COMPARISON OF TURBIDITY TO MULTI-FREQUENCY SIDEWAYS-LOOKING ACOUSTIC-DOPPLER DATA AND SUSPENDED-SEDIMENT DATA IN THE COLORADO RIVER IN GRAND CANYON

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Abstract Water clarity is important to biologists when studying fish and other fluvial fauna and flora. Turbidity is an indicator of the cloudiness of water, or reduced water clarity, and is commonly measured using nephelometric sensors that record the scattering and absorption of light by particles in the water. Unfortunately, nephelometric sensors only operate over a narrow range of the conditions typically encountered in rivers dominated by suspended-sediment transport. For example, sediment inputs into the Colorado River in Grand Canyon caused by tributary floods often result in turbidity levels that exceed the maximum recording level of nephelometric turbidity sensors. The limited range of these sensors is one reason why acoustic-Doppler profiler instrument data, not turbidity, has been used as a surrogate for suspended-sediment concentration and load of the Colorado River in Grand Canyon. However, in addition to being an important water-quality parameter to biologists, turbidity of the Colorado River in Grand Canyon has been used to strengthen the suspended-sediment record through the process of turbidity-threshold sampling; high turbidity values trigger a pump sampler to collect samples of the river at critical times for gathering suspended-sediment data. Turbidity depends on several characteristics of suspended sediment including concentration, particle size, particle shape, color, and the refractive index of particles. In this paper, turbidity is compared with other parameters coupled to suspended sediment, namely suspended-silt and clay concentration and multi-frequency acoustic attenuation. These data have been collected since 2005 at four stations with different sediment-supply characteristics on the Colorado River in Grand Canyon. These comparisons reveal that acoustic attenuation is a particularly useful parameter, because it is strongly related to turbidity and it can be measured by instruments that experience minimal fouling and record over the entire range of turbidity encountered in the Colorado River in Grand Canyon. Relating turbidity to acoustic attenuation and suspended-silt and clay concentration provides an additional benefit in that data outliers are revealed that likely identify inflow events from anomalous sources with unusual sediment characteristics.

INTRODUCTION

The completion of Glen Canyon Dam in 1963 resulted in a drastic reduction in the suspended-sediment supply of the Colorado River. Specifically, the annual supply of suspended sediment to the Colorado River in Grand Canyon is now about 5 to 15% of the pre-dam supply, depending on the specific reach of the Colorado River downstream from the dam. This reduced sediment supply has resulted in an overall decrease in suspended-sediment concentration and a clearer Colorado River in Grand Canyon than before the dam was built. Most of the suspended sediment is currently delivered to the Colorado River by two tributaries below the dam, the Paria River and the Little Colorado River (fig. 1) (Topping et al., 2000). Although completion of the dam drastically reduced the annual supply of sediment, suspended-sediment concentration downstream from the Paria River can be as high as it was prior to construction of the dam during large floods on tributaries. Thus, suspended-sediment concentrations, and therefore turbidity, vary over a larger range now than they did prior to the completion of Glen Canyon Dam. In order to aid in the management of the reduced and more highly time-varying supply of sediment, extensive monitoring of suspended sediment is conducted by the U.S. Geological Survey at four stations in Grand Canyon (fig. 1). Monitoring turbidity, which is inversely related to water clarity, in the study area is a part of this effort.

Turbidity is an important water-quality parameter to fisheries biologists in Grand Canyon. Native fish in Grand Canyon have declined in numbers, probably due in part to competition and predation from non-native fish (Andersen, 2007). Some of these non-native fish are visual feeders and thus water clarity is likely to influence their ability to visually detect and catch fish prey (Yard et al., *in review*). Turbidity monitoring in the study area is also used to improve the suspended-sediment record; high turbidity levels automatically trigger a pump sampler to collect event-based suspended-sediment samples (turbidity-threshold sampling). During periods of tributary floods, high concentrations of suspended silt and clay often result in turbidity levels that exceed the maximum recording level of nephelometric turbidity sensors. Thus, the primary purpose of this paper is to evaluate the utility of using surrogate technologies for turbidity, such as acoustic attenuation measured using sideways-looking acoustic-Doppler profilers (ADPs), to measure turbidity over a wider range of conditions than is possible using nephelometric turbidity sensors. The secondary purpose of this paper is to compare the turbidity data collected in the study area with multi-frequency acoustic-attenuation data and suspended-sediment data to evaluate whether these datasets can be used in conjunction to provide a better understanding of the physical properties of the suspended sediment in the study area.

