SUSPENDED-SEDIMENT TRANSPORT AND STORAGE: A DEMONSTRATION OF ACOUSTIC METHODS IN THE EVALUATION OF RESERVOIR MANAGEMENT STRATEGIES FOR A SMALL WATER-SUPPLY RESERVOIR IN WESTERN COLORADO

By Cory A. Williams, Hydrologist, U.S. Geological Survey, Grand Junction, CO; Rodney J. Richards, Hydrologist, U.S. Geological Survey, Grand Junction, CO; Kent Collins, Hydraulic Engineer, Bureau of Reclamation, Lakewood, CO

Abstract: The U.S. Bureau of Reclamation (USBR) and local stakeholder groups are evaluating reservoir-management strategies within Paonia Reservoir. This small reservoir fills to capacity each spring and requires approximately half of the snowmelt-runoff volume from its sediment-laden source waters, Muddy Creek. The U.S. Geological Survey is currently conducting high-resolution (15-minute data-recording interval) sediment monitoring to characterize incoming and outgoing sediment flux during reservoir operations at two sites on Muddy Creek. The high-resolution monitoring is being used to establish current rates of reservoir sedimentation, support USBR sediment transport and storage models, and assess the viability of water-storage recovery in Paonia Reservoir. These sites are equipped with in situ, single-frequency, side-looking acoustic Doppler current meters in conjunction with turbidity sensors to monitor sediment flux. This project serves as a demonstration of the capability of using surrogate techniques to predict suspended-sediment concentrations in small streams (less than 20 meters in width and 2 meters in depth). These two sites provide the ability to report near real-time suspended-sediment concentrations through the U.S. Geological Survey National Water Information System (NWIS) web interface and National Real-Time Water Quality websites (NRTWQ) to aid in reservoir operations and assessments.

INTRODUCTION

The U.S. Bureau of Reclamation and local stakeholder groups are evaluating reservoir-management strategies within Paonia Reservoir. This small reservoir fills to capacity (live storage capacity is 15,553 acre-feet) each spring and requires approximately half of the snowmelt-runoff volume from its sediment-laden source waters, Muddy Creek (Bureau of Reclamation, 2014). Paonia Reservoir supports agriculture along the North Fork Valley. Reductions in water-storage capacity in the reservoir through time from sedimentation are affecting reservoir operation procedures (timing of reservoir fill and drawdown procedures to flush sediments interfering with gate operations) and may threaten continued operations of the reservoir. Storage losses also limit the availability of late-summer irrigation water for downstream diversions, especially during dry years when precipitation and natural sources of water become most scarce. Management strategies to mobilize sediments within the reservoir are in development. Active sediment removal techniques, such as dredging, are costly; therefore, an assessment of alternate management strategies, including passive removal techniques, is being evaluated. Sediment monitoring to characterize incoming and outgoing sediment flux during reservoir operations is needed to establish current rates of reservoir sedimentation, support USBR sediment transport and storage models, and assess the viability of water-storage recovery in Paonia Reservoir.

The U.S. Geological Survey (USGS), Bureau of Reclamation (USBR) and local stakeholder groups, including the North Fork Water Conservancy District and Fire Mountain Canal and Reservoir Company, are evaluating reservoir-management strategies with a goal of maintaining or increasing water-storage capacity within Paonia Reservoir. Two high-resolution (15-minute data recording interval) suspended-sediment monitoring sites were installed to monitor suspended-sediment flux into and out of Paonia Reservoir along Muddy Creek. The data collected supports the USBR hydrodynamic modeling of sediment transport and storage within, and downstream of, the reservoir.
The use of optical and acoustic surrogate techniques to characterize suspended-sediment flux can be highly effective in many river systems (Wood, 2014; Rasmussen *et al.*, 2009). Combinations of acoustic backscatter, acoustic attenuation, optical backscatter (turbidity), and seasonal effects are used to test the utility of these parameters as surrogates for suspended-sediment concentration on Muddy Creek. This project serves as a demonstration of the capability of these surrogate techniques to be used in small streams, less than 20 meters in width and 2 meters in depth, with suspended-sediment concentrations ranging from less than 10 to greater than 20,000 milligrams per liter (mg/L).

METHODS

Two USGS water-quality sites were established near Paonia Reservoir: Muddy Creek above Paonia Reservoir, CO – 385903107210800; and Muddy Creek below Paonia Reservoir, CO – 385626107212000) (fig. 1). Each site was instrumented with a 1.5 megahertz (MHz) side-looking Acoustic-Doppler Velocity Meter (ADVM) with voltage regulator, turbidity meter, automatic-pump sampler, and satellite telemetry. Suspended-sediment samples were collected from April 2013 to October 2013.

Suspended-sediment samples were collected using the equal-width-increment (EWI) method at 10 locations along the channel cross-section and were then composited for analysis (U.S. Geological Survey, 2006). Samples were collected using (1) a cable-suspended US D-74 depth integrated suspended-sediment sampler with quart glass bottle sampling container; or (2) a US DH-81 attached to US D-95 tetrafluoroethylene (TFE) cap and nozzles with a 3-foot wading rod and a 1-liter fluorinated ethylene propylene (FEP) bottle sampling container depending on flow conditions. Automatic-pump samples were collected in 1-liter polypropylene bottles. EWI and pump samples were sent to the USGS Iowa Water Science Center sediment lab for analysis (Guy, 1969). Approximately 15 EWI samples and 200 pump samples were collected at each site and were analyzed for concentration with additional grain-size analysis. Pump samples were analyzed for percent finer than 0.063 millimeters (mm), and suspended-sediment concentrations were adjusted using ‘box coefficients’ to correct these point-concentrations to represent cross-section average concentrations based on EWI/pump concentration pairs and streamflow (Edwards and Glysson, 1999). A full grain-size analysis was done on all EWI samples. Turbidity data were collected by using an optical turbidity meter using monochrome near infra-red LED light (780 – 900 nanometer wave length) with a detection angle of 90 degrees reported in formazin nephelometric units (FNU). The meter was operated and the data processed according to guidelines described in Wagner *et al.* (2006). Additional post-processing of the turbidity record was done to correct erroneous turbidity values, typically from fouling from filamental algae. A calibration check was completed in the lab after the instrument was removed for the season and a calibration drift correction was applied if necessary.

