USE OF AN ADCP TO COMPUTE SUSPENDED SEDIMENT DISCHARGE IN THE TIDAL HUDSON RIVER, NY

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Abstract: Acoustic Doppler current profilers (ADCPs) can provide data needed for computation of suspended-sediment discharge in complex river systems, such as tidal rivers, in which conventional methods of collecting time-series data on suspended-sediment concentration (SSC) and water discharge are not feasible. ADCPs are not designed to measure SSC, thus the software for such computation is limited, and considerable post processing is needed to correct and normalize ADCP data for use as a suspended-sediment surrogate. This paper describes the sampling design and procedure used to calibrate ADCP measures of echo intensity to SSC in the computation of suspended sediment discharge at the study site near Poughkeepsie, New York.

INTRODUCTION

Computation of instantaneous suspended-sediment discharge, or the mass of suspended sediment moving past a given river cross section per unit time, requires multiplying the average suspended sediment concentration (SSC) in the river cross section by the volume of water passing that cross section per unit time (water discharge). Computation of the suspended-sediment discharge over time, requires collection of SSC and discharge data at a frequency sufficient to permit a reasonable interpolation between data points (Potterfield, 1972). Environments in which SSC and discharge change little over time require fewer data than those environments in which flow conditions change rapidly such as a tidal river. Rapidly changing conditions require a surrogate for SSC because the large number of samples required becomes difficult and costly to obtain. Acoustic Doppler current profilers (ADCPs), however, can be used to provide surrogates for both discharge (Morlock and others, 2002) and SSC (Gartner and others, 2003) through measures of velocity and echo intensity (EI), respectively.

Limitations of an Acoustic Surrogate for SSC: Currently available ADCPs are single-frequency instruments, consequently changes in sediment concentration or particle size affect EI (Reichel and Nachtnebel, 1994); therefore interpretation of EI data requires additional measures or assumptions to resolve the cause of these changes. This limitation makes any relation between SSC and EI site specific. A second limitation of an acoustic surrogate is the relation between particle circumference and ADCP frequency (Reichel and Nachtnebel, 1994). Error in SSC estimates has been found to increase as the ratio of particle circumference to acoustic wavelength approaches 1 (Gartner, 2004). A third limitation is that ADCPs are designed to detect acoustic frequency changes in current profiles and are less accurate in measuring the amplitude changes associated with EI measurements (Schaafsma and others, 1997). Other factors that complicate the development of a relation between EI and SSC include the impossibility of collecting a water sample for SSC analysis and acoustic data from the same location at the same time, the need for data corrections to account for the loss of acoustic energy with distance from the ADCP, and normalizations for fixed and dynamic differences between instruments and instrument components over time.

Because of the many complications of applying this emerging SSC surrogate technology to a variety of river systems nationwide, the U.S. Geological Survey does not currently have a standard operating procedure for the use of ADCPs for estimation of suspended-sediment discharge. This paper is not intended to be such a procedure, but rather a documentation of how a specific pair of ADCPs were used at a specific site to compute suspended-sediment discharge. This paper may prove useful to others wishing to do similar work at other sites, but the procedure and assumptions described herein may not be appropriate for other sites.

Instrumentation: Two 614-kHz RD Instruments Workhorse Sentinel (Use of trade, product, or firm names in this publication is for descriptive purposes only and does not imply endorsement by the U.S. Government) ADCPs were used (referred hereafter as $ADCP_1$ and $ADCP_2$), each with four transceivers at a 20-degree angle to the instrument face. One ADCP was mounted to a stationary tripod on the river bottom in an upward-looking orientation about 65 cm above the bottom; the other was boat-mounted to measure discharge and develop a correlation between EI and SSC. Periodically the upward-looking ADCP was recovered for service and replaced with the other ADCP thus creating a rotation of the two instruments. Individual ADCP deployments ranged from 1 week to 7 months.

The upward-looking ADCP was set to transmit 100 acoustic pulses or "pings" every 15 min. The 100 pings were transmitted, and echoes were received, by the ADCP in a span of about 20 sec. Data from each bin in each beam were averaged into a single measurement. The size of the bins was set to 0.5 meters which resulted in 31 to 34 bins containing valid data in each beam. The exact number of bins used was computed from the depth of water above the ADCP at the time of each measurement and the cosine of the beam angle; this computation avoided the incorporation of bins with interference from acoustic reflections off the water surface (Simpson and Oltman, 1993).