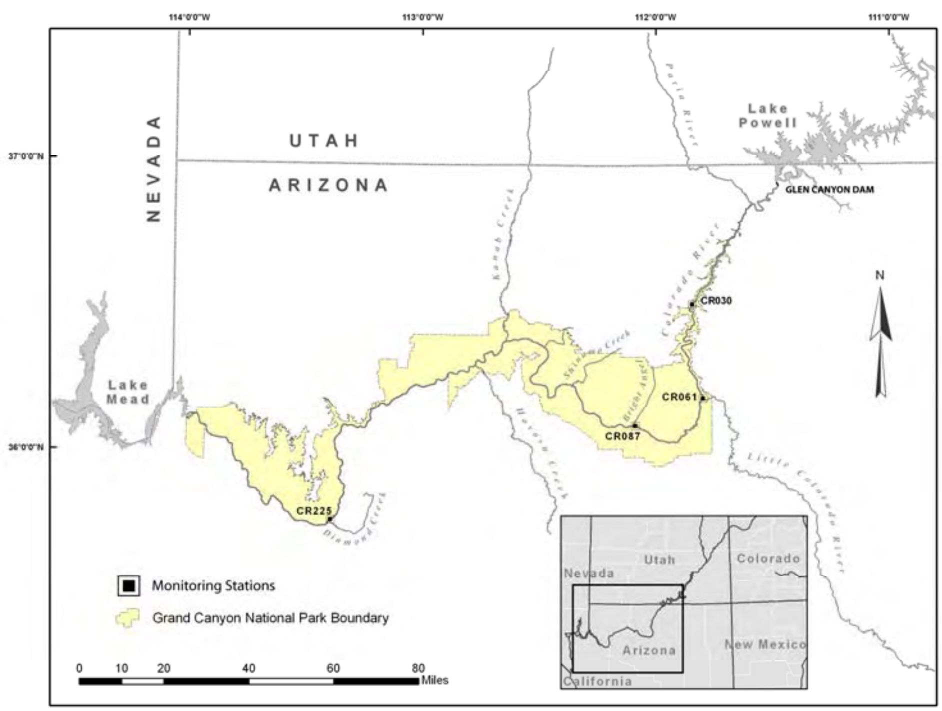

Figure 1 Map of the study area in Grand Canyon, Arizona showing the location of the monitoring stations described in this report (Refer to table 1 for station names).

Table 1 Monitoring stations (referenced in this study) for turbidity, ADP data, and suspended-sediment data on the Colorado River. The 1-MHz ADP and suspended-sediment data are concurrent with the turbidity data; collection of the 2-MHz ADP data postdates the start of the collection of the turbidity data except at the CR087 station. River miles are distances downstream from Lees Ferry; Glen Canyon Dam is 15 miles upstream from Lees Ferry.

Station name (position relative to Paria River and Little Colorado River)	**Station identifier**	**Start of turbidity record**	**Start of 2-MHz ADP record**
Colorado River near river mile 30 (between Paria River and Little Colorado River)	CR030	Mar. 21, 2006	Aug. 23, 2007
Colorado River near river mile 61 (between Paria River and Little Colorado River)	CR061	Sep. 28, 2005	Feb. 26, 2007
Colorado River near river mile 87 (below Little Colorado River)	CR087	Jan. 29, 2008	Previous to start of turbidity record
Colorado River near river mile 225 (below Little Colorado River)	CR225	Feb. 15, 2006	Dec. 18, 2007

METHODS

Instrumentation and Operation Turbidity is an expression of the scattering and absorption of light in water, rather than the transmission of light in a straight line (American Public Health Association, 2005). Turbidity in water is caused by suspended and dissolved matter, such as clay, silt, sand, finely divided organic and inorganic matter, soluble colored organic compounds, and plankton and other microscopic organisms (American Public Health Association, 2005). Several different types of instruments can be used to measure turbidity. Because turbidity readings can vary substantially among instrument types, reporting units of turbidity that identify the instrument type are recommended (Anderson, 2005). During this study, turbidity was measured using the model 6136 turbidity probe, manufactured by YSI Incorporated[1]. This sensor, which is reported in Formazin Nephelometric Units (FNU), has a single light source in the near-infrared range (860 ± 30 nanometers), with a single detector oriented 90 degrees from the incident light path. The sensor is equipped with a mechanical wiper to reduce fouling.

