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# Field Evaluation of the Sequoia Scientific LISST-ABS Acoustic Backscatter Sediment Sensor

Open-File Report 2020–1096

U.S. Department of the Interior
U.S. Geological Survey

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By Adam E. Manaster, Timothy D. Straub, Molly S. Wood, Joseph M. Bell, Daniel E. Dombroski, and Christopher A. Curran

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## Conversion Factors

International System of Units to U.S. customary units

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| centimeter (cm) | 0.3937 | inch (in.) |
| millimeter (mm) | 0.03937 | inch (in.) |
| meter (m) | 3.281 | foot (ft) |
| | Volume | |
| liter (L) | 33.81402 | ounce, fluid (fl. oz) |
| liter (L) | 2.113 | pint (pt) |
| liter (L) | 1.057 | quart (qt) |
| liter (L) | 0.2642 | gallon (gal) |
| | Mass | |
| gram (g) | 0.03527 | ounce, avoirdupois (oz) |

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as

$$°F = (1.8 \times °C) + 32.$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as

$$°C = (°F - 32) / 1.8.$$

## Supplemental Information

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L).

LISST-ABS is a term trademarked by Sequoia Scientific and refers to the Laser In-Situ Scattering and Transmissometry Acoustic Backscatter Sensor.

## Abbreviations

| | |
|---|---|
| ABS | acoustic backscatter sensor |
| SSC | suspended-sediment concentration |
| USGS | U.S. Geological Survey |

# Field Evaluation of the Sequoia Scientific LISST-ABS Acoustic Backscatter Sediment Sensor

By Adam E. Manaster,[1] Timothy D. Straub,[1] Molly S. Wood,[1] Joseph M. Bell,[1] Daniel E. Dombroski,[2] and Christopher A. Curran[1]

## Abstract

Sequoia Scientific's LISST-ABS is a submersible acoustic instrument that measures the acoustic backscatter sensor (ABS) concentration at a point within a river, stream, or creek. Compared to traditional physical methods for measuring suspended-sediment concentration (SSC), sediment surrogates like the LISST-ABS offer continuous data that can be calibrated with physical SSC samples. Data were collected at 10 U.S. Geological Survey streamflow-gaging stations between January 10, 2016, and February 21, 2018, across the contiguous United States to test the accuracy and effectiveness of using the LISST-ABS as a surrogate for measuring the concentration of suspended sediment in a dynamic fluvial system. Correlation coefficients (Pearson's *r* values) relating the ABS concentration and SSC from physical samples ranged from $r = 0.718$ to $r = 0.956$ at the 10 stations with the mean percentage of fines (percentage of the sediment less than 62.5 microns in diameter) ranging from 65 to 100 percent (with minimum and maximum values of 18 and 100 percent, respectively). The LISST-ABS instruments used in this field evaluation were factory-calibrated to accurately determine SSC for grains in the diameter range of 75–90 microns. Note that the sensor responds to grains of arbitrary sizes, but the accuracy varies at sizes other than this calibration size. For operational use, regression models could be determined for the ABS concentrations and SSC values or the instrument could be recalibrated to sediments for each fluvial environment. However, such calibrations were beyond the scope of this report.

## Introduction

The use of acoustic technologies in dynamic fluvial systems is of ever-increasing importance in hydrological practices because acoustic instruments can measure along a line of sight and are less susceptible to physical fouling compared to traditional optical sensors. In conjunction with collecting and analyzing discrete, physical sediment samples, acoustic sensors offer the possibility of in-situ continuous monitoring of target parameters through development of a surrogate relation. Sequoia Scientific's LISST-ABS, developed and released commercially in 2016, is one such instrument. The LISST-ABS is a submersible acoustic sensor that measures acoustic backscatter sensor (ABS) concentration at a point within a river, stream, or creek cross-section. The sensor accomplishes this measurement by emitting an acoustic pulse and measuring the relative strength of the backscatter (the acoustic energy scattered by sediment back toward the signal source). This backscatter strength is converted from decibels to a concentration reading, in milligrams per liter (Sequoia Scientific, 2016a).

This report summarizes and analyzes datasets from 10 U.S. Geological Survey (USGS) streamflow-gaging stations across the Nation. Measurements obtained from a LISST-ABS at these stations were compared with USGS laboratory results for physical parameters, specifically USGS lab code 80154 for suspended-sediment concentration (SSC) and lab code 70331 for percentage of fines (commonly referred to as "percent fines"). For some stations, turbidity data were also collected using turbidity sensors for comparison with the LISST-ABS data.

Turbidity is primarily caused by and attributed to suspended particles such as clay, silt, finely divided organic matter, and microscopic organisms (Anderson, 2005; Rasmussen and Gatotho, 2014). Optical turbidity sensors are more sensitive to fines than coarse particles; their sensitivity varies inversely with diameter, so that 10 times larger grains produce 10 times weaker scattering per unit concentration (Downing, 2006). For this reason, turbidity sensors have poor sensitivity to coarse sediments such as sand, which is defined as sediment between 0.0625 millimeter (mm) and 2 mm in diameter. Development and evaluation of an instrument that could be equally sensitive to a wide range of sediment grain sizes and that could be deployed in streams with limited, or predictable, SSC spatial variability is desirable. In contrast with turbidity, Sequoia Scientific's LISST-ABS has nearly uniform sensitivity

[1]U.S. Geological Survey.

[2]Bureau of Reclamation.

in the diameter range of 30–400 microns. As a result, the USGS obtained and tested the LISST-ABS in the laboratory (Snazelle, 2017) and field to evaluate its use as a sensor for SSC. For this study, data were collected across multiple stations using a factory-calibrated LISST-ABS for the field evaluations as described in this report; all data collected for this study are available in a USGS data release (Manaster, 2020). Comparing the ABS concentration data with laboratory-analyzed SSC data from physical samples, as well as turbidity and percent fines data, provides valuable insight into the accuracy and effectiveness of the LISST-ABS and possible ways to improve its existing functionality for future field evaluations.

## Purpose and Scope

The purpose of this report is to describe the accuracy and effectiveness of using factory-calibrated models of Sequoia Scientific's LISST-ABS as a surrogate for measuring the SSC in a dynamic fluvial system such as a river. Information in the report is meant to be utilized as a supplement for determining if the instrument produces measurements that can be reasonably correlated with SSC. The scope of this report is limited to 10 USGS streamflow-gaging stations across the contiguous United States where data were collected using the acoustic sensor coincident with physical sampling.

## Methods

Sequoia Scientific's LISST-ABS is an underwater acoustic sensor that emits sound at a frequency of 8 megahertz (Sequoia Scientific, 2016a) (fig. 1; table 1). The LISST-ABS is designed to measure acoustic backscatter (which is then translated to an SSC measurement) at a fixed point. This is different than using an acoustic Doppler velocity meter or profiler that uses multiple points along an acoustic beam and is processed as shown in Landers and others (2016), Wood and Teasdale (2013), and Topping and Wright (2016). When energized, the ceramic transducer of the LISST-ABS sensor emits a high-frequency pulse of sound. Particles in the water, such as sediment, scatter and thus propagate the sound pulse in all directions. The reduced portion of acoustic energy that is reflected back toward and received by the transducer is the measure of backscatter; this is the parameter that is explored for use as a surrogate in the calculation of SSC. The sample volume is at 5.5-centimeter (cm) away from the transducer. This short in-water acoustic pathlength was chosen to minimize the effects of sound attenuation, or the "loss" of acoustic energy, owing to absorption of the signal from the water and surrounding sediment (Sequoia Scientific, 2016a; Snazelle, 2017). However, the water and sediment attenuation is measured and internally used for correction. This correction extends the upper working SSC range of the LISST-ABS.

During this evaluation, the LISST-ABS remained on the factory calibration setting, meaning the sensor's calibration factor was equal to 1. Each acoustic sensor used in the field evaluation was initially calibrated by the manufacturer (Sequoia Scientific) in a laboratory using particles 75–90 microns in diameter and with equal sensitivity so that they may be interchanged (Sequoia Scientific, 2016a, 2016b). Therefore, if a particular fluvial environment only contained suspended sediment within the range of 75–90 microns in size, the LISST-ABS would theoretically measure SSC directly. The sensor responds to grains of arbitrary sizes, but the accuracy varies at sizes other than this calibration size, specifically between 30 and 400 microns in diameter, and thus can be calibrated to sense particulate matter in this range. However, it is important to note that this does not imply that the factory-calibrated LISST-ABS does not receive signal from larger particles (those greater than 400 microns in diameter). For this report, the term "factory calibrated" implies a calibration factor of 1 for the LISST-ABS.

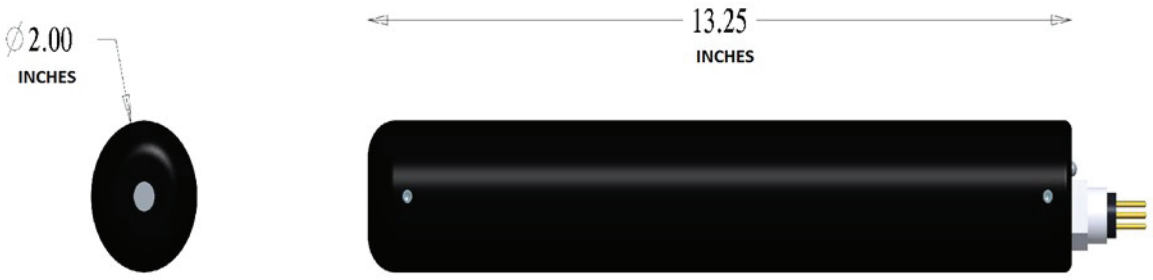


**Figure 1.** Sequoia Scientific's LISST-ABS and the dimensions of the sensor (Snazelle, 2017; image courtesy of Sequoia Scientific, 2016a, used with permission).

**Table 1.** Features and technical specifications of Sequoia Scientific's LISST-ABS (Snazelle, 2017; Sequoia Scientific, 2016a).

[cm, centimeter; MHz, megahertz; mm, millimeter; kg, kilogram; lb, pound; in., inch; mg/L, milligram per liter; g/L, gram per liter; %, percent; m, meter; VDC, volts direct current; mA, milliamp; V, volt; dB, decibel; SDI-12, Serial Digital Interface at 1200 baud; RS-232, Recommended Standard 232]

| Feature | Specification |
|---|---|
| Acoustic operation | Point sensor (5.5 cm in front of sensor) |
| Operating frequency | 8 MHz |
| Transducer | 10-mm diameter, ceramic |
| Weight | 0.5 kg or 1 lb |
| Length | 33.65 cm or 13.25 in. |
| Range | 1 mg/L to 70 g/L (in 7-micron dust)<br>1 mg/L to 50 g/L (in 200-micron sand) |
| Resolution | 0.5% of reading |
| Maximum depth | 100 m |
| Power requirements | 9–18 VDC, 100 mA |
| Output | 0–5 V for 0–100 dB analog, SDI-12 or RS-232 |
| Material | Acrylonitrile butadiene styrene plastic |

Information regarding station names/abbreviations used in this report, as well as their corresponding USGS station numbers and start and end dates of observational sampling, can be found in table 2. All sediment data collected for this study for stations listed in table 2 are available in a USGS data release (Manaster, 2020); additional data, such as streamflow data, are available from the USGS National Water Information System database (U.S. Geological Survey, 2020). LISST-ABS concentrations and turbidity were measured concurrently with physical sediment sampling using a point sampler (P-6) at USGS streamflow-gaging stations 05586300 (hereafter referred to as "Illinois River"; 25 samples), 06807000 (hereafter referred to as "Missouri River at Nebraska City"; 25 samples), 06935695 (hereafter to referred to as "Missouri River at St. Charles"; 15 samples), and 11447650 (hereafter referred to as "Sacramento River"; 22 samples) (table 2; fig. 2). At each station, concurrent measurements and samples were collected at multiple verticals and at various depths within each vertical. The goal was to collect five point-samples at each of the five verticals (25 samples in total), from the left to right banks at spacing that corresponded with the equal discharge increment locations (Edwards and Glysson, 1999) (fig. 3). The depth below surface to total depth ratio consisted of 0.2, 0.4, 0.6, 0.8, and 0.9 for each vertical. At all stations, vertical 1 samples were collected on the leftmost side of the channel, whereas vertical 5 samples were collected on the rightmost side of the channel (with the exception of Missouri River at St. Charles, which was numbered the opposite direction). Deviations from this plan are described later in this section. Turbidity was measured at Sacramento River with an RBR Concerto turbidity sensor (RBR Ltd., 2019), whereas a YSI model 6136 turbidity sensor (YSI Incorporated, 2007) was used at the other three stations. The serial number of the LISST-ABS used at Illinois River and Missouri River at Nebraska City was 6038; at Sacramento River, the serial number was 6058 and at Missouri River at St. Charles, it was 6043.

