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Monitoring Suspended Sediment: An Investigation Coincident with the Cherry Creek Reservoir Annual Flush

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14. ABSTRACT From 2017–2022, USACE, USGS, and Bureau of Reclamation (Reclamation) crews collected hydraulic and sediment data to test the capabilities and limitations of the LISST–ABS sensor, designed for suspended sediment monitoring using acoustic backscatter as a surrogate for suspended sediment concentration. The exercises were conducted during an annual reservoir flushing exercise at Cherry Creek Dam near Denver, Colorado. The instrument offers several compelling advantages, including low cost, ease of use, portability, and capability for long–term autonomous deployment. The investigation revealed challenges associated with making stable and reliable measurements; however, these drawbacks can largely be overcome through setup of a thoughtful deployment scheme and assimilation of laboratory calibration routines.				
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Prepared by:

Technical Service Center
Daniel Dombroski, Hydraulic Engineer

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DANIEL DOMBROSKI Digitally signed by DANIEL DOMBROSKI Date: 2024.03.04 12:34:19 -07'00'

Prepared by: Daniel Dombroski, P.E., Ph.D.
Hydraulic Engineer, Bureau of Reclamation Technical Service Center

ROBERT HILLDALE Digitally signed by ROBERT HILLDALE Date: 2024.03.04 12:51:20 -07'00'

Peer Review by: Rob Hilldale
Hydraulic Engineer, Bureau of Reclamation Technical Service Center

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Acronyms and Abbreviations

%		percent

Ac–ft		acre feet

Beads		Ballotini glass beads

CalF		calibration factor
cfs		cubic feet per second
Ck		known concentration
CO		Colorado

FISP		Federal Interagency Sedimentation Project

g/L		gallons per liter

IDD		Isleta Diversion Dam

lb		pound
L		liter

mg/L		milligrams per liter

PVC		polyvinyl chloride

Reclamation	Bureau of Reclamation

SSC		Suspended Sediment Concentration

USACE		U.S. Army Corps of Engineers

USGS		U.S. Geological Survey
CO	Colorado
NE	Nebraska
acoustic–optical sensor AOBS

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Executive Summary

From 2017–2022, the Bureau of Reclamation (Reclamation), United States (U.S.) Geological Survey (USGS), and U.S. Army Corps of Engineers (USACE) collaborated to monitor suspended sediment in Cherry Creek downstream of Cherry Creek Dam during a one–day annual flushing exercise. Completed in 1950, Cherry Creek Dam and Reservoir are operated by the USACE to provide flood protection to the Denver, Colorado (CO) Region from floodwaters. The flushing exercise has been conducted annually since the early 1980's to scour sediment from the area immediately upstream of the radial gates, thereby preventing detrimental buildup and maintaining operability. For six consecutive years, Reclamation deployed a LISST–ABS (Sequoia Scientific, Inc) instrument to estimate suspended sediment concentration. The annual one–day flushing event at Cherry Creek provided a convenient and cost–effective way for Reclamation to test the capabilities and limitations of the emerging technique for suspended–sediment surrogate monitoring using acoustic technology. The LISST–ABS is a relatively low–cost, fixed–point, acoustic backscatter sensor designed specifically for measuring suspended sediment concentration (Sequoia Scientific, Inc). The results are compared with suspended sediment concentrations collected at the same location by USGS field technicians using a Federal Interagency Sedimentation Project (FISP)–approved D–95 sampler. Data from both instruments were processed and synthesized to provide estimates of suspended sediment transported through the system as a function of hydraulic conditions due to reservoir gate operations. Comparisons are drawn between the yearly flushing events in order to evaluate the effectiveness of sluicing operations and proficiency of instrumentation in capturing the dynamics of the event.

The results of the study are useful in addressing questions such as:

- Do modern sediment monitoring techniques using the LISST–ABS instrument offer a feasible and cost–effective solution to meeting Reclamation's needs in addressing sediment management issues in reservoirs and rivers?

- Can continuous approaches to monitoring sediment using surrogate methods provide the resolution and depth of data necessary to guide reservoir flushing exercises and inform computational models with implications to reservoir sustainability?

- What best practices should users adhere to for ensuring consistent and robust data collected using the LISST–ABS instrument?

The project addresses the need for more comprehensive suspended sediment monitoring by exploring the capabilities and limitations of an emerging technique for suspended–sediment surrogate monitoring using acoustic technology. The use of suspended–sediment surrogate methods, such as turbidity, laser–diffraction, and acoustic methods, offer the benefits of continuous temporal monitoring, greater temporal resolution, lower cost, and safer implementation than conventional hand–held methods. The benefits of developing the capability can be widespread within Reclamation; the acquired data can be used to refine computational

and theoretical tools, as well as gauge the sediment–related effects of reservoir operations including sedimentation rates and downstream water quality. Information regarding background suspended sediment concentrations and sediment loads can be obtained when using two LISST–ABS sensors, with one instrument placed at an upstream location. The LISST–ABS instrument offers several compelling advantages, including low cost, ease of use, portability, and capability for long–term autonomous deployment. The investigation revealed challenges associated with making stable and reliable measurements; however, these drawbacks can largely be overcome through setup of a thoughtful deployment scheme and assimilation of laboratory calibration routines. The instrument may be subject to calibration "drift" and the calibration can be sensitive to the type and size of particles. It is recommended that routine recalibration be conducted to ensure reliability over time. The FISP is currently funding research regarding calibration of the instrument. This is on–going work and interested persons should follow progress here.

The project implementation benefited greatly from collaboration between USACE, USGS, and Reclamation engineers and technicians, which resulted in a mutually beneficial study through shared planning and resources. The collective results build to provide a robust dataset from which additional insights can be drawn with year–to–year comparisons. Further, the results from the study are being used to demonstrate the utility and benefits of sediment monitoring to client offices in addressing sedimentation issues at Reclamation facilities. The techniques have already been implemented at project sites with more applications expected in the future.

Background

Sedimentation is one of the most significant problems facing rivers and reservoirs today. Sedimentation is responsible for loss of conveyance, reduced flood protection, reduced power generation capacity, and ecosystem degradation. Fundamentally, the issue of reservoir sustainability is a matter of managing sedimentation. Understanding the sedimentation process and how to manage it requires the ability to accurately predict, control, and monitor sediment transport. Traditional physical sediment monitoring techniques are well–documented and generally affective and reproducible in quantifying the transport of sediments in the riverine environment (Edwards & Glysson, 1998). However, traditional sampling methods are costly and labor–intensive, limiting the practical applicability spatially and temporally. Oftentimes, important physical events are not captured because of staffing limitations or safety concerns (e.g., sampling during flood events). Calibration and analysis of numerical modeling tools are dependent on sediment monitoring data, which is often limited due to the inherent practical limitations to collecting the data (Edwards & Glysson, 1998).

In recent years, surrogate methods have been readily researched and applied for estimating sediment content in riverine environments (Landers, Straub, Wood, & Domanski, 2016; Voichick & Topping, 2014; Wood & Teasdale, 2013; Manaster, et al., 2020). Surrogate methods depend on relationships between sediment and other parameters that are more easily measured; once the relationship has been established, surrogate methods can typically be applied at greater temporal or spatial resolution, and with a greater degree of autonomy, than traditional physical sampling. Technologies commonly being applied for surrogate monitoring of suspended sediment include acoustic backscatter, turbidity, and laser diffraction; technologies being applied for bedload transport include bathymetric differencing, hydrophones, geophones, and impact plates. In addition to varying significantly in fundamental physics, the technologies vary in terms of ease of applicability and cost. The aim of this investigation was to evaluate the capabilities and limitations of an easily applicable and cost–effective method for suspended sediment monitoring.

The project was funded through the Bureau of Reclamation's (Reclamation) Research Office, Science & Technology Program with in–kind support from United States (U.S.) Army Corps of Engineers USACE Omaha (Nebraska (NE)) District. The U.S. Geological Survey (USGS) Lakewood, Colorado (CO) Field Office was contracted to perform physical sediment sampling. The work was initiated with an exploratory scoping–level effort that provided funding for activities conducted in 2017 and 2018 (Dombroski, 2018; Manaster, et al., 2020). The initial scoping project was general in nature with the goal of exploring the potential for application of surrogate methods to monitor sediment transport. Early in the scoping project, an acoustic backscatter sensor (LISST–ABS, manufactured by Sequoia Scientific, Inc.) was identified as the most–likely instrument for sediment surrogate monitoring given the low relative up–front cost (about $3500 at time of purchase) and advertised ease–of–use. Cherry Creek Lake near Denver, CO was identified as a logical site for investigations because of close proximity to the Denver Federal Center (thus limiting mobilization and travel costs) and because of the promise of interagency collaboration with USACE and USGS. USACE conducts a yearly, one–day, sediment flushing exercise at the site to maintain operability of the gates, which provides

convenient test conditions for measuring elevated sediment concentrations. A single LISST–ABS sensor was purchased and testing was conducted during the 2017 and 2018 flushing event at Cherry Creek Lake (Dombroski, 2018). The success of the 2017–2018 scoping study led to additional questions and interest in further exploration of LISST–ABS capabilities and limitations. A continuation of study was proposed to, and funded by, Reclamation's Science and Technology Program, which involved collection of data in 2019–2022 and investigation into instrument calibration and sensitivity. This report summarizes results from both the scoping study and subsequent conducting study and provides analysis of instrument calibration.

Instrumentation

The focus of the study was on testing and evaluating the LISST–ABS, an acoustic–based sediment surrogate sensor. In addition to the LISST–ABS, several other sediment sampling and monitoring devices were employed for the purposes of producing complimentary data used in the calibration, validation, and supplementary analysis.

LISST–ABS

The LISST–ABS, designed and manufactured by Sequoia Scientific, Inc. (www.sequoiasci.com), is a submersible acoustic backscatter sediment sensor. In loose terms, an acoustic signal is transmitted into the water column, reflecting off particles suspended within the sample volume; the strength of the reflected signal is correlated to the concentration of the particles. Sequoia markets the instrument as a low–cost acoustic sensor for directly measuring suspended sediment concentration (SSC) at a point (Sequoia Scientific, Inc., 2023). It is advertised as integrating easily with existing dataloggers or monitoring systems. The LISST–ABS reports backscatter signal strength at a single point about 5 cm from the transducer. Over a particle size range of approximately 30–400 microns, the instrument is factory calibrated with a variation of about 30%, an improvement over optical turbidity sensors which may vary by approximately 600% over the same size range. The factory calibration is conducted with 75–90–micron glass beads and the company notes that customer calibration with representative samples can improve accuracy in the field. A user–specified calibration factor can easily be applied prior to acquisition or in post–processing. The advertised concentration range of the instrument is 1 milligram per liter (mg/L) to 30 gallons per liter (g/L) (7–micron dust) or < 20 g/L (200–micron sand). The instrument is lightweight and easy to handle; with an outer diameter of 2 inches, it can be conveniently housed within standard pipe and tubing sizes available at home improvement stores (figure 1).

Figure 1.—Front and plan view of LISST–ABS with dimensions in English (inches) and Metric (mm) units. Photo credit Sequoia Scientific, Inc. (Sequoia Scientific, Inc., 2023).

Reclamation devised a housing apparatus for the instrument built from polyvinyl chloride (PVC) pipe, the design of which was revised over several iterations. The primary housing uses 2–inch diameter pipe and has legs with feet to stabilize the instrument and maintain a minimum sampling distance of 3.5 inches off the bottom substrate. The instrument, within the housing, was then attached to a sounding weight (figure 2) and deployed via a reel mounted to a USGS Type A crane on a four–wheel truck (figure 3). We chose to use either a 50 pound (lb) or 75 lb sounding weight depending on flow conditions; sampling in faster velocities necessitated use of a larger weight to keep the instrument stable in the water.

Although the LISST–ABS can be integrated with a datalogger for long–term, continuous deployment, we used a laptop for user control and data acquisition. The laptop was connected via USB to the power and communications cable, a setup that worked well for our scenario since it allowed for easy control of the acquisition software and because we were only deploying for up to several hours at a time.

Figure 2.—LISST–ABS within PVC housing and mounted to 75 lb sounding weight. The white circle in the middle of the LISST–ABS is the acoustic transceiver. For deployment in lower velocities, a smaller 50 lb sounding weight was used.

Figure 3.—Deployment of LISST–ABS via reel mounted to USGS Type A crane on a four–wheel truck. Note that the instrument is housed within a differently designed PVC mounting apparatus than what is shown in figure 2. Several different designs of the PVC housing were iterated upon.

D–95

USGS technicians used a FISP–approved D–95 sampler to make measurements of depth–averaged suspended sediment concentration. According to FISP specifications, the D–95 can be used in stream depths up to 15 ft and velocities ranging from 1.7 to 7.4 ft/s. Plastic one liter (L) bottles were used for sampling. Similar to the LISST–ABS deployment, the D–95 sampler was deployed via a reel mounted to a USGS Type A crane on a four–wheel truck (figure 4). USACE labs processed the samples collected in 2017 and 2018 for sediment concentration and particle size distribution. The Reclamation soils lab in Denver processed samples collected in 2019. The USGS Central Midwest Water Science Center was contracted to process samples collected in 2021 and 2022. Unfortunately, the samples collected in 2020 were lost prior to processing.

Figure 4.—USGS technicians deployed a D–95 suspended sediment sampler via a reel mounted to a Type A crane on a four–wheel truck.

Turbidimeter

For the sampling conducted in 2017, a turbidimeter was mounted to the sounding weight along with the LISST–ABS for simultaneous acquisition. A turbidimeter is an optical sensor that measures the cloudiness (turbidity) of a fluid due to the suspension of fine particles. In comparison to the LISST–ABS that correlates the scattering of an acoustic signal to concentration of particles, a turbidimeter correlates the scattering of light to concentration of particles. The turbidimeter did not produce a discernable signal above background noise level and was therefore not utilized in sampling during the 2018 or 2019 efforts. A turbidimeter was again deployed during the 2020 event using a fixed mounting site near the bank of the sampling location.

Water Level Sensors

HOBO water level loggers, manufactured by Onset Computer Corporation, record absolute pressure, which is then converted to water level readings by the software. Absolute pressure includes both the hydrostatic pressure and atmospheric pressure. Hydrostatic pressure is determined using two loggers, one of which is placed under the water column and one of which is placed outside the water and taking the pressure difference. In this way, the flow depth is determined from the pressure head. HOBO loggers were deployed during acquisition in 2017, 2018, 2020, and 2022, although the 2022 data was corrupt and unusable.

Site

Location

Cherry Creek Dam and Lake is located in Arapahoe County, Colorado on Cherry Creek, about 10 miles southeast of Denver, CO (figure 5). Cherry Creek headwaters originate in steep to moderately rolling topography upstream near Monument, Colorado, approximately 50 miles south of the reservoir. Closer to the reservoir, the basin consists of a broad valley with rolling hills. The basin elevation varies from about 7700 ft at the headwaters to about 5170 ft at its confluence with the South Platte River in Denver, CO. Cherry Creek Dam controls about 386 square miles of the 410 square mile basin. The dam, closed in 1948, was constructed by USACE for the primary purpose of mitigating flood risk to downstream Denver. The flood control capacity of the reservoir is 81,736 ac–ft (USACE Northwestern Division - Omaha District, 2023).

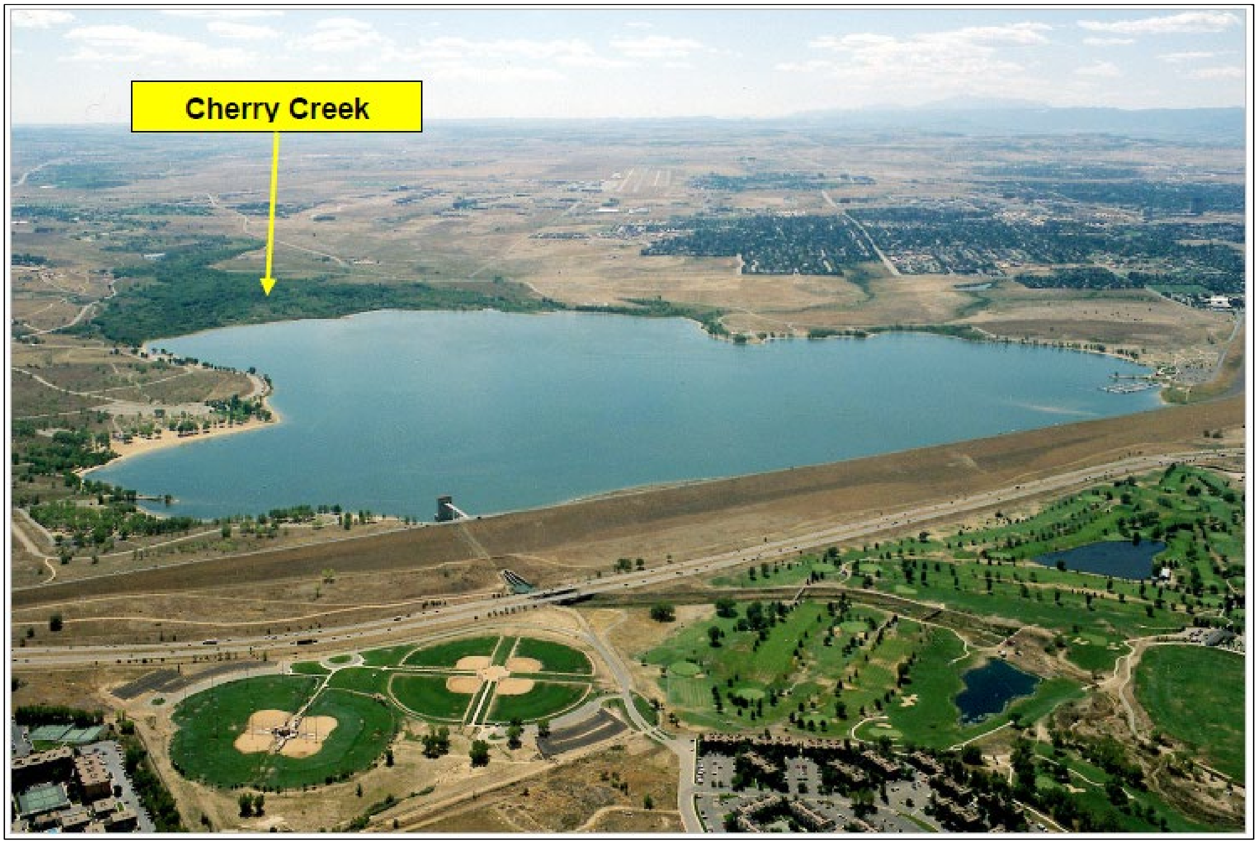

Figure 5.—Aerial photo of Cherry Creek Dam and Lake. Incoming flow from Cherry Creek (upper left) is routed through the dam outlet works (middle of image) and through Kennedy Golf Course (lower right). Figure adapted from USACE Omaha District (2023).

Dredging was conducted in December 1983 and January 1984 near the dam intake structure to remove accumulated sediment. Sediment core samples collected at that time indicated that the deposited material is generally classified as a fine–grained, silty clay (CH, Unified Soil Classification). Table 1 summarizes soils characteristics from the sediment core sampling (USACE Northwestern Division - Omaha District, 2023). Analysis of bed material samples collected within Cherry Creek Lake in 2016 using a USGS BM–54 sampler indicate predominantly silt size class with an average D_{50} of 0.0345 mm. Further analysis of Cherry Creek Lake bed material sampling is provided in USACE Omaha District (2023).