COMPUTATION OF SUSPENDED SEDIMENT CONCENTRATION

Conversion of EI data recorded by the ADCP to suspended sediment concentration requires corrections for: 1) temporal changes in transmit power, transmit length, and the size of particles in the water, 2) spatial changes in the spreading of acoustic energy away from the transducer and the behavior of acoustic energy close to the transducer, 3) temporal and spatial changes in the sound absorption by water and suspended particles, and 4) variability between transducers. EI after normalization and (or) correction for all of the above factors except temporal changes in particle size is known as Acoustic Backscatter (ABS). A constant particle size distribution over the range of observed flow conditions indicates that changes in ABS can be attributed to changes in SSC. This relation is based on the sonar equation for sound scattering (Gartner, 2004) and takes the general form:

$$SSC = 10^{(A \times ABS + B)} \tag{1}$$

where A and B are the empirically derived slope and intercept of the regression of SSC against ABS. The following sections outline the steps used to convert EI to SSC.

Echo-Intensity Conversion to Decibels: EI is recorded by the ADCP in counts. Counts are extracted from the ADCP data and multiplied by an instrument-specific and beam-specific scale factor to produce EI in units of decibels (dB). These scale factors are available from RD Instruments by request.

Transmit-Power and Transmit-Length Normalization: Transmit Power (TP) is a measure of the acoustic energy transmitted by the instrument into the water column and TP is directly proportional to EI. TP can vary among instruments and through time. The measurements in this study were obtained from widely differing power-supply voltages because the upward-looking measurements were powered by an internal battery whereas boat-mounted measurements were made by direct connection of inverted AC power. This difference caused the transmit power to vary by a factor of 2.4 to 3.8 between upward-looking measurements (about 60-98 watts) and calibration measurements (about 25 watts). Additionally, the voltage of the upward-looking ADCP power-supply battery declined during individual deployments and resulted in a drop of as much as 25 watts (26 percent) in transmit power over an individual deployment.

TP in watts was calculated from transmit current and transmit voltage extracted from the ADCP data. All EI values were multiplied by a normalization factor (*TPn*) to adjust EI to a transmit power of 25 watts, the approximate value recorded during boat-mounted measurements, as expressed in eq. 2.

$$TPn = \frac{25}{TP} \tag{2}$$

Transmit Length (TL) in counts, is directly proportional to the length of the acoustic pulse and EI and was extracted from the ADCP data. Variability in TL over a deployment was generally less than 3 counts (~4 percent) and EI values were multiplied by a normalization factor (*TLn*) to adjust EI to a transmit length of 47 counts, the approximate value observed for most ensembles, as defined in eq. 3.

$$TLn = \frac{47}{TL} \tag{3}$$

Beam Normalization: ADCP beams are not factory calibrated to produce identical values of EI for a given ensonified volume (RD Instruments, oral commun., 2004). Adjusting for this variability entailed using data gathered from a side-by-side deployment of both ADCPs over 4 weeks in October and November 2003 to normalize the beams on the two ADCPs to beam 1 on $ADCP_1$. $ADCP_1$ was set to collect a 100-ping ensemble every 15 min. and $ADCP_2$ collected 100-ping ensembles 1 min. before and 1 min. after each $ADCP_1$ ensemble. Each measurement took about 20 seconds to complete and allowed 40 seconds for the dissipation of any acoustic ringing from the previous measurements. The EI data from each $ADCP_2$ bin, collected immediately before the $ADCP_1$ measurement, were paired with data collected from the same bins immediately after the $ADCP_1$ measurement. These data pairs were first normalized to a 25-watt transmit power and a 47-count transmit length, then averaged to produce 1 value ($\overline{EI_{db}}$) for comparison with the EI value recorded by $ADCP_1$, which the data pairs bracketed. That computation is illustrated by the following equation:

$$\overline{EI_{db}} = 10 \times Log_{10}\left[\frac{\left(10^{\frac{EI_{dB}}{10}} \times TPn \times TLn\right) + \left(10^{\frac{EI'_{dB}}{10}} \times TPn' \times TLn'\right)}{2}\right] \tag{4}$$

where EI_{db} and EI'_{db} are the echo intensities in same beam and bin for the $ADCP_2$ measurement immediately before and after the $ADCP_1$ measurement

Acoustic Beam Spreading: The EI received by the ADCP is proportional to the range of the echo source particle from the ADCP. The two-way transmission loss due to beam spreading (*BS*) is:

$$BS = \psi \times 20 \times Log_{10}(R) \tag{5}$$

where R is the slant distance to the source of the return echo, in meters, defined by Deines (1999) and ψ is a transducer near-field correction (Downing and others, 1995), that accounts for the non-spherical spreading of acoustic energy close to the transducer.