LISST-ABS concentrations were measured concurrently with physical sediment sampling at USGS streamflow-gaging stations 12046260 (hereafter referred to as "Elwha River") and 01648010 (hereafter referred to as "Rock Creek") using a pump sampler at a fixed location near the LISST-ABS (table 2). However, these stations did not follow the methodology as described above (fig. 2) because the samples and measurements were collected during the course of a month and a half for Elwha River and during the course of multiple years for Rock Creek. In addition, more than 25 samples and measurements were collected at both of these stations. Note that turbidity was also measured concurrently with physical sediment sampling at Elwha River with a DTS-12 digital turbidity sensor (Forest Technology Systems, [n.d.]) and at Rock Creek with a YSI EXO2 optical turbidity sensor (YSI Incorporated, 2020). The serial number of the LISST-ABS used at Elwha River was 6019, whereas the serial number was 6020 at Rock Creek.

LISST-ABS concentrations were measured concurrently with physical sediment sampling at USGS streamflow-gaging stations 08374550 (hereafter referred to as "Rio Grande at Castolon"), 08375300 (hereafter referred to as "Rio Grande at Rio Grande Village"), and 09404200 (hereafter referred to as "Colorado River"). Samples at Rio Grande at Castolon were US DH-48 single-vertical samples, whereas samples at Rio Grande at Rio Grande Village were dip samples and samples at Colorado River were US DH-81 single-vertical samples. Individual LISST-ABS measurements were averaged over a 2-minute window centered around the time of the physical samples. The serial number of the LISST-ABS used at these stations was 6039.

**Table 2.** Summary of U.S. Geological Survey (USGS) streamflow-gaging station names, abbreviations, numbers, and start and end dates for all USGS stations incorporated in the field evaluation.

[MM, month; DD, day; YYYY, year]

| Station name | Station abbreviation | Station number | Start date (MM/DD/YYYY) | End date (MM/DD/YYYY) |
|---|---|---|---|---|
| Rock Creek at Joyce Road, Washington, D.C. | Rock Creek | 01648010 | 01/10/2016 | 02/21/2018 |
| Illinois River at Florence, Illinois | Illinois River | 05586300 | 05/23/2017 | 05/23/2017 |
| Cherry Creek below Cherry Creek Lake, Colorado | Cherry Creek | 06713000 | 05/24/2017 | 05/24/2017 |
| Missouri River at Nebraska City, Nebraska | Missouri River at Nebraska City | 06807000 | 05/25/2017 | 05/25/2017 |
| Missouri River at St. Charles, Missouri | Missouri River at St. Charles | 06935965 | 07/20/2016 | 07/20/2016 |
| Rio Grande near Castolon, Texas | Rio Grande at Castolon | 08374550 | 07/25/2016 | 07/26/2016 |
| Rio Grande at Rio Grande Village, Big Bend National Park, Texas | Rio Grande at Rio Grande Village | 08375300 | 07/28/2016 | 07/28/2016 |
| Colorado River above Diamond Creek near Peach Springs, Arizona | Colorado River | 09404200 | 11/09/2016 | 11/12/2016 |
| Sacramento River at Freeport, California | Sacramento River | 11447650 | 05/03/2017 | 05/03/2017 |
| Elwha River at Diversion near Port Angeles, Washington | Elwha River | 12046260 | 01/01/2017 | 02/15/2017 |

LISST-ABS concentrations were measured concurrently with physical sediment sampling at USGS streamflow-gaging station 06713000 (hereafter referred to as "Cherry Creek") using a US DH-95 sampler. Individual LISST-ABS measurements were averaged over a 5-minute window centered around the time of the physical samples. The serial number of the LISST-ABS used at this station was 6078.

Sacramento River presented some minor challenges because there were only three samples collected in vertical 1 and four samples collected in vertical 2, hence 22 total samples rather than 25. Likewise, Missouri River at St. Charles had no samples collected for verticals 1 and 2, hence 15 total samples rather than 25 (table 3). For both stations, it is slightly more difficult to assess the accuracy and precision of these measurements, at least in direct comparison to the other stations being analyzed in this report.

Pearson's *r* (otherwise known as the "correlation coefficient") is a measurement of the linear association between two variables (Helsel and others, 2020). This correlation coefficient varies from −1 to 1, where 1 describes a perfect, positive linear correlation between data, and −1 describes a perfect, negative linear correlation between data. An *r* value of 0 indicates there is no linear correlation between the two variables in question. For the purposes of this report, the correlation coefficient is utilized as a means to describe the linearity between ABS and SSC and between turbidity and SSC. This is the ideal method for comparing these data because the LISST-ABS was factory calibrated to a narrow range of sediment sizes (75–90 microns) and thus was not necessarily expected to show a 1:1 relation with SSC in a fluvial system with a wider range of sediment sizes. However, the factory-calibrated ABS concentrations were expected to exhibit some form of linearity when compared with SSC. Similarly, turbidity measurements were expected to show linearity when compared with SSC. Turbidity and ABS concentration values were ultimately compared with SSC to provide insight into which hydrologic measurement is more effective for the purpose of predicting SSC at the evaluated stations as detailed in this report.

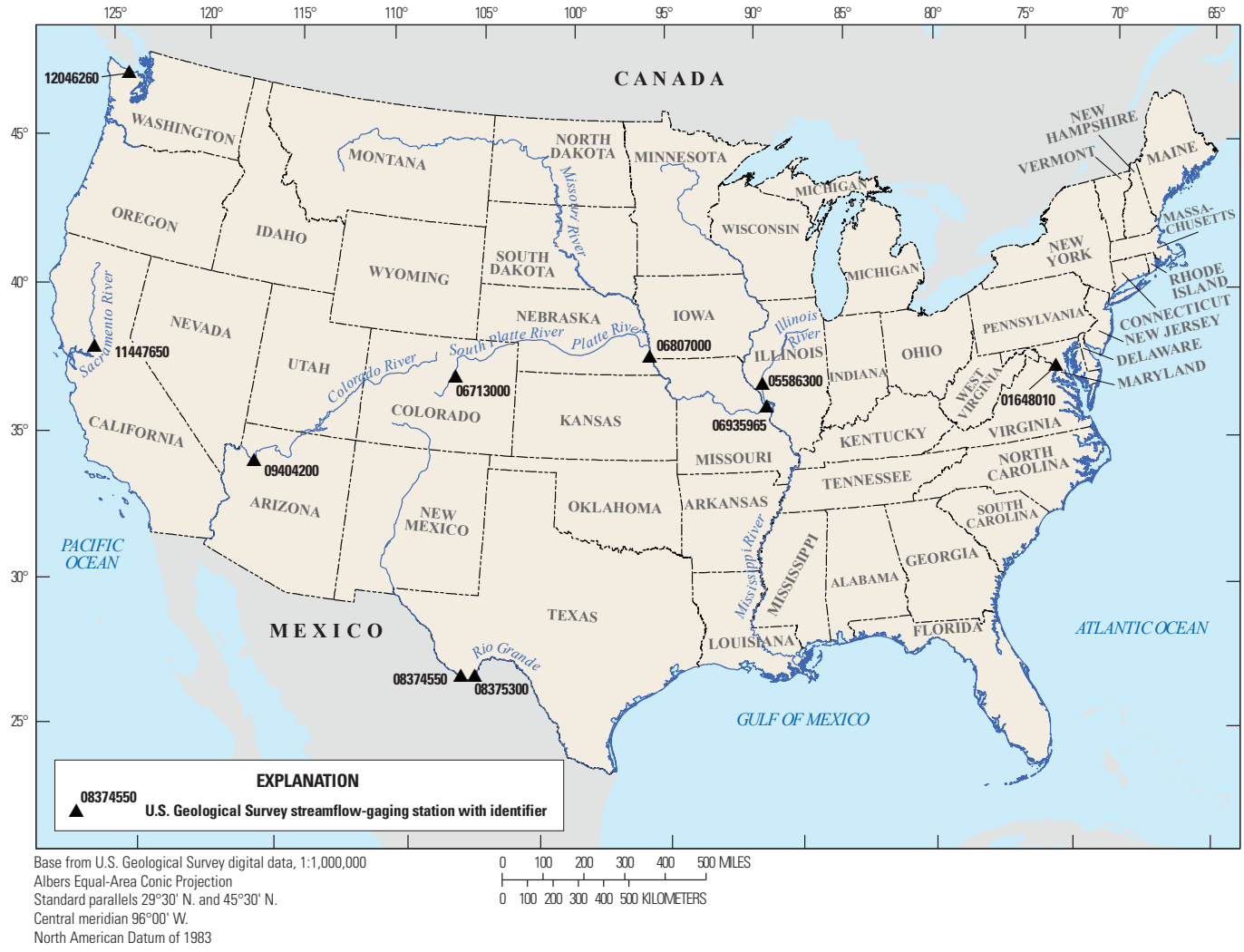


**Figure 2.** Map of the 10 U.S. Geological Survey (USGS) streamflow-gaging stations where the LISST-ABS was tested.

## Acoustic Backscatter Sensor, Turbidity, and Suspended-Sediment Concentration Relations Across Stations

The lowest correlation coefficient ($r$) value for ABS concentration and SSC from all stations was 0.718 at Sacramento River (table 4). Likewise, the lowest $r$ value for turbidity and SSC from all stations was 0.118, also at Sacramento River. The highest $r$ value for ABS concentration and SSC from all stations was 0.956 at Elwha River. Likewise, the highest $r$ value for turbidity and SSC from all stations was 0.984 at Elwha River. For every location (with the exception of Elwha River), there was a stronger linear association present (in other words, greater correlation coefficient) between ABS concentration and SSC in comparison to turbidity and SSC (table 4). Although Elwha River did not follow this pattern, both $r$ values were comparable to one another, only differing by 0.028. Although the linear associations are between different variables (ABS concentration and turbidity), they reveal the similarities in their magnitudes. The mean value of $r$, as derived from the values in table 4, was about 0.88 between ABS concentration and SSC, whereas it was about 0.60 between turbidity and SSC. The absence of turbidity data at Cherry Creek, Rio Grande, and Colorado River makes it difficult to compare the ABS concentrations to these parameters. Averaging correlation coefficients across numerous stations, all of which possess differing concentrations of sediment and were evaluated during sporadic timeframes, is obviously subject to various biases. The mean values were merely given as a reference to assess the reliability of the LISST-ABS as an instrument used to predict SSC in fluvial systems.

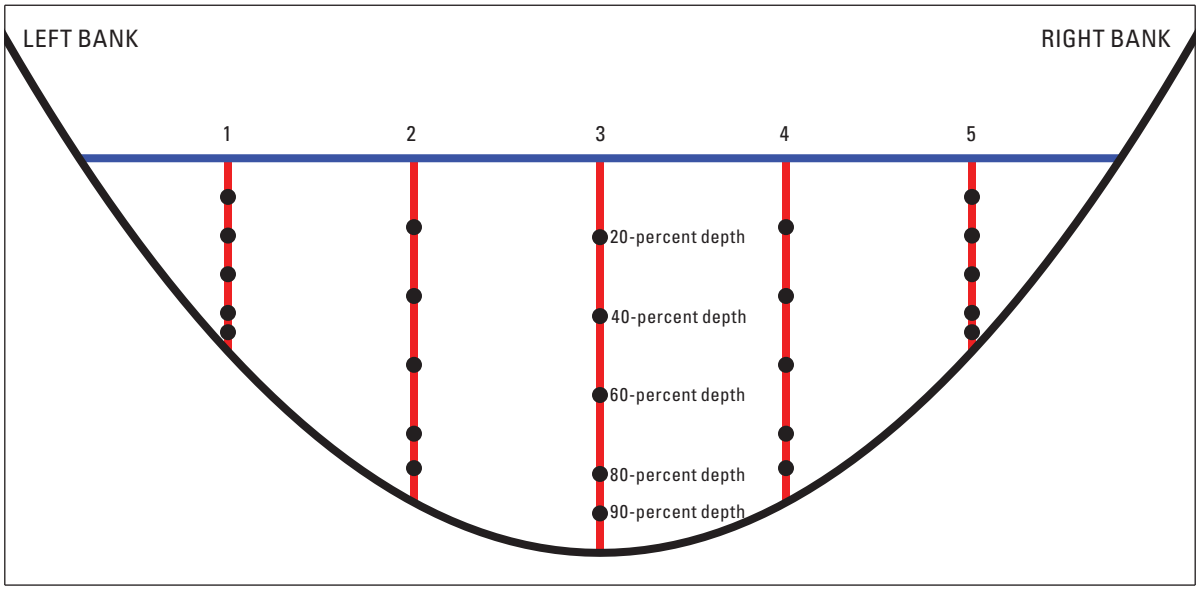


**Figure 3.** Sample locations for the LISST-ABS concentration, turbidity, and point suspended-sediment concentration (SSC) in an idealized river cross-section. Note that actual spacing between verticals varied at all stations and verticals were aligned to the center of sections of equal discharge.