Deployment of Instruments At each of the four monitoring stations, the water-quality instruments were suspended in the river at or near the river bank. Turbidity was recorded at all stations every 15 minutes in order to capture changes in turbidity caused by dam operations or flooding events in upstream tributaries. The instruments at the four stations were serviced at 1- to 6-month intervals following protocols outlined by Wagner et al. (2006).

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[1] Use of brand and firm names is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey.

Data Processing Because of instrument fouling, anomalous spikes in the data, and the limited range of the turbidity probes, processing the turbidity data was time consuming. It was useful and often necessary to compare the turbidity data with independent readings from other sensors to determine whether the turbidity data were valid. The turbidity data were verified, adjusted, or omitted based on:

- Determining the occurrence of fouling of the turbidity probe
- Determining the occurrence of calibration errors or electronic drift (determined by calibration) of the turbidity probe
- Differentiating valid turbidity events from sudden spikes in the turbidity data that were not reflective of average river conditions
- Eliminating data that reached the maximum recording level of the turbidity probe
- Comparing the data with turbidity data from adjacent monitoring stations in the study area
- Comparing the turbidity data with data from acoustic instruments deployed at the same monitoring station

At all of the monitoring stations in the study area, single high spikes in the turbidity data were fairly common. These turbidity spikes were likely caused by large particles or natural debris briefly travelling in the measuring field of the turbidity probe or by a malfunction in the probe, such as the wiper obscuring the optics during a measurement. Because they almost certainly did not represent the average conditions of the river at the monitoring station, these sudden spikes in the turbidity data were identified and omitted from the database, using an algorithm designed to eliminate a particular 15-minute turbidity value if it deviated excessively from the hourly mean surrounding it.

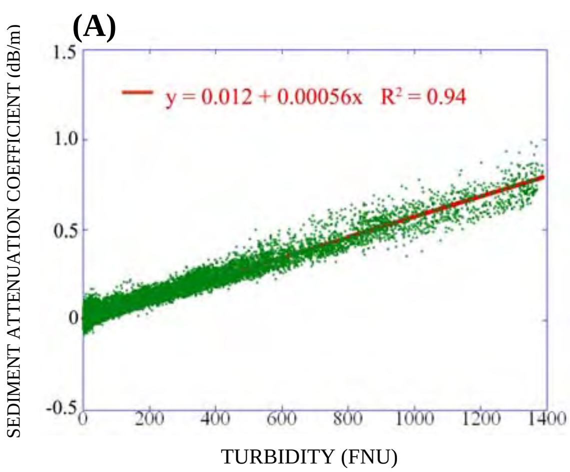
The YSI turbidity probes used in the study had a maximum recording level ranging from approximately 1,100 FNU to 2,300 FNU (identified on time-series graphs), most commonly ranging from 1,100 FNU to 1,500 FNU. Data at the maximum recording level were omitted from the record because their actual turbidity values were unknown. The maximum recording level of each individual turbidity probe differed, and the maximum recording level changed somewhat when the probe was calibrated. Thus, it was necessary to review all of the data carefully to determine when the maximum recording level was reached and hence to remove these data points from the dataset.

Comparison of trends in the time series of turbidity data between monitoring stations is possible because turbidity in the study area is influenced primarily by silt and clay inputs from only two tributaries, the Paria River and the Little Colorado River (fig. 1) (Topping et al., 2000). In the study area, the Colorado River typically has relatively low turbidity, unless either of these tributaries flood. The high turbidity pulse resulting from the flooding of these two tributaries can be monitored as it moves to downstream stations.

Sideways-looking acoustic-Doppler profilers, of varying frequencies, were deployed at all four monitoring stations and recorded data at the same 15-minute intervals as the turbidity instruments. The sediment attenuation coefficient, calculated from the ADP data, is linearly related to the turbidity data, and the ADP instruments are not prone to fouling. Thus, the sediment attenuation coefficient data were useful to distinguish valid turbidity data from erroneous turbidity caused by fouling of the instrument, non-representative high spikes in the turbidity data, and turbidity data at the maximum recording level.