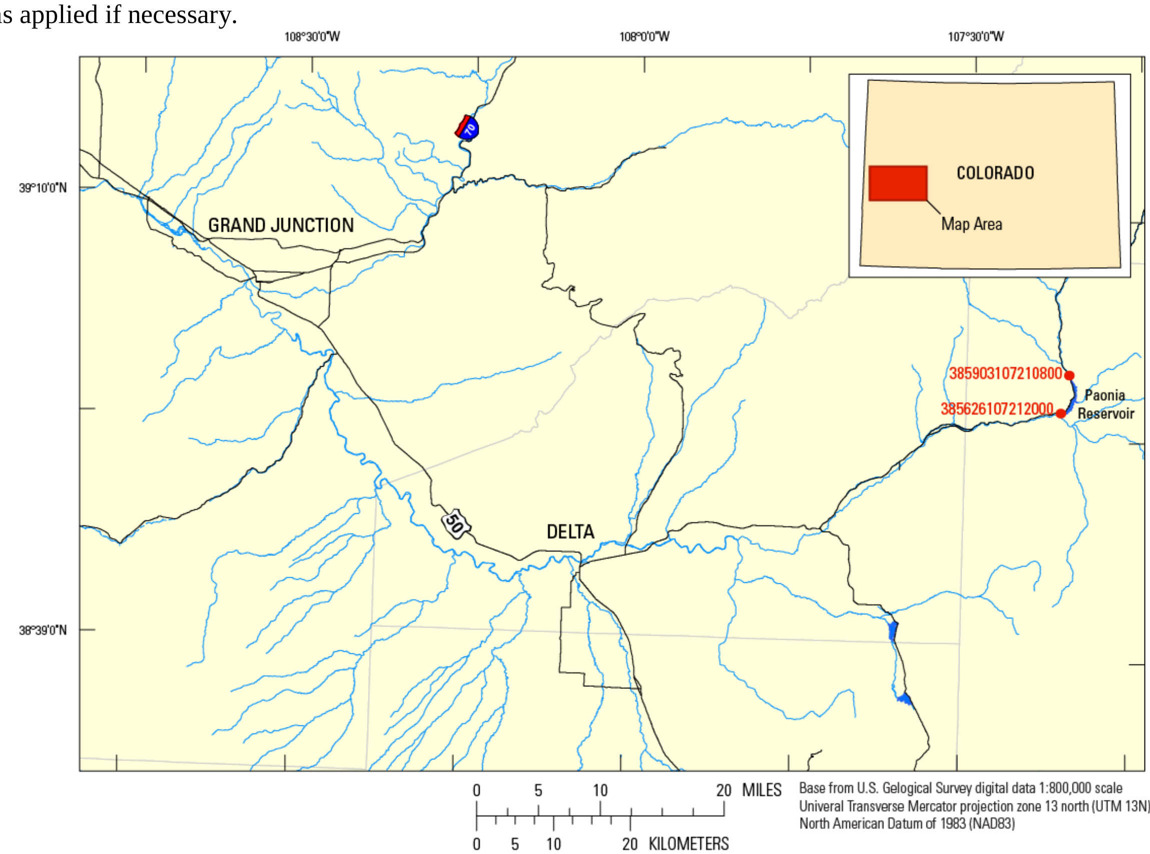

Figure 1. Map showing the location of Paonia Reservoir, and the location of USGS water-quality stations and station numbers in the North Fork Gunnison River Basin, in Western Colorado.

The multi-cell acoustic data collected by the ADVM (1,500 MHz side-looking instrument, 2.25–meter blanking distance along beam, 10 cells, 0.50-meter cell size along beam, 25° beam angle) are post-processed in a series of steps. During the deployment of the instrument, it became necessary to reconfigure the blanking distance to a length of 0.75-meters (along the beam) on August 29th in order to characterize the high-sediment concentrations associated with late-summer monsoon rain events. This was necessary because of excessive acoustic signal losses owing to the high sediment concentrations. Calculations for corrected acoustic backscatter and acoustic sediment attenuation followed the methodology outlined in Topping *et al.* (2004; 2006), Wright *et al.* (2010), and Wood and Teasdale (2013). Acoustic backscatter was corrected for losses including beam spreading (Downing *et al.*, 1995), fluid absorption (Urick, 1975), and near-field corrections (Downing *et al.*, 1995) resulting in a “fluid-corrected backscatter” profile across the 10-cell ensonified volume. The sediment attenuation was calculated from the slope of the fluid-corrected backscatter profile and represents transmission losses due to scattering, absorption, and attenuation due to sediment effects (Urick, 1975). Removing the losses from sediment attenuation from the “fluid-corrected backscatter” yields a “normalized-acoustic backscatter.” Sediment attenuation and the average “normalized-acoustic backscatter” have been used in other studies to represent the suspended-silt-and-clay (fines) and suspended-sand portions of the suspended-sediment concentrations, respectively (Topping *et al.*, 2004; 2006, Wright *et al.*, 2010; Wood and Teasdale, 2013).

Suspended- sediment concentration predictions for the two sites were used to calculate the incoming and outgoing suspended-sediment load at Paonia Reservoir. A total suspended-sediment and suspended fines (<0.0625 mm) concentration and load were calculated at Muddy Creek above Paonia Reservoir, CO; and a total suspended-sediment concentration and load were calculated at Muddy Creek below Paonia Reservoir, CO. The suspended sand concentration and load (if present) was calculated as the difference between the total suspended-sediment concentration and load and the fine suspended-sediment concentration and load.

Above Paonia Reservoir: Muddy Creek above Paonia Reservoir, CO, is located approximately 1,000 m upstream of the reservoir (U.S. Geological Survey, 2014). The system is dynamic with large seasonal changes in streamflow and suspended-sediment concentration, especially during monsoonal-rain events. High suspended-sediment concentrations are common during the snowmelt-runoff period and late-summer monsoon season with suspended-sediment concentrations exceeding 20,000 mg/L.