In general, correlation coefficients between ABS concentration and SSC close to 1 indicate that the LISST-ABS concentration is an acoustic surrogate that consistently measured ABS concentration that linearly correlated with SSCs at the tested streamflow-gaging stations. Because the instrument was factory calibrated and thus not adjusted for specific fluvial environments, it was not expected to show a 1:1 trend between ABS concentration values and SSC values; rather, it was presumed to display a reasonable linear association between these variables.

Theoretically, the relation between ABS concentration and SSC is expected to be a linear 1:1 ratio (fig. 4) because both of these measurements evaluate the concentration (in milligrams per liter) of sediment that is suspended in water. However, because all of the acoustic sensors used for this field evaluation were factory calibrated, this relation does not necessarily hold true when the sediment deviates outside of the particle size range of 75–90 microns. Calibration of the LISST-ABS to local sediment characteristics is of vital importance in obtaining accurate and precise data, because the sensor can be manually adjusted depending on the environment/system in which it is being implemented (Sequoia Scientific, 2016a, 2016b; Snazelle, 2017). Calibration of acoustic sensors is often site-specific and requires statistical analysis, specifically regression models, to accurately determine the appropriate calibration factor for the sensors (Sequoia Scientific, 2016a, 2016b; Snazelle, 2017). Multiple samples and measurements were collected to increase the validity of the dataset. Also, multiple USGS field stations were incorporated into this study for the sake of variance and to eliminate biases that may be present in one or more locations. The LISST-ABS was tested in different fluvial environments where there is variation in the amount and type of suspended sediment in the water; therefore, the acoustic units were tested across various stream orders, urban and natural watershed characteristics, and temporal and spatial extents.

For most of the stations studied in this field evaluation, there is an apparent linear trend between fine-grained SSC and sand-sized SSC in comparison to ABS concentration (fig. 5) (with the exception of fines in the Illinois River, Missouri River at Nebraska City, Missouri River at St. Charles, and Sacramento River because data were collected within a short time span with little variation in sampled fines concentration). At these stations, the ABS concentrations increase, and the fine-grained SSC values are somewhat constant throughout the cross-section (fig. 5*A*); however, figure 5*B* indicates that the presence of sands seems to cause the increase in ABS concentrations at these stations because each station clearly exhibits some form of linearity between ABS concentration and sand-sized SSC.

The plots between fine-grained/sand-sized SSC and turbidity in figure 6 exhibit opposite patterns in comparison to what is shown in figure 5. Turbidity readings are fairly responsive to changes in the concentration of fine sediment (fig. 6*A*; with the exception of Illinois River, Missouri River at Nebraska City, Missouri River at St. Charles, and Sacramento River because data were collected within a short time span with little variation in sampled fines concentration). However, in figure 6*B*, there is a broad range of sand-sized SSC values within a comparatively small range of turbidity measurements, possibly because optical turbidity sensors have difficulty picking up on the presence of sands in various fluvial environments, which differs from what is seen with the LISST-ABS.

**Table 3.** Summary of relevant data from all stations including number of observations and minimum, maximum, and mean values for suspended-sediment concentration, percentage of fine sediment, acoustic backscatter sensor concentration, and turbidity.

[SSC, suspended-sediment concentration; mg/L, milligram per liter; %, percent; ABS, acoustic backscatter sensor; FNU, formazin nephelometric unit; Min., minimum; Max., maximum; --, no data]

| Station abbreviation (table 2) | Number of observations | Lab SSC (mg/L) | | | % of fine sediment | | | ABS concentration (mg/L) | | | Turbidity (FNU) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Min. | Mean | Max. | Min. | Mean | Max. | Min. | Mean | Max. | Min. | Mean | Max. |
| Rock Creek | 68 | 3 | 422 | 2,900 | 18 | 82 | 100 | 0.2 | 674 | 5,970 | 1.6 | 155 | 830 |
| Illinois River | 25 | 61 | 70 | 98 | 62 | 90 | 99 | 11 | 16 | 46 | 42 | 48 | 52 |
| Cherry Creek | 27 | 33 | 180 | 330 | 63 | 69 | 84 | 35 | 170 | 289 | -- | -- | -- |
| Missouri River at Nebraska City | 25 | 552 | 829 | 1,800 | 29 | 67 | 93 | 252 | 476 | 952 | 161 | 172 | 186 |
| Missouri River at St. Charles | 15 | 250 | 353 | 742 | 29 | 75 | 98 | 34 | 76 | 171 | 106 | 114 | 123 |
| Rio Grande at Castolon | 4 | 43 | 55 | 78 | 98 | 99 | 100 | 0.9 | 1.0 | 1.1 | -- | -- | -- |
| Rio Grande at Rio Grande Village | 4 | 167 | 180 | 191 | 100 | 100 | 100 | 2.8 | 4.6 | 5.8 | -- | -- | -- |
| Colorado River | 6 | 1,460 | 3,970 | 7,583 | 48 | 66 | 88 | 1,061 | 2,169 | 3,193 | -- | -- | -- |
| Sacramento River | 22 | 42 | 76 | 140 | 36 | 65 | 85 | 26 | 41 | 62 | 26 | 28 | 30 |
| Elwha River | 73* | 2 | 64 | 383 | 80 | 85 | 90 | 0.7 | 27 | 266 | 2 | 39 | 255 |

*Percentage-of-fines data were only analyzed for 22 of the 73 samples.

**Table 4.** Summary of the Pearson's *r* values for acoustic backscatter sensor concentration and turbidity compared with suspended-sediment concentration at all stations with available data.

[ABS, acoustic backscatter sensor; SSC, suspended-sediment concentration; --, no data]

| Station abbreviation (table 2) | Number of observations | Pearson's *r* value ABS and SSC | Pearson's *r* value turbidity and SSC |
|---|---|---|---|
| Rock Creek | 23 | 0.897 | 0.869 |
| Illinois River | 25 | 0.821 | 0.361 |
| Cherry Creek | 27 | 0.883 | -- |
| Missouri River at Nebraska City | 25 | 0.907 | 0.762 |
| Missouri River at St. Charles | 15 | 0.909 | 0.533 |
| Rio Grande* | 8 | 0.927 | -- |
| Colorado River | 6 | 0.914 | -- |
| Sacramento River | 22 | 0.718 | 0.118 |
| Elwha River | 22 | 0.956 | 0.984 |

*Rio Grande stations were combined for plotting owing to lack of data.

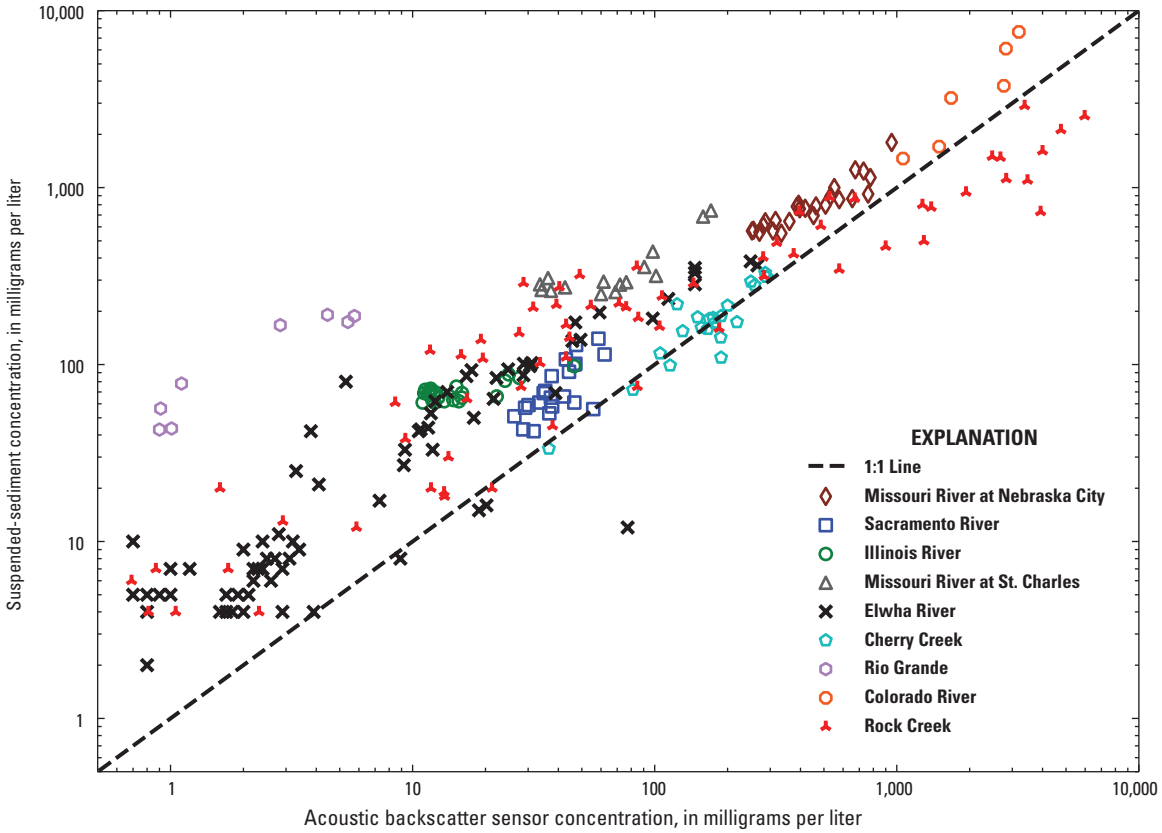


**Figure 4.** Relation between acoustic backscatter sensor concentration and suspended-sediment concentration for U.S. Geological Survey streamflow-gaging stations used in this study.

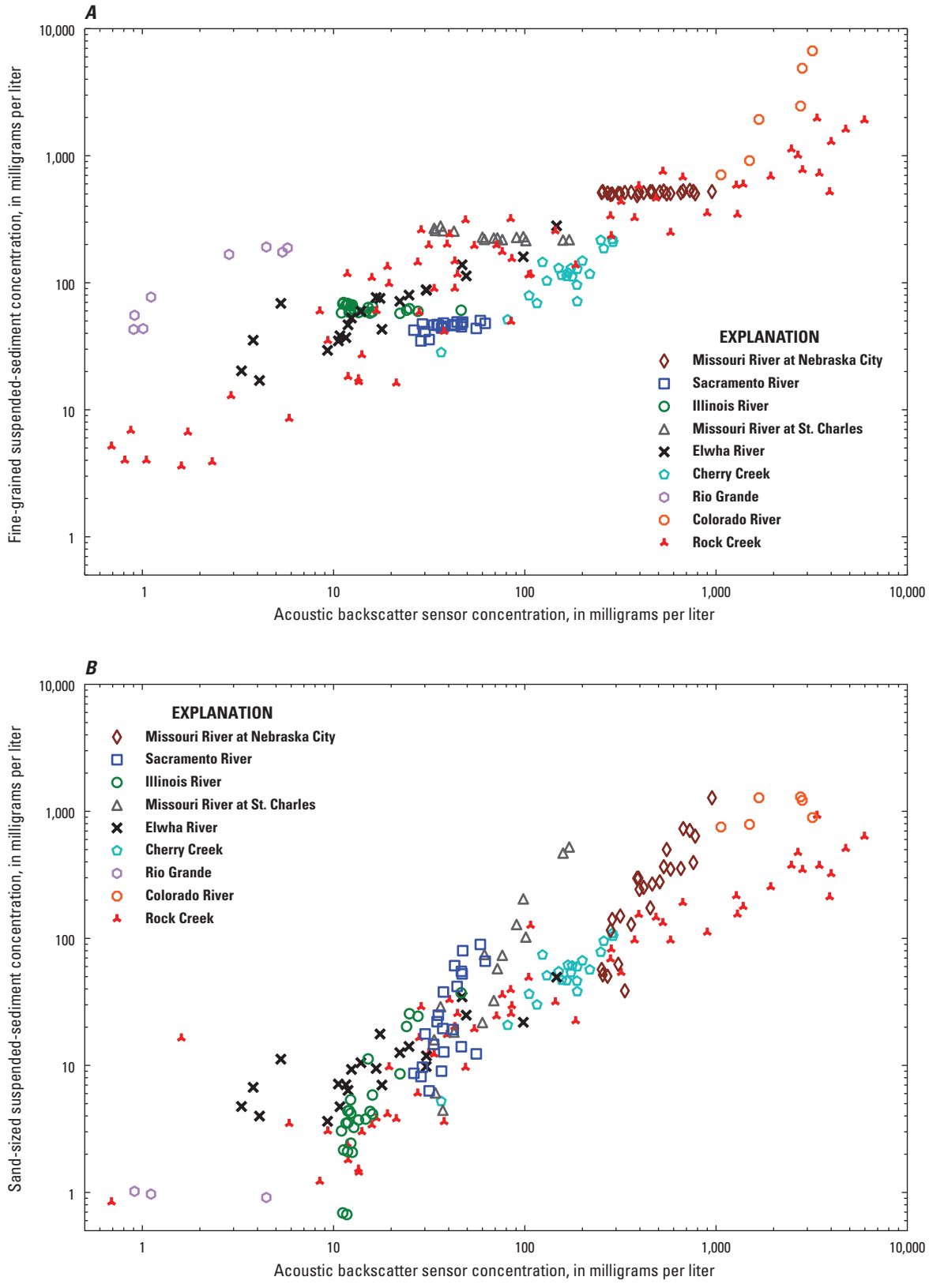


**Figure 5.** Comparison of concentrations for U.S. Geological Survey streamflow-gaging stations used in this study. *A*, Fine-grained suspended-sediment concentration (SSC) compared with acoustic backscatter sensor (ABS) concentration. *B*, Sand-sized SSC compared with ABS concentration.