Acoustic Absorption by Water: EI is also dependent on absorption of acoustic energy by the water (*WA*) according to the following equation (RD Instruments, 1996):

$$WA = 2\alpha R \tag{6}$$

where α is defined by Shulkin and Marsh (1962)

Acoustic Absorption by Sediment: Attenuation of an acoustic signal by suspended sediment can be divided into viscous, scattering, and diffraction energy loss components (Flammer, 1962). Based on Urick (1948), attenuation of 614-kHz acoustic signal is dominated by the viscous energy-loss component for particle sizes smaller than 200 microns and the scattering component dominates losses at sizes larger than this. SSC at the study site rarely exceeded 100 mg/L and silt and clay particles on average represented 96 percent of the material in suspension; therefore any attenuation due to suspended sediment was from the viscous component. The lack of information on particle size less than 62 microns, and the probability that a worst-case scenario would produce a signal loss of only a few dB over the full depth of water, led to the assumption that sound absorption by particles was negligible, and no correction was applied to account for this signal loss. The use of a higher frequency ADCP at this site could possibly invalidate this assumption, in that higher frequencies would result in greater attenuation.

Computation of Acoustic Backscatter (ABS): The 4-beam average ABS for the same bin in each beam, in decibels, is calculated by combining equations 5 and 6, which describe attenuation losses, with equations 2 (transmit-power normalization), and 3 (transmit-length normalization) and the beam-normalized factors, as follows:

$$ABS = 10 \times Log_{10}\left[\frac{\sum_{i=1}^{4}\left[10^{\frac{(EI_{dB} \times A + B)_i}{10}}\right]}{4} \times TPn \times TLn\right] + BS + WA \quad (7)$$

where A and B are the slope and intercept of the empirically derived beam-normalization factors relating observed data to data in $ADCP_1$ beam 1 and i is the beam number.

Relating Acoustic Backscatter (ABS) to Suspended Sediment Concentration (SSC): Water samples for SSC analysis and development of a relation between ABS and SSC were collected at known depths with a P-61 point-integrating isokinetic sampler suspended from the side of a boat. A downward-looking ADCP was mounted and run on the opposite side of the boat while the sample bottle filled (about 60 sec.). Echo-intensity data collected from the bin in each of the four transceiver beams closest to the depth of the P-61 sampler were averaged according to eq. 7.

River-water samples were collected at various times on the tidal cycle during several "calibration trips" when boating was possible between March and November. Typically, 3 to 6 samples were collected on these trips at different depths. Data from no more than 3 samples per trip were selected at random to avoid biasing the ABS to SSC relation toward any individual trip. The mean percentage of clay- and silt-size material (< 62 µm) in these samples was 96 percent with a standard deviation of 2.9 percent; this suggests that changes in ABS are attributable mainly to changes in SSC rather than to changes in particle-size distribution.

The relation between the base 10 logarithm of measured and predicted SSC is depicted in figure 1; predicted SSC is derived from a combination of two explanatory variables - ABS and water temperature (WT) in degrees C. Water temperature was found significant at the p<0.001 level and therefore included in the multiple regression equation. The coefficient of determination (R^2) between these variables is 0.86, and the standard deviation of the residuals (measured SSC minus retransformed-fit SSC) is 7.9 mg/L. SSC in mg/L for an individual bin after retransformation is expressed in eq. 8. The average of the retransformed regression residuals (1.033), known as the Duan smearing estimator (Helsel and Hirsch, 1992), is applied to the equation to account for bias (geometric as opposed to arithmetic means) introduced by the retransformation of SSC from logarithmic to arithmetic space.

