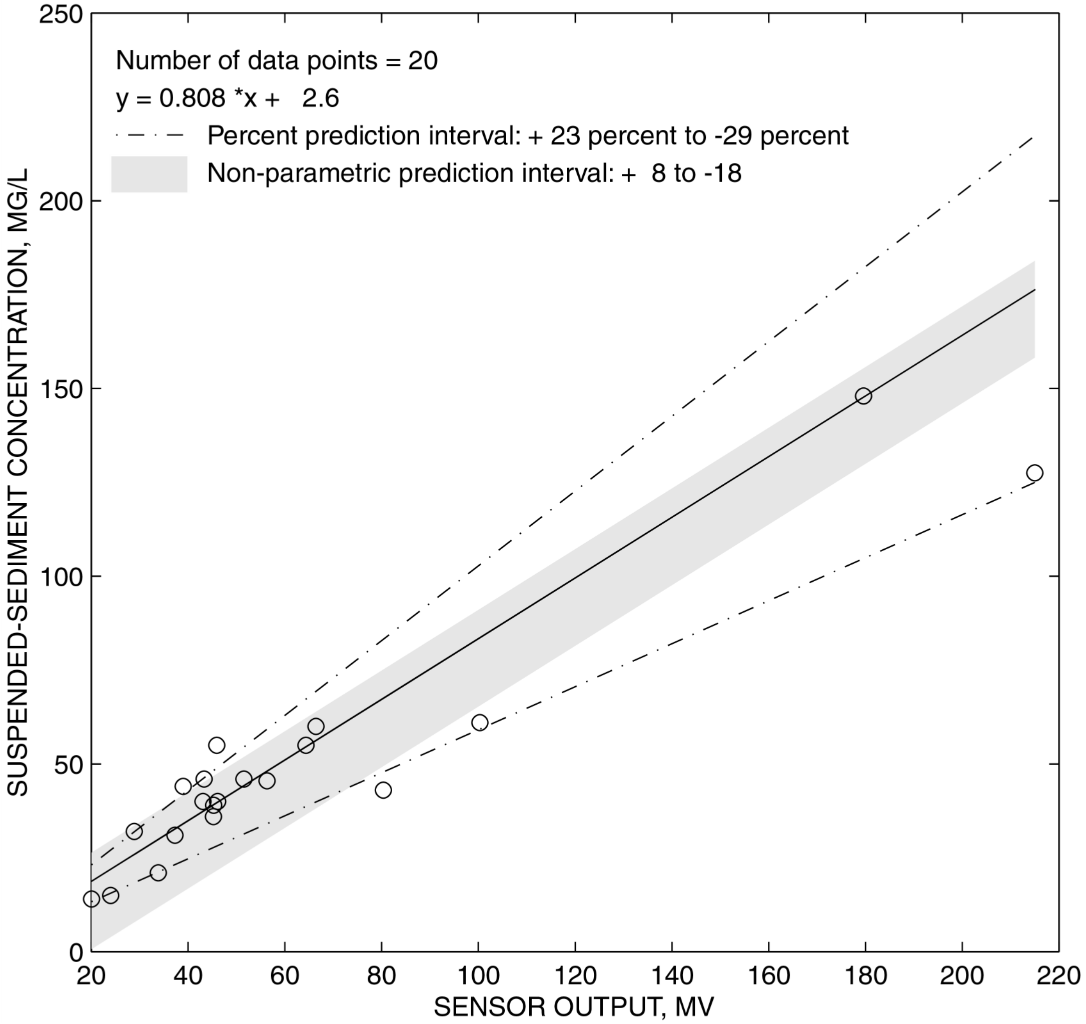

Figure 1. Calibration of an optical sensor at Freeport, Sacramento River, California, July 1998 – September 1999.

Particle size variations did not affect the calibration of the optical sensor at Freeport. The output of optical sensors is virtually zero when SSC is zero, so the ratio of concentration to voltage (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 94 percent but C/V remained constant with some scatter (fig. 2).