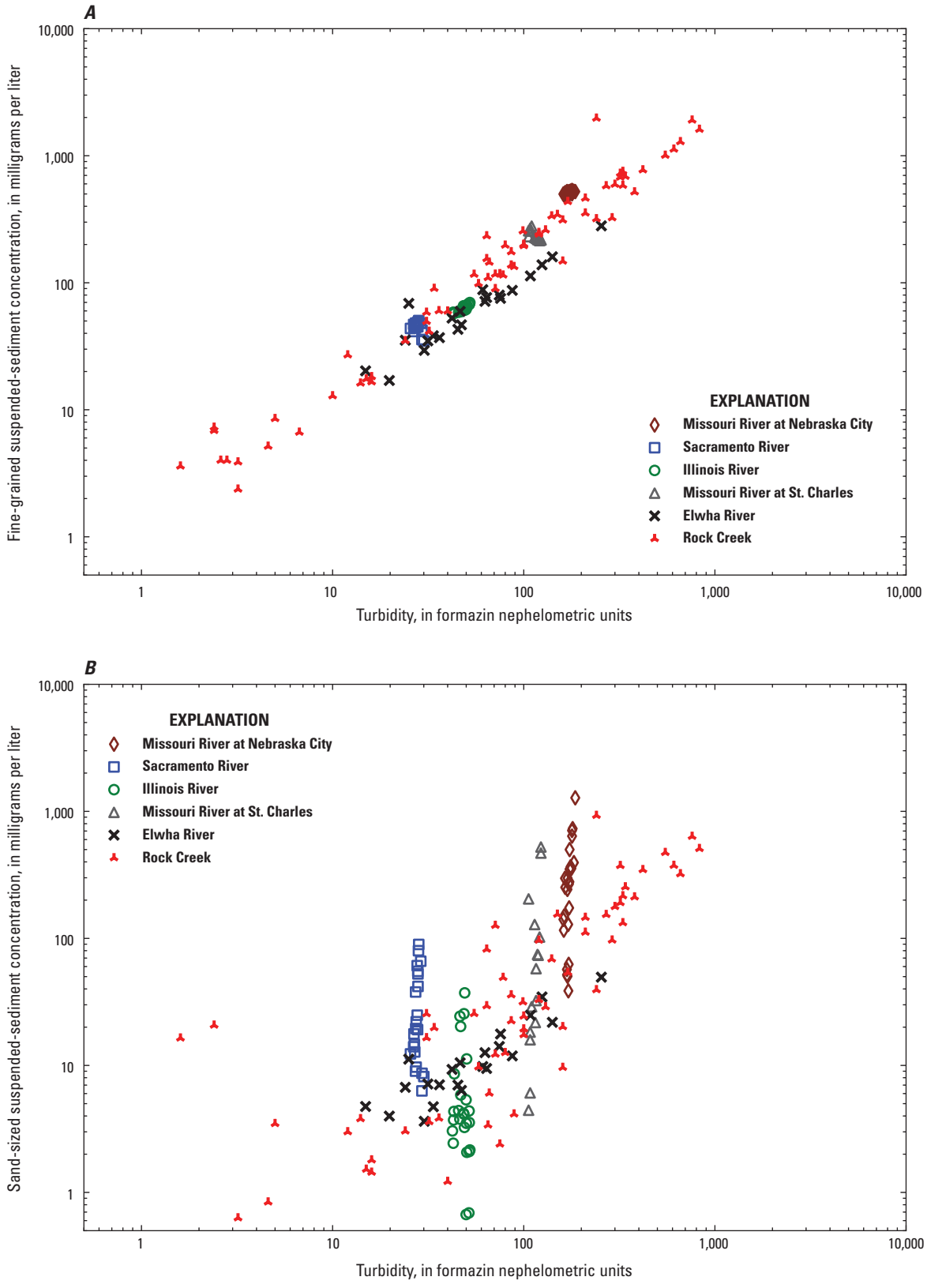


**Figure 6.** Comparison of turbidity and particle concentrations for U.S. Geological Survey streamflow-gaging stations used in this study. *A*, Fine-grained suspended-sediment concentration (SSC) compared with turbidity. *B*, Sand-sized SSC compared with turbidity.

It is important to note that the *x*- and *y*-axes for figures 4, 5, and 6 were transformed from linear space to log space to account for the wide range of measurements obtained across each station, but the data were not transformed or altered.

For the stations where data were collected during a short time period (for example, within the span of 1 day) and at a specific location/cross-section, the amount of fine-grained suspended sediment in the rivers remained relatively consistent (figs. 7–10). It is apparent that there was a more substantial variation in the amount of sand-sized suspended sediment throughout the river cross-section relative to the amount of variation in fines present when samples were collected under this set of conditions. Therefore, the only variable that caused the variation in total SSC values in these instances was the concentration of sand-sized sediment. In general, the turbidity and ABS sediment concentration graphs indicate that the total SSC increases as turbidity and ABS concentration increase (figs. 7–15). The datasets shown in figures 11–15 were collected over a longer time period than the datasets shown in figures 7–10 and therefore represent a wider range of sediment transport conditions for a given station. Although sand and fines concentrations vary at the stations depicted in figures 11, 12, 14, and 15, the amount of fine-grained suspended sediment is what predominantly increased and affected the total SSC. At some locations, like Cherry Creek (fig. 12) and Rock Creek (fig. 15), the amount of sand-sized suspended sediment increased along with the ABS concentration values, but not at the same rate as the fine-grained suspended sediment. These trends are in contrast to what is shown in figures 7–10, primarily because the variation in finer sediment is what dictates the increase in the LISST-ABS concentrations rather than the coarser sediment. Even though the relative response rate of the instrument decreases when the sediment is outside the range of 30–400 microns in diameter (Sequoia Scientific, 2016a), the ABS concentration and SSC correlation coefficients compare well, ranging from 0.718 to 0.956 (table 4). As stated earlier, it is beyond the scope of this study to categorically evaluate the LISST-ABS outside the range of 30–400 microns.

For the stations where depth below the surface of the river was recorded in tandem with ABS concentration, turbidity, and percent fines data (Illinois River, Missouri River at Nebraska City, Missouri River at St. Charles, and Sacramento River), plots were created to depict the sensitivity of the LISST-ABS and turbidity sensors to variations in the relative amounts of sand-sized and fine-grained suspended sediment, as well as to show how the percentage of fines changed when compared with depth below the surface (figs. 16–19). As depth below the surface increased, turbidity values remained relatively similar. Similarly, the LISST-ABS concentrations for the verticals along the left and right banks of the river (verticals 1 and 5), as a whole, remained relatively similar (figs. 16*A*, 17*A*, 18*A*, and 19*A*). A valid explanation for these results is that, in relatively straight reaches, there is not as much turbulence along the banks of a river in comparison to the center of its channel where water naturally travels at a higher velocity. Therefore, less sand and more fines tend to be in transport near the banks and usually presented the least amount of variation in the LISST-ABS concentrations (figs. 16–19) as evidenced through the Rouse Profiles (Rouse, 1937; Garcia, 2008). For the most part, these verticals were verticals 1 and 5 (those along the riverbanks); however, exceptions were vertical 2 in figure 17*B* and vertical 4 in figure 18*B*. It is important to note that verticals 1 and 5 for each station contained a relatively homogenous water-sediment mixture because of the nature of high percentages of fines and their positioning within the river cross-section near the banks. Therefore, a substantial change in the total SSC values is not expected for these verticals, regardless of the depth below the surface.

A common pattern, shown in figures 16*B*, 17*B*, 18*B*, and 19*B*, is that the sediment generally transitioned from being fine-grained to coarse-grained as the depth below the surface of the rivers increased, with this being particularly noticeable in verticals 2, 3, and 4. These verticals are within the center of the river's channel, so it is expected for them to possess more sands in transport relative to verticals 1 and 5 along the banks of the rivers as evidenced in the Rouse Profiles (Rouse, 1937; Garcia, 2008). Also, considering that the sedimentary particles suspended near the bed of a sand-bedded river are much coarser than the particles that would be suspended above in the flowing water, this pattern is logical (Rouse, 1937; Edwards and Glysson, 1999; Garcia, 2008). Another interesting pattern to note is that these sampled verticals (verticals 2, 3, and 4) generally displayed a substantial increase in the concentrations reported by the LISST-ABS as the depth of the river increased; concentrations measured near the bottom of the river approximately doubled or even tripled in value in comparison to those measured near the surface (figs. 16*A*, 17*A*, 18*A*, and 19*A*). However, as depth below the surface increased, turbidity values remained relatively similar even in verticals 2, 3, and 4. There was an exception for vertical 2 in figure 17*A* in that the ABS concentration measurements actually decreased as depth below the surface of the river increased. However, this vertical 2 possessed an abnormally elevated amount of fine-grained suspended sediment, indicating that this could have been the primary contributor to the vertical's unusual concentration dataset (fig. 17). In general, the visual observations for these four stations in figures 16–19 help explain the correlation coefficients in table 4 and support the statement that optical turbidity sensors have difficulty sensing coarser sediment (Downing, 2006; Rasmussen and others, 2009).

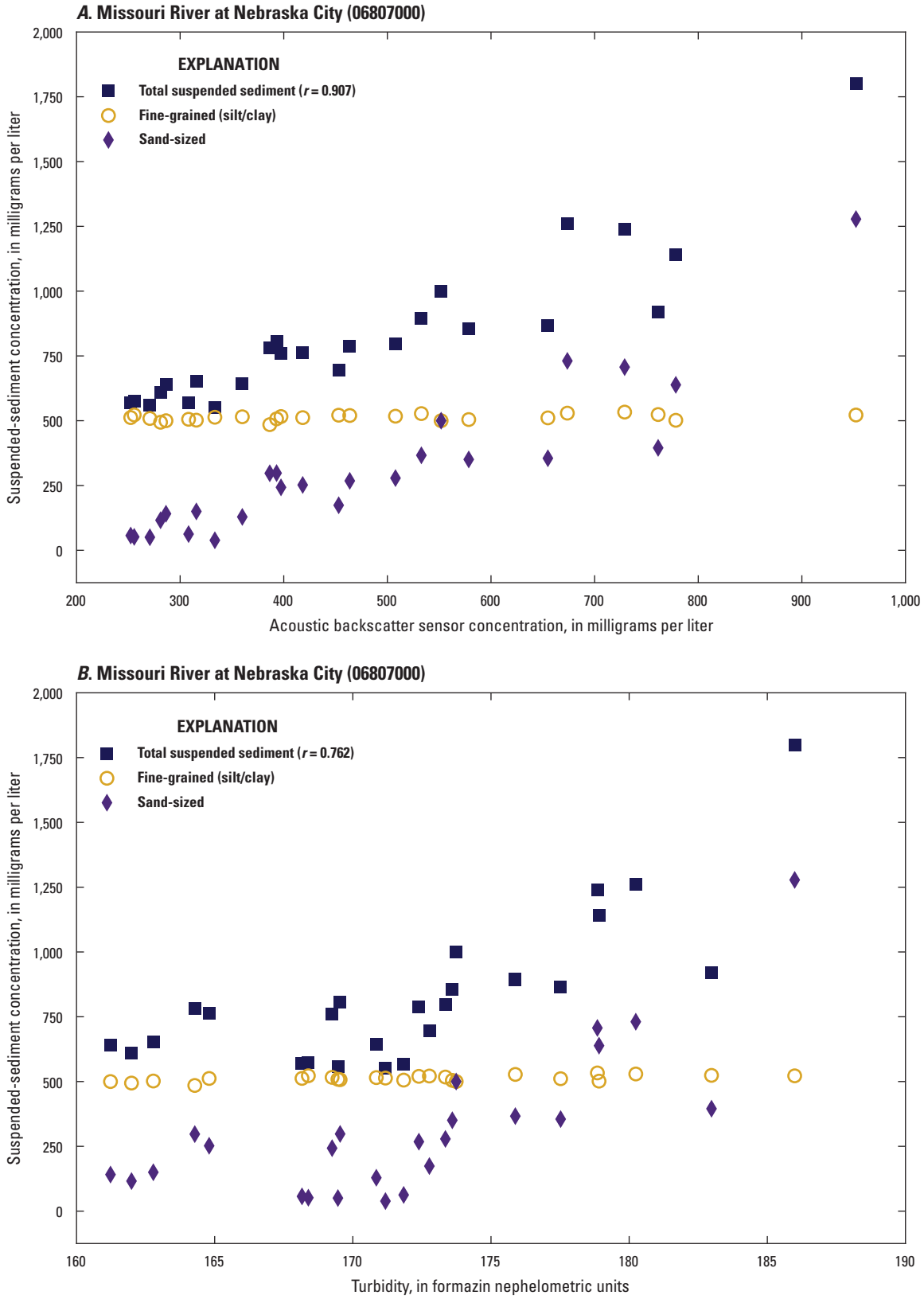


**Figure 7.** Comparison of acoustic backscatter sensor (ABS) concentration and turbidity with total, fine-grained, and sand-sized suspended-sediment concentrations (SSCs) at varying depths and verticals on the Missouri River at Nebraska City, Nebraska (U.S. Geological Survey station 06807000). *A*, ABS concentration compared with SSCs. *B*, Turbidity compared with SSCs. [*r*, correlation coefficient]

