USING ACOUSTIC BACKSCATTER TECHNOLOGY TO MEASURE SUSPENDED SEDIMENT CONCENTRATIONS IN IDAHO STREAMS

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Abstract: The U.S. Geological Survey's Idaho Water Science Center is attempting to use the acoustic backscatter values from acoustic Doppler velocity meters to predict suspended sediment concentrations at four locations in Idaho. Lack of high suspended sediment concentrations at these locations over the past few years has somewhat limited the analyses. However, initial results based on the existing data are quite encouraging. Average absolute differences between the measured and predicted SSC values ranged from 7.1 to 32.2 percent.

INTRODUCTION

The standard techniques currently used to collect fluvial sediment data in the Nation's streams tend to be manually intensive, time consuming, and therefore quite costly. In addition, some of the data-collection techniques pose certain safety risks. As a result, the amount of daily-value sediment data being collected, primarily by the U.S. Geological Survey (USGS), has declined by more than two-thirds over the past two decades (Gray, 2005).

The need to safely and cost-effectively collect fluvial sediment data has led to the advancement of so-called sediment surrogate technologies. Among these techniques is the use of the acoustic backscatter strength from acoustic Doppler velocity meters. The strength of the acoustic backscatter signal increases as more particles are available in the water to reflect the acoustic pulse. Based on this fact, acoustic backscatter strength values can be related to suspended sediment concentrations on a site-by-site basis.

The USGS Idaho Water Science Center is attempting to use this surrogate technology to provide continuous suspended sediment data at locations in four streams across the State: Kootenai River, Coeur d'Alene River, St. Joe River, and Boise River. The channel and suspended sediment characteristics of these sites differ significantly; therefore, this work may also provide some insight as to what types of sites may be most amenable to this type of surrogate technology.

ACOUSTIC TECHNOLOGY

The primary purpose of an acoustic Doppler velocity meter (ADVM) is to measure the velocity of water by applying the Doppler principle. The ADVM emits an ultrasonic pulse from a transducer into the water, and the pulse bounces off small particles of sediment and other materials that are present. After the pulse is sent, the ADVM listens for the return echo from the particles in the water and calculates the resulting Doppler shift to determine the water velocity. Each ADVM computes an index of the strength of the pulse that is returned to the instrument. In theory this index value, called the acoustic backscatter strength (ABS), can be related to the concentration of particles (primarily suspended sediment) in the area sampled by the ADVM.

METHODS

Suspended sediment concentrations (SSC) were determined over a range of discharges using standard techniques, spanning several months at each of the four sites. Relations between the SSC and ABS values were determined using ordinary least squares regression techniques. Other variables such as water temperature and discharge were also included in the analyses and were found to help improve the relations in some instances.

Two different types of ADVMs, the Nortek EasyQ (Nortek USA, 2005) and the Sontek Argonaut-SL (Sontek/YSI, Inc., 2005) are deployed at the study sites. The configurations of the ADVMs vary based on site conditions and whether or not they are being used to estimate discharge using index velocity methods. The ADVMs being used for discharge were set up for optimal velocity sampling, and those settings were not altered for the sediment surrogate work.

ANALYSES

Relations between SSC and ABS values were determined at four sites in the Kootenai, Coeur d'Alene, St. Joe, and Boise rivers in Idaho. Upstream drainage areas for these sites range from about 1,500 mi^2 to 12,700 mi^2. The channel and suspended sediment characteristics vary by site. Two of the sites are located on regulated streams where dams trap sediments. The other two sites are located on unregulated streams with significantly more sources of sediment.

Kootenai River: This site is located at the USGS streamflow gaging station 12310100, Kootenai River at Tribal Hatchery near Bonners Ferry, Idaho. The upstream drainage area for this gaging station is approximately 12,700 mi^2, of which a significant portion is located in Canada. Most of the drainage area is mountainous, with much of the precipitation resulting from winter snowfall. As a result, most of the streamflow other than baseflow is a direct result of snowmelt runoff. Streamflow at this site is regulated by Libby Dam, located about 70 mi upstream near Libby, Montana; the annual mean discharge is approximately 15,000 ft^3/s. Because discharges are regulated at this site, mean cross-sectional water velocities are fairly stable and typically range from about 1.0 to 2.5 ft/s.