A step-wise regression analysis was used to find the best-fit regression model based on normalized-acoustic backscatter, sediment attenuation (hereafter, *SedAtt*), turbidity (hereafter, *Turb*), and seasonality terms (Helsel and Hirsch, 2002). The final linear regression models for total suspended-sediment concentration and fine suspended-sediment concentration are:

$$\ln(totalSSC) = 4.7102 - 0.2261\ln(Q) + 0.7967\ln(SedAtt) + 0.6914\ln(Turb) + 3.3129(Sin) - 0.3699(Cos) \qquad (1)$$

$$\ln(finesSSC) = 4.2950 + 0.7987\ln(SedAtt) + 0.7776\ln(Turb) + 3.7232(Sin) - 0.5886(Cos) \qquad (2)$$

where *totalSSC* is the predicted total suspended-sediment concentration, in milligrams per liter (mg/L); *finesSSC* is the predicted suspended-sediment concentration for grain sizes less than 0.063 mm, in mg/L; *Q*, is streamflow, in cubic feet per second; *SedAtt* is the sediment attenuation, in decibels per meter; *Turb* is the turbidity 0–1,600, in formazine nephelometric units (FNU); *Sin*, is the sine wave component and *Cos*, is the cosine wave component of a Fourier Series seasonality term. A bias correction factor (smearing) was applied to each transformed prediction (Helsel and Hirsch, 2002). The linear regression diagnostics for the regression models are presented in table 1 and table 2.

Table 1. Regression diagnostics for sites bracketing Paonia Reservoir along Muddy Creek, April–October, 2013.
[R^2, coefficient of determination; RSE, residual standard error, in milligrams per liter; BCF, bias correction factor; mm, millimeters; --, no data]

Sediment size	**Number of samples**	**R^2**	**RSE**	**BCF**
Muddy Creek above Paonia Reservoir – 385903107210800				
Less than 2.0 mm	146	0.97	1.35	1.045
Less than 0.063 mm	146	0.98	1.28	1.031
Muddy Creek below Paonia Reservoir – 385626107212000				
Less than 2.0 mm	141	0.99	13.0	--

Table 2. Variance Inflation Factors for equations 1 and 2 at Muddy Creek above Paonia Reservoir, April–October, 2013.

[--, no data; *, VIF calculation excludes non-significant Cos term in Fourier Series seasonality term; ln(*Q*), natural logarithm of streamflow; ln(*SedAtt*), natural logarithm sediment attenuation; ln(*Turb*), natural logarithm turbidity; (*Sin*), sine component of Fourier Series; (*Cos*), cosine component of Fourier Series]

	Variance Inflation Factor (VIF)				
	ln(*Q*)	ln(*SedAtt*)	ln(*Turb*)	(*Sin*)	(*Cos*)
Equation 1*	1.2	2.3	2.6	2.8	--
Equation 2	--	2.2	2.6	3.2	1.5

Below Paonia Reservoir: Muddy Creek below Paonia Reservoir, CO, is located immediately downstream of Paonia Reservoir. The system is regulated and releases are governed by downstream water rights. The reservoir is filled in the spring during the snowmelt-runoff period and excess water spills over the spillway once the reservoir is at capacity. Releases during the summer and fall are from an elevated release structure (tower) within the reservoir. Due to the height and position of the tower in the reservoir dead pool, sand-sized sediments (0.063–2 mm) were not observed in waters leaving the reservoir in 2013.

A step-wise regression analysis was used to find the best-fit regression model based on backscatter, attenuation, turbidity, streamflow, and seasonality terms. The final linear regression model for total suspended-sediment concentration (very little sand was observed at this site, therefore no separate fine suspended-sediment model was needed) is:

$$totalSSC = 3.2215 + 0.5856(Turb) \tag{3}$$

where *totalSSC* is the predicted total suspended-sediment concentration, in mg/L, and *Turb* is the turbidity 0–1,600, in FNU. The linear regression model diagnostics are presented in table 1.

RESULTS

Above Paonia Reservoir: Predictions of total suspended-sediment are plotted against measured concentrations in figure 2. The regression analyses (eq. 1) indicates that for concentrations between 0 and 2,000 mg/L the predictions are very near the mean response; however, as the predicted concentration increases above 6,000 mg/L, greater error in the predictions are evident in the widening of the 95-percent confidence intervals (fig. 2B).

Overall, the predictions of total suspended-sediment concentration are near the mean response with a residual standard error of 1.35 mg/L (table 1), indicating that the loads calculated from the predictions are generally well defined (fig. 2). Additional sampling of conditions at higher concentrations in future years will provide improved characterization and opportunities for additional regression model refinement or continued validation of regression predictions.

The predicted fine suspended-sediment concentrations derived from equation 2 follow the same general trend as the total suspended-sediment concentrations. Predicted fine suspended-sediment concentrations below 2,000 mg/L are near the mean response with increases in error for predictions of greater concentrations. Similar to the predicted total suspended-sediment concentration, the relation of predicted and measured concentrations remains near the mean response with a residual standard error of 1.28 mg/L (table 1), indicating that the loads calculated from the predictions are generally well defined (fig. 3). Additional sampling of conditions at higher concentrations in future years will provide improved characterization and opportunities for additional regression model refinement or continued validation of regression predictions.

The total suspended-sediment concentrations vary throughout the year along with the grain size of the particles (fig. 4). Higher concentrations of total suspended sediment are observed in April and May during snowmelt runoff. During this period, larger portions of sand-sized particles are being suspended and mobilized. As the snowmelt period ends, in June, the total suspended-sediment concentration decreases rapidly and becomes much finer in grain size. Medium silt-sized to clay-sized particles dominate the system throughout much of the year. Large increases in total suspended-sediment concentration occur in the late-summer and early-fall months during monsoonal rains. These rain events produce the highest suspended-sediment concentrations of the year and are composed of silt-sized and clay-sized particles (figs. 4 and 5). Muddy Creek becomes very turbid during these events and concentrations of suspended sediments are great enough to impede the effectiveness of the surrogate sensors. As a result, during some periods of the year, the total suspended-sediment load was estimated due to obscured turbidity and acoustic signals. Estimates of missing data were made such that the shape of the concentration peaks matched observed conditions of previous concentration peaks following techniques described in Porterfield (1972).