Table 1.—Soil parameters from 1983–1984 sediment core sampling. Table adapted from USACE Omaha District (2023)

Test Parameter	Mean	Median	No. of Samples	Range
Liquid Limit	87	90	6	53 – 109
Plasticity Index	59	68	6	25 – 70
Void Ratio	7.5	3.6	10	2.56 – 48.90
% Water Content	196	170	10	128 – 446
% Material < 0.1 mm	----	----	9	95 – 99
% Material < 0.002 mm	47	46	3	42 – 53
Soil Activity	----	----	3	1.36 – 1.50

Immediately downstream of the outlet works, Cherry Creek continues its path through Kennedy Golf Course towards its confluence with the South Platte River in Denver, CO. Kennedy Golf Course features several bridges allowing carts to pass over the creek; the bridges were utilized for Reclamation's yearly sediment sampling exercises as they offered the most–upstream (closest to dam outlet works) locations available (figure 6). Figure 7 and figure 8 contain photos of the cart bridges at the upper sampling location (approximately 1,400 feet downstream of the dam outlet works) and lower sampling locations (approximately 2,800 feet downstream of the dam outlet works), respectively. As is evident in the photos, the cart bridge at the lower sampling location is smaller and has a lower deck; consequently, the lower sampling location is subject to overtopping during high flow conditions.

Figure 6.—Site map in vicinity of sediment sampling locations just downstream of Cherry Creek Dam outlet works. Shown are Cherry Creek Dam and outlet works, Kennedy Golf Course, upper and lower sampling locations, and USGS gaging site no. 06713000.

Figure 7.—Cart bridge on Kennedy Golf Course indicated as the Upper Sampling Location in figure 6. The Upper Sampling Location is approximately 1400 feet downstream of the dam outlet works.

Figure 8.—Cart bridge on Kennedy Golf Course indicated as the Lower Sampling Location in figure 6. The Lower Sampling Location is approximately 1400 feet downstream of the dam outlet works. The cart bridge at the lower sampling location was subject to overflow during high flow conditions; consequently, the cart bridge at the upper sampling location was alternatively used when the lower location was inaccessible.

Operations

Sediment deposition on the face of the intake structure at Cherry Creek Dam has been a recurring problem (USACE Northwestern Division - Omaha District, 2023). The dredging operations conducted in 1983–1984 were necessitated out of the discovery of approximately 20 feet of sediment accumulation at the bottom of the intake structure. A number of different options were explored for strategically removing sediment from the vicinity of the gates; sediment flushing operations were determined to be least costly and disruptive. Annual flushing operations have been carried out intermittently since the mid–1980's. In recent years, the magnitude of the flushing operations have been systematically alternated from year–to–year between a "low flush" event and a "high flush" event. The "low flush" events feature a maximum release of approximately 250 cfs while the "high flush" events feature a maximum release of approximately 1,300 cfs. Typical base flows released from the dam into Cherry Creek are around 50 cfs. A given flushing event in any year typically spans several hours on a single day in late May, beginning around 9:00 am and reaching completion around noon. The outlet works features five hydraulic slide gates that are independently operated during the flushing exercise, such that

only one gate is open at a time. The result is an oscillating hydrograph downstream of the dam in which measured discharge varies rapidly over a time scale of minutes (figure 9). The real–time operation of the gates may differ somewhat from scheduled, and the facility operators typically publish the timeline of actual operation post–release.

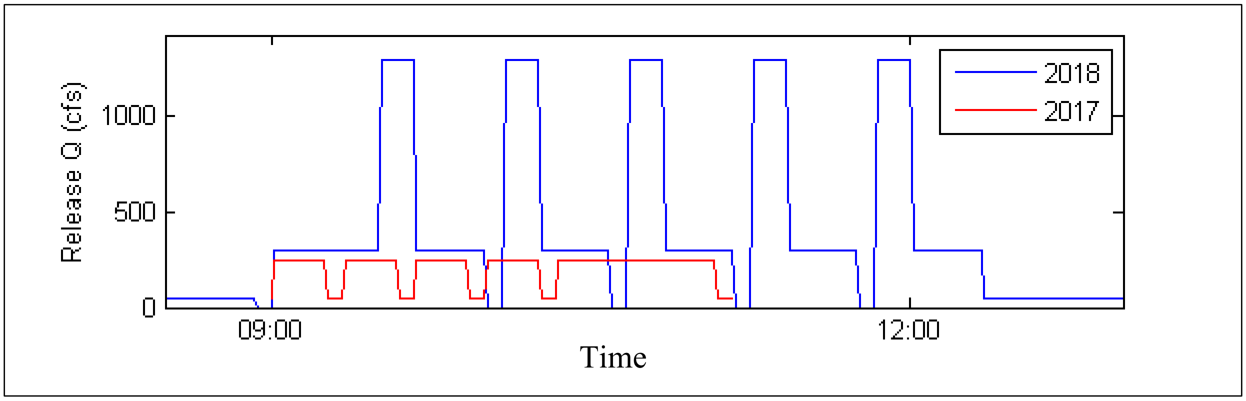

Figure 9.—Representative gate release hydrographs associated with a "low flush" event (2017) and a "high flush" event (2018). The hydrographs were generated from the scheduled operation of the gates, where each peak is associated with the operation of a single gate. The result is an oscillating hydrograph in which discharge varies rapidly over a time scale of minutes.

There is a USGS gaging station (Cherry Creek below Cherry Creek Lake–06713000) located at Kennedy Golf Course, approximately intermediary between the upper sampling location and lower sampling location (figure 6). The close proximity of the gaging station to the sampling locations is convenient for capturing the measured hydrograph, which has dispersed peaks relative to the release at the gates. Figure 10 compares the gate operations (scheduled and actual) to the measured discharge from USGS gage 06713000 for the flushing event conducted in 2017. The plot demonstrates the dispersion of the hydrograph peaks that occurs between the outlet works and the distance downstream to the vicinity of the sampling locations.

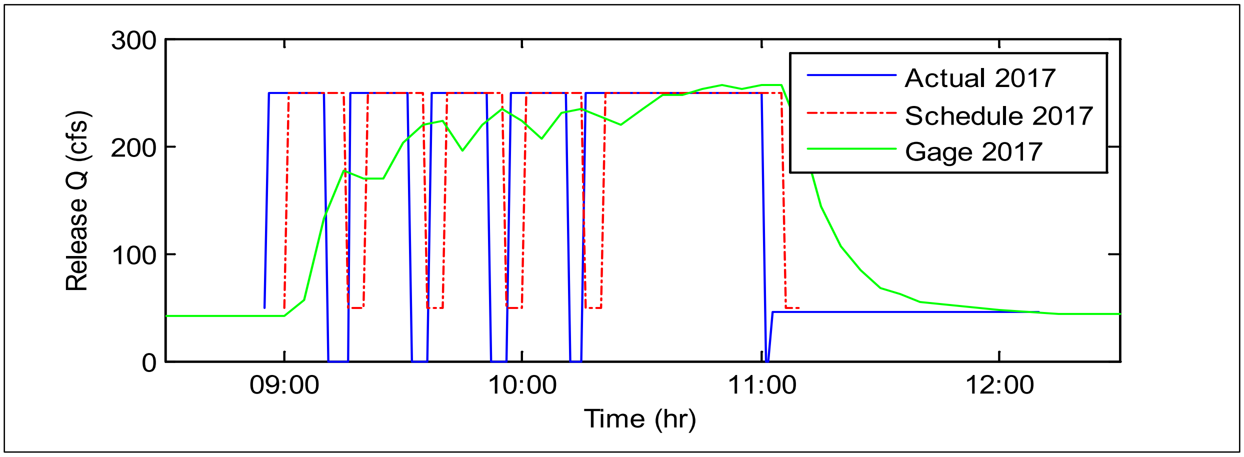

Figure 10.—Comparison of scheduled gate operation, actual gate operation, and measured discharge from USGS Gage No. 06713000. The measured discharge from the gage reflects wave dispersion as the flow advects downstream from the outlet works to the sampling locations.

Results

2017 Flushing Event

The 2017 flushing event at Cherry Creek Lake marked the debut of the study and first testing of the LISST–ABS sensor, although the flushing release itself had been conducted annually for many years prior. The release hydrograph was characterized as a "low flush" event (figure 9) and sampling was conducted at the lower sampling location (figure 6 and figure 8). In 2017, 33 one L bottles were processed for determining sediment concentration from the physical sediment sampling with the D–95 sampler. The LISST–ABS was mounted within the PVC housing to a 50–lb sounding weight along with a turbidimeter. Although the LISST–ABS is capable of continuous, autonomous operation, it was necessary to periodically raise the instrument to clear debris from the A–Reel cable and data communications line. As a result, the data reported from the instrument is divided into files with variable temporal breaks in between. Further, different methods of sampling were used:

- Suspending the instrument at constant distance from the bed over the duration of sampling period for each file
- Vertically translating the instrument through the water column
- Varying the lateral stationing of the instrument along the bridge

The concept behind systematically changing the sampling methodology was to gauge the spatial variability of the measurements through the water column and also to test the viability of producing a depth–averaged concentration measurement analogous to how the D–95 sampler is operated.

A compilation of the discharge, stage, and suspended sediment concentration data for the 2017 Cherry Creek flushing event is presented in figure 11. The top panel compares the release from the gates to the measured discharge at the gage just upstream of the sampling location. The second panel provides the record of pressure head (a surrogate for stage) as measured by the HOBO logger at the sediment sampling location. A stage reading was also available and shown for comparison. The third panel presents the record of sediment concentration measurements from the LISST–ABS compared to that as collected using the D–95 sampler. The bottom panel shows mean (with error bars indicating one standard deviation) record of sediment concentration measurements from the LISST–ABS compared to data collected using the D–95 sampler. The mean LISST–ABS values represent 1–min average intervals centered round the D–95 sampling time of acquisition. In the third panel of figure 11, the vertically oriented distributions of points from the LISST–ABS represent collection of a vertical profile of concentration measurements through the water column. The wide range of values observed is indicative of vertical stratification of suspended sediment.

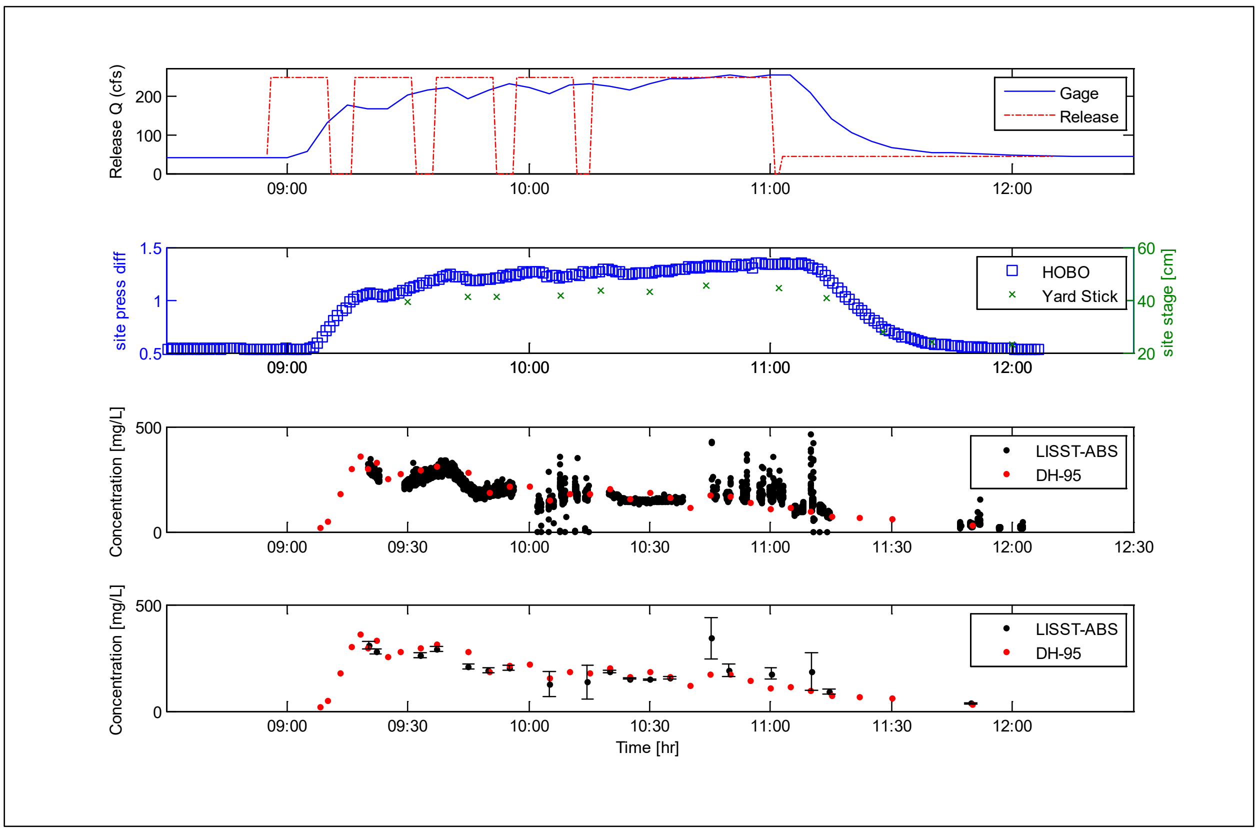

Figure 11.—Compilation of results from the 2017 Cherry Creek flushing event. Panels from top to bottom correspond to: (1) flow release from Cherry Creek Dam outlet works compared to measured discharge at gage, (2) Pressure and hydraulic head reported from HOBO pressure transducer logger and stage, (3) Continuous record of LISST–ABS measurements compared to D–95 measurements, (4) mean values of LISST–ABS measurements compared to D–95 measurements.

To better illustrate the temporal and spatial distribution of suspended sediment observed, figure 12 shows a snapshot of the overall record of LISST–ABS values reported for the flushing event. Sediment concentration through the water column is generally expected to increase with depth below the water surface due to the balance of forces involved with keeping particles suspended. However, vertical profiles of suspended concentration collected with the LISST–ABS during the 2017 flushing event indicate a trend opposite what would be expected. The valley shape of the distribution recorded from each vertical profile indicate that suspended sediment concentration was highest at the top of the water column, declining towards the bed. This may have been due to the presence of a bed feature causing a vertical disturbance in the velocity field just upstream of the sampling location, driving sediment upwards in the water column.

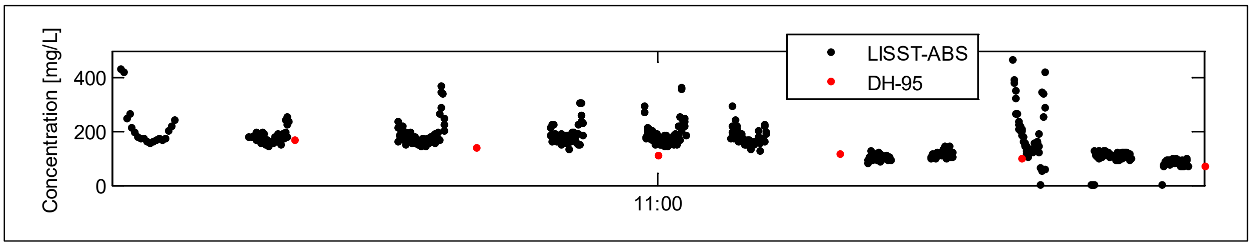

Figure 12.—Record of sediment concentration measurements from LISST–ABS collected during the 2017 Cherry Creek flushing event over the period 10:45 am–11:15 am (subset of data shown in Figure 11, panel 3). Each grouping of points represents a vertical profile through the water column. The valley shape of the profiles indicates that suspended sediment concentration was higher near the water surface and lower near the bed.

Results from the LISST–ABS were also compared to results from a turbidimeter that was co–mounted to the sounding weight. Figure 12 presents instantaneous measurements from both instruments; the poor correlation between the signal from the LISST–ABS and turbidimeter led to discontinued use of a turbidimeter in subsequent flushing events (except the 2020 event).

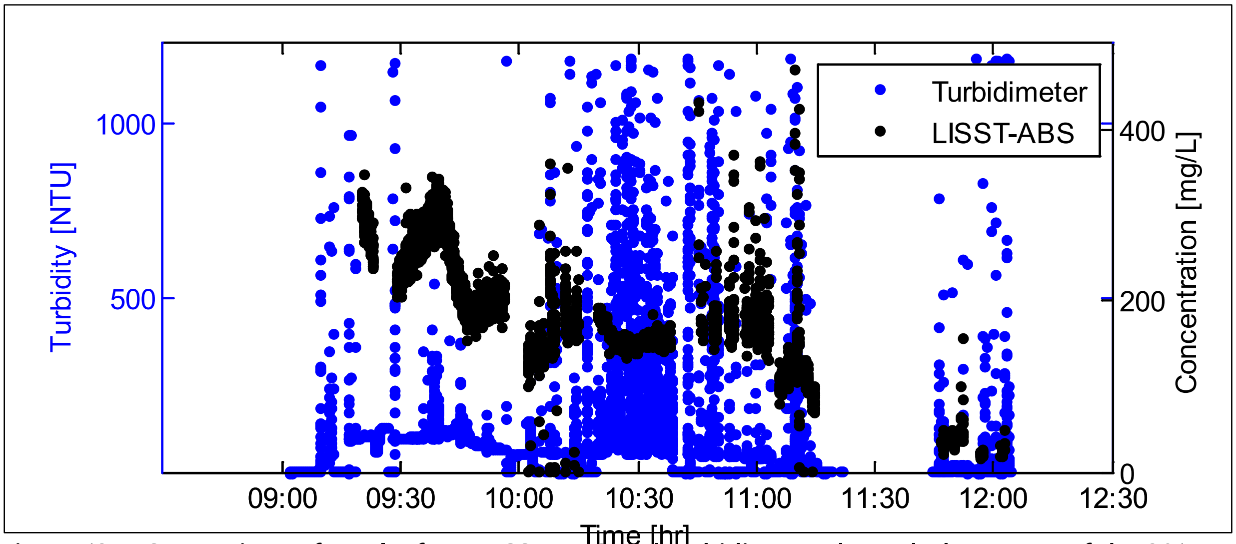

Figure 13.—Comparison of results from LISST–ABS and turbidimeter through the course of the 2017 Cherry Creek flush. The poor correlation between the measurements led to discontinued use of the turbidimeter in subsequent flushing events.

Sediment size distribution as reported from the processing of data collected using the D–95 sampler is presented in figure 14. A Malvern laser diffraction analyzer was used to measure particle size. Outliers are observable in the distributions, possibly caused by entrainment of large bed material into the sampler. A mean distribution is also shown, computed by averaging the individual sample curves. The average D_{50} for the samples is about 0.03 mm, indicating that the material in suspended transport is dominated by silt. The distributions indicate that the mobilized size classes range from clays to fine sands. The significant fines component of the sediment in suspension may be related to the poor correlation between the results from the LISST–ABS and turbidimeter. The LISST–ABS is most sensitive to grain sizes of approximately 0.03–0.4 mm, which is larger than the measured D_{50} of the samples. On the other hand, optical sensors such as the turbidimeter are most sensitive to fine sediment gradations.