The portion of the Kootenai River below Libby Dam is essentially "sediment starved". A majority of the SSC values immediately downstream of Libby Dam ranged from 2 to 10 mg/l between 1972 and 2002 (Barton, 2004). Sediment is introduced to the system from several major tributaries between Libby Dam and Bonners Ferry. However, SSC values near Bonners Ferry are still relatively low, ranging from 1 to 100 mg/l or less in most instances. Based on limited data, the particle-size distributions seem to vary, as may be expected, by discharge and resulting water velocities. Silts and clays account for about 75 percent or more of the suspended sediments at low discharges (less than about 10,000 ft^3/s), while they only account for about 50 percent of the suspended sediments at high discharges (greater than about 25,000 ft^3/s).

For this project, suspended sediment samples were collected eight times at this site during the spring and summer of 2005. Samples were collected using the equal-width-increment (EWI) method. Analysis of the initial sample data and acoustic backscatter data from acoustic Doppler current profiler (ADCP) discharge measurements indicate that the suspended sediments at this site are well mixed.

A 1.5 MHz Argonaut-SL (Sontek/YSI, Inc., 2005) ADVM is deployed at this location, primarily for the purpose of determining river discharges using index-velocity methods. Each of the two beams is configured to sample a volume of water from 0.5 to 15.0 meters horizontally outward from the ADVM. Velocity data, and thus ABS data, are recorded at 15-minute intervals. The ADVM continuously sends acoustic pulses into the water for one 5-minute period during each 15-minute interval. The ABS values from each beam measured during that 5-minute period are averaged to obtain the final ABS value for that beam. The values for the two beams are then averaged to obtain the final ABS for the site.

Multiple linear regression analyses were used to determine the best-fit relation between SSC and various parameters at this site. The final averaged ABS value (ABS_{avg}), the instantaneous temperature in degrees Centigrade (T), and the instantaneous discharge were all considered as possible variables for the final equation. Log transformations of all of the variables were used in the analyses. Based on the multiple linear regressions, an equation that includes ABS and temperature provides the best estimation results for SSC. Following a transformation back to linear units, the equation is as follows:

$$SSC = 4.0 \times 10^{-14} T^{-1.003} ABS_{avg}^{\ 7.403} . \qquad (1)$$

Based on the data used to develop the equation, a plot of predicted versus measured SSC values was derived (figure 1). The average absolute difference between the predicted and measured SSC values is 7.1 percent. The differences range from -19.3 to +14.8 percent.

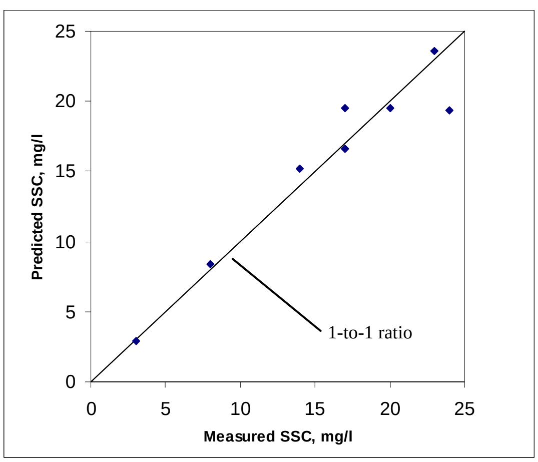

Figure 1 Measured versus predicted suspended sediment concentrations for the Kootenai River at Tribal Hatchery near Bonners Ferry, Idaho (12310100).

Coeur d'Alene River: This site is located at the USGS streamflow gaging station 12413860, Coeur d'Alene River near Harrison, Idaho. The upstream drainage area for this gaging station is about 1,475 mi^2. The gaging station is located at the mouth of the Coeur d'Alene River where it flows into Coeur d’Alene Lake. Because of the proximity to the lake, backwater conditions are prevalent at this location. Most of the drainage area is mountainous, with much of the precipitation resulting from winter snowfall. As a result, most of the streamflow other than baseflow is a direct result of snowmelt runoff. Streamflows at this site are unregulated and generally unaffected by outside factors other than a few minor diversions for irrigation or mining uses. The annual mean discharge is approximately 2,500 ft^3/s. Mean cross-sectional water velocities at this site range from as little as about 0.02 ft/s during low discharges and high lake levels to as much as 3.0 ft/s or more during annual runoff events.