DATA SUMMARY

<u>Relation between Turbidity and Acoustic Data</u> Two sideways-looking acoustic-Doppler profilers with different frequencies, 1 and 2 MHz, were deployed previous to the turbidity probes at each of the four monitoring stations in the study area except where noted in table 1. A third 600-kHz instrument was deployed previous to the turbidity probe at the CR087 station. Data from these instruments have been used primarily to measure the concentration of the suspended sand, and the suspended silt and clay, as well as the median grain size of the suspended sand (Topping et al., 2007). The sediment attenuation coefficient, a component of the sonar equation (Urick, 1975), is calculated from the ADP data by correcting for transmission losses due to beam spreading, and attenuation due to absorption by the water, which in the study area varies primarily with water temperature (Topping et al., 2006). The sediment attenuation coefficient is linearly related to the suspended-silt and clay concentration (Topping et al., 2007). Because silt and clay are the main contributors to the turbidity of the Colorado River in the study area, the sediment attenuation coefficient is also linearly related to turbidity, with the slope of the relation directly proportional to the ADP instrument frequency (fig. 2).



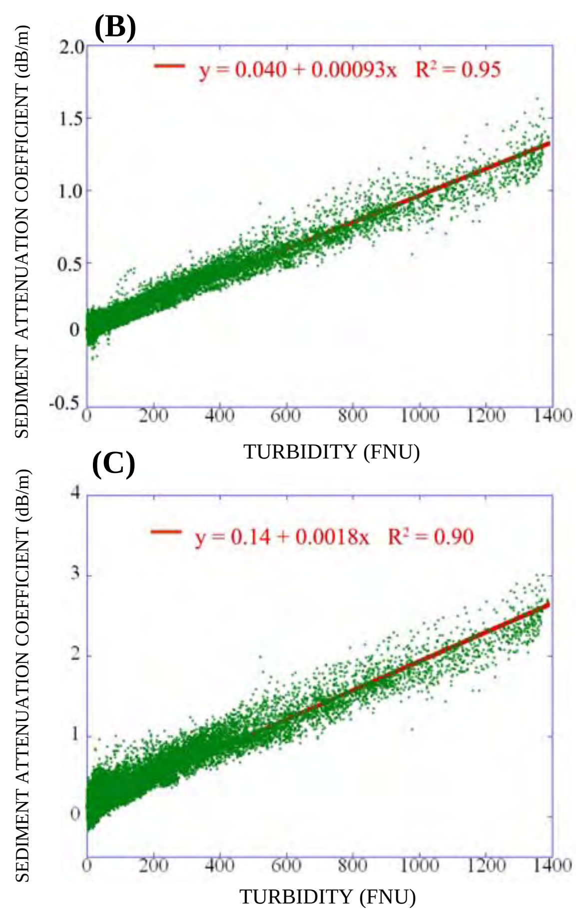


Figure 2 Relation between turbidity and the sediment attenuation coefficient at monitoring station CR087 from 3 instruments: **(A)** 600-kHz Nortek Aquadopp, **(B)** 1-MHz Nortek EasyQ, and **(C)** 2-MHz Nortek EasyQ. Turbidity was measured with YSI model 6136 probes.

The plots of the sediment attenuation coefficient and turbidity from some of the monitoring stations contain multiple outliers from the same date. Several outliers from July 24, 2007, are above the regression line on the plots from both the CR030 and CR061 monitoring stations (fig. 3). The July 24, 2007, outliers are likely to represent valid turbidity and sediment attenuation coefficient values because they show the same trend at both monitoring stations, recorded from two different turbidity probes and three different ADP instruments. These outliers were most likely caused by a tributary flooding event from a drainage located upstream of the CR030 station (fig. 1), from a source other than the Paria River (which did not flood during the days prior to July 24, 2007), resulting in an input of silt and clay with different physical (that is, acoustic or optical) properties than the typical tributary flooding event.