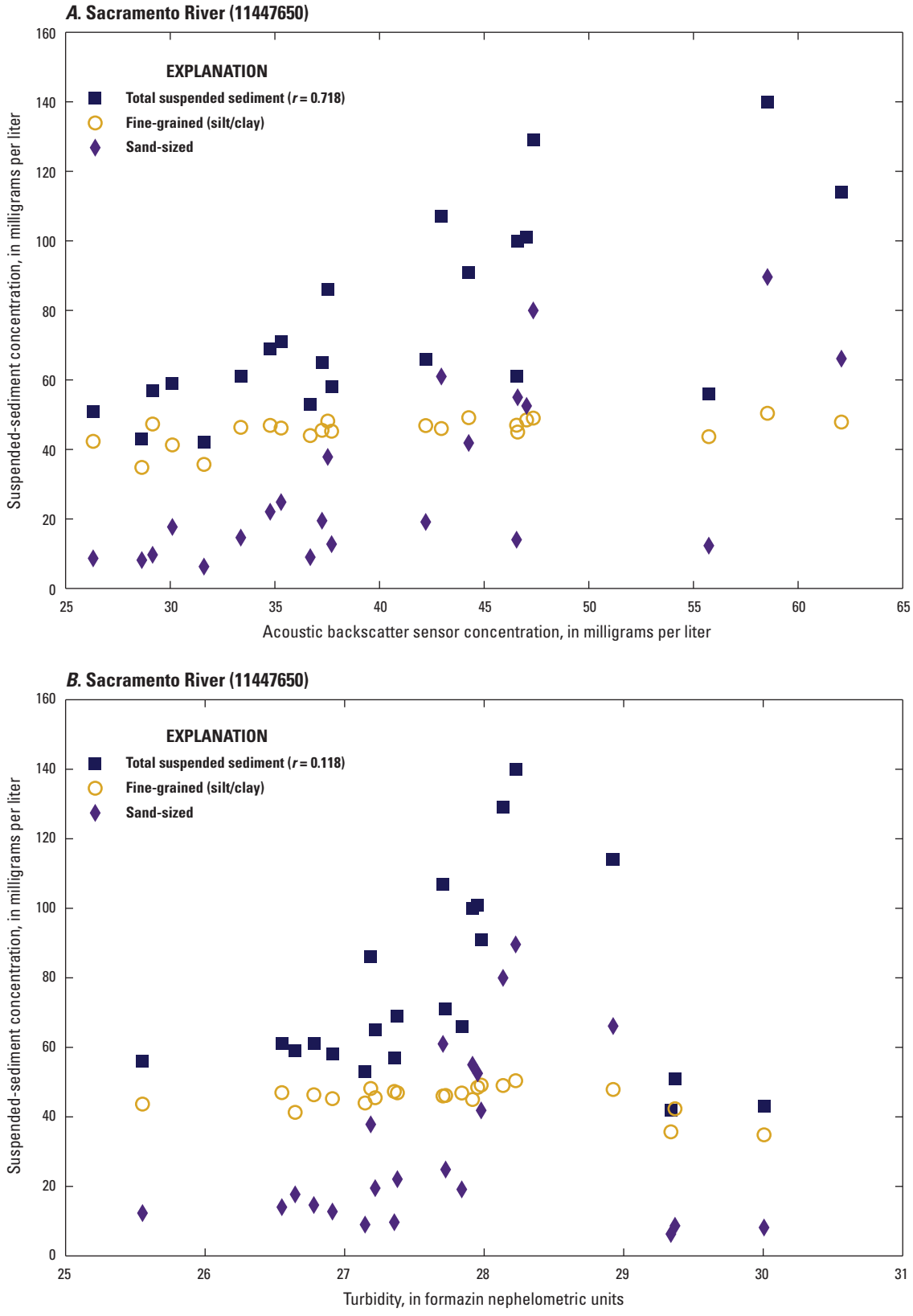


**Figure 8.** Comparison of acoustic backscatter sensor (ABS) concentration and turbidity with total, fine-grained, and sand-sized suspended-sediment concentrations (SSCs) at varying depths and verticals on the Sacramento River at Freeport, California (U.S. Geological Survey station 11447650). *A*, ABS concentration compared with SSCs. *B*, Turbidity compared with SSCs. [*r*, correlation coefficient]

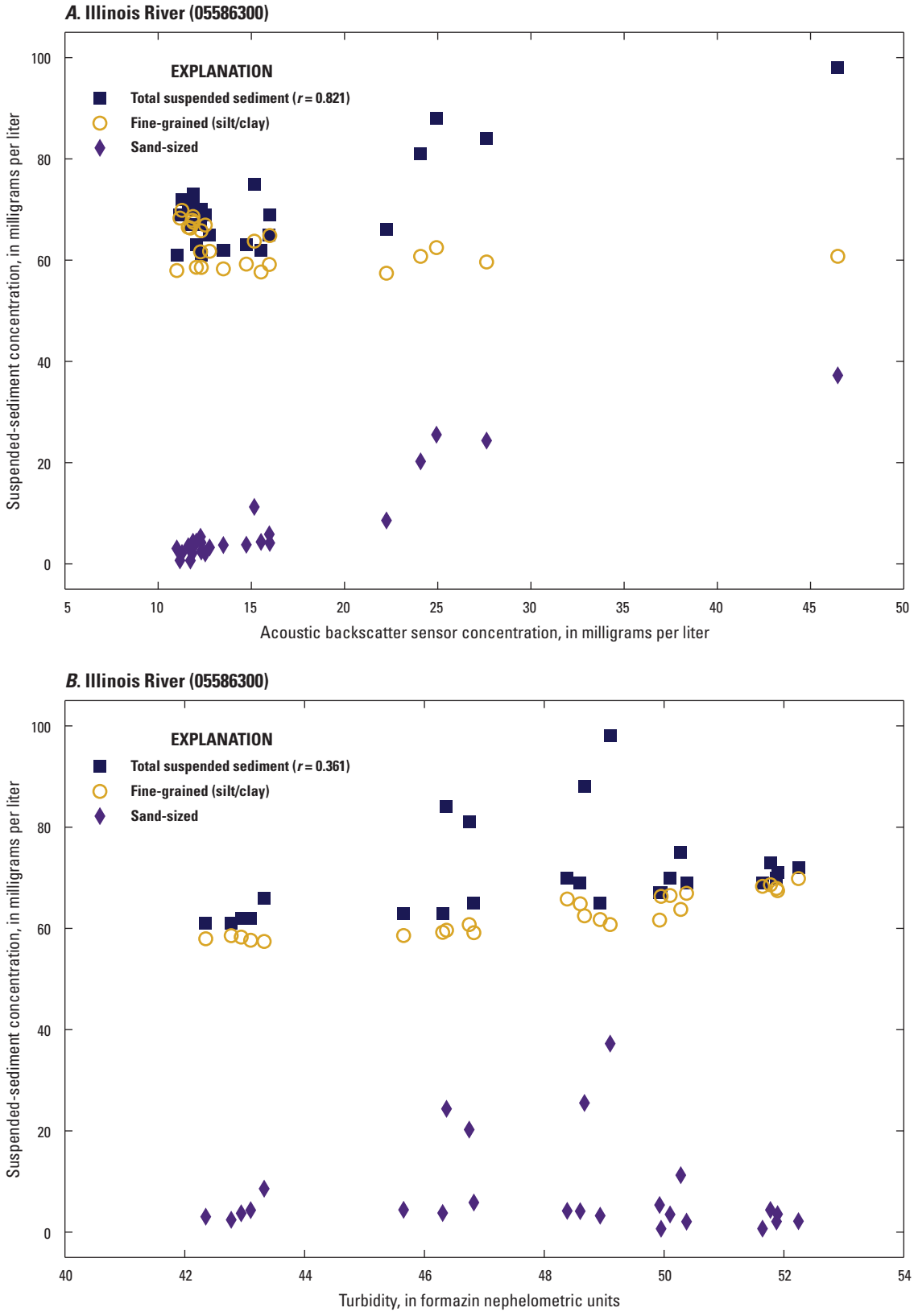


**Figure 9.** Comparison of acoustic backscatter sensor (ABS) concentration and turbidity with total, fine-grained, and sand-sized suspended-sediment concentrations (SSCs) at varying depths and verticals on the Illinois River at Florence, Illinois (U.S. Geological Survey station 05586300). *A*, ABS concentration compared with SSCs. *B*, Turbidity compared with SSCs. [*r*, correlation coefficient]

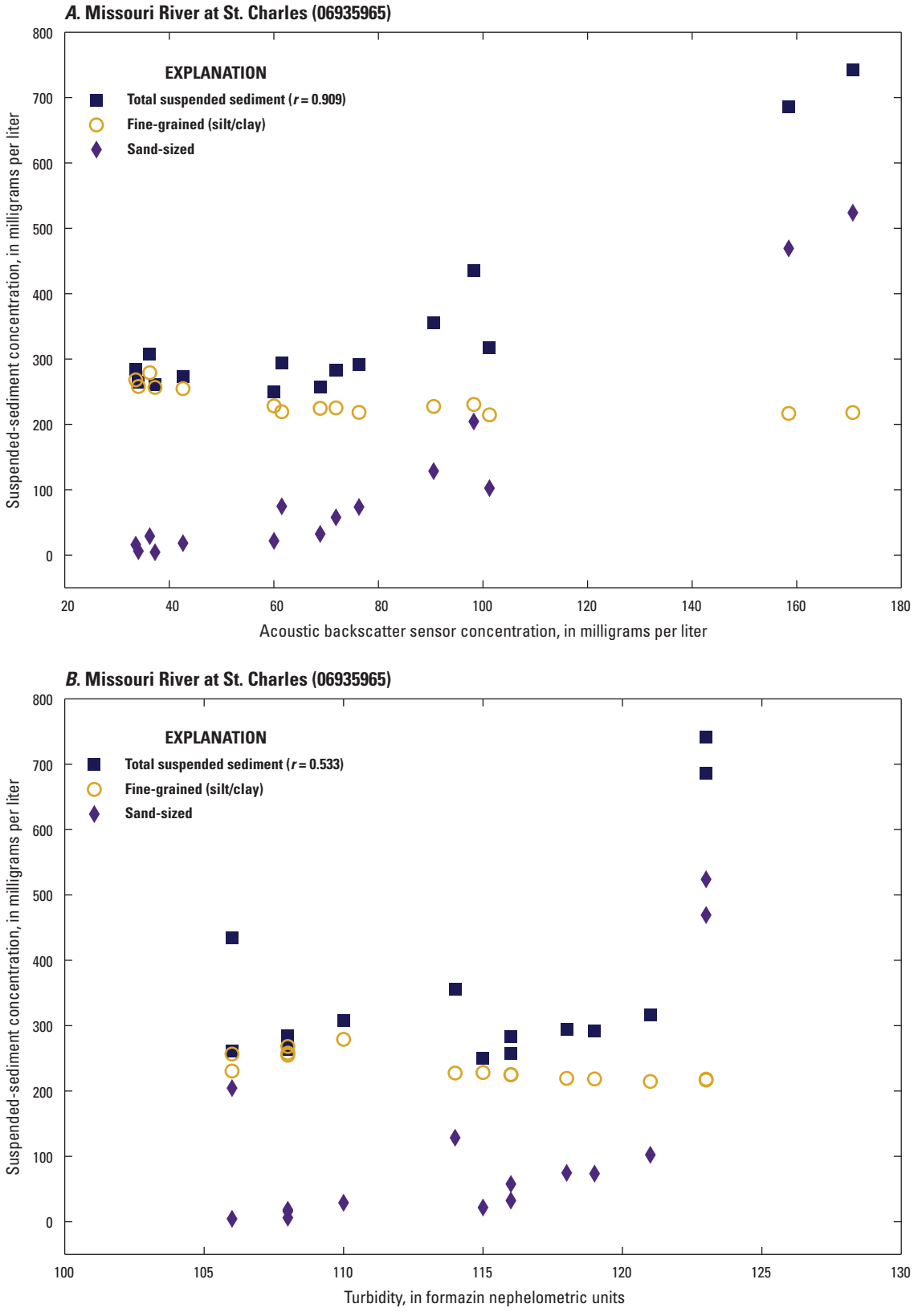


**Figure 10.** Comparison of acoustic backscatter sensor (ABS) concentration and turbidity with total, fine-grained, and sand-sized suspended-sediment concentrations (SSCs) at varying depths and verticals on the Missouri River at St. Charles, Missouri (U.S. Geological Survey station 06935965). *A*, ABS concentration compared with SSCs. *B*, Turbidity compared with SSCs. [*r*, correlation coefficient]