SSC values at this site typically range between 1 and 100 mg/l. Extreme runoff events have produced SSC values approaching 400 mg/l. Particle-size distributions from nearly 200 recent and historic samples vary significantly, ranging from less than 20 to more than 90 percent silts and clays. Based on these data, the particle-size distributions seem to vary, as may be expected, with discharge and resulting water velocities.

For this project, suspended sediment samples were collected 12 times at this site beginning in October of 2003. Samples were collected using the EWI method. Analysis of previous sample data and acoustic backscatter data from ADCP discharge measurements indicate that the suspended sediments at this site are well mixed.

A 2.0 MHz EasyQ (Nortek USA, 2005) ADVM is deployed at this location, primarily for the purpose of determining river discharges using index-velocity methods. Each of the two beams is configured to sample in three separate 1.5 meter “cells” extending from 0.8 meters to 5.3 meters horizontally outward from the ADVM. Velocity data, and thus ABS data, are recorded at 15-minute intervals. The ADVM continuously sends acoustic pulses into the water for one 10-minute period during each 15-minute interval. The ABS values for each cell in each beam are averaged over that 10-minute period to obtain the ABS values for each of the six cells. This configuration results in 6 separate ABS values for each 15-minute period.

Multiple linear regression analyses were used to determine the best-fit relation between SSC and various parameters at this site. The final averaged ABS values for each cell, the instantaneous temperature, and the instantaneous discharge were all considered as possible variables for the final equation. Log transformations of all of the variables were used in the analyses. Based on the multiple linear regressions, an equation that includes temperature in degrees Centigrade (T) and ABS values from cell 2, beam 2 (C2B2) and cell 3, beam 2 (C3B2) provides the best estimation results for SSC. Following a transformation back to original units, the equation is as follows:

$$SSC = 14.26 T^{-0.730} C2B2^{-18.944} C3B2^{20.460} \quad (2)$$

Based on the data used to develop the equation, a plot of predicted versus measured SSC values was derived (figure 2). The average absolute difference between the predicted and measured SSC values is 32.2 percent. The differences range from -56.1 to +92.1 percent.

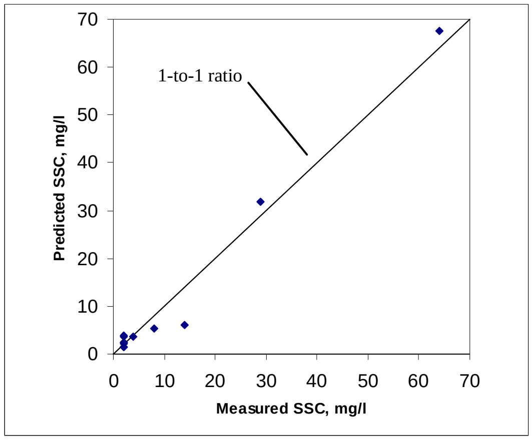

Figure 2 Measured versus predicted suspended sediment concentrations for the Coeur d'Alene River near Harrison, Idaho (12413860).

St. Joe River: This site is located at the USGS streamflow gaging station 12415140, St. Joe River near Chatcolet, Idaho. The upstream drainage area for this gaging station is about 1,720 mi^2. The gaging station is located at the mouth of the St. Joe River where it flows into Coeur d'Alene Lake. Because of the proximity to the lake, backwater conditions are prevalent at this location. Most of the drainage area is mountainous, with much of the precipitation resulting from winter snowfall. As a result, most of the streamflow other than baseflow is a direct result of snowmelt runoff. Streamflows at this site are unregulated and generally unaffected by outside factors other than a few minor diversions for irrigation. The annual mean discharge is about 2,700 ft^3/s. Mean cross-sectional water velocities at this site range from as little as about 0.05 ft/s during low discharges and high lake levels to as much as 2.5 ft/s or more during annual runoff events.