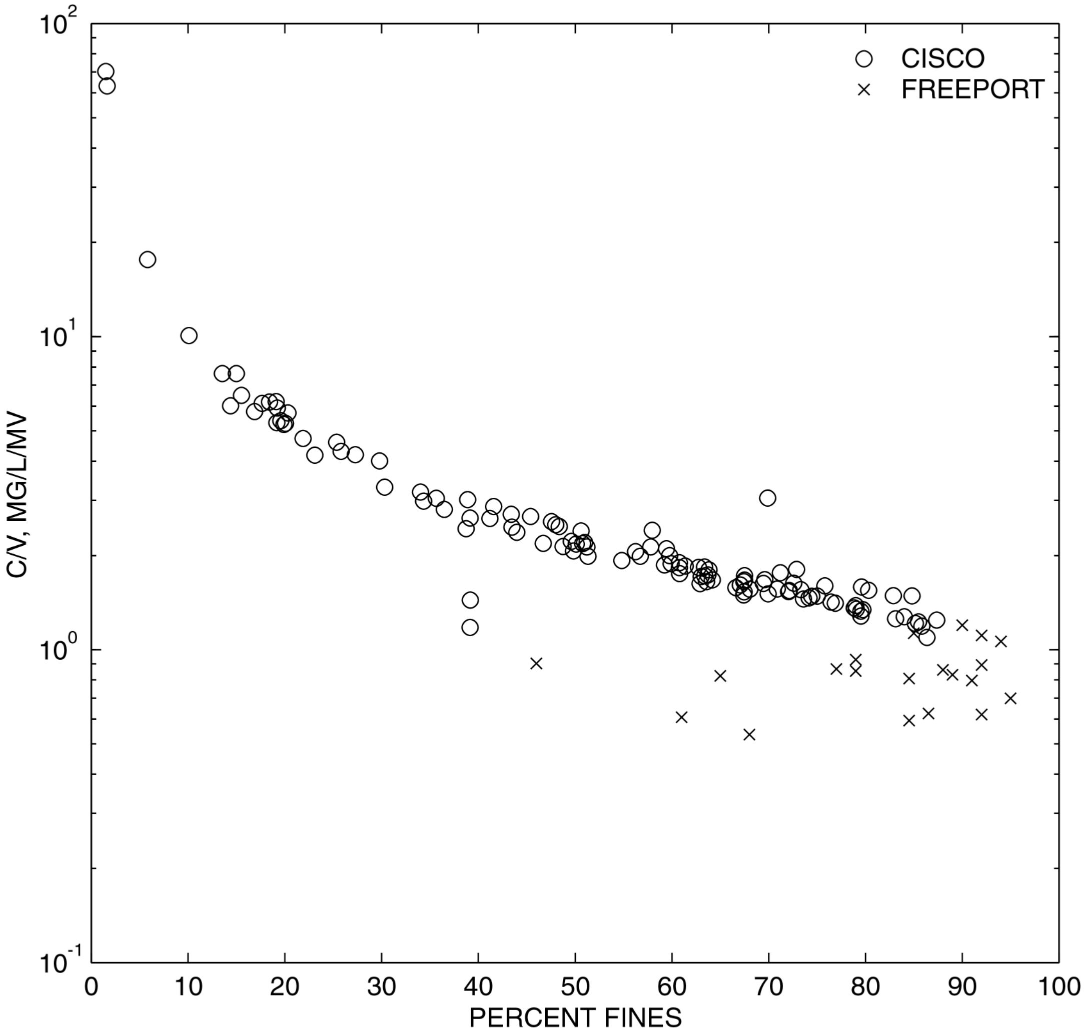

Figure 2. Ratio of suspended-sediment concentration to voltage (C/V) as a function of the fraction of fine sediment, at Freeport on the Sacramento River and Cisco on the Colorado River. C/V for any data point is approximately equal to the slope of a calibration line through that point. A different sensor was used at each site and each sensor has slightly different optical characteristics, so the difference in the trend of C/V should be compared between the two sites, not the absolute value of C/V.