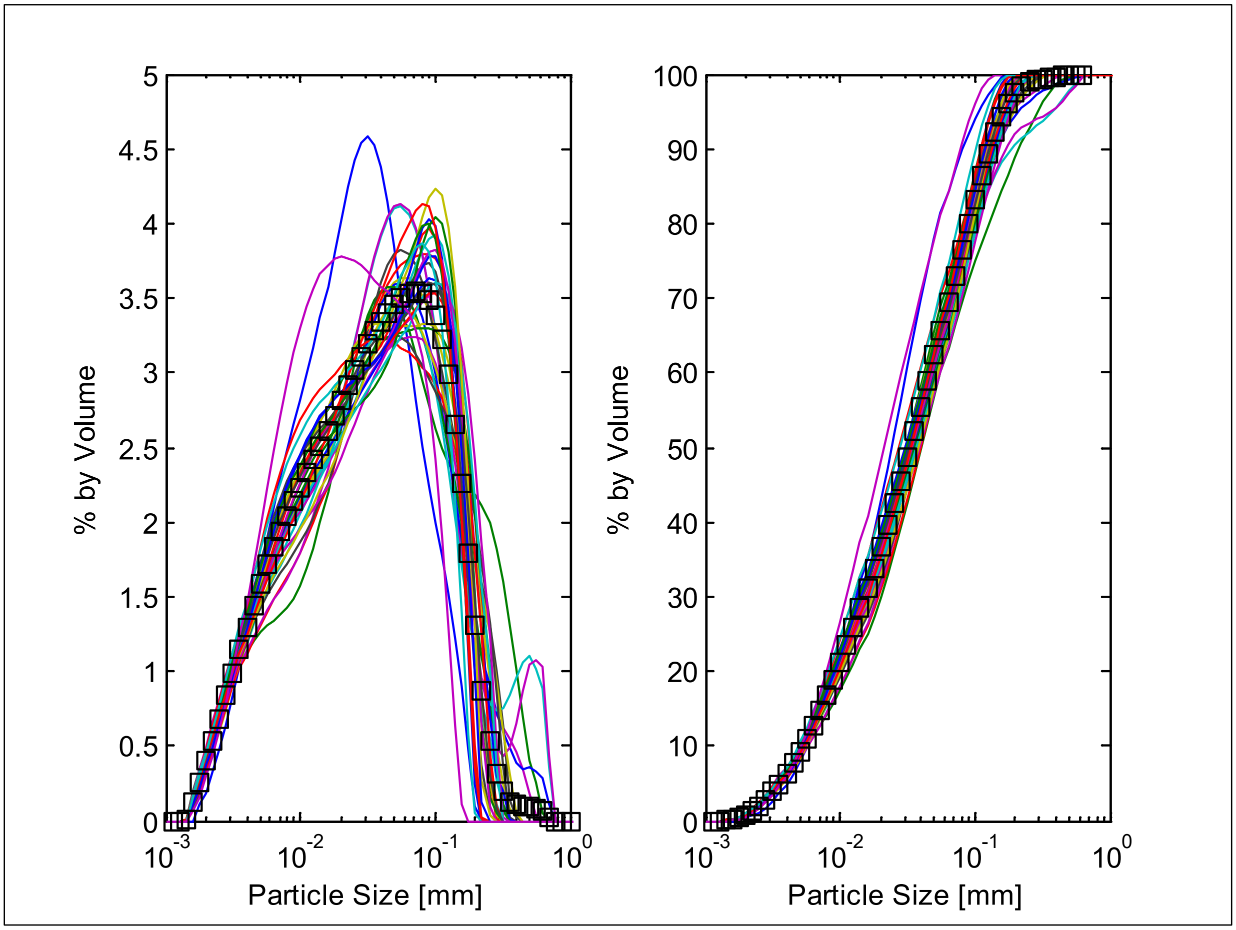

Figure 14.—Sediment size distribution reported from samples acquired using the D–95 sampler during the 2017 Cherry Creek flushing event. Black squares indicate mean of all curves. Left panel shows discrete fraction and right panel shows cumulative fraction. The x–axis is plotted on log scale. According to the manufacturer, the calibration range of the LISST–ABS sensor over 0.03–0.4 mm range is constant to within +/–30%.

2018 Flushing Event

In the second year of the project–supported sediment monitoring, the release hydrograph was characterized as a “high flush” event. The lower sampling location that was used during the 2017 sampling was inaccessible due to overtopping associated with the higher discharge of the 2018 event (figure 15); consequently, sampling was conducted at the upper sampling location (figure 6 and figure 7). In 2018, 44 one L bottles were processed for determining sediment concentration from the physical sediment sampling with the D–95 sampler. The LISST–ABS was mounted within the PVC housing to a 75 lb sounding weight. The larger sounding weight was chosen because of the anticipated higher velocities associated with the “high flush” event. The higher stage and velocities associated with the event mobilized large amounts of debris from the banks, necessitating frequent raising of the instrument to clear debris from the cabling (figure 16). As a result, the data reported from the instrument is divided into files with variable

temporal breaks in between. At no point was it evident that the collection of debris during data collection was affecting the sensor or readings from the instrument; the concern over debris collection was primarily related to the increase in drag and weight on the line.

Figure 15.—Overtopping of the cart bridge at the lower sampling location (used in the 2017 flushing event) due to the higher discharge associated with the 2018 Cherry Creek flushing event necessitated conducting sampling at the upper sampling location.

Figure 16.—The "high flush" event in 2018 resulted in higher stage and velocities than the "low flush" event in 2017, mobilizing significant quantities of debris from the banks of Cherry Creek. The instrument was raised frequently to remove debris caught up on the cabling.

Two sampling methods were utilized during the 2018 sampling event: (1) suspending the instrument at constant distance from the bed over the duration of sampling period for each file and (2) vertically translating the instrument through the water column. It was decided to keep the lateral stationing of the instrument constant and in close proximity to the D–95 sampler, in contrast to the 2017 sampling approach that varied the lateral stationing along the bridge.

A compilation of the discharge, stage, and suspended sediment concentration data for the 2018 Cherry Creek flushing event is presented in figure 17. The top panel compares the release from the gates to the measured discharge at the gage just upstream of the sampling location. The second panel provides the record of pressure head (a surrogate for stage) as measured by the HOBO logger at the sediment sampling location. The third panel presents the record of sediment concentration measurements from the LISST–ABS compared to that as collected using the D–95 sampler. The bottom panel shows mean (with error bars indicating one standard deviation) record of sediment concentration measurements from the LISST–ABS compared to data collected using the D–95 sampler. The mean LISST–ABS values represent 1–min average intervals centered round the D–95 sampling time of acquisition. The gage discharge (top panel) and stage (second panel) demonstrate a more dramatic rise and fall of the hydrograph relative to the 20 events (figure 11). The difference is attributed to the "high flush" in 2018 having greater variation in discharge. In the third panel of figure 17 the vertically oriented distributions of points from the LISST–ABS represent collection of a vertical profile of concentration measurements through the water column. The wide range of values observed is indicative of vertical stratification of suspended sediment.

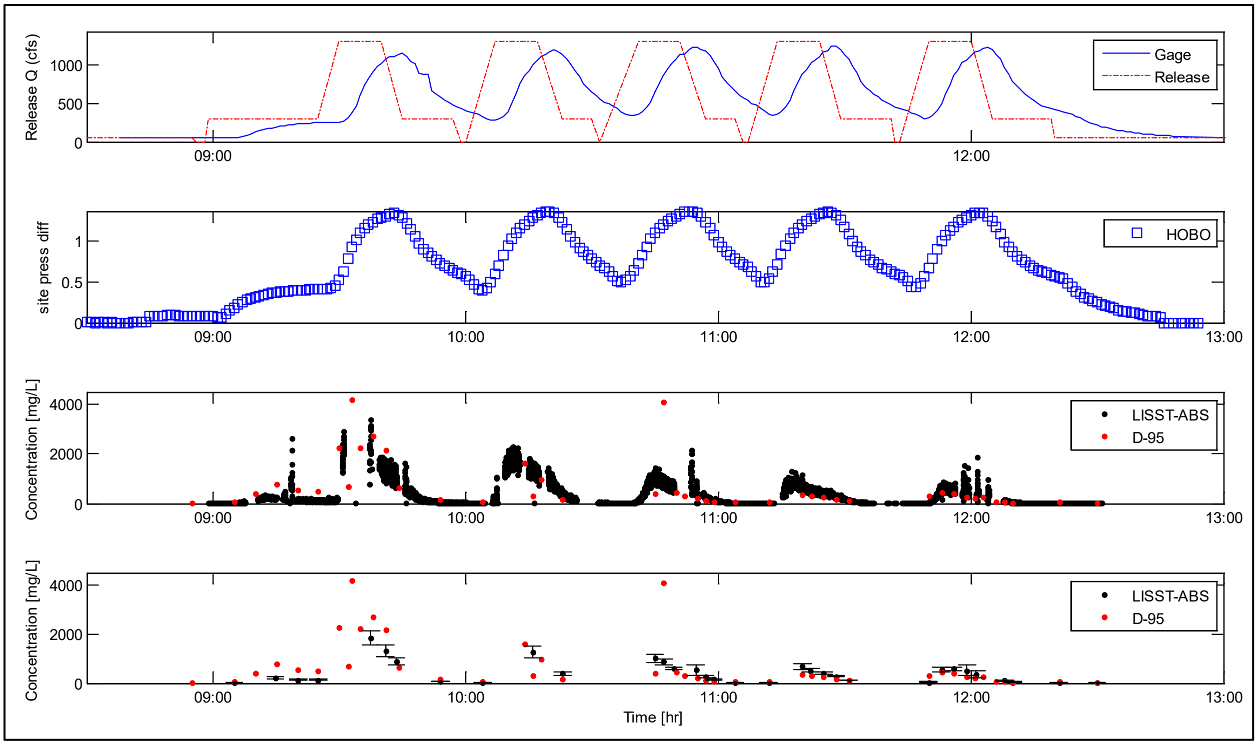

Figure 17.—Compilation of results from the 2018 Cherry Creek flushing event. Panels from top to bottom correspond to: (1) flow release from Cherry Creek Dam outlet works compared to measured discharge at gage, (2) Pressure head reported from HOBO pressure transducer logger, (3) Continuous record of LISST–ABS measurements compared to D–95 measurements, (4) mean values of LISST–ABS measurements compared to D–95 measurements.

Vertical profiles of suspended sediment concentration collected with the LISST–ABS during the 2018 flushing event (figure 18) show a trend consistent with that generally expected in the water column; the peaked shape of the distributions indicate that concentration is highest near the bed and declines toward the water surface. Further, the maximum concentrations observed during the 2018 event were approximately five times higher than observed during the 2018 events. The difference in vertical sediment concentration distributions between the 2017 and 2018 events is likely due to a combination of local hydraulics at the measurement sites as well as the gross variation in sediment–mobilizing flows between the “low flush” and “high flush” events. The higher peak flows in 2018 mobilized larger sediment size classes, including coarse sand. The larger particles settle more readily than the fine grains and tend to concentrate lower in the water column.

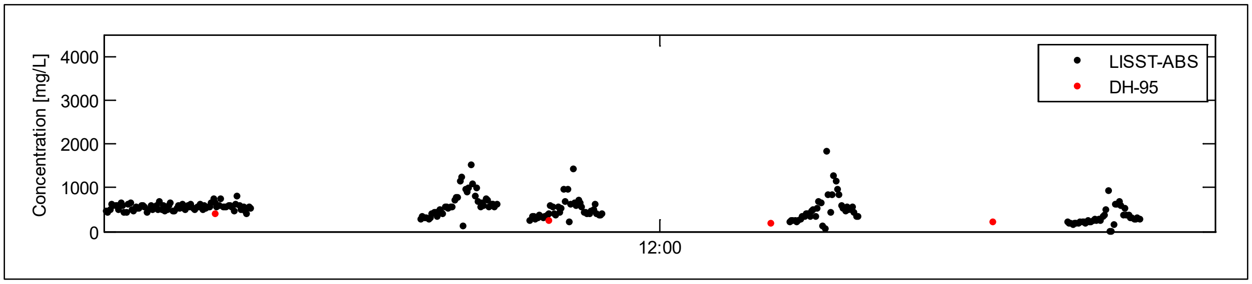

Figure 18.—Record of sediment concentration measurements from LISST–ABS collected during the 2018 Cherry Creek flushing event over the period 11:55 am–12:05 pm (subset of data shown in figure 17, panel 3). Each grouping of points represents a vertical profile through the water column. The peaked shape of the profiles indicates that suspended sediment concentration was higher near the bed and lower near the water surface, typical of vertical stratification, but in contrast to the 20 Cherry Creek measurements (figure 12).

Sediment size distribution as reported from the processing of data collected using the D–95 sampler is presented in figure 19. A Malvern laser diffraction analyzer was used to measure particle size. Outliers are observable in the distributions, possibly caused by entrainment of large bed material into the sampler. The much broader particle size distribution observed from samples taken during the 2018 event is a function of the higher peak discharge (figure 9) which was capable of mobilizing larger particle sizes (higher velocity and shear stress) and accessing bank deposits (higher stage). A mean distribution is also shown in each plot, computed by removing the outlying curves and averaging. The average D_{50} for the samples is about 0.08 mm, indicating that the material in suspended transport is dominated by very fine sand. The distributions indicate that the mobilized size classes range from clays to very coarse sands.

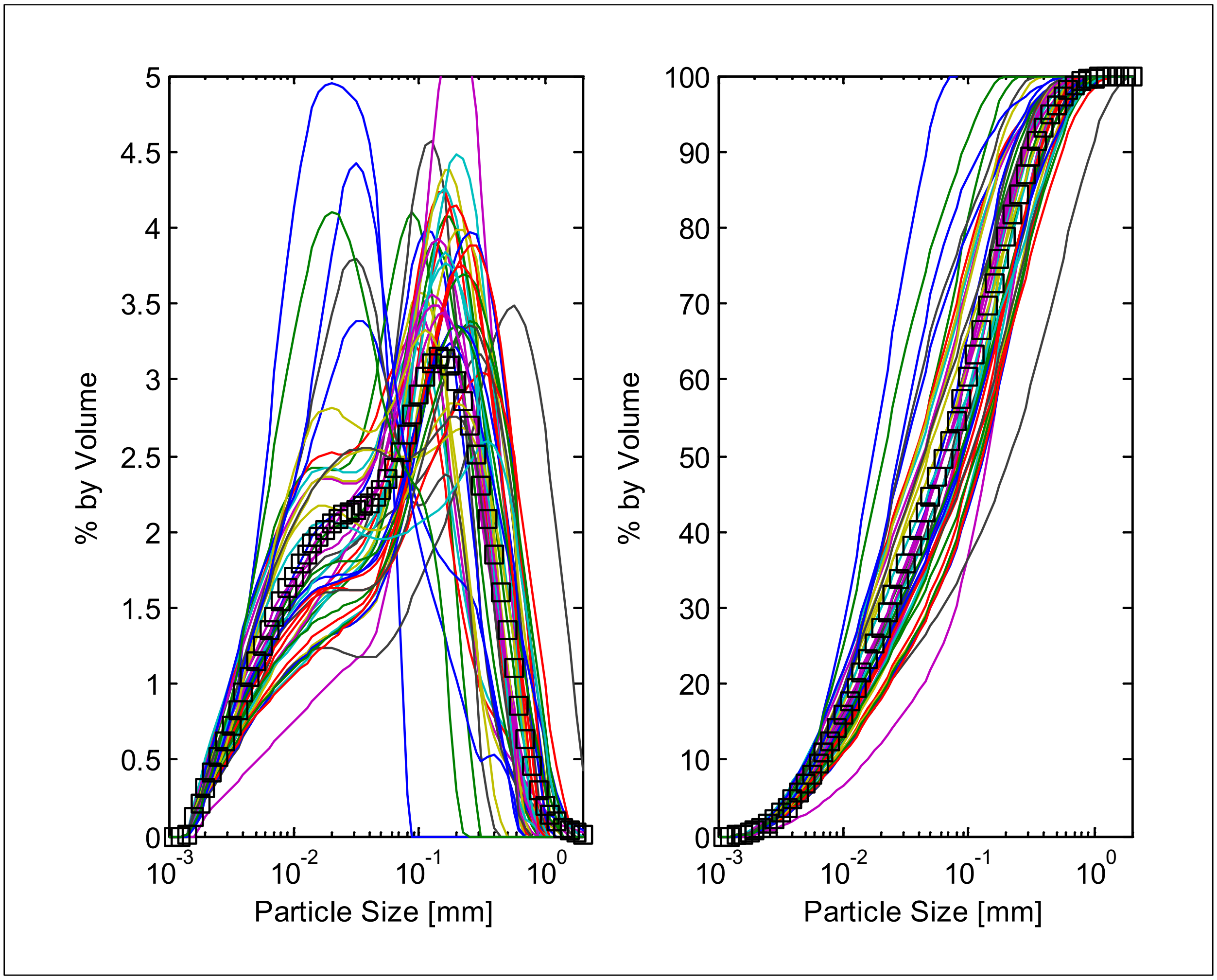

Figure 19.—Sediment size distribution reported from samples acquired using the D–95 sampler during the 2018 Cherry Creek flushing event. Black squares indicate mean with outliers removed. According to the manufacturer, the calibration range of the LISST–ABS sensor over 0.03–0.4 mm range is constant to within +/–30%.

2019 Flushing Event

In the third year of the project–supported sediment monitoring, the release hydrograph was characterized as a "low flush" event. Sampling was conducted at the lower sampling location (figure 6 and figure 8), consistent with the 2017 events. In 2019, 25 one L bottles were processed for determining sediment concentration from the physical sediment sampling with the D–95 sampler. The LISST–ABS was mounted within the PVC housing to a 50–lb sounding weight. The smaller sounding weight was chosen because of the anticipated lower velocities associated with the "low flush" event. Two sampling methods were utilized during the 2019 sampling event: (1) suspending the instrument at constant distance from the bed over the duration of sampling period for each file and (2) vertically translating the instrument through the water column. It was

decided to keep the lateral stationing of the instrument constant and in close proximity to the D–95 sampler, in contrast to the 2017 sampling approach that varied the lateral stationing along the bridge.