No historic SSC data are available for this site. Recent SSC values ranged between 2 and 18 mg/l. Particle-size distribution data are also extremely limited. Recent data (5 samples) indicate that silts and clays make up between 75 and 95 percent of the suspended sediments.

For this project, suspended sediment samples were collected 11 times at this site beginning in December of 2003. Samples were collected using the EWI method. General analysis of acoustic backscatter data from ADCP discharge measurements indicate that the suspended sediments at this site are well mixed.

A 2.0 MHz EasyQ (Nortek USA, 2005) ADVM is deployed at this location, primarily for the purpose of determining river discharges using index-velocity methods. Each of the two beams is configured to sample in three separate 1.5 meter "cells" extending from 0.5 meters to 5.0 meters horizontally outward from the ADVM. Velocity data, and thus ABS data, are recorded at 15-minute intervals. The ADVM continuously sends acoustic pulses into the water for one 10-minute period during each 15-minute interval. The ABS values for each cell in each beam are averaged over that 10-minute period to obtain the ABS values for each of the six cells. This configuration results in 6 separate ABS values for each 15-minute period.

Multiple linear regression analyses were used to determine the best-fit relation between SSC and various parameters at this site. The final averaged ABS values for each cell, the instantaneous temperature, and the instantaneous discharge were all considered as possible variables for the final equation. Log transformations of all of the variables were used in the analyses. Based on the multiple linear regressions, an equation that includes ABS values from cell 1, beam 2 (C1B2) and cell 3, beam 1 (C3B1) provides the best estimation results for SSC. Following a transformation back to original units, the equation is as follows:

$$SSC = 3.15 \times 10^{-20} C1B2^{19.540} C3B1^{-7.887} \quad (3)$$

Based on the data used to develop the equation, a plot of predicted versus measured SSC values was derived (figure 3). The average absolute difference between the predicted and measured SSC values is 24.6 percent. The differences range from -31.3 to +50.1.

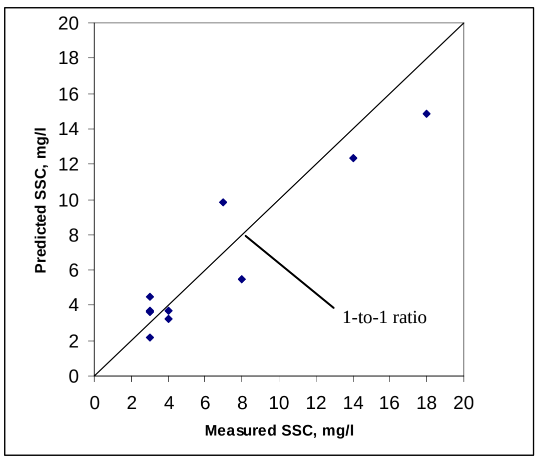

Figure 3 Measured versus predicted suspended sediment concentrations for the St. Joe River near Chatcolet, Idaho (12415140).

Boise River: This site is located at the USGS streamflow gaging station 13213000, Boise River near Parma, Idaho. The upstream drainage area for this gaging station is approximately 3,970 mi^2. Streamflow is regulated by Lucky Peak Dam located about 60 mi upstream. The upper portion of the basin (about 2,500 mi^2) is mountainous, with much of the precipitation resulting from winter snowfall. The lower portion of the basin lies in a broad, alluvium-filled area with several terraces. Most of the streamflow other than baseflow is a direct result of snowmelt runoff. The annual mean discharge is approximately 1,650 ft^3/s. Mean cross-sectional water velocities at this site typically range from about 1.5 to 2.5 ft/s.

The main channel of the Boise River below Lucky Peak Dam is essentially “sediment starved”. A majority of the SSC values about 5 mi downstream of Luck Peak Dam ranged from 2 to 5 mg/l between 1989 and 2002 (Hardy and others, 2005). Significant amounts of additional sediment are introduced to the system primarily from the several irrigation return drains located between Lucky Peak Dam and Parma. SSC values near Parma are significantly higher, ranging from about 5 to 250 mg/l between 1989 and 2002 (Hardy and others, 2005). Particle-size distributions (based on about 100 recent and historic samples) vary significantly, ranging from less than 10 to more than 90 percent silts and clays. There is no significant relation between the particle-size distributions and discharges or stream velocities.