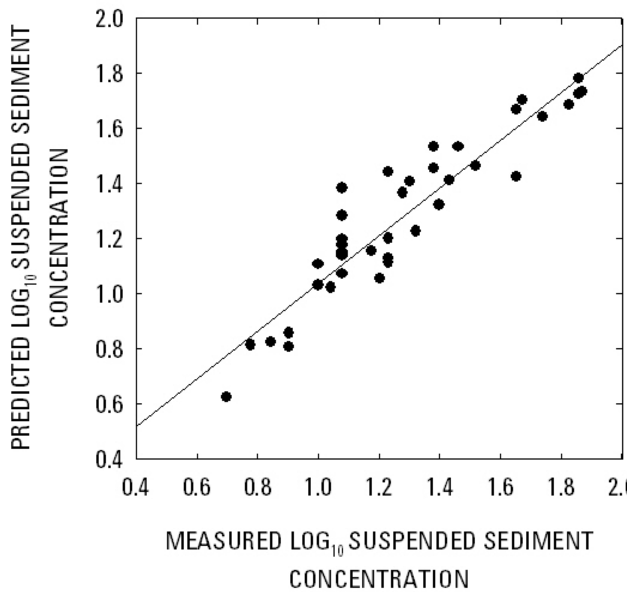

Figure 1: Relation between the base10 logarithm of suspended-sediment concentration and the predicted base10 logarithm of suspended-sediment concentration derived from acoustic backscatter and water temperature data measured at the same depth and time.

$$SSC_{bin} = 10^{ABS \times 0.034 - WT \times 0.019 - 1.018} \times 1.033 \quad (8)$$

Cross-Sectional Average Suspended Sediment Concentration (SSC): The ADCP-derived average SSC in the measured part of the water column above the upward-looking ADCP was compared with cross-sectional measurements of SSC to produce a cross-section correction factor. The average SSC measured above the upward-looking ADCP (SSC_{Pavg}) was computed as:

$$SSC_{Pavg} = \frac{\sum_{bin=1}^{n}\left(SSC_{bin} \times \left|Vp_{bin}\right|\right)}{\sum_{bin=1}^{n}\left|Vp_{bin}\right|} \tag{9}$$

where SSC_{bin} is the SSC in an individual bin defined by eq. 8,
Vp_{bin} is the projected downstream water velocity in an individual bin, and
n is the bin farthest from the ADCP.

The large size of the Hudson River at the site (~800m width) and constantly changing flow conditions, make conventional methods of sample collection in the full cross section, such as the equal-width or equal-discharge methods (U.S. Geological Survey, 1999) infeasible for accurate measurement of the average cross-sectional concentration (SSC_{Xavg}) for a given point in time. Boat-mounted cross-sectional ADCP measurements, however, provided sufficient data from which to calculate this value while minimizing time averaging measurements. The width of a given bin in an acoustic beam is dependent on the speed of the boat; therefore cross-sectional averaging of computed SSC values was weighted by the discharge, instead of velocity, in each bin or unmeasured zone and calculated as:

$$SSC_{Xavg} = \frac{\sum_{bin=1}^{n}\left(SSC_{bin} \times \left|Q_{bin}\right|\right) + \sum_{e=1}^{z}\left(\left(SSC_{top} \times \left|Q_{top}\right|\right)_e + \left(SSC_{bot} \times \left|Q_{bot}\right|\right)_e\right) + \left(SSC_l \times \left|Q_l\right|\right) + \left(SSC_r \times \left|Q_r\right|\right)}{\left|Q_{Total}\right|} \tag{10}$$

Where Q_{bin} is discharge in an individual bin,
n is the last measured bin in the cross section, and
Q_{Total} is the cross-section discharge.

Estimates of SSC in the unmeasured zones near the river bottom (SSC_{bot}) and water surface (SSC_{top}) of each ensemble (e) were made by fitting an ordinary least-squares line through the SSC_{bin} data from each ensemble and extrapolating to the center of the top and bottom of the respective unmeasured zones. Concentrations in these unmeasured zones were then weighted by the respective estimated discharges (Q_{bot} and Q_{top}) in each zone for each ensemble. Discharge estimates in the unmeasured near-surface zone were based on a 3-point solution (RD Instruments, 2003) when applicable and otherwise a constant-extrapolation method was used (RD Instruments, 2003). Discharge estimates for the unmeasured near-bottom zone were based on a power curve solution (RD Instruments, 2003).