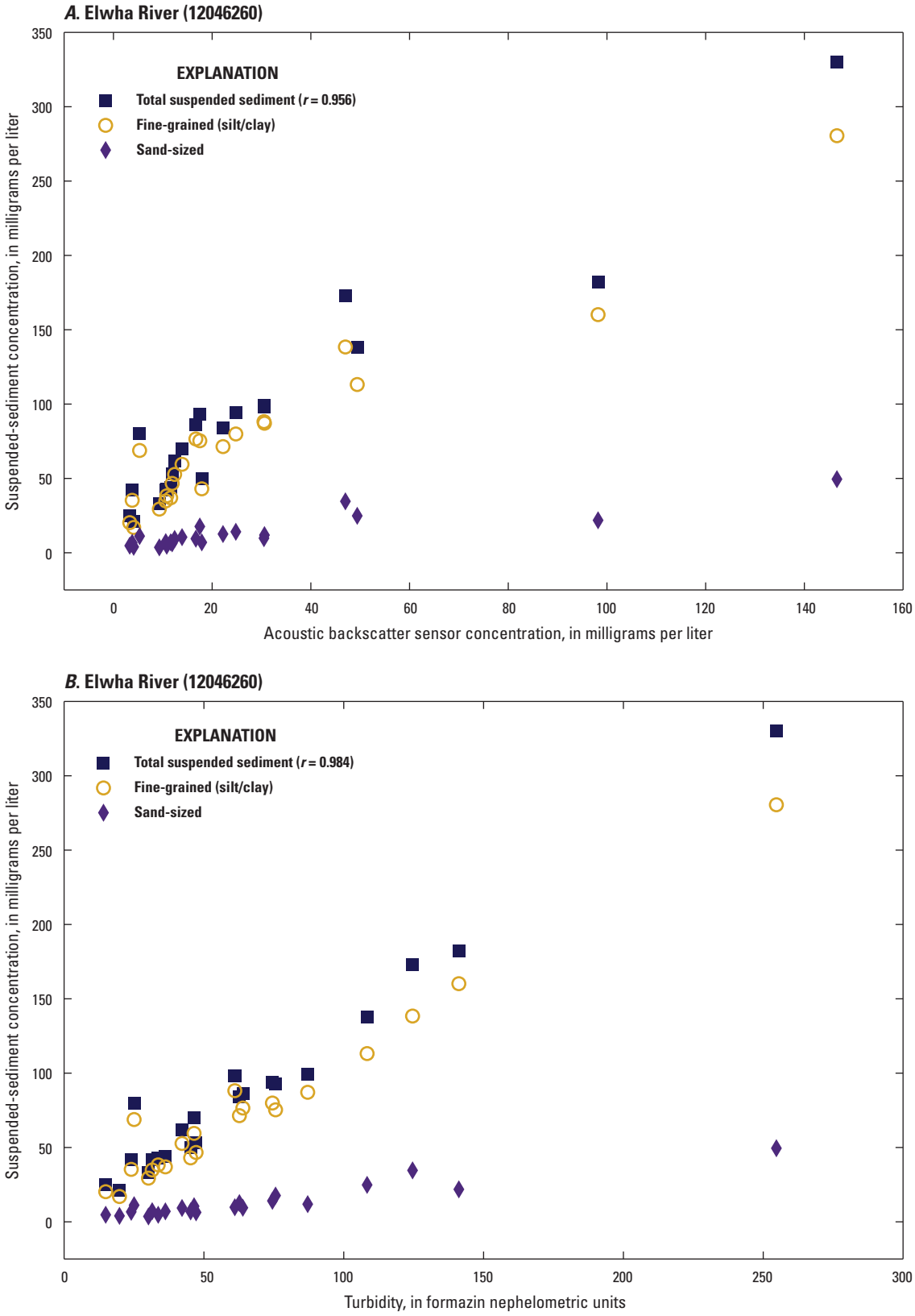


**Figure 11.** Comparison of acoustic backscatter sensor (ABS) concentration and turbidity with total, fine-grained, and sand-sized suspended-sediment concentrations (SSCs) at a fixed location on the Elwha River at Diversion near Port Angeles, Washington (U.S. Geological Survey station 12046260). *A*, ABS concentration compared with SSCs. *B*, Turbidity compared with SSCs. [*r*, correlation coefficient]

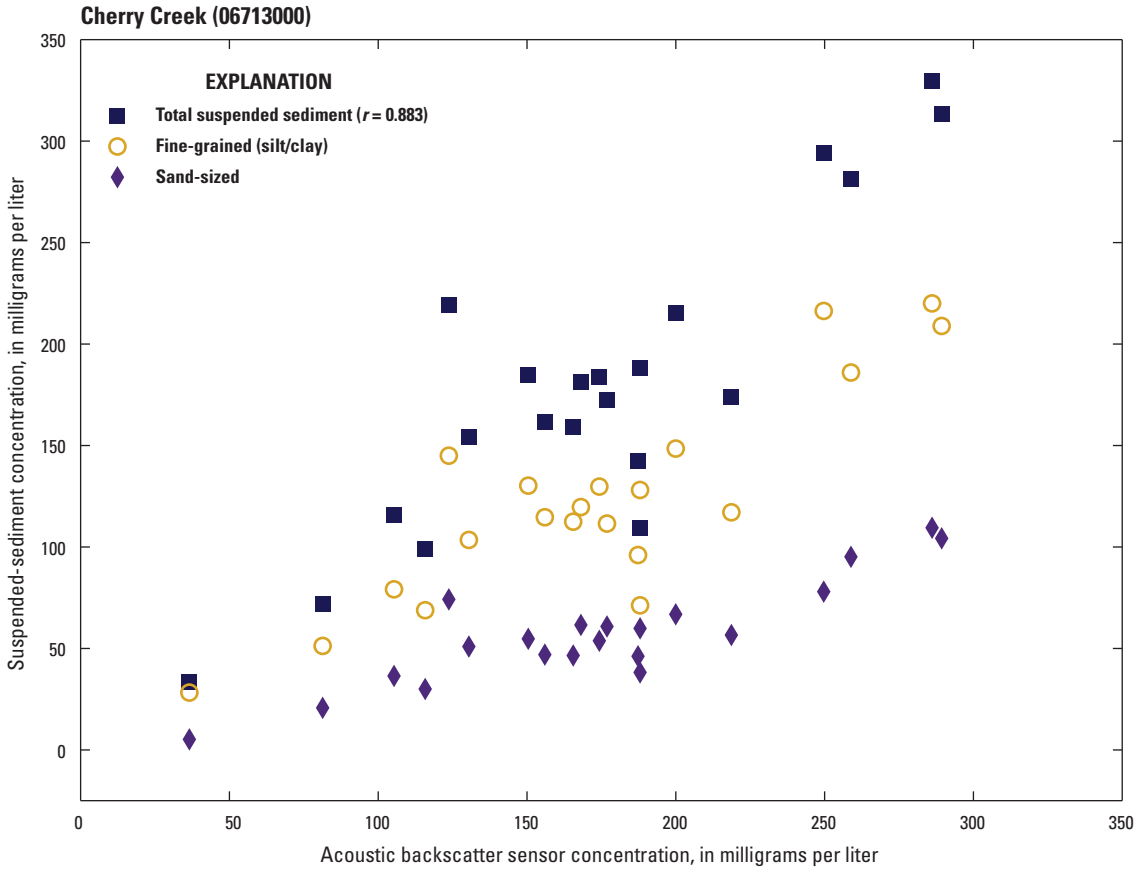


**Figure 12.** Comparison of acoustic backscatter sensor concentration with total, fine-grained, and sand-sized suspended-sediment concentrations at varying verticals and methods on Cherry Creek below Cherry Creek Lake, Colorado (U.S. Geological Survey station 06713000). [*r*, correlation coefficient]

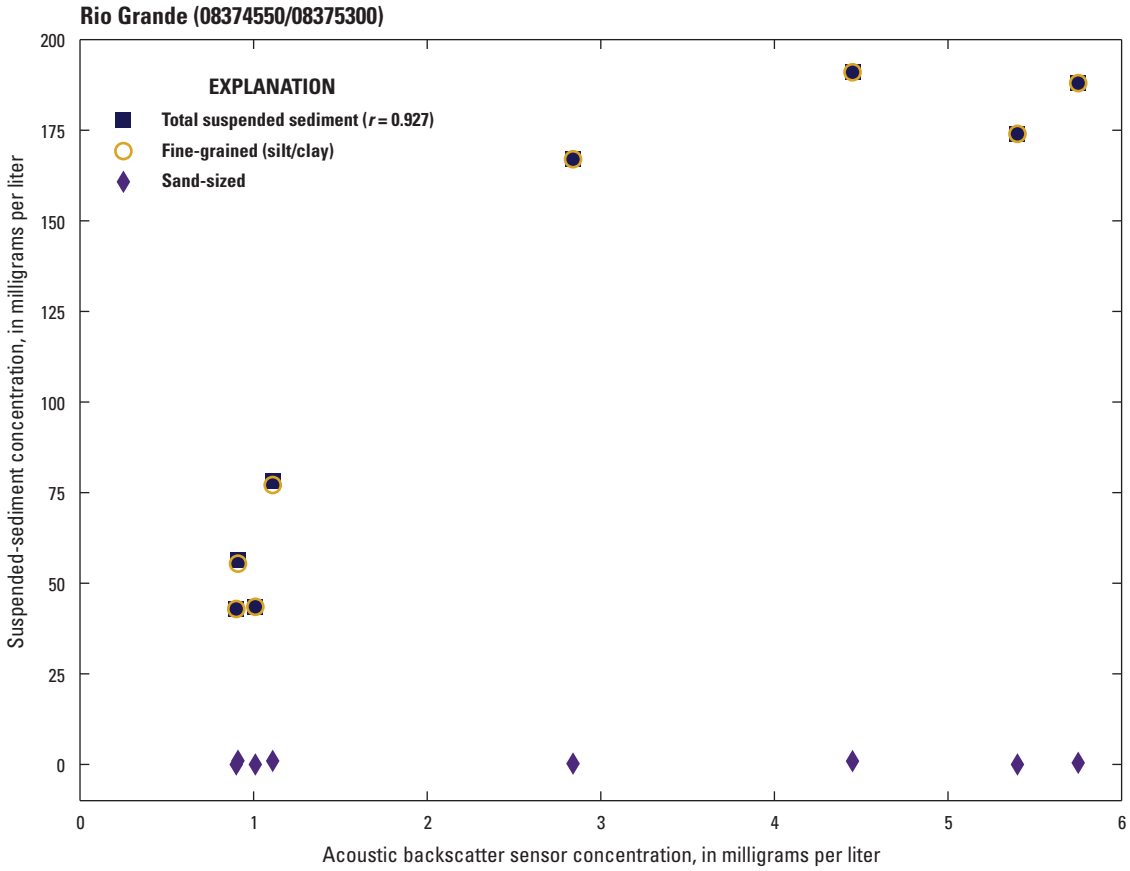


**Figure 13.** Comparison of acoustic backscatter sensor concentration with total, fine-grained, and sand-sized suspended-sediment concentrations at a fixed location on the Rio Grande near Castolon, Texas (U.S. Geological Survey station 08374535) and at Rio Grande Village, Texas (U.S. Geological Survey station 08375295). [*r*, correlation coefficient]

