EVALUATION OF SEDIMENT SURROGATES IN RIVERS DRAINING TO LOWER GRANITE RESERVOIR, ID AND WA

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Abstract Elevated levels of fluvial sediment can reduce the biological productivity of aquatic systems, impair freshwater quality, and decrease reservoir storage capacity. The need to measure fluvial sediment has led to the development of sediment surrogate technologies, particularly in locations where streamflow alone is not a good estimator of sediment transport because of regulated flow and varying sediment sources. An effective surrogate technology is low-maintenance and robust over a range of hydrologic conditions, and measured variables can be modeled to estimate suspended sediment concentration (SSC) and duration of elevated levels on a real-time basis. Among the most promising techniques is the measurement of acoustic backscatter strength using acoustic Doppler velocity meters (ADVMs) deployed in rivers. The U.S. Geological Survey, in cooperation with the U.S. Army Corps of Engineers Walla Walla District, is evaluating the use of acoustic backscatter and other surrogates to estimate real-time SSC and loads in rivers flowing into Lower Granite Reservoir. The study is part of the U.S. Army Corps of Engineers' Lower Snake River Programmatic Sediment Management Plan to identify and manage sediment sources in watersheds draining into lower Snake River reservoirs.

Commercially-available acoustic instruments have shown great promise in sediment surrogate studies because they require relatively little maintenance and measure profiles of the surrogate parameter across a sampling volume rather than at a single point. The strength of acoustic backscatter theoretically increases as more particles are suspended in the water to reflect the acoustic pulse emitted by the ADVM. ADVMs of different frequencies (0.5MHz, 1.5MHz, and 3MHz) are being tested to target various sediment grain sizes. Laser diffraction (a Sequoia LISST 100X and a Sequoia LISST Streamside) and turbidity (a YSI 6136 turbidity probe) are also being tested as surrogate technologies. Relations between SSC and surrogate variables are evaluated using ordinary least squares regression. Based on a preliminary analysis of available data from May 2008 through August 2009, acoustic backscatter using an ADVM has been the most robust estimator of SSC of the various surrogate technologies tested. In general, acoustic backscatter appears to be a good estimator of SSC if the selected ADVM frequency is appropriate for observed grain sizes and the amount of organic matter transported in the stream is low or constant.

INTRODUCTION

The U.S. Geological Survey (USGS) Idaho Water Science Center, in cooperation with the U.S. Army Corps of Engineers (USACE) Walla Walla District, is evaluating surrogate technologies to estimate suspended sediment concentrations (SSC) in the Clearwater River at Spalding, Idaho, and the Snake River near Anatone, Washington, (figure 1) to help quantify sediment transport to Lower Granite Reservoir in northern Idaho/eastern Washington. USACE is developing strategies for managing sediment movement and deposition in lower Snake River reservoirs, which has negatively impacted navigation and flow conveyance. Historically, sediment has been managed through periodic dredging of the federal navigation channel; however, USACE hopes to identify more opportunities for controlling sediment by quantifying sediment sources and transport in contributing watersheds, particularly the Clearwater, Grande Ronde, Snake, and Salmon River watersheds.