The temporal variations in the fine suspended-sediment concentrations are very similar to those of the total suspended-sediment predictions. During the snowmelt period, however, the fine suspended-sediments contribute less to total concentration than the sand-sized sediments, and from June through October, suspended-sediment concentration is almost entirely composed of silt-and clay-sized particles (fig. 5).

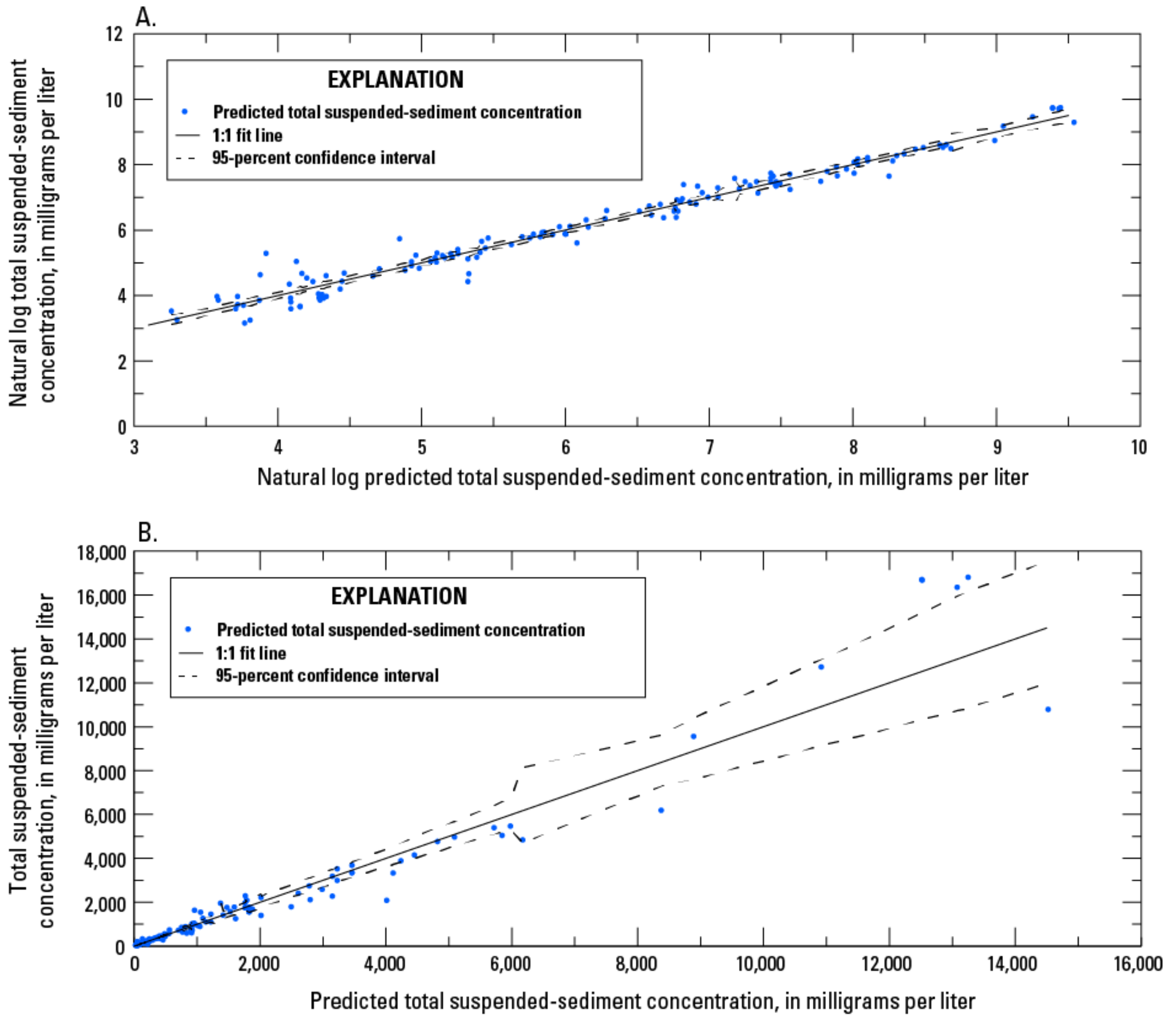

Figure 2. Relations between predicted and total suspended-sediment concentration with 95-percent confident interval for Muddy Creek above Paonia Reservoir in (A) logarithmic, (B) and normal space, April–October, 2013.