A compilation of the discharge, stage, and suspended sediment concentration data for the 2019 Cherry Creek flushing event is presented in figure 20. The top panel compares the release from the gates to the measured discharge at the gage just upstream of the sampling location. The second panel provides the record of hydraulic head as measured by the stage at the sediment sampling location. The third panel presents the record of sediment concentration measurements from the LISST–ABS compared to that collected using the D–95 sampler. The bottom panel shows mean (with error bars indicating one standard deviation) record of sediment concentration measurements from the LISST–ABS compared to data collected using the D–95 sampler. The mean LISST–ABS values represent one–minute average intervals centered round the D–95 sampling time of acquisition. Note that the y–axis scaling is different in the third and fourth panels to better resolve the measurements in the figures. The gage discharge (top panel) and stage (second panel) demonstrate similar magnitude but slightly more dramatic rise and fall of the hydrograph relative to the 2017 “low flush” event (figure 11). The difference is attributed to slightly different operation of the gates. In the third panel of figure 17, the vertically oriented distributions of points from the LISST–ABS represent collection of vertical profiles of concentration measurements through the water column. Noteworthy is the extreme stratification of the sediment concentration as measured by the LISST–ABS during the 2019 event. Individual concentration readings near the bed peak at nearly 8,000 mg/L, approximately double the maximum concentrations recorded during the 2018 “high flush” event and an order of magnitude higher than the prior “low flush” event in 2017. The wide range of values observed is indicative of vertical stratification of suspended sediment within the water column for LISST–ABS measurements that were taken as a vertical profile. Figure 21 shows subsets of the instantaneous LISST–ABS data presented in the third panel of figure 20 in order to better resolve the variation in concentration readings. Although the maximum concentration values reported during vertical profiling are much higher than in prior year events, the readings during stationary acquisition are comparable in magnitude to the 2017 “low flush” event.

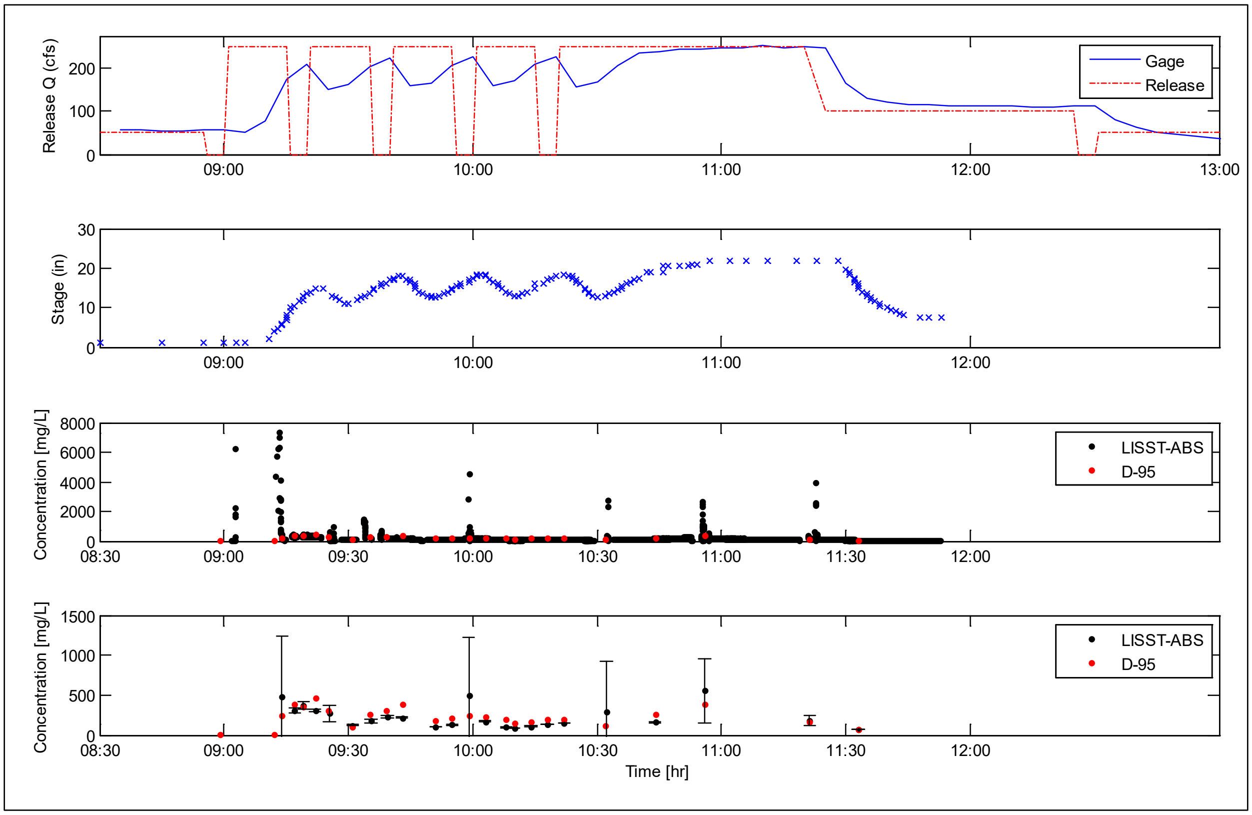

Figure 20.—Compilation of results from the 2019 Cherry Creek flushing event. Panels from top to bottom correspond to: (1) flow release from Cherry Creek Dam outlet works compared to measured discharge at gage, (2) stage reading, (3) Continuous record of LISST–ABS measurements compared to D–95 measurements, (4) mean values of LISST–ABS measurements compared to D–95 measurements.

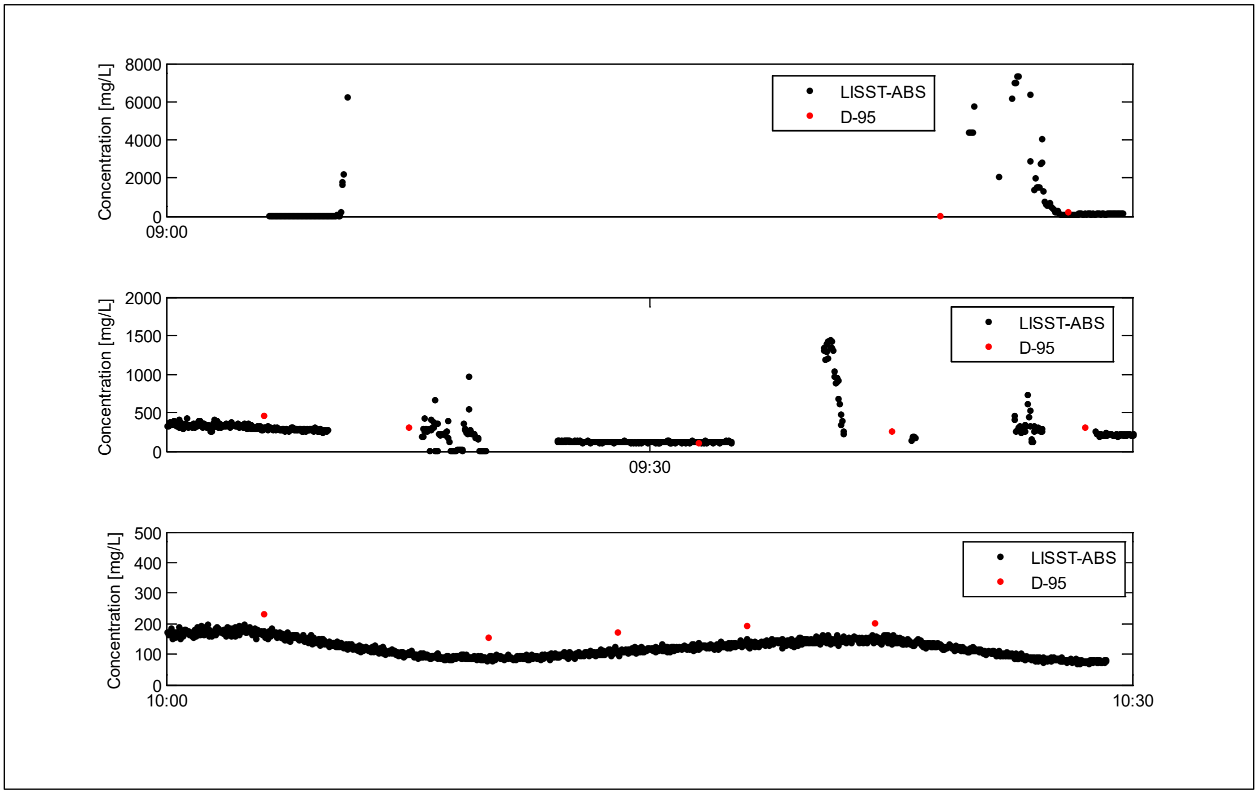

Figure 21.—Record of sediment concentration measurements from LISST–ABS collected during the 2019 Cherry Creek flushing event over the period 9:00 am–9:15 am (panel 1), 9:20 am–9:40 am (panel 2), and 10:00 am–10:30 am (panel 3). The comparison demonstrates the large difference in concentration readings between vertical profiling (panel 1) and stationary measurements (panel 3), attributed to stratification of the vertical sediment distribution through the water column. Maximum concentrations reported for the 2019 event were much higher than recorded in the prior year events.

The D–95 samples collected during the 2019 event were processed by the Reclamation Concrete, Geotechnical, and Structural Laboratory at the Technical Service Center in Denver, CO. The samples were composited and then tested for gradation by wet sieving. Figure 22 shows the grain size distribution reported from the testing. In comparison to the mean gradation reported from prior events, the 2019 flush apparently mobilized sediment of coarser size than in 2019 (figure 14) and of similar size to that of 2018 (figure 17). The coarser size of sampled sediment in 2019 may partially explain the high stratification observed. Coarser sediment requires more energy to sustain in suspension than smaller particles. The smaller discharge of the "low flush" events likely has less energy than the "high flush" events, and therefore it is straightforward to assume that inclusion of coarse materials would induce greater stratification than a flow with finer material.

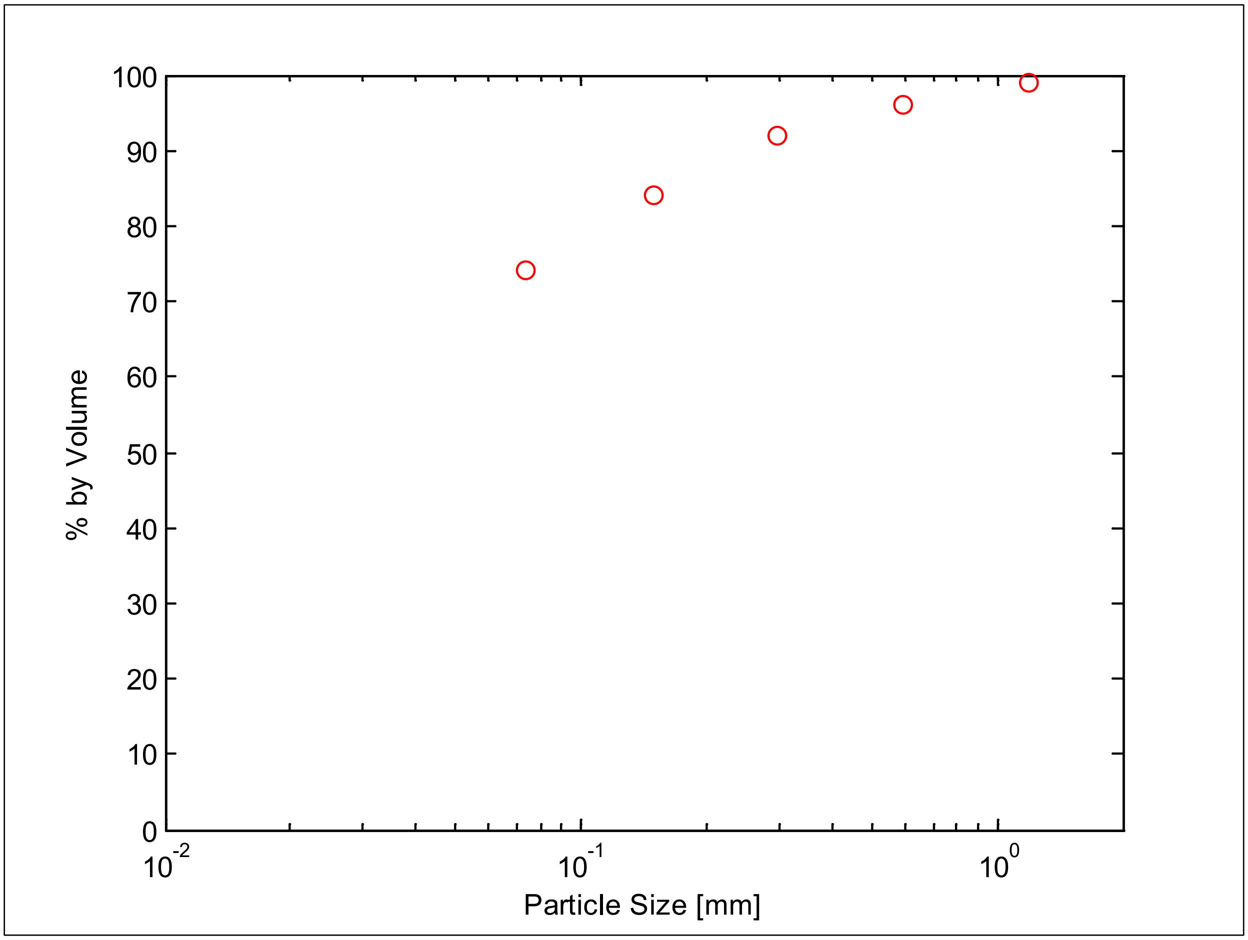

Figure 22.—Sediment size distribution reported from samples acquired using the D–95 sampler during the 2019 Cherry Creek flushing event. Red circles indicate mean of all samples collected. According to the manufacturer, the calibration range of the LISST–ABS sensor over 0.03–0.4 mm range is constant to within +/–30%.

2020 Flushing Event

In the fourth year of the project–supported sediment monitoring, the release hydrograph was characterized as a "high flush" event. Sampling was conducted at the upper sampling location (figure 6 and figure 7), consistent with the 2018 event. Although physical sampling with the D–95 sampler was conducted, the sample bottles were lost prior to laboratory analysis and a comparison is not available. The LISST–ABS was mounted within the PVC housing to a 75–lb sounding weight. The larger sounding weight was chosen because of the anticipated higher velocities associated with the "high flush" event. Less floating debris was encountered during the 2020 event than in previous years and as a result, more continuous monitoring was possible (required infrequent raising of instrument to clear debris). The instrument was primarily held in a stationary location, approximately 6/10 of depth, throughout the event.

A compilation of the discharge, stage, and suspended sediment concentration data for the 2020 Cherry Creek flushing event is presented in Figure 23. The top panel compares the release from the gates to the measured discharge at the gage just upstream of the sampling location. The second panel provides the record of pressure head (a surrogate for stage) as measured by the HOBO logger at the sediment sampling location. The third panel presents the record of sediment concentration measurements from the LISST–ABS. The bottom panel shows one minute mean (with error bars indicating one standard deviation) record of sediment concentration measurements from the LISST–ABS. The gage discharge (top panel) and stage (second panel) demonstrate similar magnitude but slightly more dramatic rise and fall of the hydrograph relative to the 2018 "high flush" event (figure 17). The difference is attributed to greater spacing between gate operations during the 2020 event, which engaged four of the five gates due to one gate being inoperable. The third and fourth panels in figure 23 show maximum concentrations reported from the LISST–ABS that compare favorably with that measured in 2018.

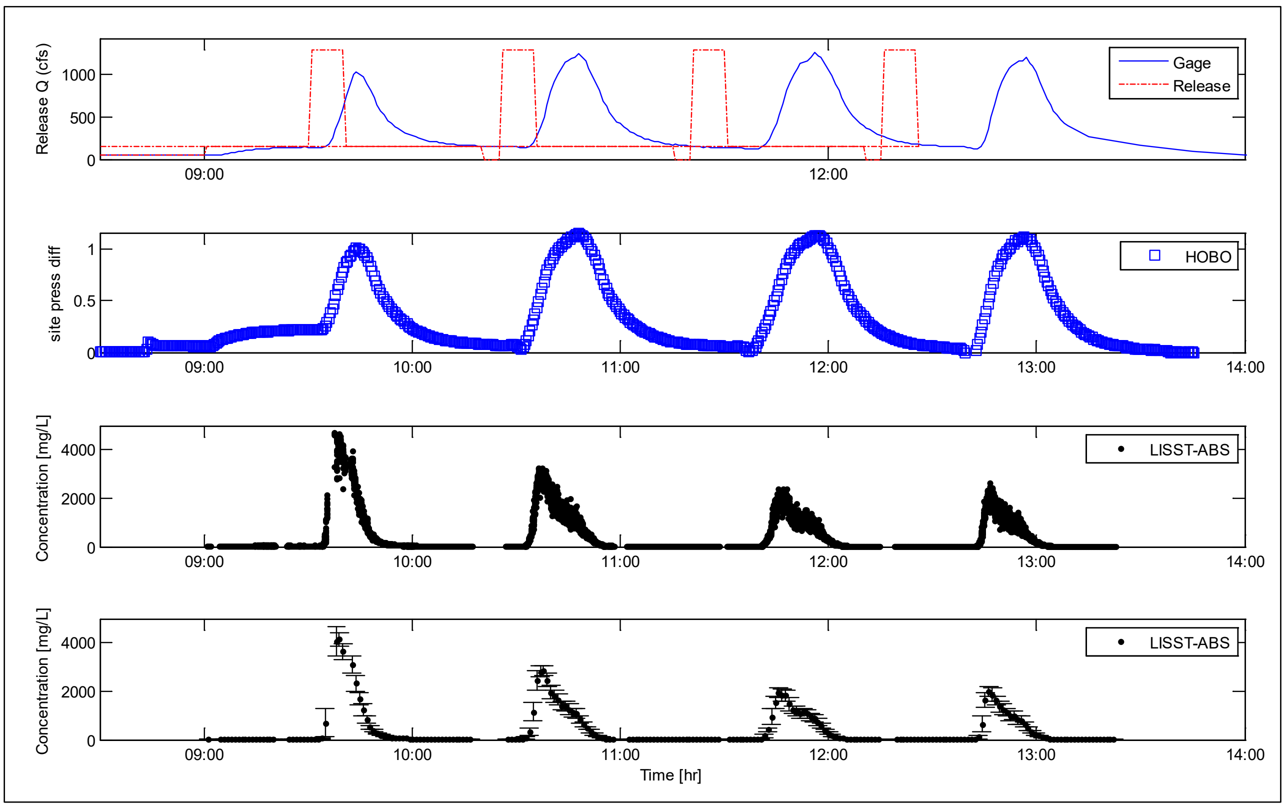

Figure 23.—Compilation of results from the 2020 Cherry Creek flushing event. Panels from top to bottom correspond to: (1) flow release from Cherry Creek Dam outlet works compared to measured discharge at gage, (2) Pressure head reported from HOBO pressure transducer logger, (3) Continuous record of LISST–ABS measurements, (4) mean values of LISST–ABS measurements. No D–95 results are available for comparison.

A turbidimeter was deployed during the 2020 event, and figure 24 shows a comparison of results from the LISST–ABS and turbidimeter. In contrast to the 2017 events, the turbidimeter was mounted to a fixed pole driven into the bed of the creek. The correlation between the turbidimeter and LISST–ABS measurements is strong; it is unclear whether the difference in mounting configuration, size gradation of sediment in suspension, or some combination of both, is responsible.