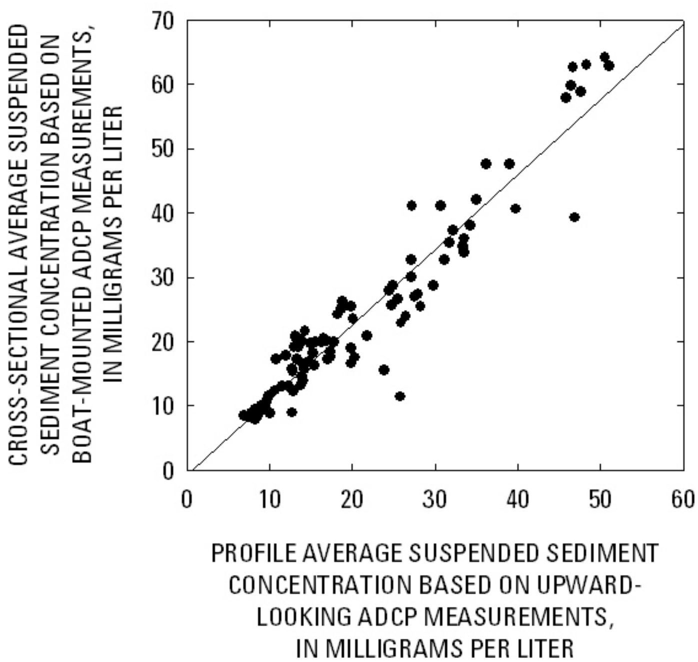

Figure 2: Relation between estimates of SSC based on upward-looking ADCP measurements and those based on boat-mounted ADCP measurements of full cross-section

SSC values for near-bank areas where the boat could not reach shore, or where the water was too shallow for the ADCP were estimated for the left and right banks (SSC_l and SSC_r); these terms represent the flow-weighted average SSC_{bin} values in the 10 ensembles closest to the left and right banks, respectively. The SSC values for each bank were weighted by corresponding estimates of discharge (Q_l and Q_r) from the same 10 ensembles for each bank in accordance with standard methods (RD Instruments, 2003).

The estimated cross-sectional average SSC values are plotted against the velocity-weighted SSC average estimated by the upward-looking ADCP in figure 2. A linear regression equation relating these parameters was generated to adjust the upward-looking ADCP estimate to conditions in the full cross section. If necessary, an SSC value was interpolated between upward-looking ADCP measurements to correspond with the mean time of the cross-section measurement. The number of cross-section measurements made in each calibration trip varied; therefore, bias toward a particular calibration trip was avoided by a random sampling of no more than 4 measurements and no fewer than 3 from each trip (3 measurements were made on 2 trips). The resulting equation (eq. 11) represents 94 cross-section measurements made during 24 calibration trips between 2002 and 2004; it has an R^2 of 0.90 and a residual standard error of 4.55 mg/L.

$$SSC_{avg} = 1.17 \times SSC_{Pavg} - 0.75 \tag{11}$$

The percent error for each of the correction and normalization factors discussed above for these specific instruments at this site during a single 208-day deployment is summarized in table 1.

Table 1. Percent error resulting from omission of corrections and normalizations to data collected during a 208-day ADCP deployment in the Hudson River near Poughkeepsie, NY

Factor	Observed Range	Percent Error in Calculated Suspended-Sediment Discharge Without Accounting for Factor
Transmit power	71 to 65 watts	36 (-5.1)[1]
Transmit length	45-47 units	-1.0 (-0.3)[1]
Beam normalization	Slopes from 96 to 101% of $ADCP_1$ Beam 1	6.5
Beam spreading	~0.9 to 17.4m depth	-71
Near-field correction	Not applicable	0.8
Sound absorption	~0.9 to 17.4m depth	-18
Bias correction	Not applicable	-3.2
Cross section correction	Not applicable	-13

[1]First number accounts for both changes during deployment and differences between calibration and deployment. Numbers in parenthesis only include changes during the deployment

COMPUTATION OF SUSPENDED-SEDIMENT DISCHARGE

Instantaneous suspended-sediment discharge was computed by multiplying SSC_{avg} from equation 11 by the corresponding discharge, and converting units. Suspended-sediment discharge calculated for tidal settings, over periods other than tidal cycles, are biased with respect to one another, because the calculated difference between two periods of equal duration may be attributable to the part of the tidal cycle over which the respective periods were computed (fig. 3). Suspended-sediment discharge computation over successive tidal cycles, however, is awkward to manage in the context of a calendar day. Mathematically filtering the time-series data removes the semidiurnal tide signal from the data and the resulting bias from summing the discharge over incomplete tidal cycles. Similarly, computing long-term totals of instantaneous suspended-sediment discharge over periods much longer than a tidal cycle has the effect of minimizing this bias as indicated in fig. 3C. Therefore an annual suspended-sediment discharge, for example, computed either using a tidal filter or by simple summation of instantaneous data, should produce nearly identical results.