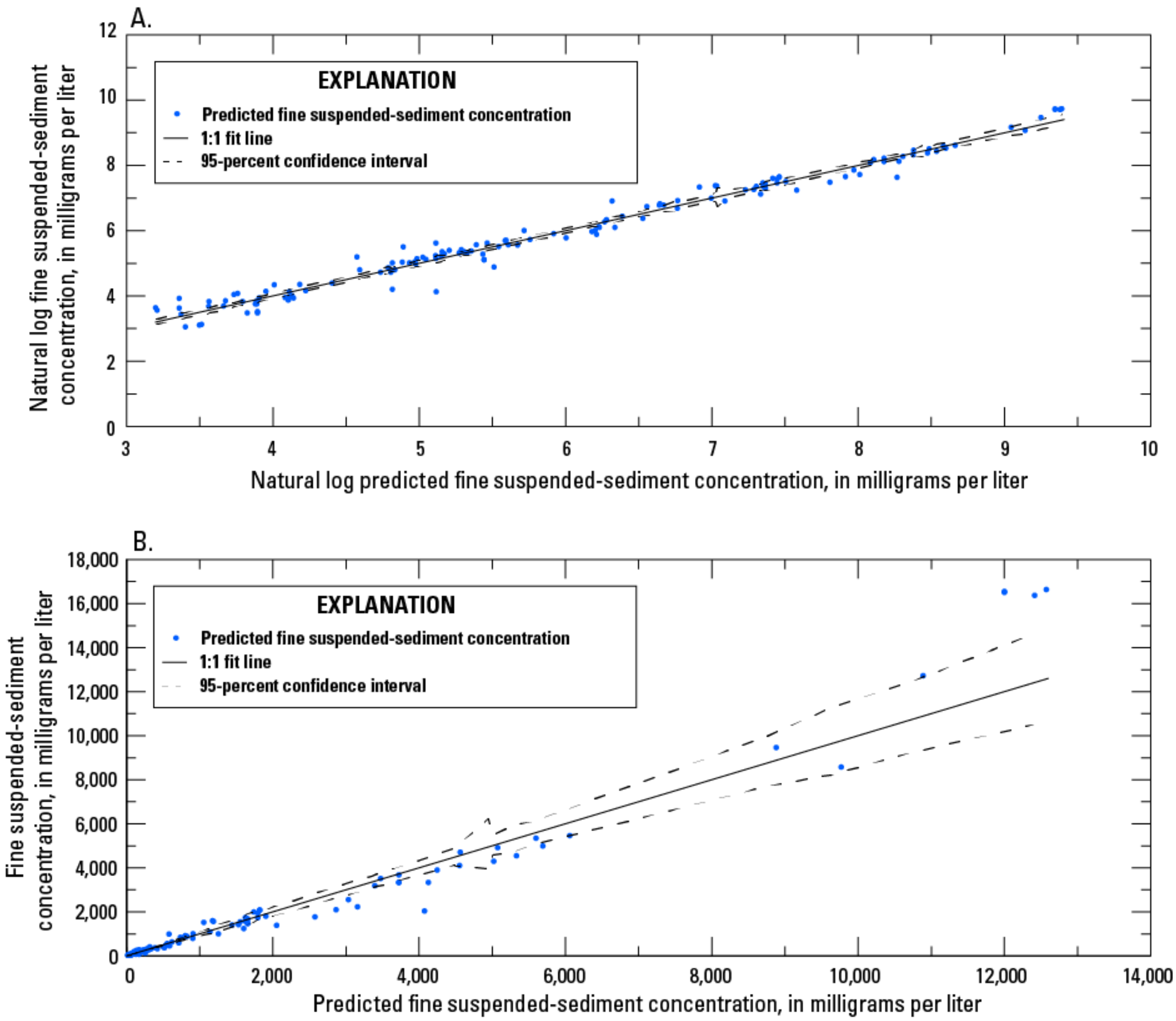

Figure 3. Relations between predicted and fine (grain size less than 0.063 millimeters) suspended-sediment concentration with 95-percent confident interval for Muddy Creek above Paonia Reservoir in (A) logarithmic, (B) and normal space, April–October, 2013.

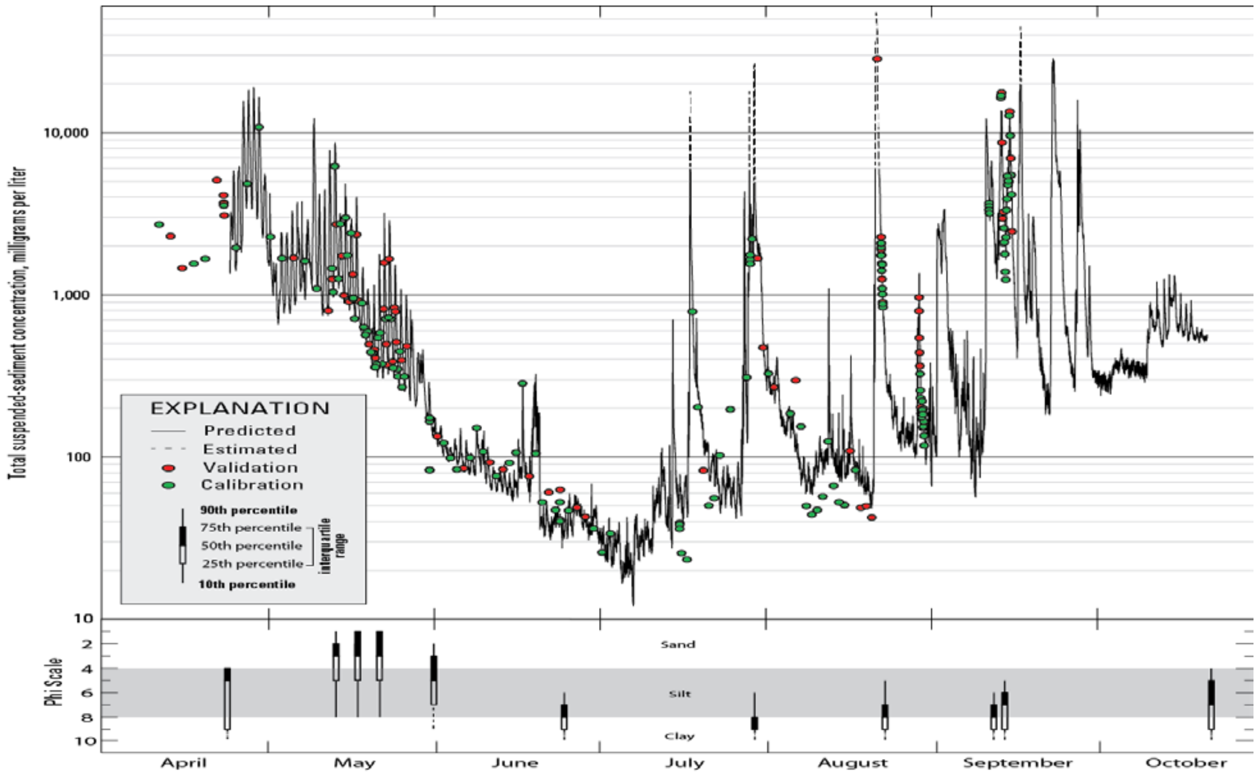

Figure 4. Predicted total suspended-sediment concentration with calibration data points, validation data points, and equal-width interval sample grain-size analyses for Muddy Creek above Paonia Reservoir, April–October, 2013.