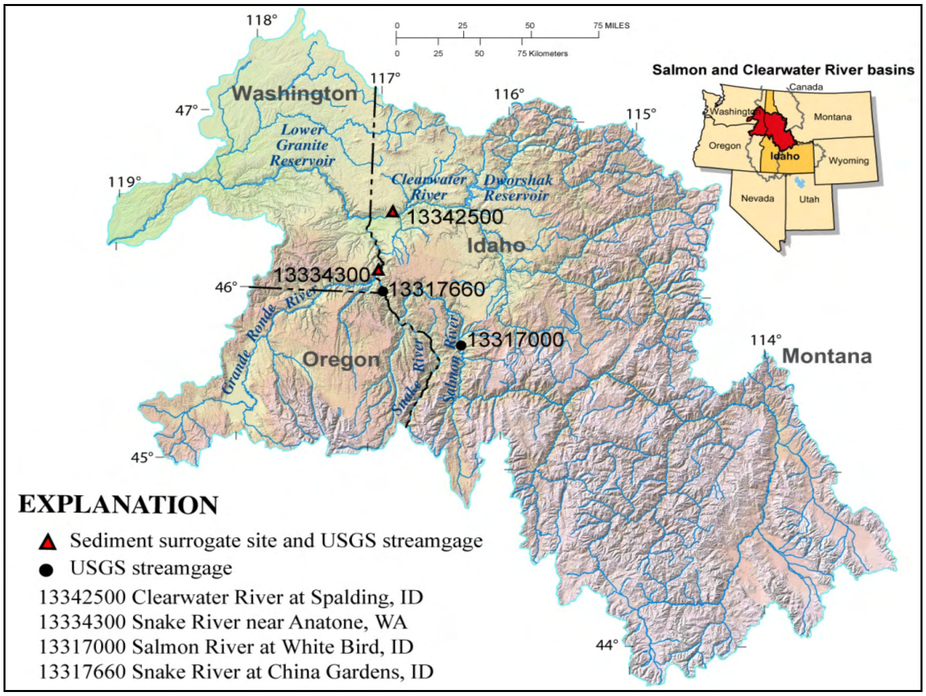

Figure 1 Map of study area and sediment surrogate monitoring sites.

The USGS conducted a sediment sampling program in the Clearwater and Snake Rivers from 1972 to 1979 and developed transport curves based on streamflow for suspended and bed sediment. The results of the 1970s study are presented in Jones and Seitz (1980). One of the goals of the current study, which began in May 2008, is to determine whether the 1970s sediment transport curves are representative of current sediment transport conditions.

This paper documents the ability and limitations of using acoustic backscatter, laser diffraction, and turbidity to estimate SSC on a continuous basis in the Snake and Clearwater Rivers draining to Lower Granite Reservoir. Also evaluated is whether these surrogate technologies provide improved estimates of SSC in comparison with transport curves generated using 2008-09 and 1970s streamflows.

Background Acoustic backscatter has been used with success as a surrogate for SSC or suspended solids concentration in the San Francisco Bay (Gartner, 2004), Florida estuaries (Patino and Byrne, 2004), Colorado River (Topping and others, 2004), and Hudson River (Wall and others, 2006). An acoustic device emits an acoustic pulse into the water, and the strength of the reflected pulse, called backscatter, theoretically increases when more particles are present in the water. Acoustic instruments have shown great promise in sediment surrogate studies because they are robust to biological fouling and measure profiles of backscatter across a sampling volume rather than at a single point in the stream (Gartner and Gray, 2005). Multiple acoustic frequencies were selected for this study to maximize sensitivity of backscatter to dominant grain size (lower frequency for the coarse fraction and higher frequency for the fines fraction) and minimize errors due to changing grain size distribution, as recommended in Gartner (2004) and Topping and others (2004).

Turbidity has been used successfully as a surrogate for SSC in Kansas (Rasmussen and others, 2005) and Florida (Lietz and Debiak, 2005), among other locations. A nephelometric turbidity probe measures light scattered at 90 degrees from incident light. For the Yellow Springs Instruments (YSI) 6136 turbidity probe used in this study, the light source is a near-infrared light emitted at 780-900nm (Yellow Springs Instruments, 2006). The larger the amount of light scattered, the larger the turbidity reading. In theory, this should equate to a larger amount of suspended material in the measurement volume.

The concept of laser diffraction is documented in Agrawal and others (2008). In essence, a laser is passed through a water sample, and a receiving lens in the instrument focuses the light that is scattered by particles in the water onto a series of ring detectors. The detectors interpret a volumetric concentration of sediment in 32 size classes. Data can be converted to a mass concentration by multiplying the volumetric concentration by a known sediment density, or the volumetric concentrations can be used alone in a calibration with measured SSC.