Cisco: Vertical profiles of optical sensor measurements and suspended sediment were collected from the Colorado River near Cisco, Utah, from May 10-12, 1995. While measuring vertical profiles at 3 stations, 118 pairs of optical sensor measurements and suspended-sediment samples were collected from near the bed to near the water surface with an optical sensor attached to the side of a US P61 suspended-sediment sampler (Edwards and Glysson 1999) behind the nozzle. The optical sensor was much smaller than the sampler and probably had negligible effect on the isokinetic properties of the sampler. Optical sensor measurements were averaged over the time period that the nozzle of the sampler was open. Water samples were analyzed for SSC and percent fines. Near the bed, almost all of the suspended sediment was sand, and near the surface there was very little suspended sand. SSC was greater at Cisco than at Freeport, with a median of 849 mg/L and a range of 476 to 40,300 mg/L.

Particle size variation precluded successful calibration of the optical sensor at Cisco. As the fraction of fine sediment increased from 1 to 87 percent, C/V decreased exponentially by almost two orders of magnitude (fig. 2). The Cisco data have less scatter than the Freeport data because the Cisco optical sensor was very close to the nozzle of the sampler whereas the Freeport optical sensor was near the right bank and the samples were collected over the entire cross section.

In summary, optical sensor calibration was satisfactory at Freeport but not at Cisco. Therefore, successful application of optical sensors depends on local conditions, and the effect of particle size variation on optical sensors should not be presumed.

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SUSPENDED-SEDIMENT DISCHARGE

The calibrated optical sensor on the Sacramento River at Freeport has been used to successfully measure suspended-sediment discharge. Output from the sensor was converted to a time series of discharge-weighted cross-sectionally averaged SSC with the calibration line shown in figure 1. This concentration is multiplied by the water discharge measured by a calibrated ultrasonic velocity meter every hour (Webster and others 2000) to calculate the suspended-sediment discharge.

The hourly suspended-sediment discharge from the optical sensor compares well with daily suspended-sediment discharge from a sediment station operated by the USGS at Freeport (fig. 3, Webster and others 2000). Thus, the output of the optical sensor can be used as an index value that is calibrated to cross-sectionally averaged SSC and multiplied by discharge to determine the suspended-sediment discharge. In this case, the same water discharge time series was used to calculate both time series of suspended-sediment discharge.