A low-pass digital filter was used to remove the semi-diurnal tide signal from the time series data. The filter residual represents the net, or downriver, suspended-sediment discharge. Each filtered data point was assumed to represent the instantaneous suspended-sediment discharge at any point in time over the next 15 minutes; therefore, each filtered value was multiplied by 15 to provide an estimate of the total sediment discharge over the 15 minutes that followed the measurement. Summation of the 96 15-min suspended-sediment discharge values for each day constitutes the net daily suspended-sediment discharge.

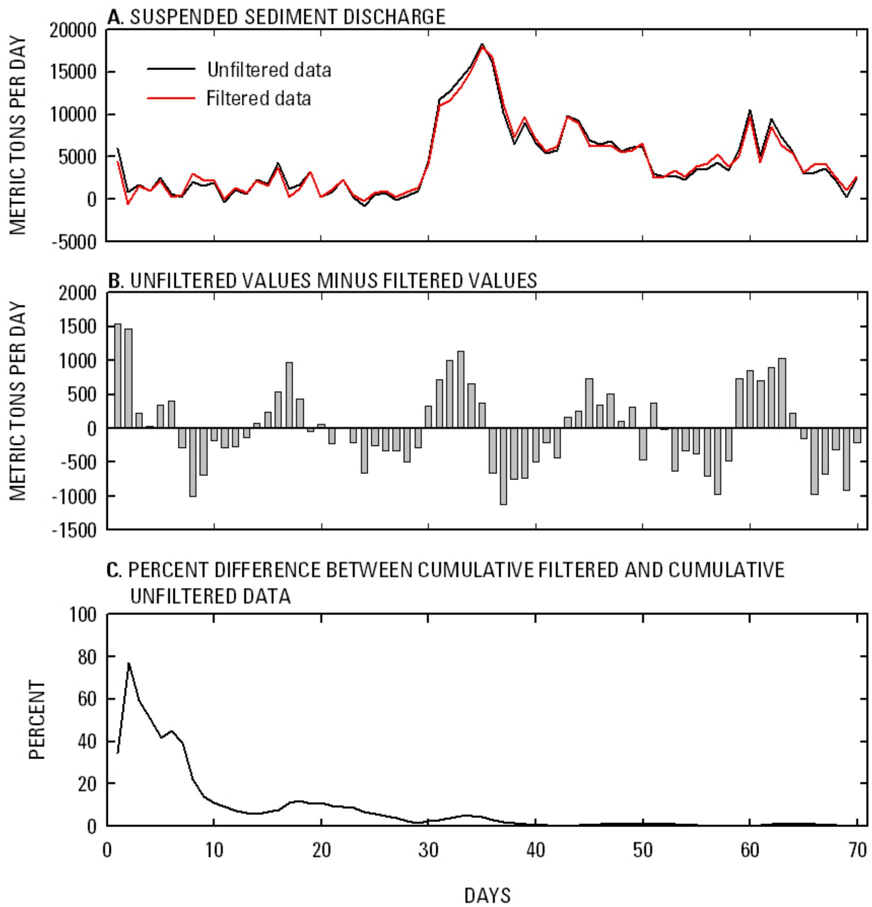

Figure 3: Differences between filtered and unfiltered suspended-sediment discharge data.

SUMMARY

Suspended-sediment discharge of a tidal river was computed using measures of echo intensity and velocity from an ADCP. Adjustments to EI data included an instrument and beam-specific EI conversion to decibels, normalizations for temporal and instrument variations in transmit power and length, beam-to-beam variability, and range-dependent corrections. Calibration of EI to SSC involved the collection of boat-mounted ADCP data from bins corresponding to the depth of a P-61 isokinetic water sampler lowered from the opposite side of the boat. Cross-sectional SSC estimates, based on boat-mounted ADCP measurements were used to adjust data collected by the fixed-position, upward-looking ADCP to conditions in the river cross section. Net suspended-sediment discharge was computed by filtering 15-minute time series data of instantaneous suspended-sediment discharge with a low-pass digital filter that used a fast-Fourier transform to remove the semidiurnal tidal signal in the data.

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