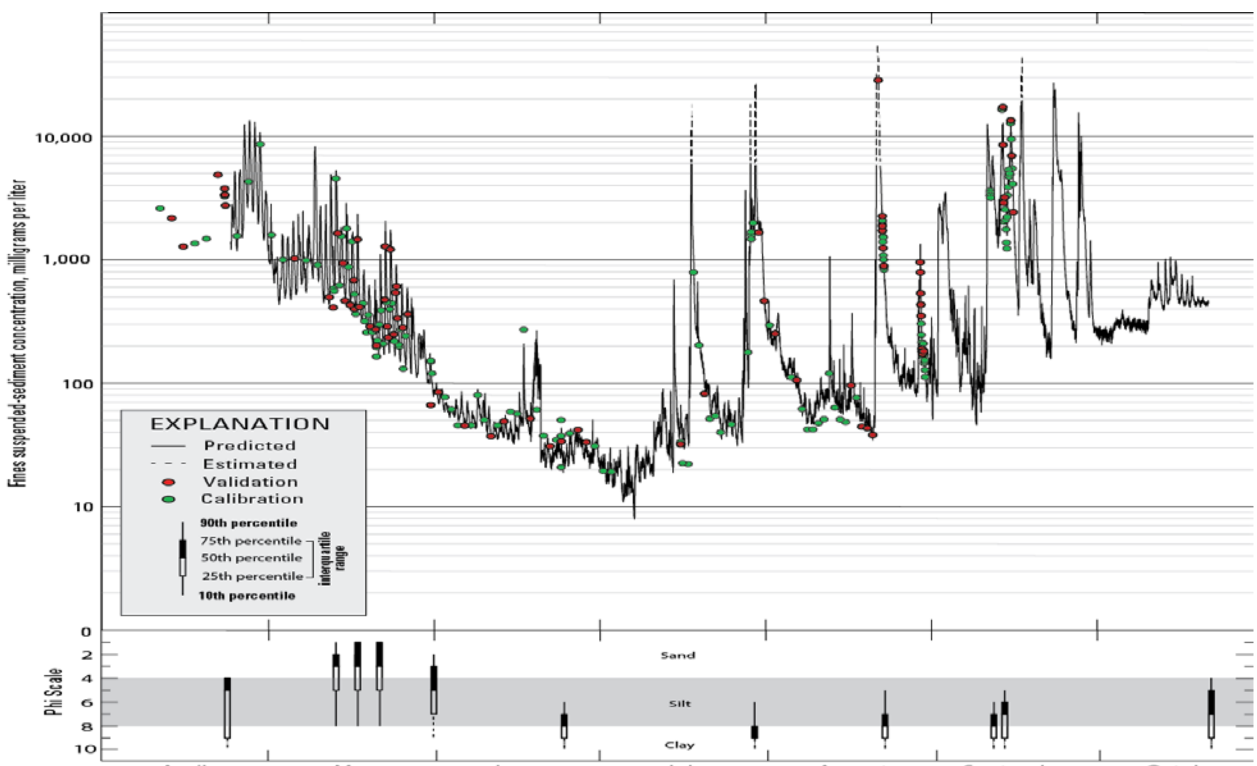

Figure 5. Predicted fine suspended-sediment concentration with calibration data points, validation data points, and equal-width interval sample grain-size analyses for Muddy Creek above Paonia Reservoir, April–October, 2013.

Below Paonia Reservoir: Predictions of total suspended-sediment concentrations are plotted against measured concentrations in figure 6. The predicted total suspended-sediment concentration from the regression analyses (eq. 3) indicates that the predictions scatter around the mean response with a residual standard error of 13.0 mg/L (table 1), indicating that the loads calculated from the predictions are well defined. The regulated nature of flows downstream of the reservoir result in less variability than suspended-sediment concentrations observed at the upstream site (fig. 7).

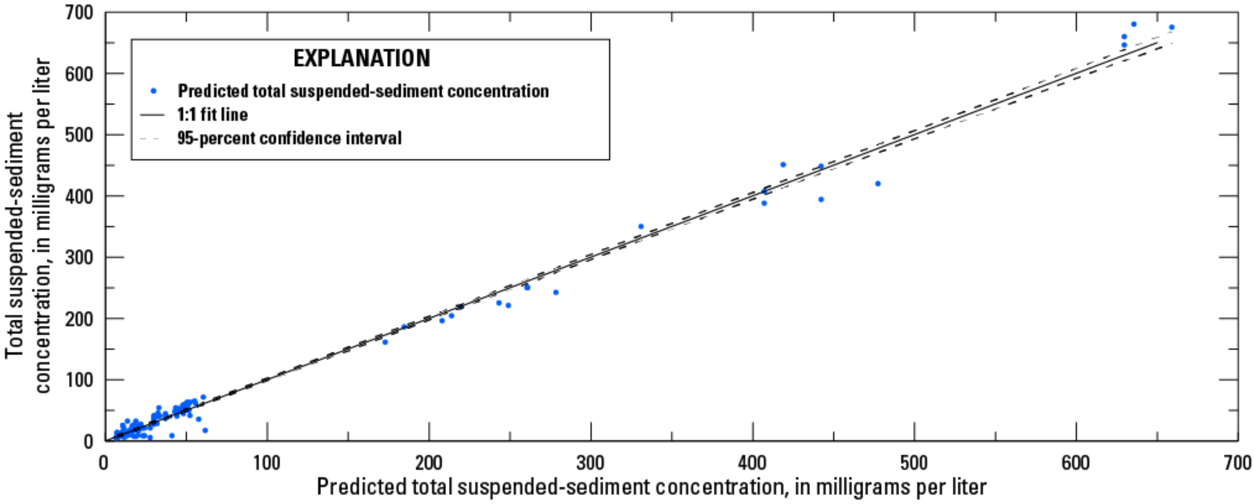

Figure 6. Relations between predicted and fine suspended-sediment concentration with 95-percent confident interval for Muddy Creek below Paonia Reservoir, April–October, 2013.