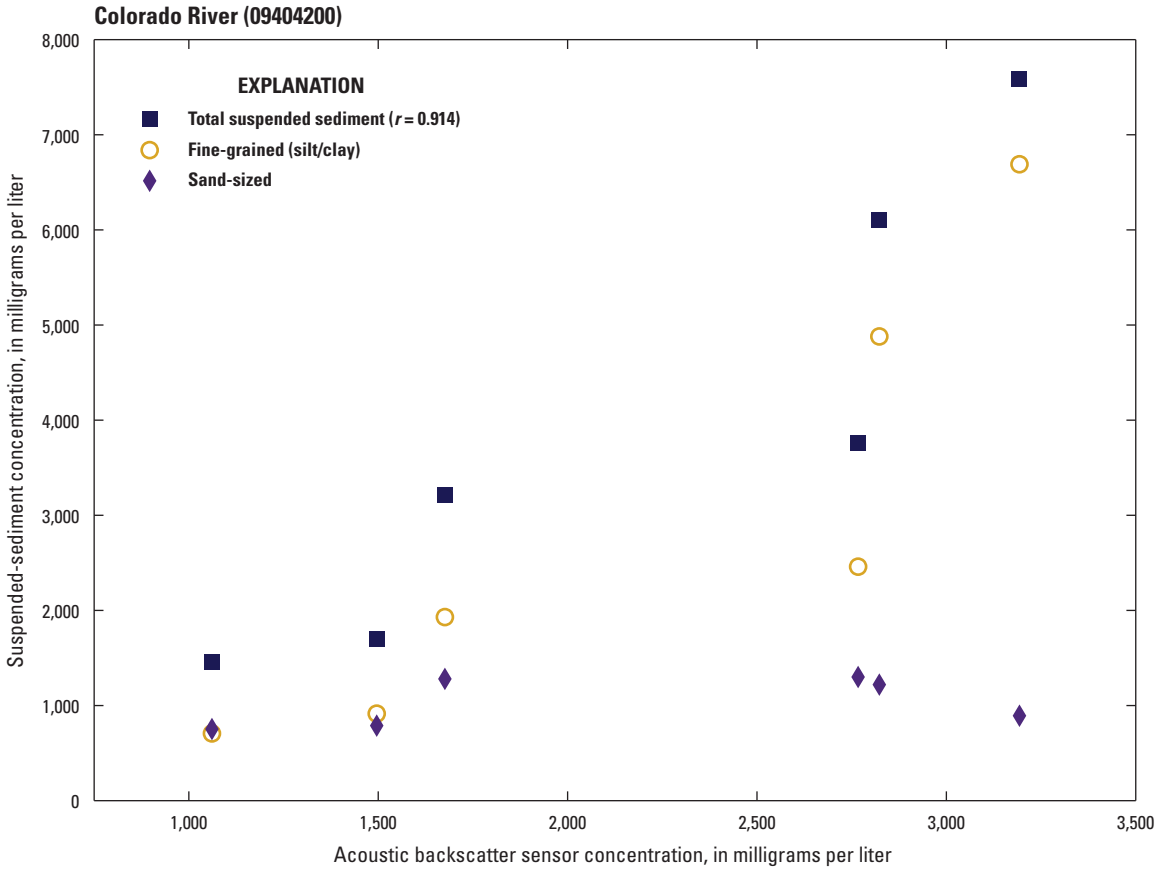


**Figure 14.** Comparison of acoustic backscatter sensor concentration with total, fine-grained, and sand-sized suspended-sediment concentrations at a fixed location on the Colorado River above Diamond Creek near Peach Springs, Arizona (U.S. Geological Survey station 09404200). [*r*, correlation coefficient]

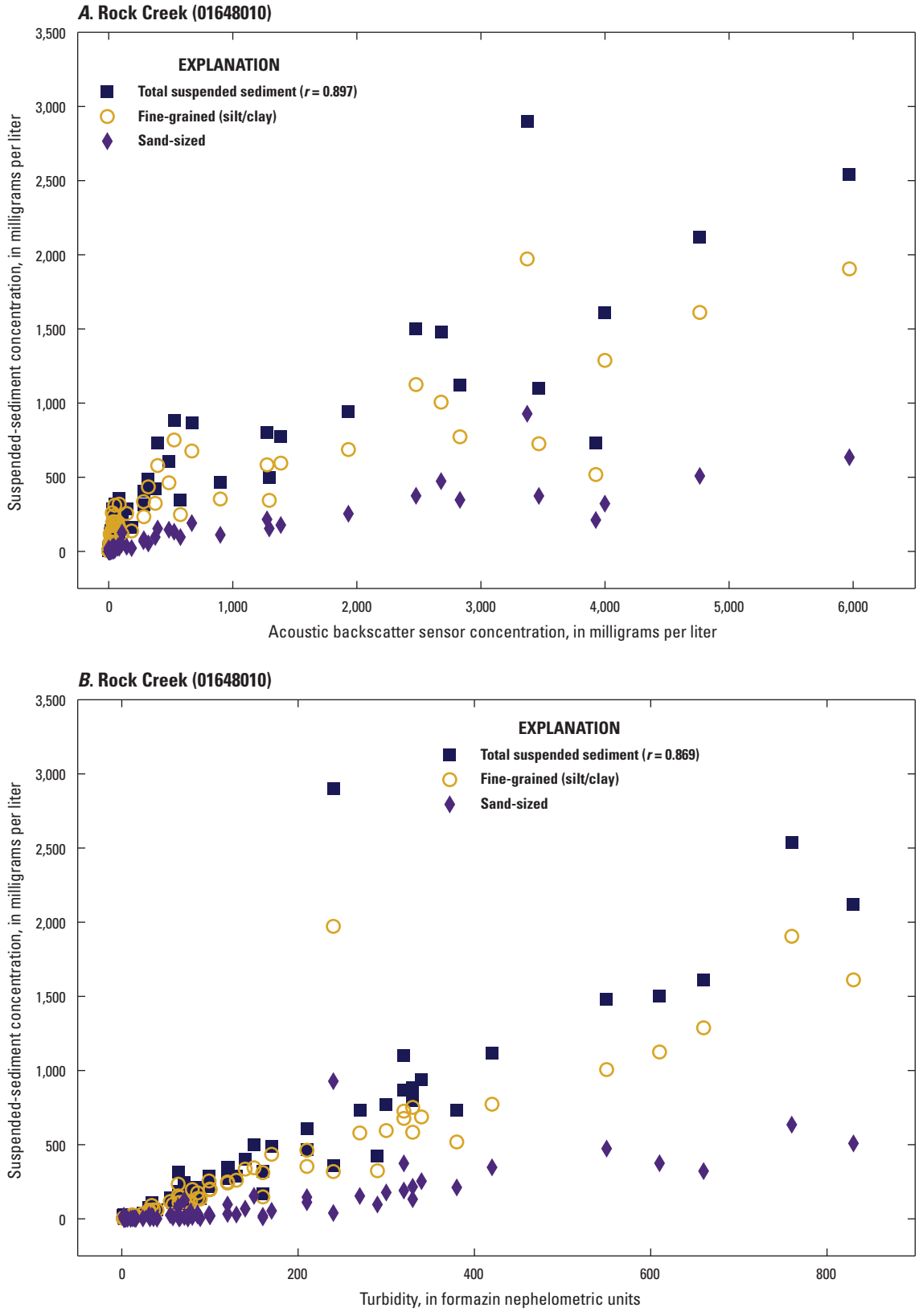


**Figure 15.** Comparison of acoustic backscatter sensor (ABS) concentration with total, fine-grained, and sand-sized suspended-sediment concentrations (SSCs) at a fixed location on Rock Creek at Joyce Road, Washington D.C. (U.S. Geological Survey station 01648010). *A*, ABS concentration compared with SSCs. *B*, Turbidity concentration compared with SSCs. [*r*, correlation coefficient]

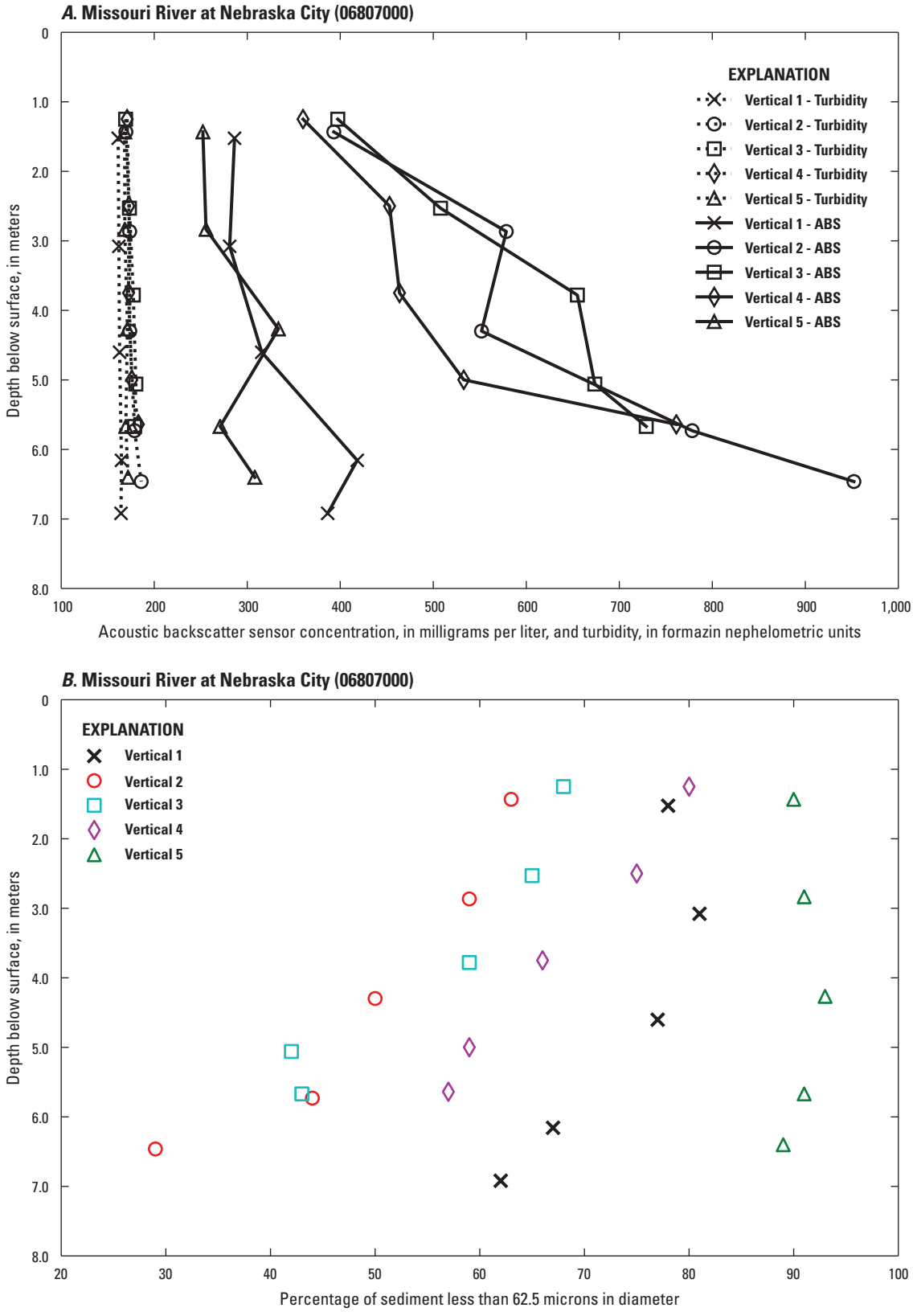


**Figure 16.** Comparison of acoustic backscatter sensor (ABS) concentration with turbidity and percent fines in relation to depth below the water surface at five verticals on the Missouri River at Nebraska City, Nebraska (U.S. Geological Survey station 06807000). *A*, ABS concentration compared with turbidity. *B*, Percent fines in discrete samples in each vertical.