STUDY SITES AND METHODS

Clearwater River Study Site The Clearwater River study site is co-located with USGS streamgage #13342500 on the left streambank at Spalding, Idaho. Part of the streamflow passing the study site is regulated by Dworshak Dam located upstream of the site on the North Fork Clearwater River. The site is equipped with a Sequoia Scientific LISST 100X laser diffraction instrument, a Sequoia Scientific LISST Streamside laser diffraction instrument, a 0.5MHz Sontek acoustic Doppler velocity meter (ADVM), a 3MHz Sontek ADVM, and a YSI 6600EDS water-quality sonde with a 6136 turbidity probe. The site is also equipped with a datalogger and satellite telemetry for collecting and transmitting data on a real-time basis. The ADVMs, LISST 100X, turbidity probe, and telemetry were installed in May 2008; the LISST Streamside was installed in July 2008. The LISST 100X was on temporary loan from Sequoia and was pulled from the site in August 2008. The LISST 100X was deployed in-situ, but the LISST Streamside is deployed inside a gagehouse. A pump draws water from the river into the LISST Streamside's optical analyzer box. The intended advantage of the LISST Streamside over other laser diffraction instruments is improved data quality through reduced stream contact and resulting biological fouling. Unforeseen configuration problems in the LISST Streamside that resulted in poor pump operation and the formation of bubbles in the line prevented reliable measurements for most of the study period. The manufacturer of the LISST Streamside, Sequoia Scientific, is working closely with the USGS to resolve the problems. Further testing is needed to determine whether the instrument will perform as intended once these issues are resolved.

The ADVMs, turbidity probe, LISST 100X, and LISST Streamside pump intake are mounted on a 13.5 m aluminum slide track mount that can be raised and lowered as needed to service equipment. The 0.5MHz and 3MHz ADVMs measure backscatter in 10 discrete, equally-sized cells in a horizontal sampling volume, 1.5 – 58.5 m and 1.0 – 6.0 m from the instrument, respectively. The sampling volume for each ADVM was selected based on meter frequency, availability of suspended material to reflect the acoustic pulse, and any obstructions in the beam path. The ADVMs sample 2 out of every 15 minutes. The water-quality sonde measures turbidity adjacent to the instrument every 15 minutes and is equipped with an automated wiper mechanism to reduce biological fouling on the face of the probe. Both laser diffraction instruments measure volumetric SSC and grain size distribution every 30 minutes. The sampling line for the LISST Streamside is flushed prior to each measurement for 2-5 minutes (duration changed during study period), and readings are then averaged over a 30-second period.

Snake River Study Site The Snake River study site is co-located with USGS streamgage #13334300 on the left streambank near Anatone, Washington. Part of the streamflow passing the study site is regulated by numerous dams along the Snake River, including Hells Canyon Dam located 50 km upstream. The Salmon and Grande Ronde Rivers join the Snake River upstream from the study site and contribute the majority of sediment measured at the site (Gregg Teasdale, USACE, oral communication, 2008). The site is equipped with a YSI 6600EDS water-quality sonde with a 6136 turbidity probe, a 0.5MHz Sontek ADVM, and a 1.5MHz ADVM. Like the Clearwater study site, the Snake River site is equipped with a datalogger and satellite telemetry. The water-quality sonde and telemetry were installed in May 2008; the ADVMs were installed in April 2009. The water-quality sonde is mounted in a plastic pipe with holes, extending from the left bank near the gagehouse. The ADVMs could not be co-located with the streamgage and water-quality sonde because streambed features limited profiling across the channel. The ADVMs were installed in a more suitable measurement location about 300 m upstream from the streamgage.

The 0.5MHz and 1.5MHz ADVMs are configured to measure backscatter in 5 discrete, equally-sized cells in a horizontal sampling volume, 2.0 – 62.0 m and 2.0 – 18.0 m from the instrument, respectively. The ADVMs sample 2 out of every 15 minutes. The water-quality sonde measures turbidity adjacent to the instrument every 15 minutes and is also equipped with an automated wiper mechanism.

Sediment Sample Collection Suspended sediment samples were collected using the equal-width-increment sampling method (U.S. Geological Survey, 2006) with a cable-suspended, US D-96 depth-integrating, isokinetic water sampler. Sampling was targeted towards the ascending limb, the peak, and the descending limb of the snowmelt runoff hydrograph for each river. About 19 suspended sediment samples were collected per site during the study period May 2008 to August 2009. Samples submitted for analysis were a composite representative of the entire cross section. However, to quantify cross-sectional variability, 10 individual bottles, each from a separate vertical section, were submitted for analysis for 2 of the samples at each site. Organic content was analyzed through a loss-on-ignition test on 12 samples at the Clearwater River site and 16 samples at the Snake River site. Sediment samples were analyzed at the USGS Cascades Volcano Observatory Sediment Laboratory in Vancouver, Washington.

Surrogate Calibrations Surrogate measurements were averaged over a one-hour time period bracketing each sediment sample to obtain concurrent measurements for surrogate calibrations. Due to periodic equipment malfunctions, data anomalies, and varying installation dates, surrogate data were not available for all of the samples collected. The number of samples used for each surrogate calibration is presented in the Discussion section.