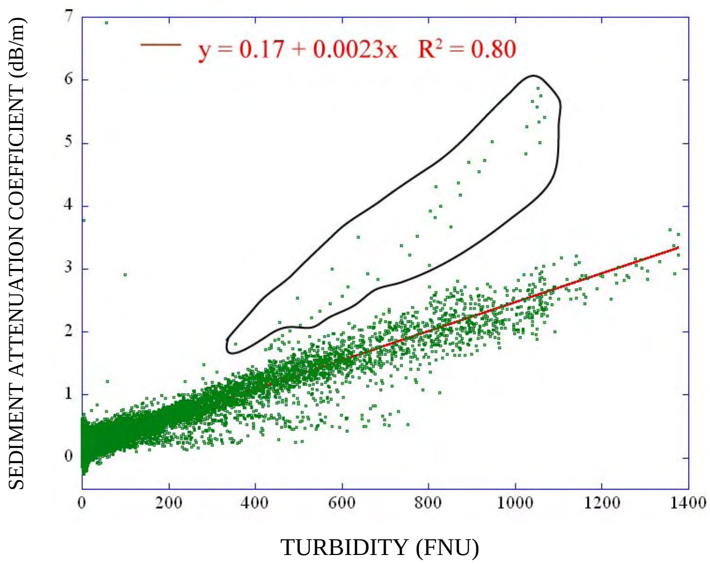


Figure 3 Relation between turbidity and the sediment attenuation coefficient from a 2-MHz Nortek EasyQ at monitoring station CR061. The circled data are from July 24, 2007.

Relation between Turbidity and Silt and Clay Concentration Turbidity at the individual monitoring stations over the period of record (table 1) was plotted against suspended-silt and clay concentrations analyzed from samples collected by ISCO pump samplers, as well as fewer samples from Equal-Width-Increment (EWI) measurements (CR030 and CR061 stations) and Equal-Discharge-Increment (EDI) measurements[2] (CR087 and CR225 stations) (fig. 4). The data were not log10 transformed because residual plots show increased curvature of the log-transformed data (Rasmussen et al., 2009). Furthermore, residual plots and a Breusch-Pagan test (Breusch and Pagan, 1979) of the data show significant heteroscedasticity of both the log-transformed and untransformed data. The relation between turbidity and suspended-sediment concentration can vary significantly between flooding events (Lewis, 2002), which may explain some of the variability in the data (fig. 4). A tighter relation between turbidity and suspended-silt and clay concentration may be established at the monitoring stations when additional samples are analyzed for silt and clay concentrations, especially samples collected during periods of higher turbidity.

[2] EWI and EDI measurements are described in Edwards and Glysson (1999).

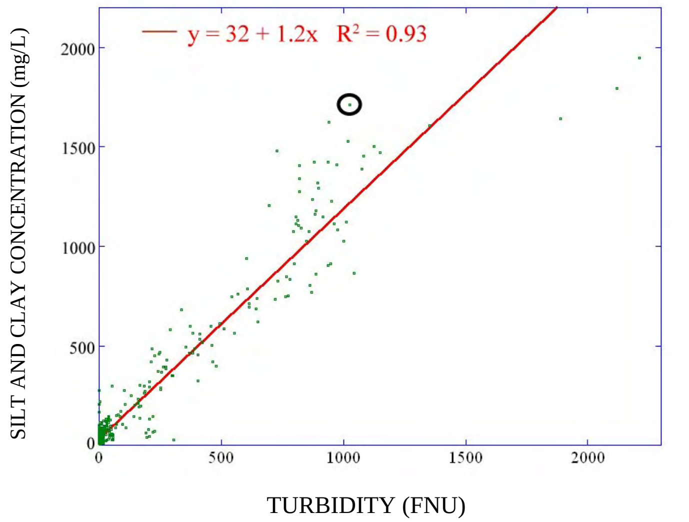


Figure 4 Relation between turbidity and suspended-silt and clay concentration at monitoring station CR061. The circled data point is from July 24, 2007.

Only one data point on the silt and clay concentration - turbidity plot from station CR061 (fig. 4) corresponds to the July 24, 2007, outliers on the sediment attenuation coefficient - turbidity plot (fig 3). This data point (fig. 4) is difficult to define as an outlier because of the non-normal distribution of the data (Helsel and Hirsch, 2002). Regardless, the distribution of the July 24, 2007, data from both plots (figs. 3 and 4) suggests that turbidity readings on July 24, 2007, from station CR061 are low relative to both the sediment attenuation coefficient and silt and clay concentration. A likely explanation for the anomalous data is that the sediment causing the turbidity event came from a different source than usual[3], perhaps with an atypical particle size, density, and/or color. However, turbidity and the acoustic data are both affected by the physical properties of the sediment, and further analysis is necessary to determine the specific cause of the anomalous data.

DISCUSSION AND CONCLUSIONS

Because of the design of the turbidity probes, and the nature of the suspended silt and clay in the study area, monitoring and processing turbidity in the study area had limitations. Despite these limitations, significant benefits and conclusions can be drawn from the turbidity data in the study area, especially when coupled with other data sources.