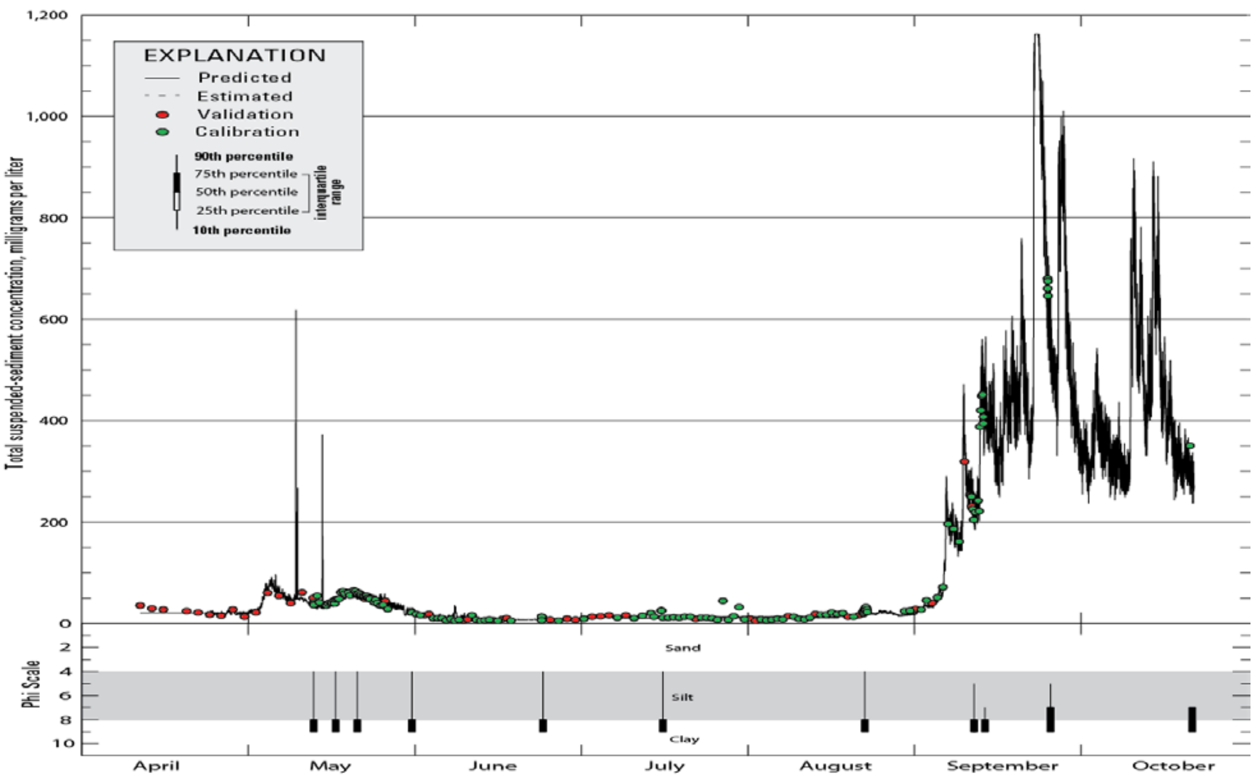

Figure 7. Predicted total suspended-sediment concentration with calibration data points, validation data points, and equal-width interval sample grain-size analyses for Muddy Creek below Paonia Reservoir, April–October, 2013.

Generally, total suspended-sediment concentrations below Paonia Reservoir remain minimal in comparison to the upstream site and are dominated by silt-sized and clay-sized sediments. Rapid, short-duration increases in total suspended-sediment concentration occur in May and are associated with the opening and closing of the gate on the outlet tower that controls water releases. In June, the reservoir is typically at full capacity and additional streamflow entering the reservoir exits through a combination of releases and spills. Reservoir geometry and sediment residence under these conditions trap much of the sediment entering the reservoir. When water levels in Paonia Reservoir are drawn down (typically by the end of the summer and early fall) greater suspended-sediment concentrations are observed as Muddy Creek meanders through newly exposed reservoir sediment deposits (fig. 7).

Sediment storage: A mass-balance analysis of incoming against outgoing total suspended-sediment load, calculated using the selected surrogate models, is shown in figure 8. Sediment monitoring in 2013 shows that approximately 75,000 tons of suspended sediment entered the reservoir (red line), and approximately 4,000 tons of suspended sediment was transported downstream (blue line). The majority of the total suspended sediment entering the reservoir occurred during snowmelt-runoff (~62,000 tons, in the light-yellow shaded region) with an additional increase occurring during the monsoon season (~12,000 tons, in the dark-yellow shaded region). The suspended-sand load (green line) also occurs during the snowmelt period with little sand being mobilized in suspension after the snowmelt period ends. The suspended-sediment load leaving the reservoir (4,000 tons) occurs later in the year and represents approximately 5 percent of the incoming load.