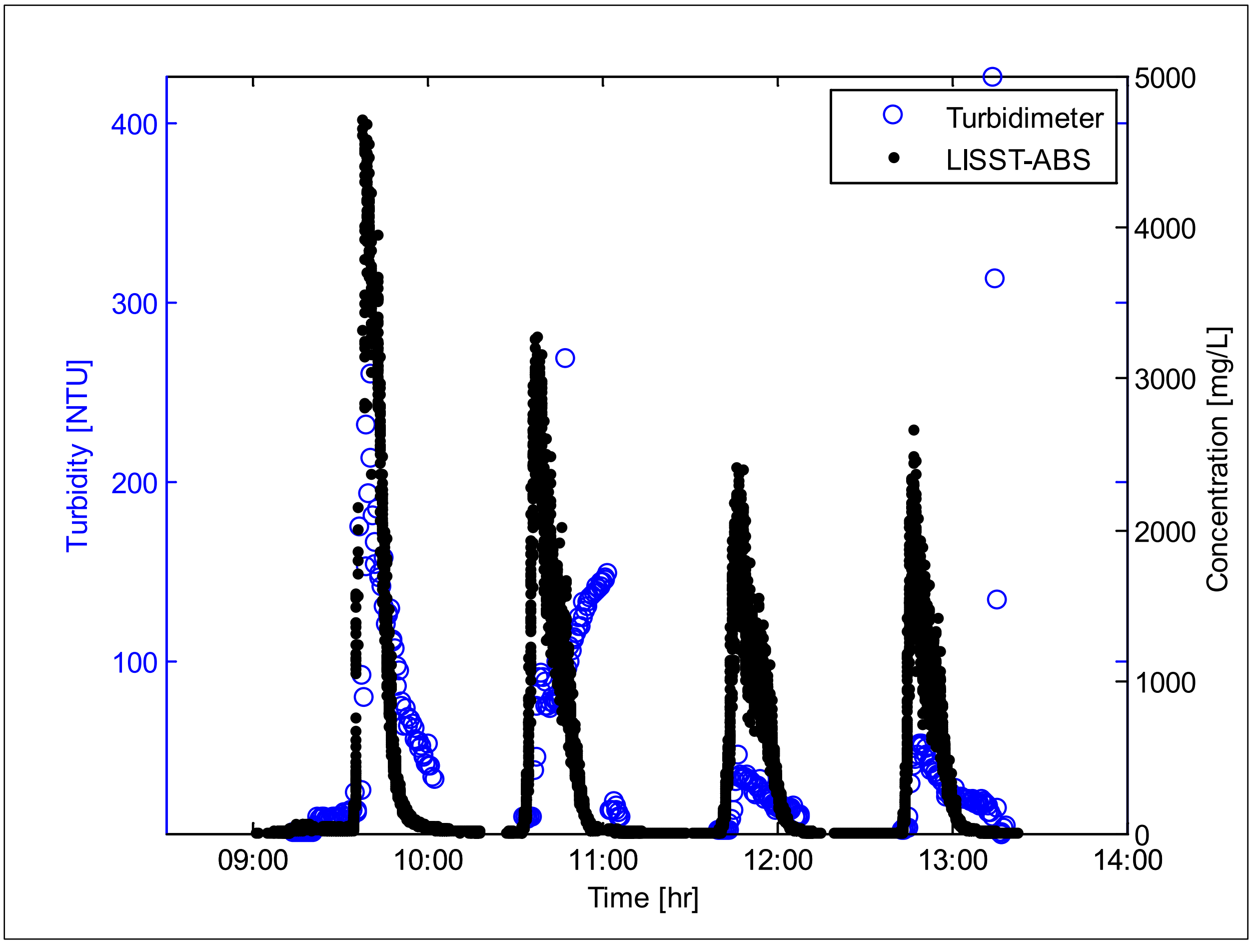

Figure 24.—Comparison of results from LISST–ABS and turbidimeter through the course of the 2020 Cherry Creek flush. The correlation between the measurements is much better than for the 2017 events (figure 13).

2021 Flushing Event

In the fifth year of the project–supported sediment monitoring, the release hydrograph was characterized as a “low flush” event. The lower sampling location (figure 6 and figure 8) was unavailable due to construction at the site, and therefore monitoring was conducted at the upper sampling location (figure 7), deviating from the “low flush” events in 2017 and 2019.

In 2021, 11 one L bottles were processed for determining sediment concentration from the physical sediment sampling with the D–95 sampler. The LISST–ABS was mounted within the PVC housing to a 50–lb sounding weight. The smaller sounding weight was chosen because of the anticipated lower velocities associated with the “low flush” event. Little floating debris was encountered during the 2021 event, so continuous monitoring was possible (required infrequent raising of instrument to clear debris). The instrument was primarily held in a stationary location, approximately 6/10 of depth, throughout the event.

A compilation of the discharge, stage, and suspended sediment concentration data for the 2021 Cherry Creek flushing event is presented in25. The top panel compares the release from the gates to the measured discharge at the gage just upstream of the sampling location. The second panel provides the record of hydraulic head as measured by the stage at the sediment sampling location–unfortunately, only limited readings were recorded. The third panel presents the record of sediment concentration measurements from the LISST–ABS compared to that collected using the D–95 sampler. The bottom panel shows mean (with error bars indicating one standard deviation) record of sediment concentration measurements from the LISST–ABS compared to data collected using the D–95 sampler. The mean LISST–ABS values represent 1–min average intervals centered round the D–95 sampling time of acquisition. The gage discharge (top panel) indicates that the magnitude and timing of the flushing event was very similar to what was performed in the 2017 “low flush” event (figure 11). The third and fourth panels in figure 23 show concentration distributions reported from the instrumentation that compare favorably with that measured during the 2017 events. The concentrations reported from the LISST–ABS are generally lower than that reported in 20 and lower than the D–95 measurements. The observation indicates that the LISST–ABS may be underreporting the sediment concentration being transported through Cherry Creek during the 2021 event. The apparent mismatch and need for instrument calibration is discussed below in the section on Calibration.

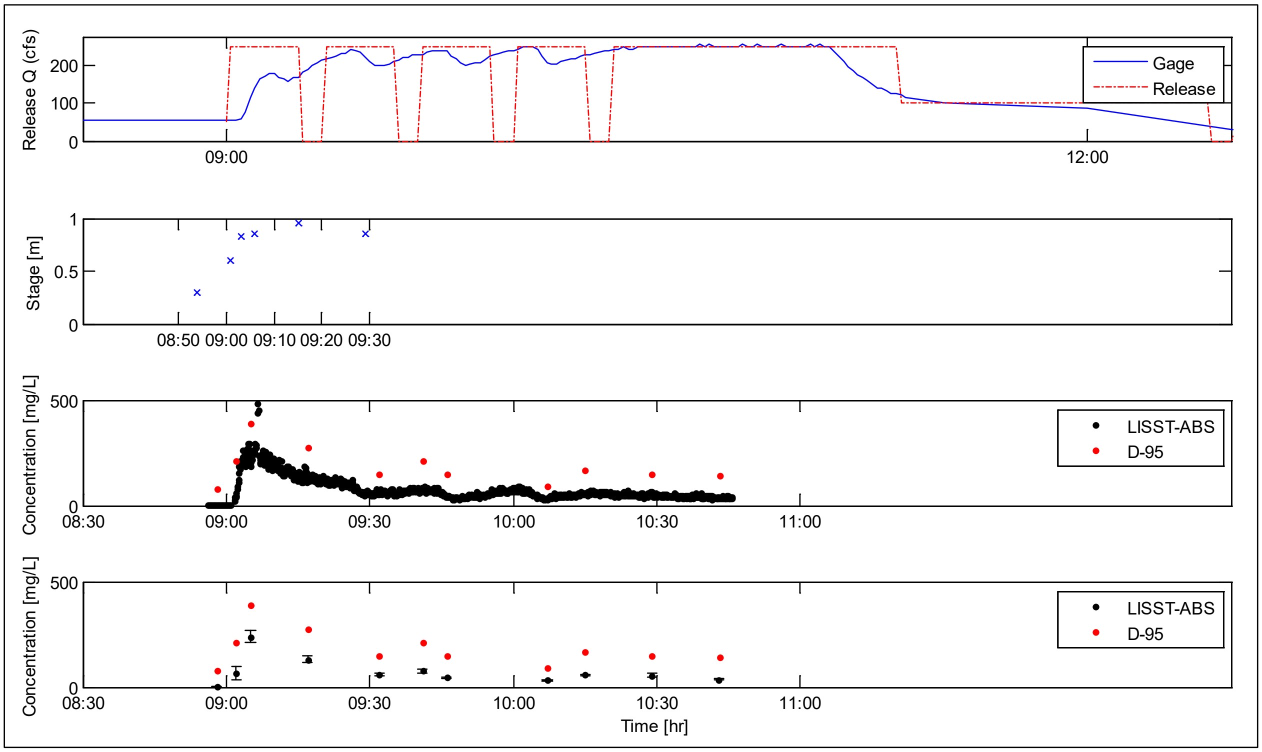

Figure 25.—Compilation of results from the 2021 Cherry Creek flushing event. Panels from top to bottom correspond to: (1) flow release from Cherry Creek Dam outlet works compared to measured discharge at gage, (2) Stage reading, (3) Continuous record of LISST–ABS measurements compared to D–95 measurements, (4) mean values of LISST–ABS measurements compared to D–95 measurements.

The D–95 samples collected during the 2021 event were processed through a contract with the USGS Central Midwest Water Science Center Sediment Lab in Iowa City, Iowa. The samples were composited and then tested for gradation by a combination of wet sieving, visual–accumulation tube, and pipette method. Figure 26 shows the grain size distribution reported from the testing. The distribution aligns closely with the gradation measured from the 2017 "low flush" sampling results for sizes greater than 0.01 mm. At sizes 0.01 mm and below, the 2021 distribution shows greater proportion of fine material. It is possible that the greater proportion of fines component in the suspended sediment is below the sensitivity limit of the LISST–ABS which could explain why the instrument seems to be underreporting concentration values associated with the 2021 event.

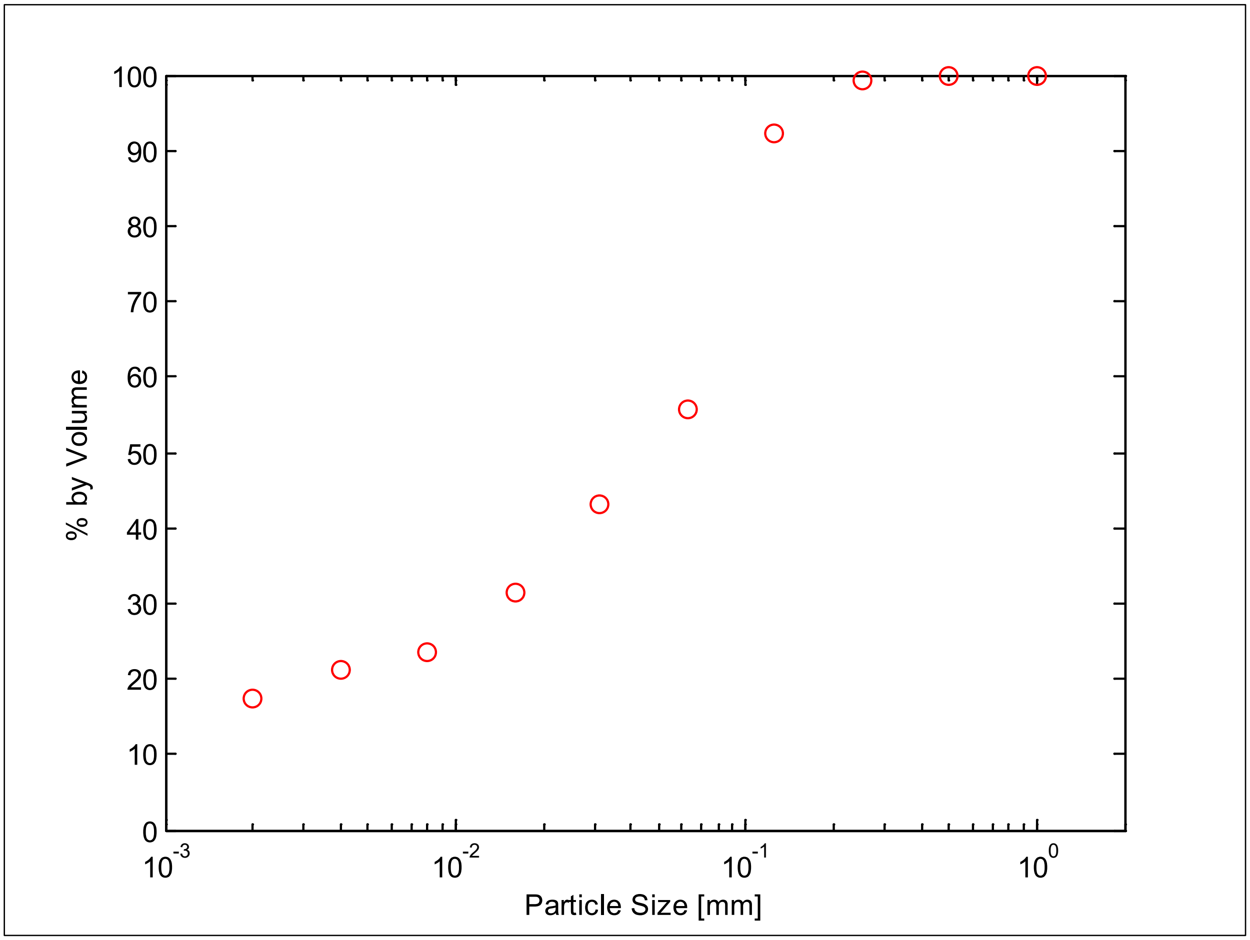

Figure 26.—Sediment size distribution reported from samples acquired using the D–95 sampler during the 2021 Cherry Creek flushing event. Red circles indicate mean of all samples collected. According to the manufacturer, the calibration range of the LISST–ABS sensor over 0.03–0.4 mm range is constant to within +/–30%.

2022 Flushing Event

In the sixth and final year of the project–supported sediment monitoring, the release hydrograph was characterized as a "high flush" event. Sampling was conducted at the upper sampling location (figure 6 and figure 7). In 2022, 13 one L bottles were processed for determining sediment concentration from the physical sediment sampling with the D–95 sampler. The LISST–ABS was mounted within the PVC housing to a 75–lb sounding weight. The larger sounding weight was chosen because of the anticipated higher velocities associated with the "high flush" event. The higher stage and velocities associated with the event mobilized large amounts of debris from the banks, necessitating frequent raising of the instrument to clear debris from the cabling (figure 16). As a result, the data reported from the instrument is divided into files with variable temporal breaks in between. Two sampling methods were utilized during the 2022 sampling event: (1) suspending the instrument at constant 6/10 depth over the duration of

sampling period for each file and (2) vertically translating the instrument through the water column. It was decided to keep the lateral stationing of the instrument constant and in close proximity to the D–95 sampler.

A compilation of the discharge, stage, and suspended sediment concentration data for the 2022 Cherry Creek flushing event is presented in Figure 27. The top panel compares the release from the gates to the measured discharge at the gage just upstream of the sampling location. The second panel provides the record of pressure head (a surrogate for stage) as measured by the HOBO logger at the sediment sampling location. A stage reading was also available and shown for comparison, which was beneficial as a backup because a failure of the HOBO logger led to erroneous readings. As can be seen from the hydrograph and stage readings, only four out of the five outlet gates were operational for the flushing event. The third panel in Figure 27 presents the record of sediment concentration measurements from the LISST–ABS compared to that as collected using the D–95 sampler. The bottom panel shows mean (with error bars indicating one standard deviation) record of sediment concentration measurements from the LISST–ABS compared to data collected using the D–95 sampler. The mean LISST–ABS values represent one minute average intervals centered around the D–95 sampling time of acquisition. In the third panel of Figure 11, the vertically oriented distributions of points from the LISST–ABS represent collection of a vertical profile of concentration measurements through the water column. The wide range of values observed is indicative of vertical stratification of suspended sediment. Overall, the values reported from the LISST–ABS appear to be somewhat higher than what was reported in prior “high flush” events. Figure 28 shows subsets of the instantaneous LISST–ABS data presented in the third panel of Figure 27 to better resolve the variation in concentration readings (note that the y–axis scaling is different in each panel). The first panel of Figure 28 shows background concentrations before the first pulse release, 9:00 am–9:30 am. The second panel shows collection during the first pulse release, which included a vertical profile, 9:30 am–10:00 am. The third panel shows collection during the final pulse release, 12:15–12:45 pm. It appears that the LISST–ABS may be underreporting values at low concentrations (first panel). Because the background measurements we made prior to the first pulse release, it is likely that only fine material were suspended in the water column, which may be below the sensitivity range of the instrument and responsible for the low concentration readings. In contrast, the second panel indicates the high stratification in concentration that is established during the peak of a pulse release, where values range from background levels at the top of the water column to approximately 10,000 mg/L near the bed. The third panel represents measurements taken during the final pulse release at a stationary height of 6/10 depth. Figure 29 shows the grain size distribution reported from the testing. As would be expected, the distribution is coarser than what was observed during the 2021 “low flush” and is similar to what was observed during the 2018 “high flush”. A notable difference is evident at sizes 0.01 mm and below, where the distribution from the 2022 data collection indicates greater fines component of the sediment in suspension.

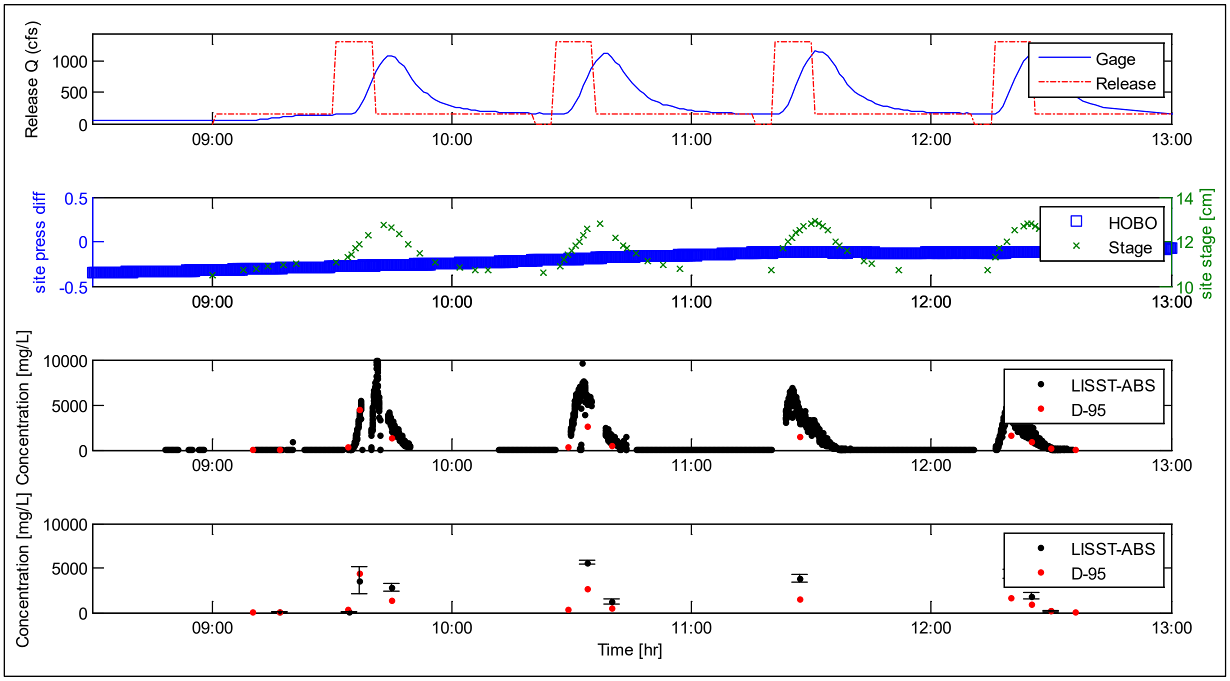

Figure 27.—Compilation of results from the 2022 Cherry Creek flushing event. Panels from top to bottom correspond to: (1) flow release from Cherry Creek Dam outlet works compared to measured discharge at gage, (2) Pressure and hydraulic head reported from HOBO pressure transducer logger and stage, (3) Continuous record of LISST–ABS measurements compared to D–95 measurements, (4) mean values of LISST–ABS measurements compared to D–95 measurements. A failure of the HOBO logger led to erroneous pressure head readings.