Acoustic backscatter data were corrected for transmission losses due to absorption by water, absorption or attenuation by sediment, and beam spreading. Methods for correcting acoustic backscatter data are documented in Flammer (1962), Thevenot and Kraus (1993), Urick (1975), and Gartner (2004). Turbidity data were corrected for calibration drift and fouling errors as described in Wagner and others (2006).

Relations between SSC and surrogate variables were evaluated using ordinary least squares regression techniques. Log transformations were performed on SSC and streamflow to improve distribution and fit prior to their evaluation in the regression model. Acoustic backscatter data are already reported in a log-based scale and do not require a transformation. Regression models were selected based on statistical significance of explanatory variables (p-values) and various regression statistics such as coefficient of determination (R^2), root mean square error (RMSE), Mallow's Cp, and PRESS statistics. A nonparametric bias correction factor described in Duan (1983) was applied to each regression model to correct for low bias induced by log transformation and subsequent re-transformation of the dependent variable. Duan's bias correction factor is calculated by averaging the exponents of residuals of the dependent variable in the data set used to develop the regression model. The factor was used to correct each value of SSC as well as upper and lower 95 percent confidence intervals estimated by a regression model.

RESULTS AND DISCUSSION

During the study period from May 2008 – August 2009, measured SSC in the Clearwater River ranged from about 3 to 210 mg/L with a median of 13 mg/L. Fines content (< 63 microns) ranged from 31 to 89 percent. In the Snake River, measured SSC ranged from 7 to 389 mg/L with a median SSC of 23 mg/L. Fines content ranged from 32 to 94 percent. Fines content at both sites typically decreased with increasing concentration. In general, acoustic backscatter was the best estimator of SSC of all of the evaluated surrogate technologies. Significant variability was observed in the turbidity and laser diffraction relations, which may be due to cross-sectional variability in sediment. At each study site, tributary inflows enter the main channel on the left bank less than 2 km upstream from the measurement site. These tributaries have been observed discharging sediment laden water which hugs the left bank downstream to where the surrogate equipment is located. Since the laser diffraction and turbidity instruments make point measurements, these calibrations are biased high at times by these inflows. However, because the ADVMs are able to profile backscatter in a larger part of the channel, they do capture some of the cross-sectional variability. Comparison of data with the 1970s sediment transport curves based on streamflow shows that there have been some changes in the relationship between streamflow and sediment concentration at both sites that require use of a different technique to estimate SSC.

Clearwater River Study Site A summary of each surrogate's performance in estimating SSC at the Clearwater Study Site is presented in table 1, ordered from best to worst estimator. Relative percent difference (RPD) was calculated between each pair of measured and estimated SSC values according to:

$$\text{RPD} = [(\text{Estimated SSC} - \text{Measured SSC})/\text{Measured SSC}]*100 \qquad (1)$$

Table 1 Results from regression models developed from sediment surrogate technologies evaluated at the Clearwater River study site. [Abbreviations: R^2, coefficient of determination; RPD, relative percent difference; RMSE, root mean square error; ADVM, acoustic Doppler velocity meter; NA, not applicable]

Sediment Surrogate	Number of samples compared	R^2	Average RPD	RMSE
3MHz ADVM Backscatter	17	0.96	+4.1%	0.123
0.5MHz ADVM Backscatter	17	0.92	+8.1%	0.164
Laser Diffraction – LISST 100X	7	0.87	+26%	0.300
2008-09 Streamflow Transport Curve	19	0.65	+34%	0.275
Turbidity	17	0.62	+43%	0.360
1970s Streamflow Transport Curve	NA	NA	+61%	NA
Laser Diffraction – LISST Streamside	5	0.07	+73%	0.634

Backscatter from the 3MHz ADVM was the best estimator of SSC, likely because sediment is dominated by fine sands and silt which seems to be well-targeted by the higher frequency ADVM. Topping and others (2004) found that, in the Colorado River, attenuation of the acoustic pulse is closely related to the fines fraction, and backscatter is closely related to the coarse fraction. However, backscatter alone was found to be a good estimator of the combined fines and coarse fractions in the Clearwater River. Non-zero attenuation at low SSC, perhaps due to the presence of organic matter, created significant variability in the relation between attenuation and the fines fraction.