For this project, suspended sediment samples were collected 11 times at this site beginning in May of 2005. Samples were collected using the EWI method. Analysis of sample data indicate that the suspended sediments at this site are well mixed.

A 2.0 MHz EasyQ (Nortek USA, 2005) ADVM is deployed at this location. Each of the two beams is configured to sample in three separate 1.0 meter "cells" extending from 0.5 meters to 3.5 meters horizontally outward from the ADVM. Velocity data, and thus ABS data, are recorded at 15-minute intervals. The ADVM continuously sends acoustic pulses into the water for one 2-minute period during each 15-minute interval. The ABS values for each cell in each beam are averaged over that 10-minute period to obtain the ABS values for each of the six cells. This configuration results in 6 separate ABS values for each 15-minute period.

Multiple linear regression analyses were used to determine the best-fit relation between SSC and various parameters at this site. The final averaged ABS values for each cell, the instantaneous temperature, and the instantaneous discharge were all considered as possible variables for the final equation. Log transformations of all of the variables were used in the analyses. Based on the multiple linear regressions, an equation that includes temperature in degrees Centigrade (T) and the ABS values from cell 1, beam 1 (C1B1) provides the best estimation results for SSC. Following a transformation back to original units, the equation is as follows:

$$SSC = 5.78 \times 10^{13} T^{-3.422} C1B1^{-4.482} \tag{4}$$

Based on the data used to develop the equation, a plot of predicted versus measured SSC values was derived (figure 4). The average absolute difference between the predicted and measured SSC values is 24.5 percent. The differences range from -40.2 to +51.4 percent. The largest measured SSC value had one of the largest percent differences. Additional data collection and analyses are needed to determine if there are problems with predicting larger SSC values at this location.

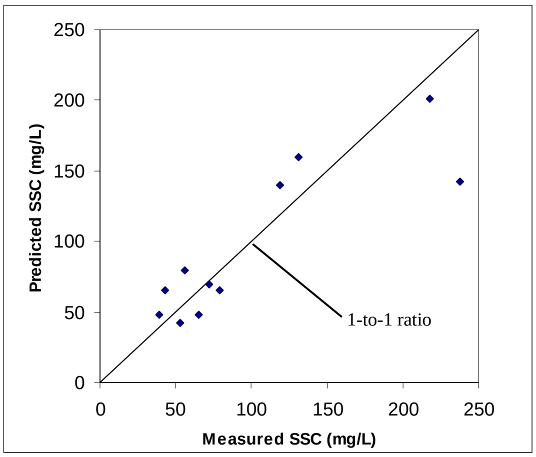

Figure 4 Measured versus predicted suspended sediment concentrations for the Boise River near Parma, Idaho (13213000).

CONCLUSIONS

Attempts to relate SSC to ABS values from ADVMs at four locations in Idaho have yielded initial results that are quite encouraging. Based on limited data (8 to 12 sample pairs per location), various combinations of ABS data or combinations of ABS and temperature data predicted SSC reasonably well. Average absolute differences between the measured and predicted SSC values ranged from 7.1 to 32.2 percent. Lack of SSC data at higher concentrations has limited the analyses. Additional data collection and analyses are needed to verify these initial results and to determine the applicability of the current relations at higher concentrations.

Because of the limited data, it is difficult at this time to determine whether site characteristics significantly influence the quality of the ABS vs. SSC relations. The relation for the Kootenai River site resulted in the smallest percent differences between measured and predicted values. More sand-sized particles seem to be transported in suspension at this site. However, this result was based on only 8 suspended sediment samples and 5 particle-size analyses.

The cost of sediment monitoring could be reduced if these relations are improved with additional data and if the error of prediction is acceptable. Sediment sampling may be only needed for quality control or extreme events that are outside the modeled measurements. In addition, this approach may be eventually acceptable for the prediction of chemical constituents whose concentration compares well with suspended sediment concentration.

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