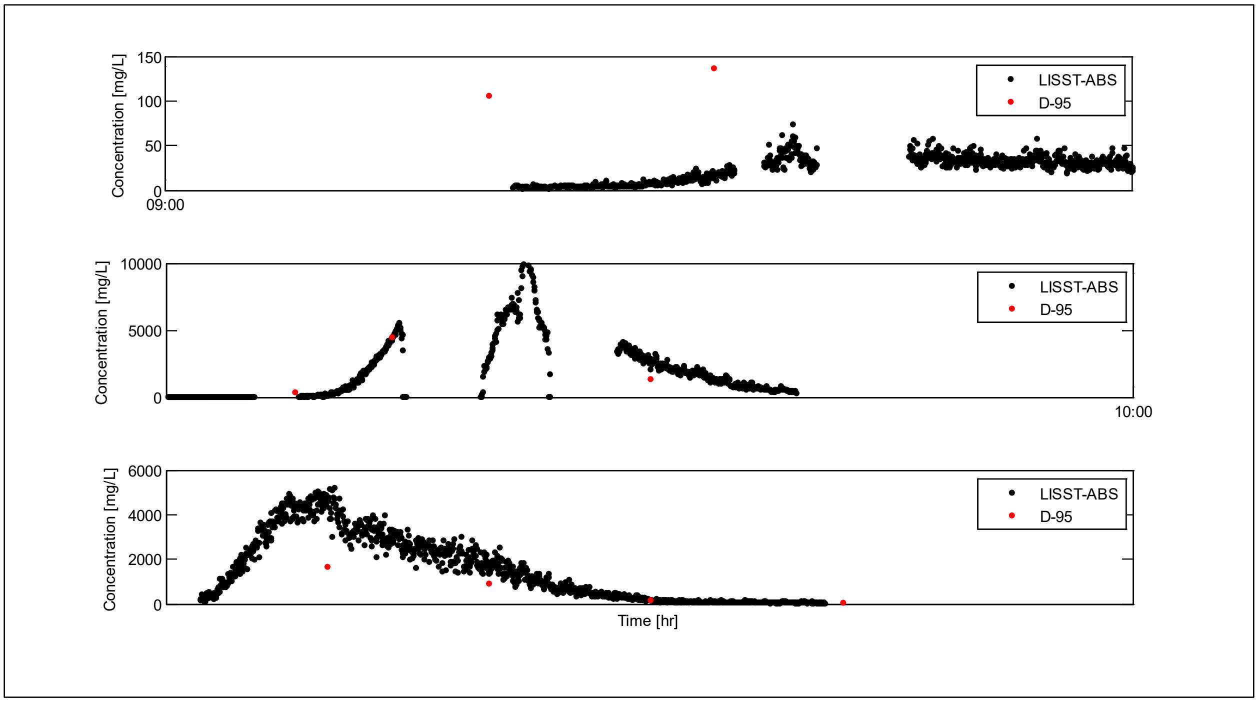

Figure 28.—Record of sediment concentration measurements from LISST–ABS collected during the 2022 Cherry Creek flushing event over the period 9:00 am–9:30 am (panel 1), 9:30 am–10:00 am (panel 2), and 12:15 pm–12:45 pm (panel 3). The comparison demonstrates the large difference in concentration readings between background (panel 1), vertical profiling (panel 2), and stationary measurements (panel 3). Maximum concentrations reported for the 2022 event were somewhat higher than prior year "high flush" events.

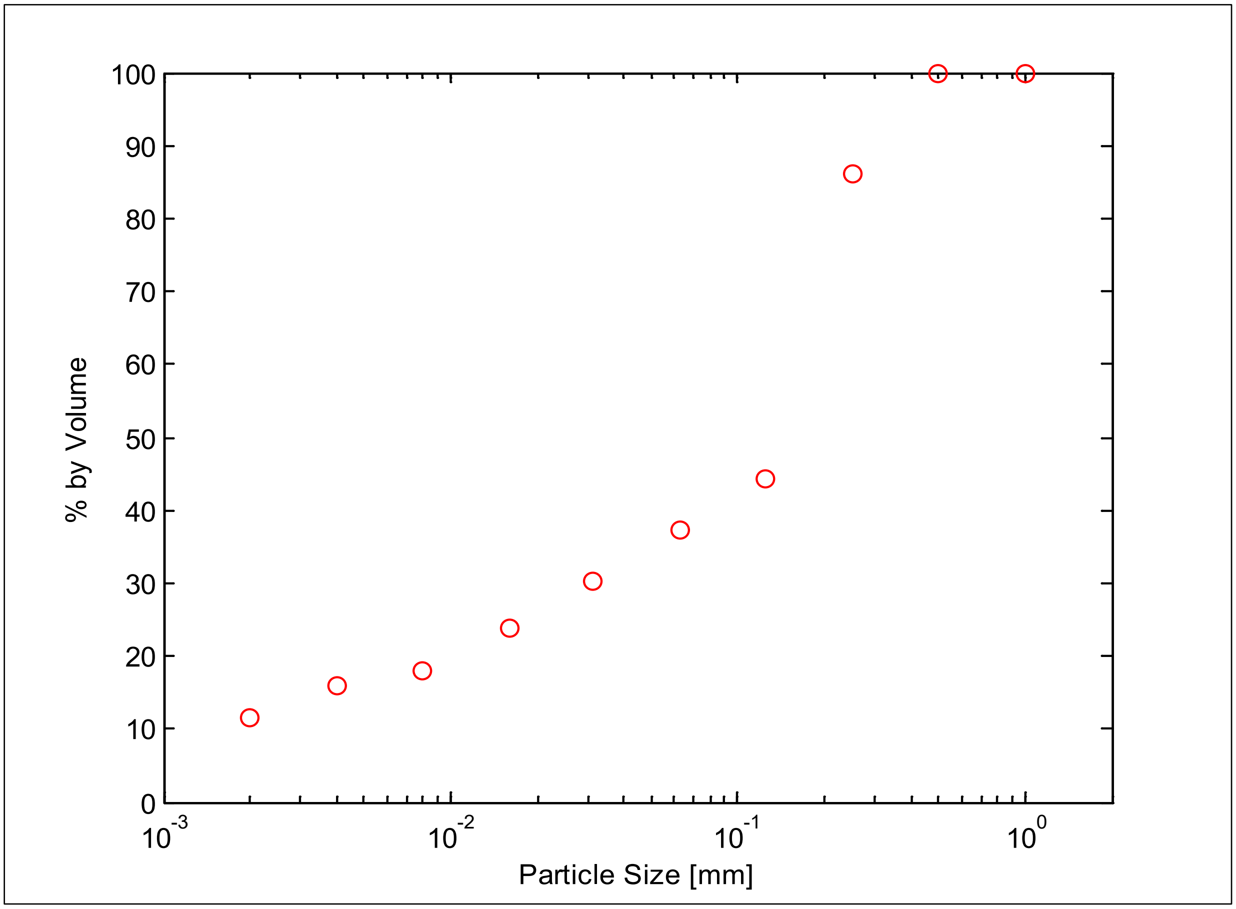

Figure 29.—Sediment size distribution reported from samples acquired using the D–95 sampler during the 2022 Cherry Creek flushing event. Red circles indicate mean of all samples collected. According to the manufacturer, the calibration range of the LISST–ABS sensor over 0.03–0.4 mm range is constant to within +/–30%.

Sediment Flux

A primary question in evaluating the effectiveness of flushing exercises is the quantity of sediment being mobilized and transported as a function of the flow released. The volumetric rate of sediment transport can be estimated from the concentration in the water column multiplied by the discharge. Figure 31 presents instantaneous estimates of volumetric sediment transport for each year of the flushing event. The data from the LISST–ABS was averaged on 1–minute intervals and multiplied by the discharge from the USGS gage (with appropriate unit conversions) to produce the records of transport. The estimates are a rough approximation of the true rate of transport because implicit in the calculation is the assumption that the LISST–ABS readings are representative of the entire river cross–section. Despite the approximation, the comparison is instructive in a relative sense. The "high flush" events (2018, 2020, 2022) are predicted to transport sediment at a rate that is about an order of magnitude greater than the "low flush" events (2017 , 2019, 2021). A consistency among the trends is that there exists a gradual decline in the quantity of transport with each consecutive pulse of flow released. Because each

pulse is associated with a unique gate within the outlet work structure, the declining trend of transport suggests that a significant amount of the mobilized sediment measured by the sampling is derived from the creek downstream of the outlet works. The finding also underscores the challenge of establishing sediment rating curves since a given volumetric sediment transport rate is not simply dependent on the flow rate.

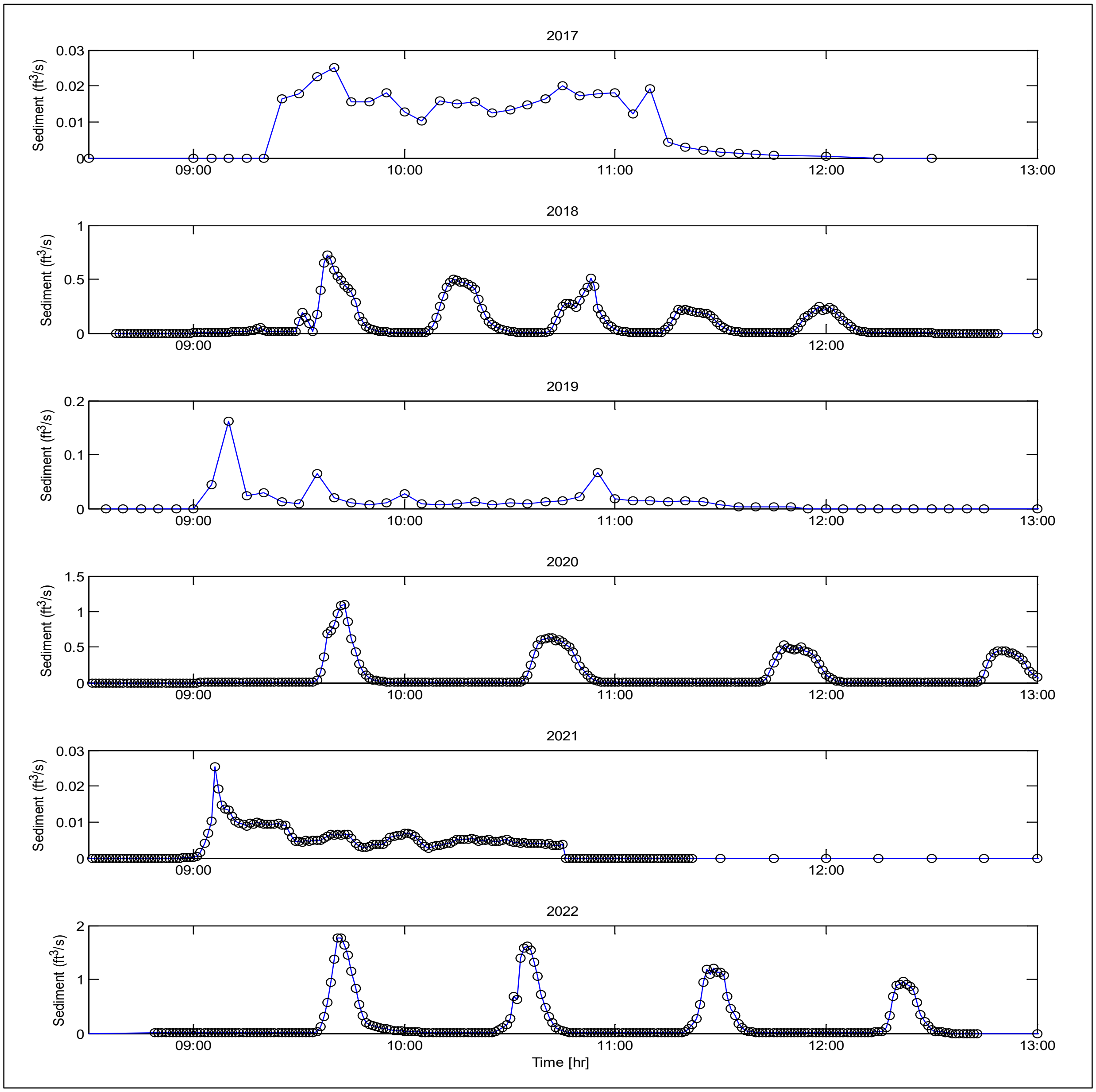

Figure 30.—Instantaneous volumetric sediment transport rate, estimated from the sediment concentration (LISST–ABS) and the discharge record (USGS gage). The data from the LISST–ABS was averaged on one minute intervals for each year of acquisition. The estimated transport rate for the “high flush” events is approximately one to two orders of magnitude larger than for the “low flush” events.

Table 2 presents, for each year of acquisition, the estimated total volume of water released and the total flux of sediment through the sampling location. The estimates were obtained by integrating the curves in Figure 30 with respect to time. Also shown in Table 2 are the mean values for the "low flush" events and "high flush" events. The results show that for an approximately three times increase in the total volume of water released ("high flush" vs. "low flush"), the total volume of sediment in transport past the sampling location increased by approximately sixteen times. It is important to note that this does not necessarily imply the increased sediment delivery was derived from the reservoir, as the sampling locations were downstream of the outlet gates (figure 7.and figure 8). Most likely, a significant portion of the transported sediment was derived from the channel of the creek. The data in table 2 also suggest that just the total volume of water released is not solely responsible for the volume of sediment mobilized, but that *how* the volume of water is released is also important. For example, the 2022 flush was estimated to have mobilized the greatest volume of sediment, but with the smallest total volume of water relative to the "high flush" events. Likely, the mobilization of sediment is dependent on a combination of the peak discharge and the cycling between that peak and the low flow condition.

Table 2.—Summary of total volume of water released and total volume of sediment transported past the sampling site for each year of data acquisition. Also shown for the "low flush" and "high flush" events, respectively, are the mean total discharge and mean total sediment flux estimated from the LISST–ABS results

Year	Total Discharge (ac–ft)	Total Sediment Flux (ft^3)
2017	47	114
2018	189	1400
2019	55	207
2020	153	10
2021	57	38
2022	128	2721
Mean "low"	53	120
Mean "high"	157	1944

A typical methodology for gaging the effectiveness of reservoir flushing exercises in releasing sediment would be to monitor the bathymetric change as a result of the events. Repeated bathymetric surveying is used to achieve such estimates and derive trends in sedimentation. A bathymetric survey was conducted before and after the 2018 flushing event at Cherry Creek Lake to test whether the sediment mobilization and release in the vicinity of the gates (cone of influence) could be estimated from differences in measured bottom surface elevation (Kim & Collins, 2018). Unfortunately, the change in measured elevation was within the range of detectability of the boat–deployed instrumentation. A conclusion of the study was that in some cases, alternative ways of estimating the transport of sediments may be needed in order to evaluate management actions.

Summary

The Cherry Creek flushing events from 2017–2022 provided an opportunity to test the capabilities and limitations of the LISST–ABS over a period of six consecutive years under highly dynamic conditions. It is instructive to delve into direct comparisons of the results from year–to–year to better understand what factors may contribute to variability in the instrument readings. Figure 31 presents plots of the sediment concentration measurements from the D–95 sampler compared to mean readings from the LISST–ABS for each year of data collection. The left panel shows all the data acquired and the right panel is scaled to better show the clustering of data near the ordinate. The solid line shows the 1:1 correspondence, and the dashed lines show 30% deviation (estimated error bounds of the instrument according to the manufacturer), for reference. The LISST–ABS points shown are mean values calculated from 1–minute averages centered around the D–95 sampling time. In examining the plots, the following summary observations can be made:

- The data collected in 2017 (red circles) shows the best agreement between LISST–ABS readings and the D–95 measurements.

- The data collected in 2018 (green triangles) shows the greatest scatter between LISST–ABS readings and the D–95 measurements.

- The data collected in 2019 (blue crosses) shows comparable, but slightly greater, scatter than the 20 measurements.

- The data collected in 2021 (magenta squares) shows a consistent bias such that the LISST–ABS readings were underreporting concentration relative to the D–95 by roughly 50%.

- The data collected in 2022 (cyan asterisks) shows a bias such that the LISST–ABS readings were underreporting concentration relative to the D–95 for readings less than 200 mg/L, but overreporting concentration for readings above 200 mg/L.

To generalize observations, the LISST–ABS data collected in 2017, 2018, and 2019 exhibit general scatter around the 1:1 correspondence line with the sediment data from the D–95, whereas the LISST–ABS data collected in 2021 and 2022 exhibit more persistent bias relative to the D–95. This suggests that perhaps the highly dynamic conditions under which the measurements were made were primarily responsible for the semi–random data scatter in 2017–2019, whereas some sort of systematic error was responsible for differences observed in 2021 and 2022. For comparison, figure 32 presents LISST–ABS data collected at a variety of sites for rivers of differing size around the United States. The figure and compilation of data is adapted from Manaster et al. (2020). Included in the comparison is the data collected during the 2017 Cherry Creek flush. The authors present an analysis of the sensitivity according to percent fines

within the suspended sediment collected. Qualitatively, the comparison shows that the results from the Cherry Creek flushing exercises are consistent with deployment of the LISST–ABS at other sites.