The selected regression based on 3MHz acoustic backscatter represented 96% of the variability in SSC and resulted in an average RPD between measured and estimated SSC of 4.1%. RMSE for the 3MHz model was lower than all other models indicating best fit. The highest SSC sample (210 mg/L) was slightly better represented by the 0.5MHz ADVM (-30% RPD compared to -43% RPD for 3MHz) because of a higher sand content, though as a whole, the 3MHz ADVM represented SSC better than the 0.5MHz ADVM. The ADVMs were relatively low maintenance and robust compared to other surrogates evaluated; however, post-processing of the data was more difficult.

Samples collected to assess cross-sectional variability in SSC show that inflows from the upstream tributary Lapwai Creek are not well-mixed with the Clearwater River at the study site. Because water from Lapwai Creek hugs the bank on the same side of the river as the ADVMs, they seem to measure a zone of average to above-average SSC relative to the entire cross-section. This most likely explains the average overestimation of sediment using the surrogates. However, the ADVMs seem able to represent cross-sectional variability better than other surrogates.

Following a transformation back to original units, the selected regression model for estimating SSC at the Clearwater River site is:

$$SSC = 10^{[-3.54 + (0.057 * 3MHz\_ABScorr)]} * 1.007 \quad (2)$$

where SSC is the suspended sediment concentration, 3MHz_ABScorr is the range-normalized acoustic backscatter from the 3MHz ADVM corrected for two-way transmission losses, and 1.007 is Duan's bias correction factor.

A plot of measured versus estimated SSC based on the selected model (equation 2) is shown in figure 2. The upper and lower 95 percent confidence level is plotted for each estimated value. RPD for individual observations ranged from -43 to +73 percent, but most of the high RPDs occurred at low SSC, when small differences between estimated and measured values can result in high percent differences. At high SSC (greater than 100 mg/L), mean RPD was -27 percent, meaning that in general, the regression model underestimated true SSC when high. At low SSC (less than 100 mg/L), mean RPD was +8.4 percent, meaning that in general, the regression model overestimated true SSC when low. Average percent organic matter was 10 percent at high SSC and 26 percent at low SSC. Higher percent organic matter at low SSC is a possible cause of high positive RPD since the ADVMs likely interpret the organic matter as sediment.

A time series plot of measured and estimated daily mean suspended sediment load based on the selected model with 3MHz acoustic backscatter as well as with transport curves developed from 2008-09 and 1970s streamflows is presented in figure 3. As compared to the measured daily loads, the 2008-09 and 1970s transport curves both overestimated sediment transport, except during hydrograph peaks, when both curves tended to underestimate SSC. Streamflow alone appears to be a poor estimator of sediment over a hydrograph probably due to hysteresis and inflow of smaller sediment-laden tributaries. Some differences were observed in sediment loads estimated using transport curves developed from 2008-09 and 1970s streamflows, especially during a low flow period in September through November 2008. Overall sediment supply in the Clearwater system was reduced dramatically after the construction of the Dworshak Dam on the North Fork Clearwater River in 1972-1973. However, the 1970s transport curves would have