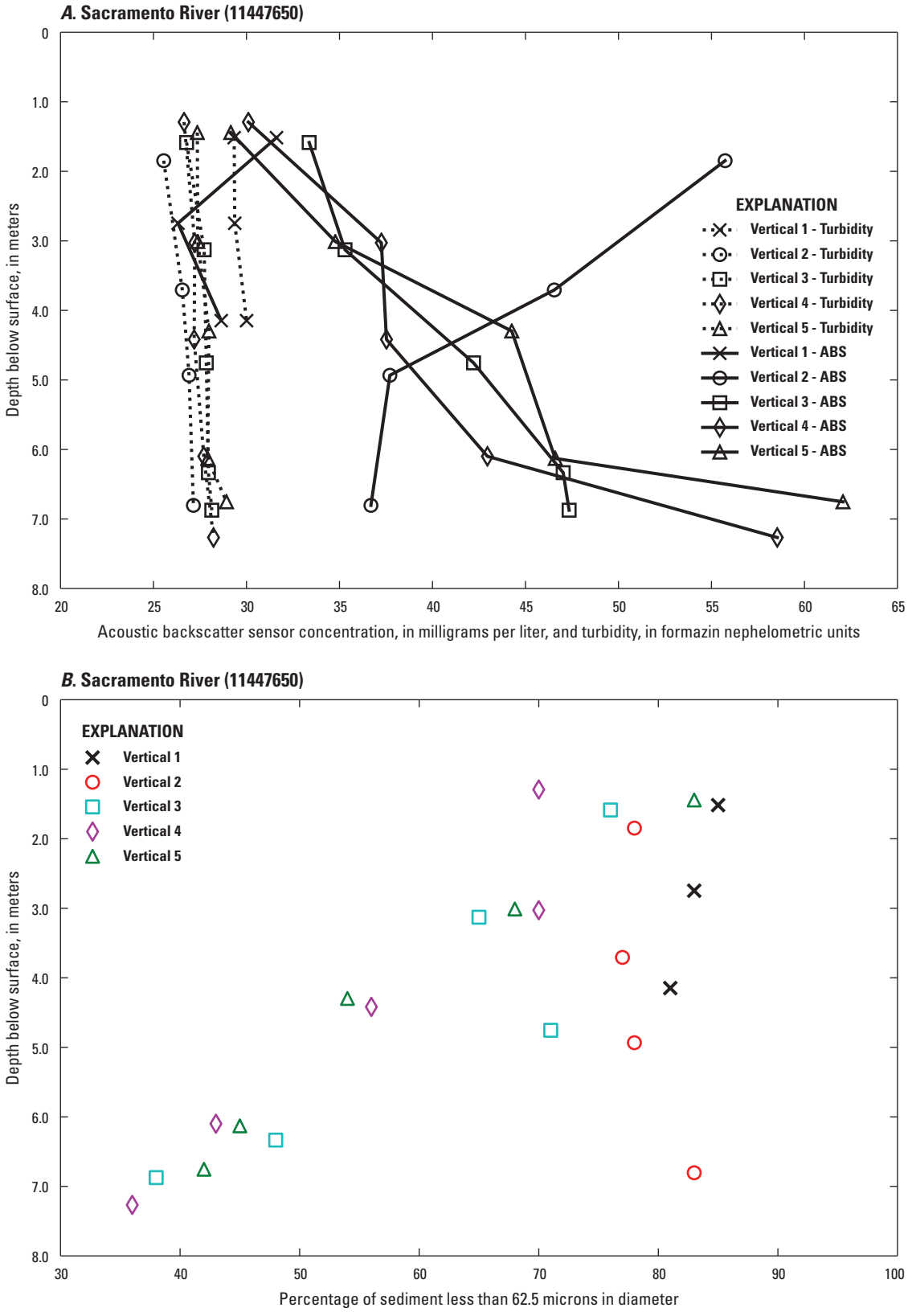


**Figure 17.** Comparison of acoustic backscatter sensor (ABS) concentration with turbidity and percent fines in relation to depth below the water surface at five verticals on the Sacramento River at Freeport, California (U.S. Geological Survey station 11447650). *A*, ABS concentration compared with turbidity. *B*, Percent fines in discrete samples in each vertical.

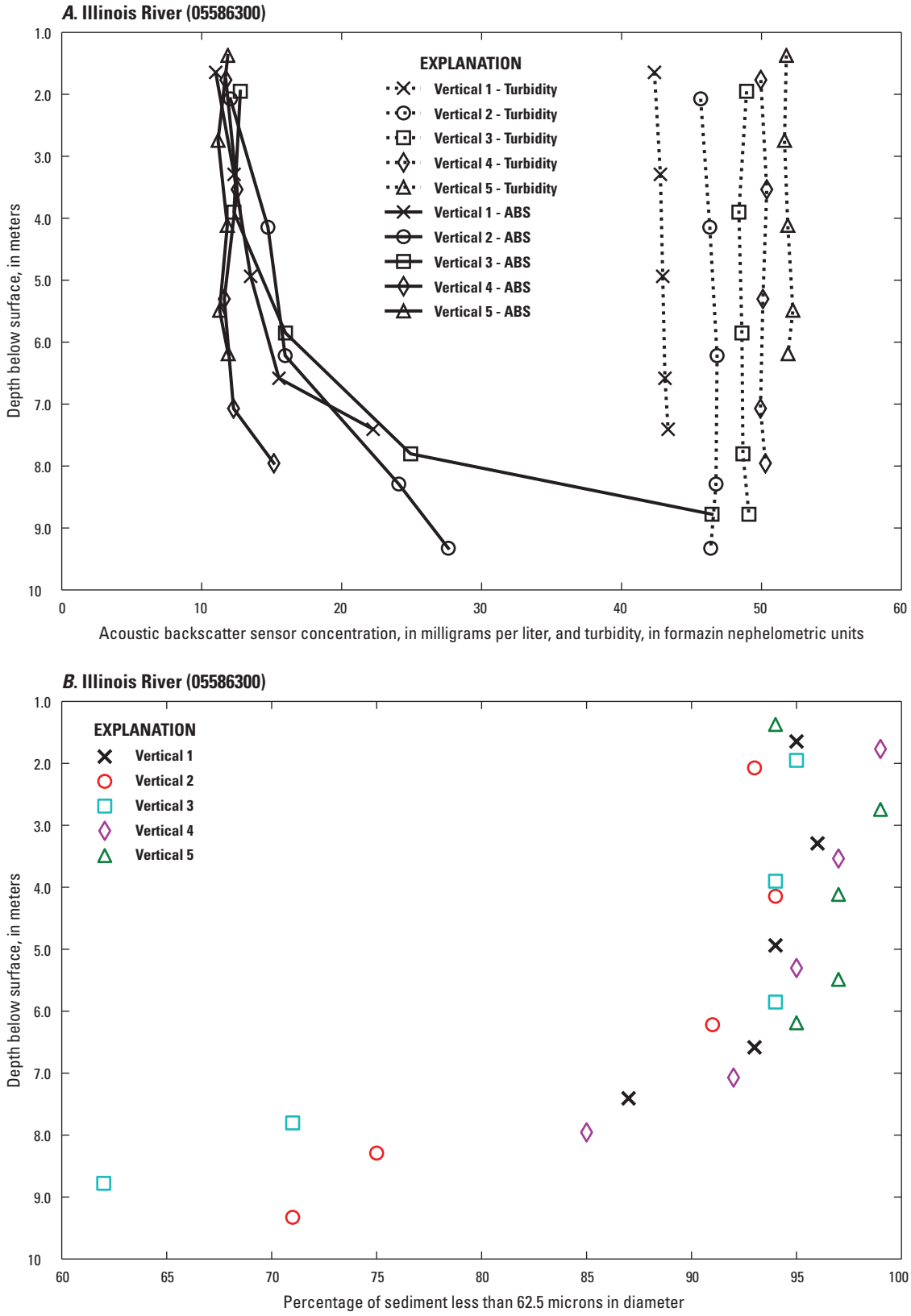


**Figure 18.** Comparison of acoustic backscatter sensor (ABS) concentration with turbidity and percent fines in relation to depth below the water surface at five verticals on the Illinois River at Florence, Illinois (U.S. Geological Survey station 05586300). *A*, ABS concentration compared with turbidity. *B*, Percent fines in discrete samples in each vertical.

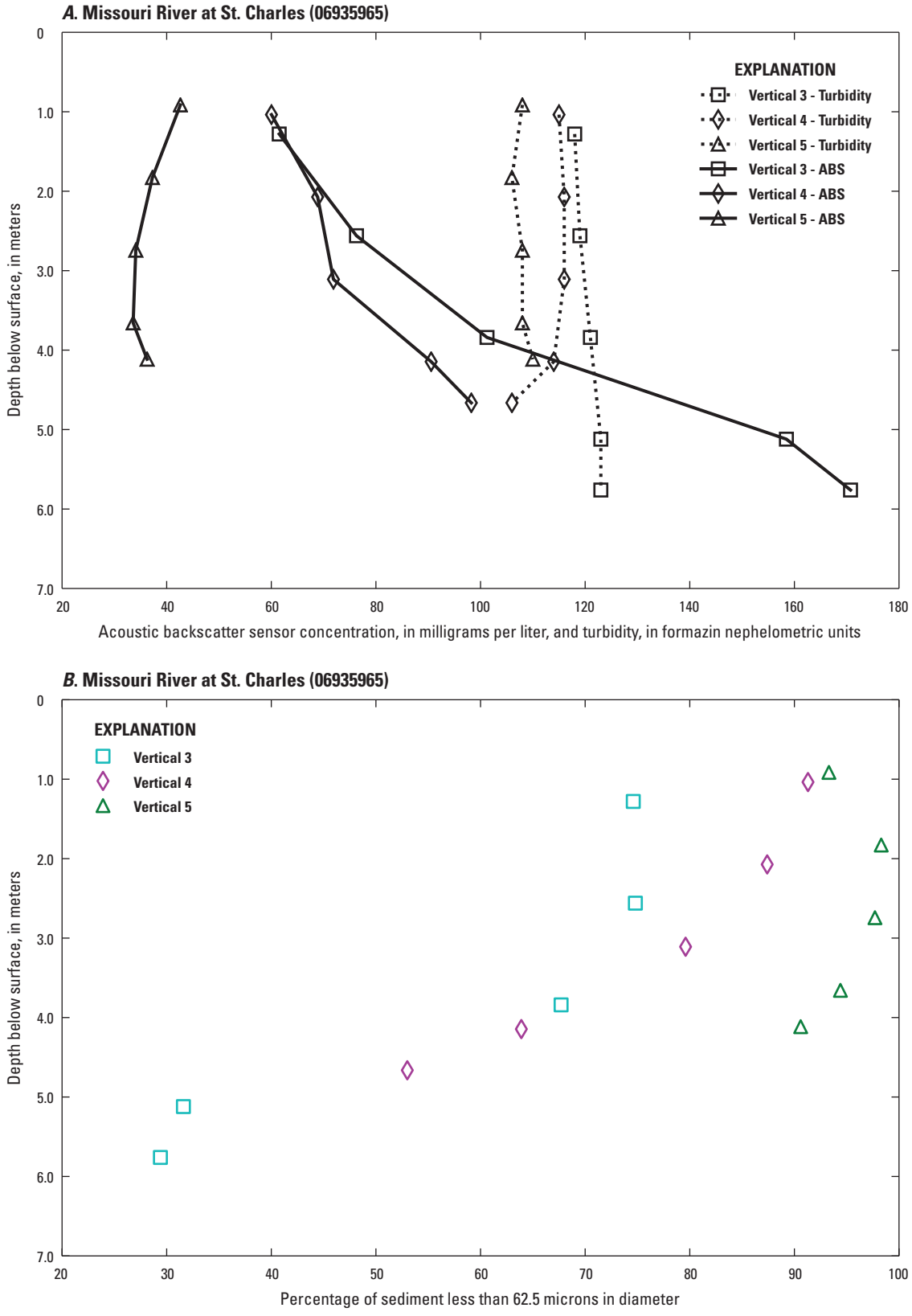


**Figure 19.** Comparison of acoustic backscatter sensor (ABS) concentration with turbidity and percent fines in relation to depth below the water surface at three verticals on the Missouri River at St. Charles, Missouri (U.S. Geological Survey station 06935965). *A*, ABS concentration compared with turbidity. *B*, Percent fines in discrete samples in each vertical.

## Summary

Sequoia Scientific's LISST-ABS is a submersible acoustic instrument used to measure the acoustic backscatter sensor (ABS) concentration at a point source within a river, stream, or creek. Compared to traditional physical methods for measuring suspended-sediment concentration (SSC), sediment surrogates like the LISST-ABS offer continuous data that can be correlated with physical SSC samples. Data were collected at 10 U.S. Geological Survey streamflow-gaging stations between January 10, 2016, and February 21, 2018, across the contiguous United States for the purpose of testing the accuracy and effectiveness of using the LISST-ABS concentrations as a surrogate for measuring SSC in a dynamic fluvial system. ABS concentration and SSC Pearson's $r$ values ranged from $r = 0.718$ to $r = 0.956$ at 10 stations where the mean percent fines results ranged from 65 to 100 percent (with minimum and maximum values of 18 and 100 percent, respectively). The sensitivity of the instrument decreases when the sediment being measured is less than 30 microns in diameter or greater than 400 microns in diameter. Turbidity and SSC correlation coefficients at six stations ranged from $r = 0.118$ to $r = 0.984$ where the mean percent fines results ranged from 65 to 90 percent (with minimum and maximum values of 18 percent and 100 percent, respectively). Overall, the LISST-ABS was more sensitive than the optical turbidity sensors in sensing sand variations with depth in the water column, where vertical profiles of ABS, turbidity, and sediment samples were collected.

Using the LISST-ABS as a surrogate for measuring SSC in a dynamic fluvial system shows promise given the results of the ABS concentration and SSC correlation coefficients at the 10 stations tested using factory-calibrated instruments. Understanding the size, concentration, and distribution of sediment in a fluvial system, as well as the potential spatial and temporal variation of these quantities, is important in analyzing the correlation and will be critical for operational use of the instrument in developing regression models for the ABS concentration and SSC values or recalibrating the instrument for each unique fluvial environment.

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