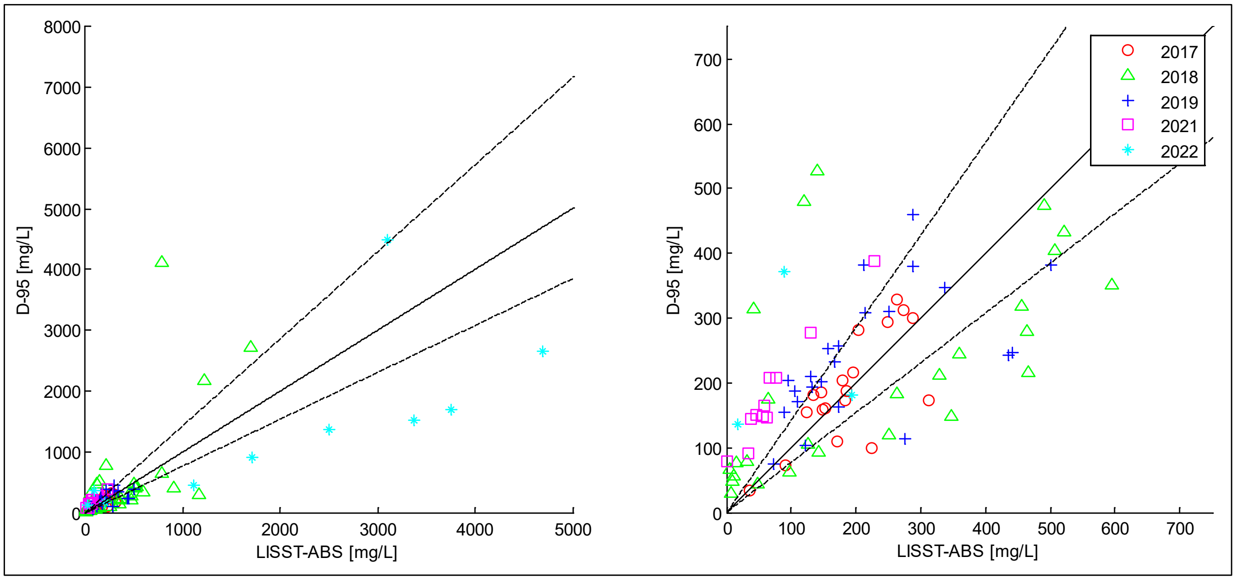

Figure 31.—D–95 sediment concentration measurements plotted against the mean LISST–ABS readings as a function of the year of the flushing event. The left panel shows all data and the right panel shows the same data with rescaled axes to better illustrate the clustering of data near the ordinate. The solid line shows the 1:1 correspondence, and dashed lines show 30% deviation bounds, for reference. Years 2017 , 2019, and 2021 were "low flush" events, while years 2018 and 2022 were "high flush" events.

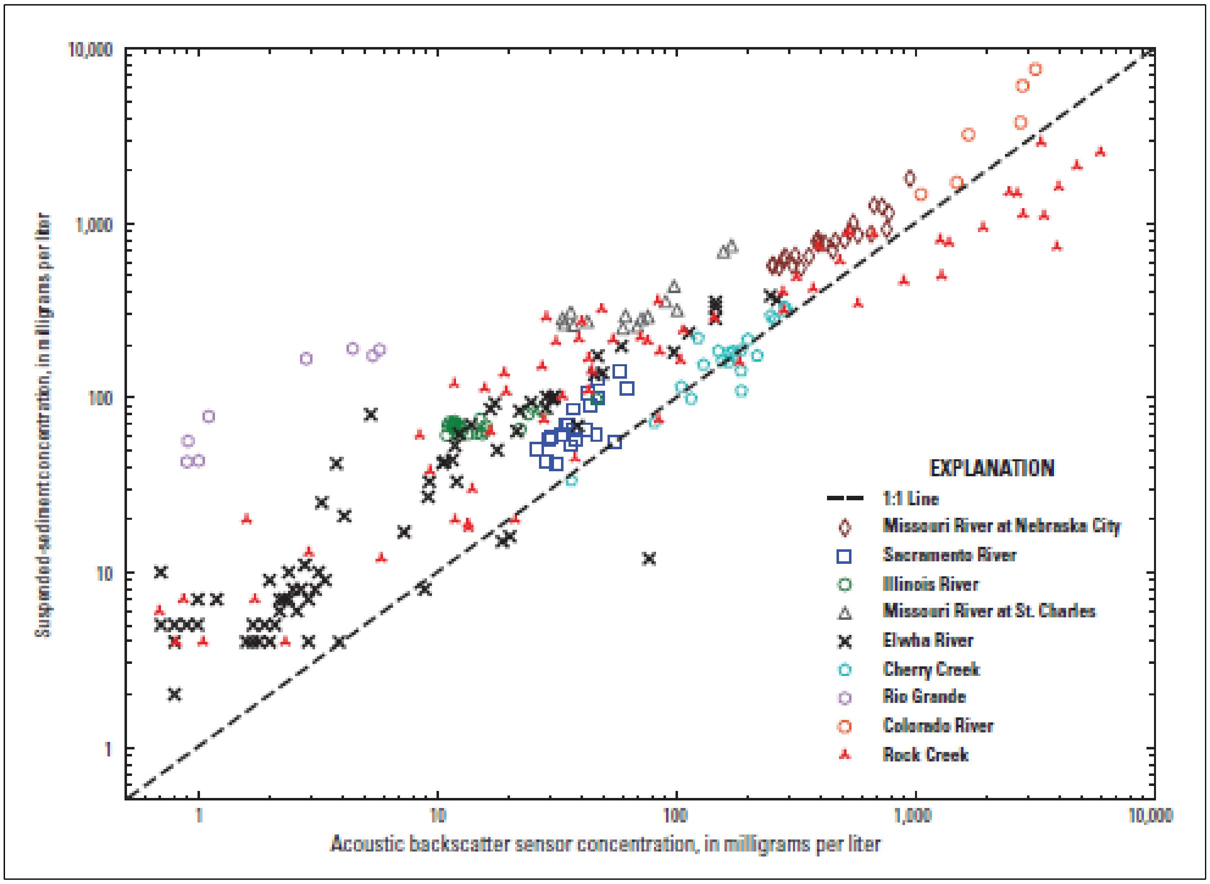

Figure 32.—Suspended sediment concentration plotted against LISST–ABS readings for various sampling locations in the United States. Figure adapted from Manaster (2020). The plot includes data collected during the 2017 Cherry Creek flushing event. The sites sampled include a wide variety of sizes of rivers and sediment gradations.

Calibration

Background

Over the six years of consecutive suspended sediment monitoring at Cherry Creek, application of LISST–ABS instruments at the project level began in earnest within Reclamation. Two units were purchased and installed in a physical model at the Denver Technical Center hydraulics laboratory as part of a project analyzing sediment dynamics in support of design alternatives developed for the Pueblo Isleta Diversion Dam in New Mexico (Baird, Sayer, Kubitschek, & Pizzi, 2023). The units were then installed at the actual site to monitor suspended sediment being diverted into irrigation canals. Concurrently, USGS scientists documented results from application of LISST–ABS instruments at a variety of sites (Manaster, et al., 2020) and began investigation into the long–term reliability of the instrument performance. During analysis of results from the application at Isleta Diversion Dam, questions began to be raised regarding

variation in the calibration of the instruments from factory specifications. The concerns were based on observation of instrument–to–instrument variation in readings and differences between readings from LISST–ABS and physical sampling results. Informal consultation with USGS scientists (Jason Alexander, Supervisory Hydrologist, personal communication, October 2022) revealed that similar observations were made with some LISST–ABS units and that the USGS was actively working on establishment of standardized procedures for routine calibration tests. Subsequent communication with representatives at Sequoia Scientific, Inc. (personal communication, October 2022) confirmed that drift in calibration of the LISST–ABS instruments is a known phenomenon and that they recommended sending the units owned by Reclamation in for further evaluation by the manufacturer. Three Reclamation–owned LISST–ABS units (including the instrument used in the monitoring at Cherry Creek) were sent to Sequoia Scientific, Inc. in January 2023 for evaluation and recalibration. As was suspected, all the instruments were found to have deviated from the original factory–calibrated values and were recalibrated according to the manufacturer specifications. The cost for the evaluation and recalibration was approximately $750 per unit. Based on recommendation from USGS hydrologists (Jason Alexander, Supervisor Hydrologist, personal communication, October 2022), the instruments were then evaluated as part of a calibration procedure conducted by the Reclamation Hydraulics Investigations Laboratory at the Technical Service Center in Denver.

Sequoia Scientific

In January 2023, evaluation and recalibration of three LISST–ABS instruments was conducted by Sequoia Scientific, Inc. According to the technician at Sequoia, the sensors with serial numbers 6218 and 6166 were both reading approximately 20% low for tests conducted at known concentrations of 1,000 mg/L and 10,000 mg/L. The sensor with serial number 6078, which was used for the sampling at Cherry Creek, exhibited a more complicated deviation. At known test concentrations of 100 mg/L, 1,000 mg/L, and 10,000 mg/L, the instrument readings were about 10% high, 10% low, and 30% high, respectively (figure 32). All three instruments received factory recalibration at that time, and sensor 6078 also received a firmware update. The factory calibration is conducted with 75–90–micron glass beads; the company notes that customer calibration with representative samples can improve accuracy in the field.

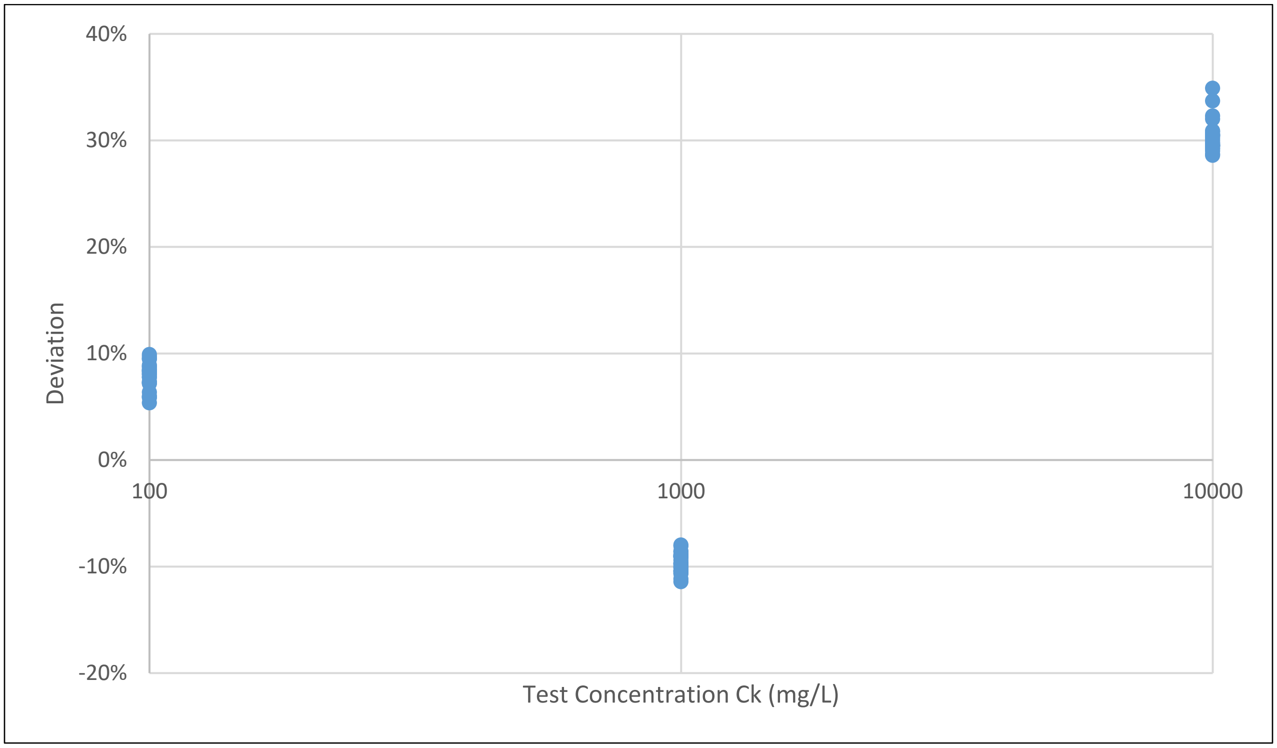

Figure 33.—Results from laboratory testing of LISST–ABS (S/N 6078) conducted by Sequoia Scientific, Inc. At known test concentrations of 100 mg/L, 1,000 mg/L, and 10,000 mg/L, the instrument readings were about 10% high, 10% low, and 30% high, respectively. The instruments were then recalibrated by Sequoia using 75–90–micron glass beads in order to correct the deviation.

Technical Service Center

After the LISST–ABS instruments were received from evaluation and calibration at Sequoia Scientific, further testing and calibration was conducted at the Reclamation Technical Service Center Hydraulics Investigations Laboratory. Three LISST–ABS instruments were evaluated and the work was conducted in collaboration with the Isleta Diversion Dam Sluiceway Modifications analysis as part of the Middle Rio Grande Project (Baird, Sayer, Kubitschek, & Pizzi, 2023). The goal of conducting an additional analysis was three–fold: (1) Evaluate how the factory calibration compares to "in–house" calibration, (2) Establish a baseline calibration that can be systematically tested for drift over time, and (3) Test the sensitivity of calibration to actual sediment collected from a sampling site. For the first goal above, an open question among the researchers involved was whether a factory calibration would be reproducible in the laboratory environment without specialized equipment. Ongoing work by USGS (Jason Alexander, Supervisor Hydrologist, personal communication, October 2022) indicated that a simple continuously mixed container with known concentrations of 40–90–micron Ballotini glass beads was successful in establishing a comparable and reproducible instrument calibration. The procedure is also useful in addressing the second stated goal by establishing a baseline calibration prior to deployment that can be tested periodically without needing to send the instrument back to the manufacturer (although it may be necessary to return the instrument for

factory recalibration and service if it is found that the in–house calibration is not stable over time). To address the final goal, sediment acquired on–site at Isleta Diversion Dam in New Mexico was used in the laboratory investigation. The sediment was collected from a spoils pile that was excavated from deposits in the diversion channel and is understood to be representative of the material in suspension. Details of the laboratory investigation and results of the calibration are presented in Appendix A–LISST–ABS Laboratory Calibration Checks. Results of the investigation demonstrated that the calibration (a) differed from factory specification (b) is dependent on the gradation of material in suspension, (c) varied from instrument–to–instrument, and (d) is sensitive to the concentration in suspension (figure 32). Figure 33 presents sediment size distributions from samples taken from the diversion channel at Isleta Diversion Dam. The mean of the distributions is shown as black squares. The coarsest fraction is comparable to what was found in samples analyzed from Cherry Creek, although Cherry Creek samples showed considerably greater fines content. In principal, the instrument is less sensitive to fines contribution below approximately 0.03 mm in size, so that the difference in gradation may not have a large effect. All three instruments, when calibrated to the sediment from Isleta Diversion Dam, exhibited a consistent trend of reducing calibration factor with increasing concentration (up to 1,000 mg/L). Above 1,000 mg/L, the concentration factors for each instrument were approximately constant. The trend was different; however, when the same calibration process was conducted with Ballotini glass beads (see figure 32 and Appendix A–LISST–ABS Laboratory Calibration Checks), underscoring the need for instrument calibration specific to the media the user is measuring.

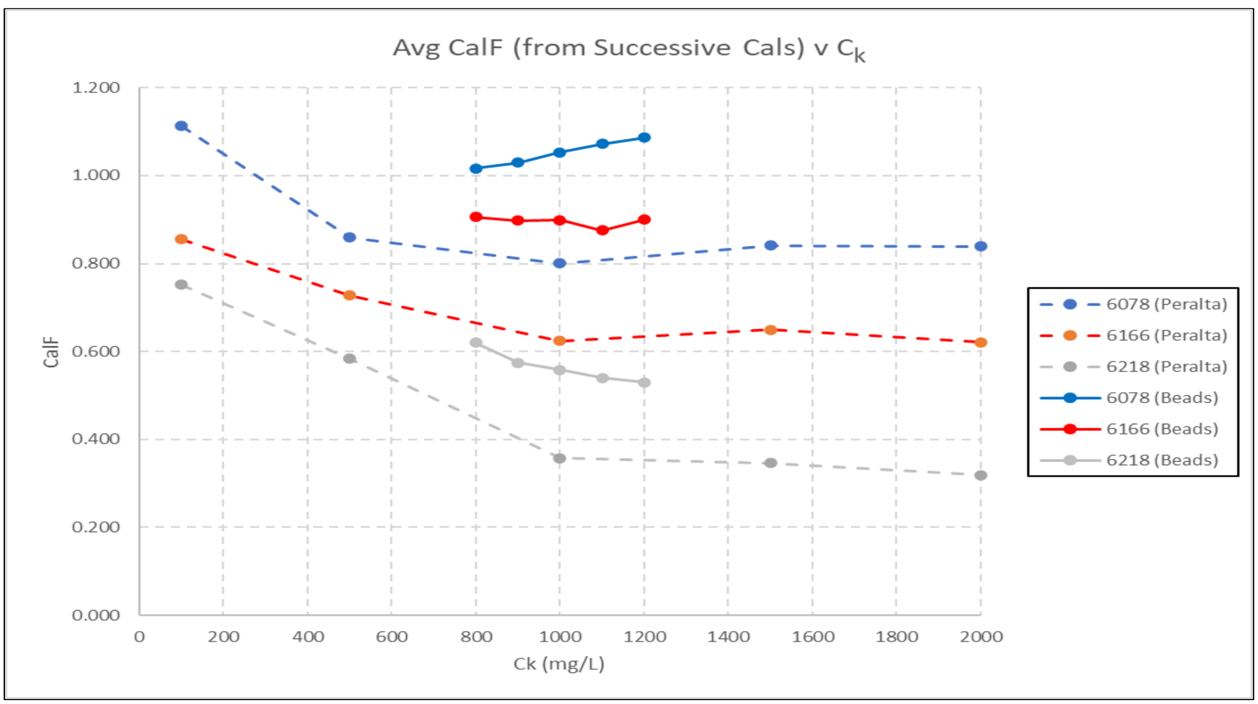

Figure34.—Computed calibration factor CalF as a function of known concentration Ck for three LISST–ABS instruments (serial numbers 6078, 6166, and 6218). The evaluation was conducted for two different media in suspension: sediment from site at Isleta Diversion Dam (Peralta) and Ballotini glass beads (Beads). See further details in Appendix A–LISST–ABS Laboratory Calibration Checks.