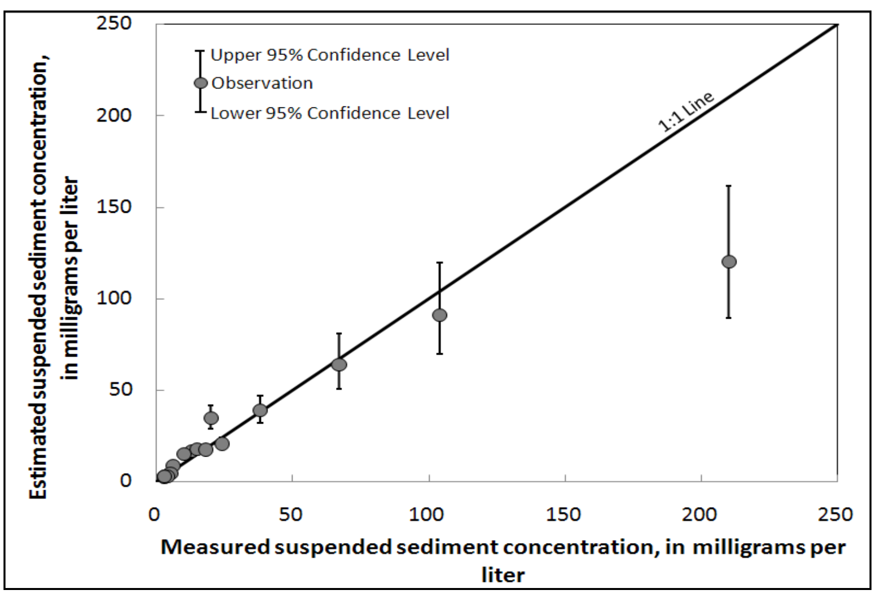

Figure 2 Relation between measured and estimated suspended sediment concentrations at the Clearwater River study site based on a regression model with 3MHz acoustic backscatter.

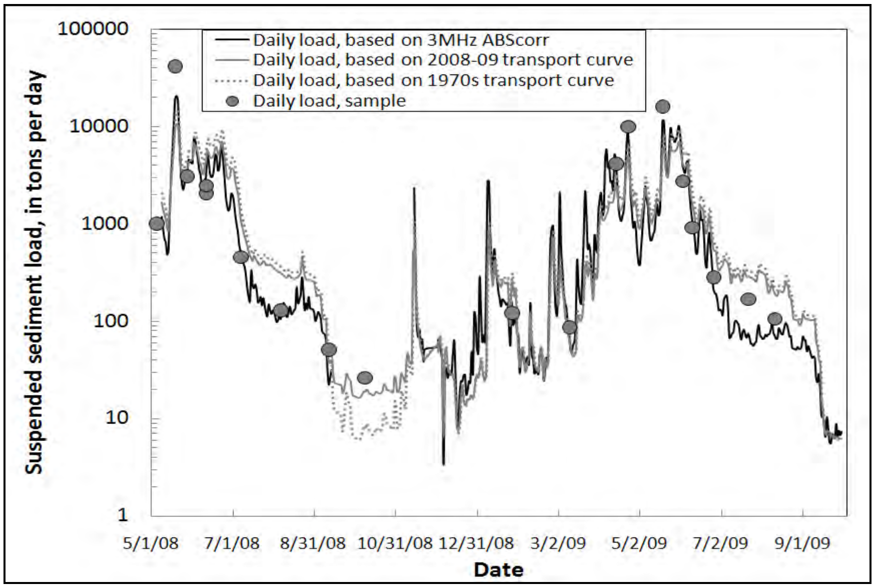

Figure 3 Time series plot of estimated daily sediment loads at the Clearwater River study site based on a regression model with 3MHz acoustic backscatter and sediment transport curves developed using data collected in the 1970s and 2008-09.

captured this reduction in sediment, so other changes in the watershed or flow regime are likely responsible for the observed small changes in sediment transport. However, as stated previously, streamflow from either period is not the best estimator of sediment at this site.

Snake River Study Site A summary of each surrogate's performance in estimating SSC at the Snake River site is presented in table 2, ordered from best to worst estimator. Acoustic backscatter alone was not as good of an estimator for SSC in the Snake River as it was in the Clearwater River. This may be due to a shorter period of record during which the ADVMs were installed and fewer samples available for the calibration. However, the inclusion of an additional variable that represents the ratio of relatively unregulated streamflow from the Salmon and Grande Ronde Rivers to the overall streamflow passing the study site explains some of the remaining variability. This variability may be due to differences in grain size distribution and other sediment characteristics in these two tributaries. The variable, called Fraction of Unregulated Flow (FUF), is calculated as:

$$FUF = [Q13317000 + (Q13334300 - Q13317660)]/Q13334300 \quad (3)$$

where Q13317000 is the streamflow measured in the Salmon River at White Bird, ID (USGS gage 13317000), Q13334300 is the streamflow measured in the Snake River nr Anatone, WA (USGS gage 13334300), and Q13317660 is the streamflow measured in the Snake River at China Gardens, ID (USGS gage 13317660). The difference in streamflow on the Snake River between the China Gardens and Anatone gages is intended to represent inflows from the Grande Ronde River and other smaller tributaries entering the Snake River downstream of its confluence with the Salmon.