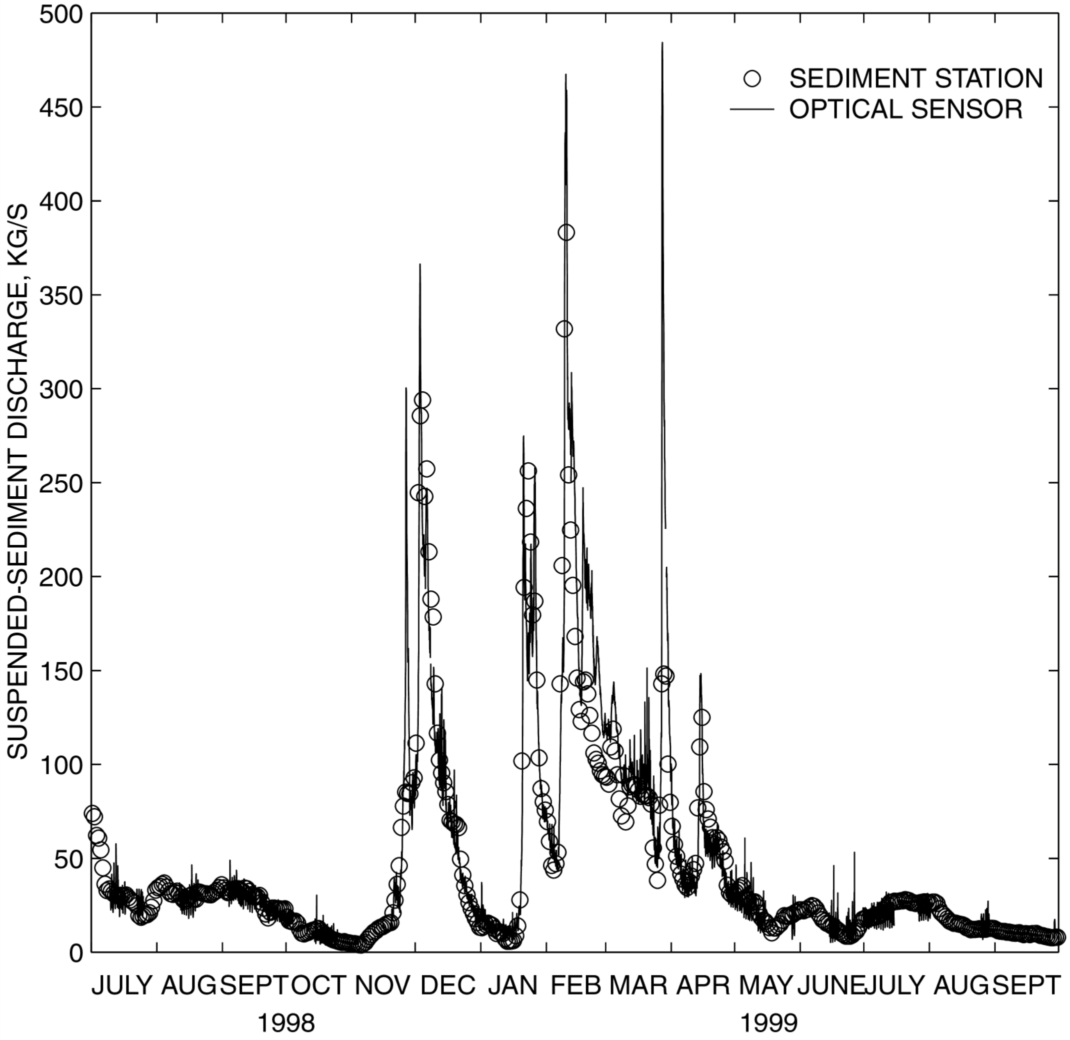

Figure 3. Suspended-sediment discharge at Freeport, Sacramento River, California, July 1998 – September 1999. Sediment station data are daily and optical sensor data are hourly.

Advantages and disadvantages of the optical sensor are demonstrated in this time series. The optical sensor 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 to 5 days later (Schoellhamer and Dinehart 2000). As flow increases, resuspension decreases the supply of erodible sediment on the bed, therefore, the first peak begins to diminish in 1 to 2 days. Because particle size variations did not adversely affect the sensor calibration, the primary disadvantage was that only 61 percent of the data were valid due to fouling. The fouling problem was subsequently reduced by having an observer clean the sensor weekly.

CONCLUSIONS

Optical sensors can successfully monitor suspended sediment in rivers if particle size effects do not preclude sensor calibration. In the Colorado River at Cisco, the approximate slope of the calibration line (C/V) varied by two orders of magnitude over the range of particle size, but in the Sacramento River at Freeport C/V did not vary with particle size. The sensor output at Freeport was successfully calibrated to discharge-weighted cross-sectionally averaged suspended-sediment concentration. This concentration was multiplied by water discharge to determine an hourly time series of suspended-sediment discharge that compared well with daily suspended-sediment discharge from a USGS sediment station. The appropriateness of using optical sensors in rivers should be evaluated on a site-specific basis and consider the objective of the measurement, potential particle size effects, and potential fouling.

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