Assessing turbidity in the study area using the YSI model 6136 turbidity probe had two major limitations: the extensive amount of time required to process the data, and the range of data that the probes were not able to record. Processing the data was time consuming, especially correcting for high spikes in the data, fouling of the turbidity sensor, and data recorded at the maximum recording level; it took several months to process 15 years of data. Turbidity at the monitoring stations was above the maximum recording level of the turbidity probes an average of only 4% of the time (table 2). However, these relatively infrequent periods represent

[3] Most of the suspended sediment passing this station is supplied by the Paria River.

important events when the sediment load was the greatest. Based on the highest sediment attenuation coefficient values recorded at the monitoring stations, turbidity in the study area reached a maximum of approximately 17,000 FNU at the CR030 station and 20,000 FNU at the CR225 station during the period of record (extrapolating from the linear relation between turbidity and the sediment attenuation coefficient). These maximum turbidity values equate to a silt and clay concentration of approximately 23,800 mg/L at the CR030 station and 24,000 mg/L at the CR225 station. Based on these maximum turbidity values, approximately 90% of the range in turbidity in the study area was not recorded by the turbidity probes. However, some turbidity instruments are designed to measure a larger range of turbidity values (Sadar, 1998). For instance, optical backscatter sensors (OBS) measure turbidity up to 10,000 Nephelometric Turbidity Units (NTU). One drawback to OBS sensors is that they are not equipped with a mechanical wiper and are thus more prone to fouling if not serviced frequently, resulting in data which often cannot be corrected and must be discarded (Downing, 2006). This is of concern because other optical sensors in the study area not equipped with a wiper (laser-diffraction instruments) have become fouled (due to biological growth on the lens) in less than one month after visitation. Some of the monitoring stations in the study area are remote and several months may elapse between visits. Another drawback to changing turbidity instruments is that data from different types of turbidity instruments are often difficult to compare, because of differences in optical design, with the result that they are essentially measuring different partitions in the water (often with differing reporting units) (Downing, 2006; Uhrich and Bragg, 2003). In fact, turbidity readings of the same water can differ between instrument types by a factor of two or more (Anderson, 2005), and it is not always possible to calculate equivalent readings among instrument types without locally derived conversions specific to the water and sediment matrix of interest.

Table 2 Summary of turbidity statistics over the period of record for all monitoring stations. Percent of missing data represents the percentage of days of missing data over the station's period of record (table 1).

Station Name	**Station identifier**	**Percent of missing data**	**Percent of data that is above the maximum recording level of the turbidity probe**
Colorado River near River Mile 30	CR030	16	1
Colorado River near River Mile 61	CR061	18	1
Colorado River near River Mile 87	CR087	7	7
Colorado River near River Mile 225	CR225	16	8

Turbidity in the study area is not used to calculate sediment concentration or load; the acoustic data has proven to be a successful surrogate technology for that purpose (Topping et al., 2007). The ADP instruments do not have the limitations of the turbidity probes; calculation of the sediment attenuation coefficient, the parameter used to estimate silt and clay concentration, is straightforward and quick. Additionally, the ADP requires minimal maintenance, usually on a 6-month interval, and is much less prone to fouling than the turbidity probes. The ADP is also able to capture the entire range of silt and clay concentrations (and turbidity) seen in the study area. The fairly strong linear relations between turbidity and the acoustic sediment attenuation coefficients make it possible for the ADP data to complete the part of the turbidity record immeasurable using optical probes, or perhaps altogether replace the turbidity data collected using optical turbidity probes.

An argument for continuing to use the turbidity probes in the study area is their ability to strengthen the suspended-sediment record through the process of turbidity-threshold sampling. The turbidity probes trigger ISCO pump samplers to collect water samples during the episodic tributary floods typical of the study area, critical times for collecting sediment data. Some of the variability in the relation between the turbidity and the sediment attenuation coefficient data and the turbidity and silt and clay concentration data is due to positive or negative biases of the turbidity (and ADP) readings caused by variation in the physical properties of the suspended sediment, such as concentration, grain size, and particle color (Anderson, 2005). When coupled with the acoustic, suspended-sediment, and perhaps the laser-diffraction data (in the process of being analyzed), the turbidity data can be used to help identify the variation in physical properties of sediment from individual flooding events. With further laboratory analysis, this combination of data from multiple sources could lead to the identification of the source of sediment from flooding events originating in different tributaries in the study area. Thus a wider range of data, gathered from a wider range of sources and instruments, will result in a more accurate assessment of suspended sediment (and turbidity) in the study area than relying simply on the ADP data.

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