Following a transformation back to original units, the selected regression model for estimating SSC at the Snake River site is:

$$SSC = 10^{[-4.42 + (0.050 * 1.5MHz\_ABScorr) + (1.53 * FUF)]}*1.007 \quad (4)$$

where SSC is the suspended sediment concentration, 1.5MHz_ABScorr is the range-normalized acoustic backscatter from the 1.5MHz ADVM corrected for two-way transmission losses, FUF is the fraction of unregulated flow measured at the study site, and 1.007 is Duan's bias correction factor.

Table 2 Results from regression models developed from sediment surrogate technologies evaluated at the Snake River study site. [Abbreviations: R^2, coefficient of determination; RPD, relative percent difference; RMSE, root mean square error; ADVM, acoustic Doppler velocity meter; FUF, fraction of unregulated flow; NA, not applicable]

Sediment Surrogate	**Number of samples compared**	**R^2**	**Average RPD**	**RMSE**
1.5MHz ADVM Backscatter + FUF	8	0.92	+4.9%	0.148
1.5MHz ADVM Backscatter	8	0.85	+12%	0.216
2008-09 Streamflow Transport Curve	19	0.84	+17%	0.244
1970s Streamflow Transport Curve	NA	NA	-25%	NA
Turbidity	15	0.64	+36%	0.331
0.5MHz ADVM Backscatter	8	0.54	+37%	0.380

A plot of measured versus estimated SSC based on the selected model (equation 4) is shown in figure 4. RPD for individual observations ranged from -31 to +73 percent, but most of the high RPDs occurred at low SSC, when small differences between the estimated and measured values can result in high percent differences. At high SSC (greater than 100 mg/L), mean RPD was -12 percent, meaning that in general, the regression model underestimated true SSC when high. At low SSC (less than 100 mg/L), mean RPD was +11 percent, meaning that in general, the regression model overestimated true SSC when low. Similar to the Clearwater River site, percent organic matter at low SSC was higher (17 percent) than at high SSC (4 percent) and is a possible cause of high positive RPD in those samples. Overall, however, the comparison between measured and estimated SSC was very good, especially with the small number of available samples. More sample data are needed to fully evaluate the performance of the ADVMs under a wider range of flow conditions.

A time series plot of measured and estimated daily mean suspended sediment load based on the selected regression model as well as with transport curves based on 2008-09 and 1970s streamflows is shown in figure 5. Data collected before the period of ADVM deployment are not shown. As a whole, the loads calculated using the 1970s sediment transport curve underestimate current sediment transport, particularly during the ascending limb and peaks of the hydrograph. In contrast, the estimates using the 1970s transport curve slightly overestimate current sediment transport during the descending limb of the hydrograph as is typical due to hysteresis. Estimates based on the 2008-09 transport curve follow a similar pattern, though on average, they tend to overestimate the measured SSC and load. Similar to the Clearwater River study site, some differences were observed in sediment loads estimated using transport curves developed from 2008-09 and 1970s streamflows, meaning that changes in the watershed or flow regime may have caused changes in sediment transport.

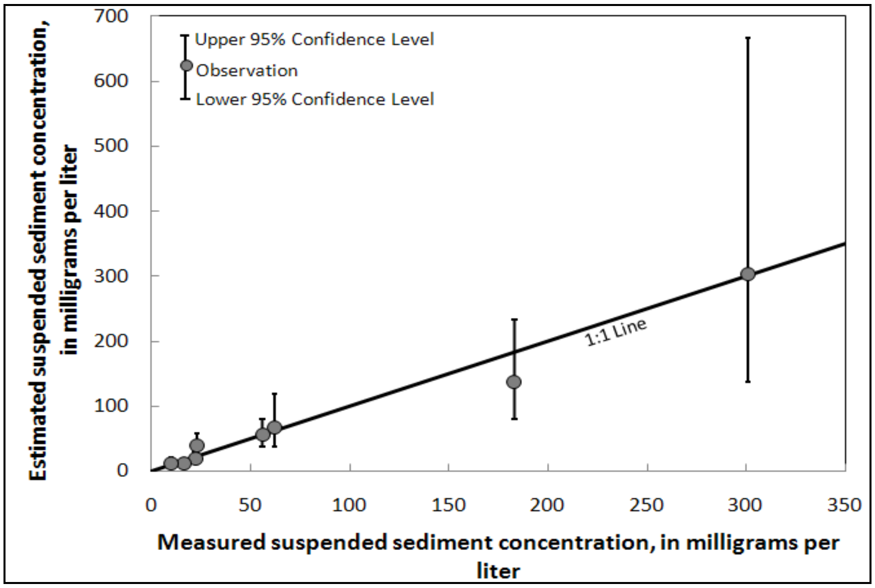

Figure 4 Relation between measured and estimated suspended sediment concentrations at the Snake River study site based on a regression model with 1.5MHz acoustic backscatter and fraction of unregulated streamflow.