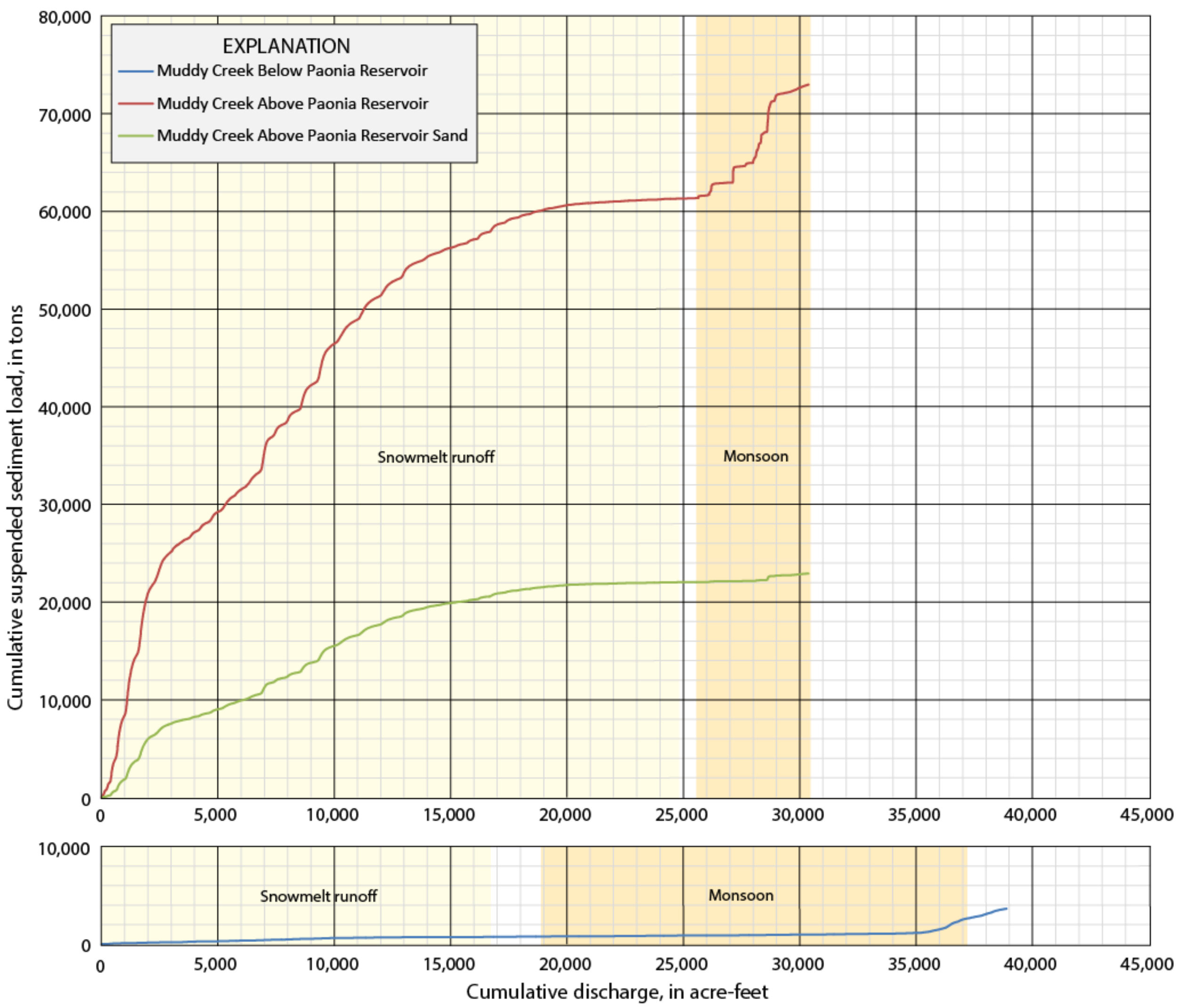

Figure 8. Mass curve of cumulative suspended-sediment load relative to cumulative discharge at Muddy Creek above Paonia Reservoir and Muddy Creek below Paonia Reservoir, April–October, 2013.

DISCUSSION

The development of regression models using suspended-sediment surrogates to characterize suspended-sediment concentration and flux is helpful in developing a management strategy to protect existing water storage and potentially increase lost storage due to sediment infilling. Based on the results from one year of observation and analyses, there is a substantial imbalance in the sediment transported into and out of Paonia Reservoir along Muddy Creek. The incoming suspended-sediment load consists of some finer sands, but silt-sized and clay-sized sediments dominate the suspended system. Most if not all of the sand portion of the incoming suspended load appears to be deposited in the reservoir. The outgoing suspended-sediment load appears to be dominated by clay-sized sediments with little to no fine-or-medium sand moving downstream of the reservoir. Differences in grain size of these sediments can be important to reservoir managers during calculation of storage-volume loss due to differences in the porosity (void spaces) associated between sediment deposits of differing grain-sizes. Additionally, the difference in grain size can be important when considering reservoir modifications to decrease retention of sediments (reservoir trap efficiency).

Using optical and acoustic high-resolution sediment monitoring to characterize suspended-sediment at Paonia Reservoir has shown to be an effective metric for evaluation of reservoir operational strategies. In 2013, substantial differences between incoming and outgoing total suspended-sediment loads indicate that mitigation efforts were largely unsuccessful. This is due, in part, to perceived limitations in the 2012 snowpack, and concerns that insufficient runoff may result in water shortages. This meant that reservoir operations during the early portion of the snowmelt runoff period were not used for sediment-flushing strategies. These flushing strategies include an approach where operations target delayed capture of later season flows for reservoir filling. The USBR hypothesizes that this operational strategy may help remove exposed reservoir sediments (while the reservoir storage level is near operational dead pool and much of the reservoir bed is exposed) because Muddy Creek is able to remobilize these deposited sediments and transport them towards the outlet tower. Reservoir filling began immediately in 2013, however, limiting options to flush sediments until late fall when reservoir levels were again exposing these sediments as water level in the reservoir fell. Additional modifications to the outlet tower may be necessary if mobilization of sand or coarser sediment is desired.

Successful monitoring of suspended sediment within this system using surrogates is useful in determining the type of management strategies that would be effective in increasing reservoir capacity or decreasing the present rate of capacity loss. Use of turbidity as a suspended-sediment surrogate within a simple-linear regression was appropriate for this study for conditions where sand-sized particles were absent. When present, sand-sized particles were not well characterized by changes in turbidity and incorporation of additional parameters (sediment attenuation, seasonality, and/or streamflow) was necessary. Exploring the relation between acoustic backscatter, sediment attenuation, turbidity, and seasonality effects has allowed for a more complex linear regression model to be developed that is effective in predicting suspended-sediment concentrations. It should be noted, however, that the regressions developed to date could change as subsequent data are incorporated into the regression under flow and reservoir management strategies of future years. Differences in seasonal streamflow patterns or reservoir management may change which combination of variables are statistically significant in predicting suspended-sediment concentrations in future monitoring efforts. Future plans for these two suspended-sediment monitoring stations include incorporation of near real-time reporting of suspended-sediment concentrations through the U.S. Geological Survey National Water Information System (NWIS) web interface (*http://watedata.usgs.gov.nwis*) and National Real-Time Water Quality websites (NRTWQ; *http://nrtwq.usgs.gov*) to aid real-time reservoir operations and assessments.

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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