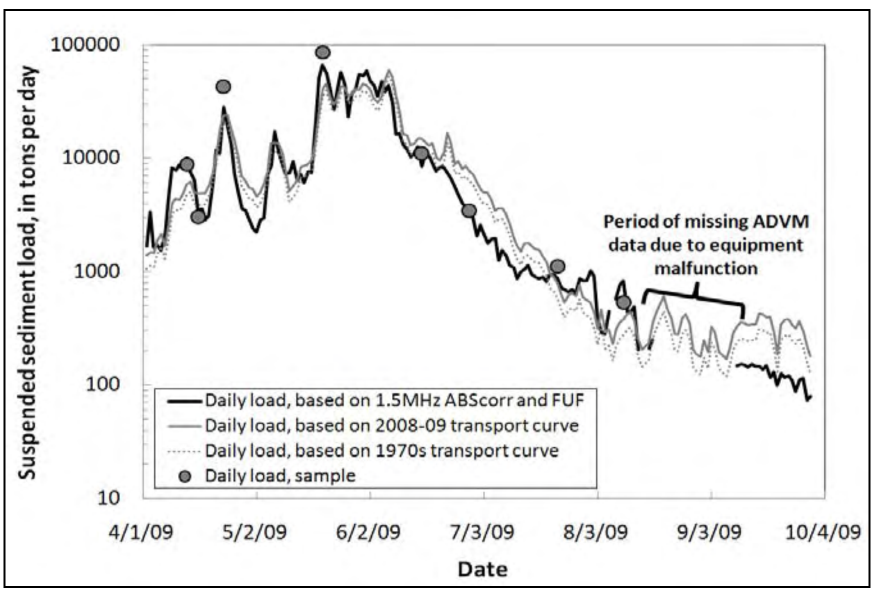

Figure 5 Time series plot of estimated daily sediment loads at the Snake River study site based on a regression model with 1.5MHz acoustic backscatter and fraction of unregulated streamflow and sediment transport curves developed using data collected in the 1970s and 2008-09.

SUMMARY

At both study sites, acoustic backscatter was deemed the most promising surrogate technology for estimating suspended sediment concentrations and ultimately transport of sediment into Lower Granite Reservoir. Acoustic backscatter is a promising surrogate technology because the acoustic instruments are less affected by biological fouling and are able to profile backscatter in a larger part of the channel than other evaluated surrogates. As a result, they are able to capture more of the cross-sectional variability that is represented in samples collected at the study sites. Although organic matter concentrations were low at both sites, they likely contributed to model error, especially when concentrations of suspended sediment were low. A single frequency acoustic device appears to be adequate to represent SSC in the majority of streamflow conditions at both study sites. Optimal frequency is dependent on sediment characteristics. An additional variable representing unregulated streamflow was helpful to represent changing sediment grain sizes and sources from upstream tributaries at the Snake River site.

Sediment surrogate technologies, such the use of acoustic backscatter to estimate SSC, can be a cost-effective component of a long-term fluvial sediment monitoring program. Once an initial regression model is developed between surrogate data and SSC, sediment samples can be collected less frequently, thus reducing long-term operation and maintenance costs for a sediment monitoring station. Sediment surrogates also allow the estimation of sediment when it is unsafe to sample the stream, such as during flood events. Traditional SSC estimation techniques using streamflow alone may provide poor results over small time scales or in streams with a combination of regulated and unregulated flow, as is the case for the Clearwater and Snake Rivers. The use of sediment surrogate technologies may be the only way to obtain continuous, accurate estimates of SSC in such cases. Continuous estimation of SSC using surrogates could also be a useful tool for water managers tracking short- and long-term changes in sediment transport resulting from land use changes and/or best management practices implemented within a watershed. In the Clearwater and Snake Rivers, estimates of SSC using surrogate technology will allow water managers and scientists to identify the timing, magnitude, and duration of high sediment transport and to better evaluate long-term watershed response to sediment management strategies.

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