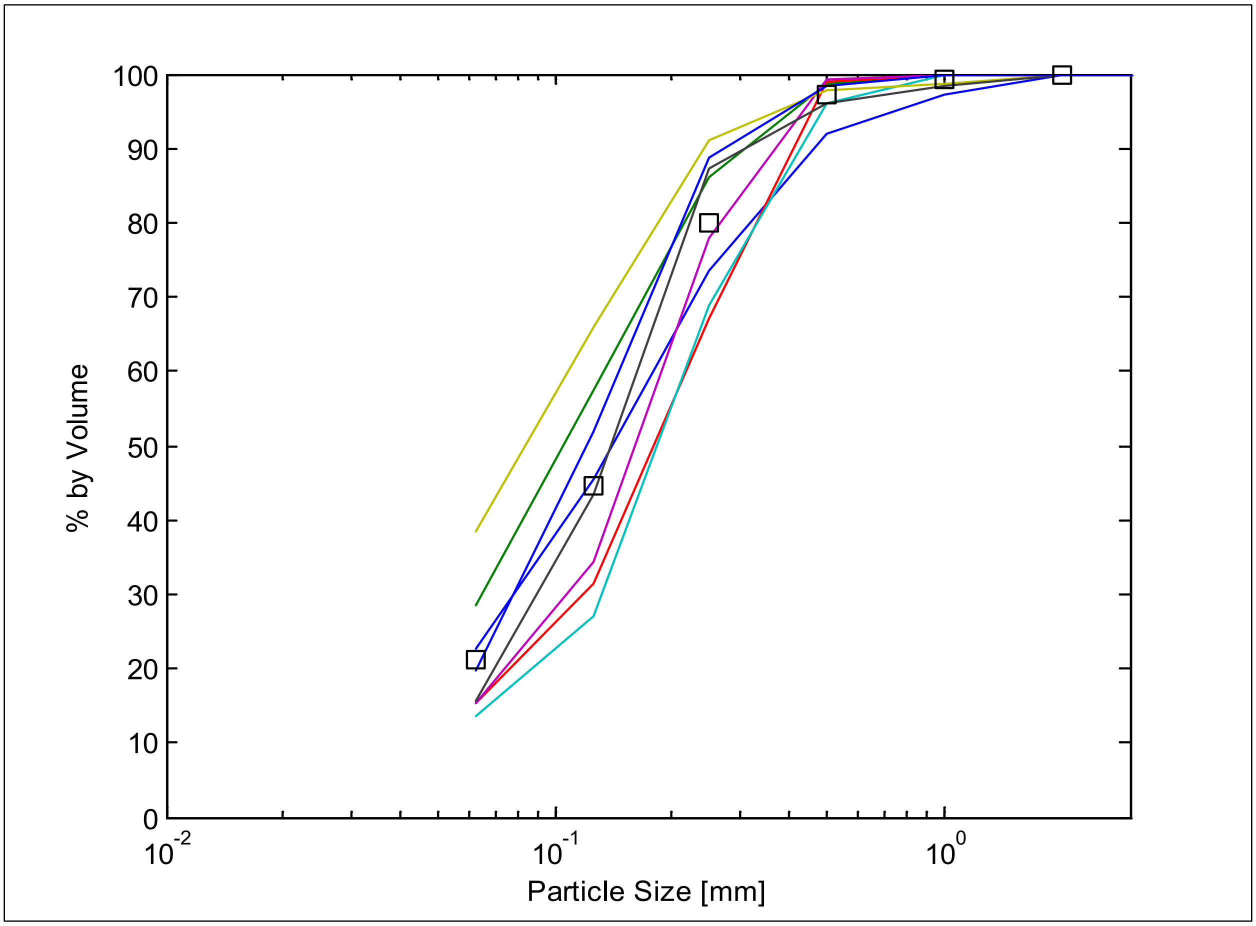

Figure 35.—Sediment size distribution reported from samples acquired from diversion channel at Isleta Diversion Dam in New Mexico. According to the manufacturer, the calibration range of the LISST–ABS sensor over 0.03–0.4 mm range is constant to within +/–30%. Black squares indicate the mean of the distribution.

Application

The factory calibration developed through laboratory testing by the manufacturer is applied internal to the LISST–ABS at the firmware level. A separate calibration factor can be applied through the user interface as a static value that acts as a multiplier to the output from the instrument. The user–specified calibration factor can be less than, or greater than, unity. The calibration factor defaults to unity until it is changed by the user. User–specified calibration can also be applied in post–processing, which offers the benefit of using non–static values. In other words, a user–specified calibration factor that varies with measured concentration or time could be applied. The evaluation performed both by Sequoia and by the Reclamation Technical Service Center showed that calibration can be dependent on the concentration measured, implying that a static calibration factor may be inadequate. Figure 35 shows the collection of calibration curves plotted together as a function of measured concentration by the LISST–ABS with serial number 6078. The applied calibration is unity since the calibration curves were developed after data

acquisition; the results presented above used only the original default calibration prior to the recalibration applied by Sequoia in January 2023. Unfortunately, we have no way of knowing over what time period the instrument internal factory calibration drifted from what was originally provided by the manufacturer when the instrument was purchased. Hypothesizing that the loss of factory calibration is likely affecting the most recently acquired data, we explore how retroactively applying the calibration curves in figure 35 changes the results from the 2022 flushing event at Cherry Creek.

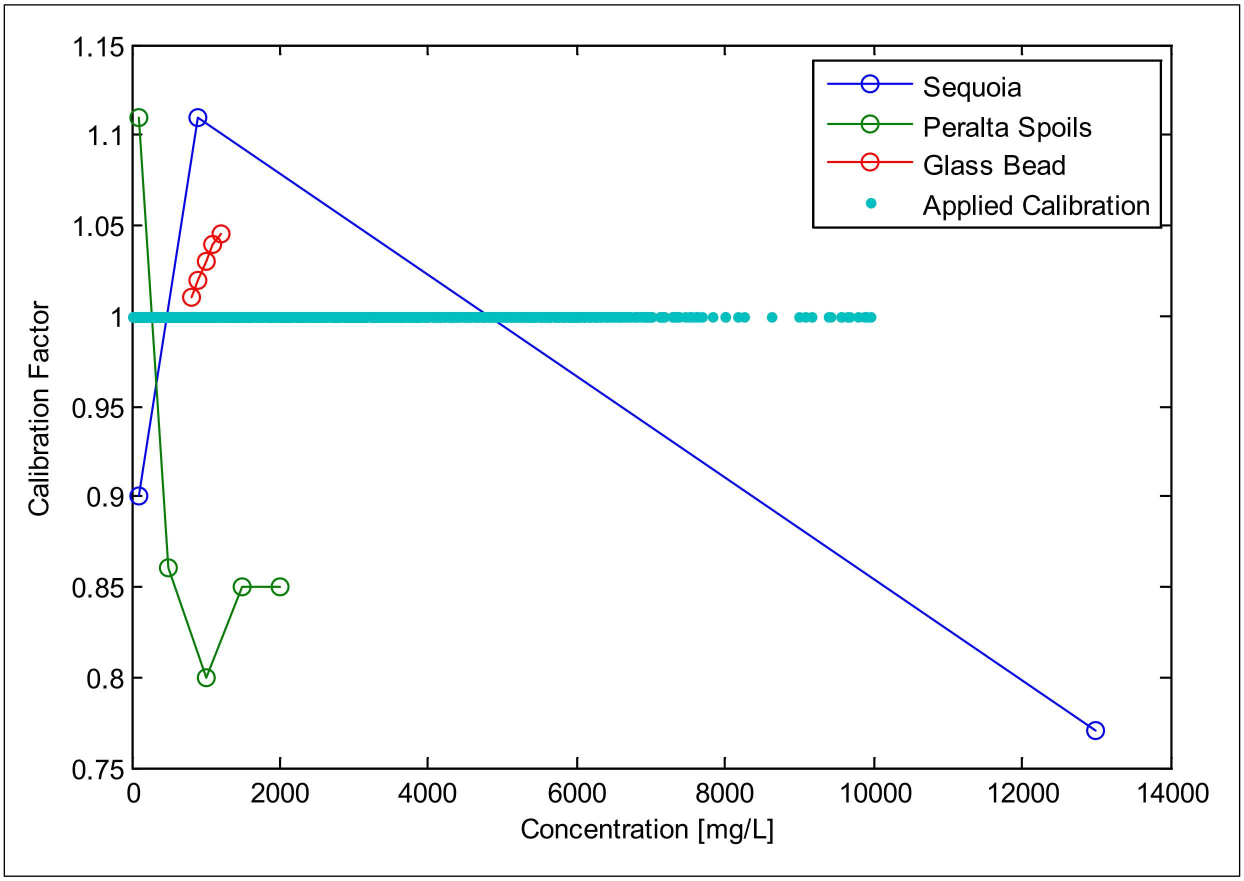

Figure 36.—Calculated calibration factors from evaluation by Sequoia and Reclamation Technical Service Center for LISST–ABS serial number 6078. The blue line represents the factory recalibration that was applied by Sequoia in January 2023. Subsequent testing by Reclamation Technical Service Center produced the green (Peralta Spoils from Isleta Diversion Dam site) and red (Beads) lines. The applied calibration is unity for all concentrations because the calibration curves were developed after data acquisition but can be applied in post–processing.

Figure 36 shows a summary of how recalibration of the LISST–ABS data from the 2022 Cherry Creek flushing event affects the relationship to sediment measurements made with the D–95 sampler. The top panel shows the calibration factor applied, which represents the product of the Sequoia calibration and the Peralta calibration shown in figure 35. The bottom panel shows

D–95 sediment concentration measurements plotted against the mean LISST–ABS readings. The black line shows the 1:1 correspondence, for reference. The black circles represent the original, uncalibrated data and the blue circles represent the calibrated data. As can be seen from the comparison in the bottom panel of the figure, applying the calibration in post–processing does offer some improvement in the correspondence between the D–95 measurements and LISST–ABS readings. It is unknown whether additional improvement in the correspondence, and to what degree, would be achievable with calibration performed using sediment samples from what was in suspension at Cherry Creek. Some general scatter around the 1:1 correspondence would be expected even with calibration.

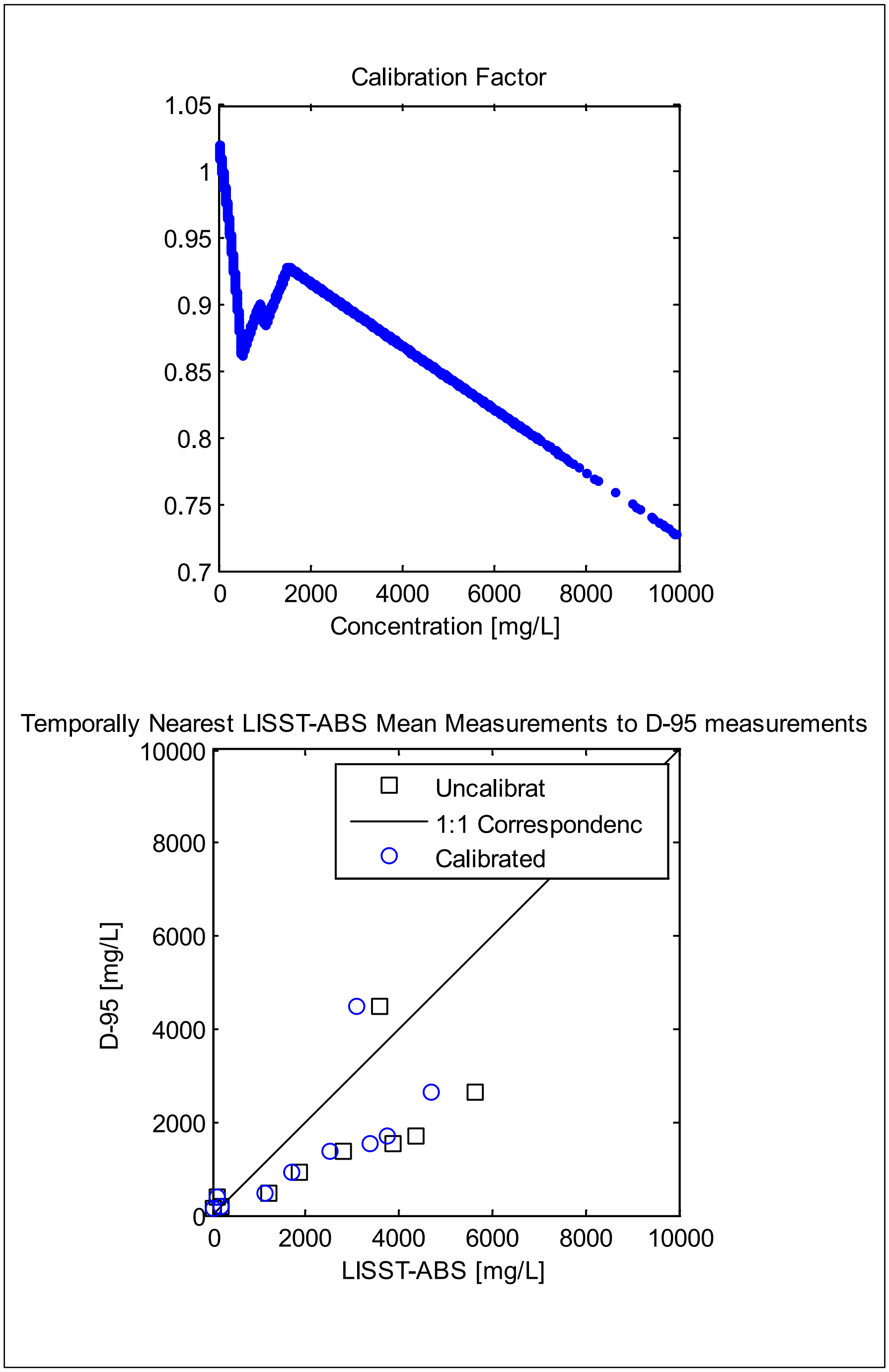

Figure 37.—Recalibration of LISST–ABS data collected during the 2022 Cherry Creek flushing event. The top panel shows the calibration factor applied, which represents the product of the Sequoia calibration and the Peralta calibration shown in Figure 35. The bottom panel shows D–95 sediment concentration measurements plotted against the mean LISST–ABS readings. The black line shows the 1:1 correspondence, for reference. The black circles represent the original, uncalibrated data and the blue circles represent the calibrated data.

Conclusion

A six consecutive year suspended sediment data collection campaign was reported on. The exercises leveraged an annual flushing exercise conducted by USACE to maintain operability of the outlet gates at Cherry Creek Dam. The capabilities and limitations of an acoustic sensor for monitoring suspended sediment were evaluated in the context of investigating reservoir flushing as well as more widespread use within Reclamation. The LISST–ABS offers many benefits, such as low cost of operation, ease of use, portability, and the capability of long–term autonomous deployment. For these reasons, it may be useful in a wide variety of Reclamation projects. For example, in the case of the annual Cherry Creek flushing event, history has shown that the exercise is an effective approach for managing sediment and gate operability despite the fact that bathymetric differencing was unsuccessful in discerning a measurable effect. Monitoring of suspended sediment through use of an instrument like the LISST–ABS may provide a useful tool within the context of reservoir sediment management. The instruments have since been deployed within projects at the Reclamation hydraulics laboratory and on–site monitoring of differential sediment concentration between sluiceways and diversion channels. Measurements of the hydraulic and sediment dynamics can be used to improve empirical predictive relationships and inform numerical models used to improve flushing efficiency (Lai & Greimann, 2020).

Despite the clear benefits associated with use of the LISST–ABS, there are several challenges associated with producing stable and meaningful results over space and time. The six years of data collection and exploration of instrument calibration elucidated some trends and recommended strategies for future users. Variability in measurements in a dynamic system can be caused by temporal or spatial dis–location from a common reference point–i.e., insufficient co–location of sampling in space or time. The rapidly changing conditions caused by opening and closing of outlet gates may cause significant differences in sediment mobilization and transport over short distances or time spans, which can produce scatter as observed in 2017, 2018, and 2019 data. This underscores the importance of diligence when it comes to establishing a data acquisition scheme, especially when making direct comparisons between instruments or collection methodologies. On the other hand, a systematic bias in measurements of one direction or another may indicate an instrument–related issue that can be corrected through instrument calibration. The effect of sediment gradation needs to be explored more. If the study were continued, we would incorporate a laboratory–based calibration using samples of sediment in suspension at the collection site at Cherry Creek. Having a baseline calibration in a laboratory setting is shown to be important not only for tuning the instrument response for more accurate readings at a particular site and point in time, but also in evaluating how the instrument response may be changing over time due to unknown factors. The spatially and temporally dynamic nature of the flushing events at Cherry Creek is likely a robust test case for the instrument capabilities and limitations, as the exercise presents rapidly changing hydraulic conditions and a wide range of sediment concentrations in suspension. Overall, we believe that the investigation underscores the importance of conducting periodic and systematic calibration using media in suspension that is representative of what is found in the field. It should be noted that an updated combined acoustic–optical sensor (LISST–AOBS) is now available and is advertised as having the benefits of both the traditional LISST–ABS and a turbidimeter; the combined sensors may offer particular benefit in flows containing significant fines component.

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Appendix A

LISST–ABS Laboratory Calibration Checks

Appendix A–LISST–ABS Laboratory Calibration Checks

Joe Kubitschek, Hydraulic Investigations and Laboratory Services

Purpose and Objectives

The primary purpose of this testing was to independently evaluate calibrations for three LISST–ABS sensors (SN 6078, 6166, 6218) following factory recalibration and prior to use of two sensors (SN 6166 and 6218) for continuous field monitoring at Isleta Diversion Dam (IDD). Testing was performed with sediment obtained from the field site (Isleta Diversion Dam–Peralta Main Spoil Pile) and glass beads similar to that which is used for factory calibration. The primary objectives were to identify the inter–instrument variability as well as the measurement variability. The former is important since these instruments will be used to measure concentration ratios for establishing field operating criteria at IDD. Furthermore, testing over a range of concentrations provides the opportunity to evaluate how instruments calibration varies with concentration.

Test Setup

The test setup at Reclamation's Hydraulics Laboratory consisted of a 200 L barrel of tap water and an air operated propeller–type mixer. Known sediment concentrations (mg/L) were established using a scale to obtain weights of sediment added to the 200 L barrel of water (figure 1). The mixture was continuously agitated and concentrations were measured separately with each of the three ABS sensors at each known concentration. The first series of tests used material obtained from the field site followed by limited testing using Ballotini® glass beads (45–90 micron). The volume of water in the barrel was estimated to be within ± 5 L and measured weights within ± 500 mg to give an estimated uncertainty of ± 25 mg/L for a known concentration of 1000 mg/L (± 2.5%). The primary requirement for testing was that conditions are "well mixed". However, initial testing showed the existence of a weak vertical gradient such that concentrations lower in the mixing barrel were larger than at locations higher in the barrel. Recognizing this limitation in the test setup, ABS 6078 was used to establish the vertical location where the measured concentration (C_m) reasonably matched the known concentration (C_k) at 100 mg/L with a 1.0 calibration factor setting. All subsequent testing was performed at this depth.

Testing

Each ABS was tested at known concentrations (C_k) of 100, 500, 800, 900, 1,000, 1,100, 1,200, and 2,000 mg/L using field sediment with calibration factors set to 1.0 (for information on calibration factors see LISST–ABS User's Manual). All data were acquired at a sample (or output) rate of 1 Hz for 10 minutes. Figure 2 provides the time–average results of two trials (given as C_m v C_k) for the range of concentrations tested. Each of the sensors indicated different measured concentrations, all of which resulted in discrepancies in comparison with the known concentrations. In the case of SN 6218, the measured concentrations were larger than known concentrations by a factor greater than 3. After identifying this large disparity, testing was performed to obtain calibration factors (using the ABS software) for each sensor via five successive calibrations at known concentrations, C_k = 100, 500, 1,000, 1,500, and 2,000 mg/L. Figure 3 shows the results plotted as calibration factor (CalF) versus known concentration (C_k). Each of the instruments exhibited variability in the CalF over the range of known concentrations tested, suggesting poor linearity.

Similar testing was performed using glass beads (45–90 micron), the results of which are presented as figure A–4 along with the results using field sediment. While the calibration factors are somewhat closer to 1.0 using glass beads, the results (except perhaps for SN 6166) still show relatively poor linearity over the range of concentrations tested.

Conclusions & Recommendations

In general, these results highlight unexpectedly large differences in measured concentrations between the three ABS sensors using the field sediment. The best performing sensor (SN 6078) tended to be within about 20% of the known concentrations (using a calibration factor of 1.0) for the range of concentrations tested. It is recognized that these sensors are inherently sensitive to variations in sediment size/gradation. In fact, the manufacturer recommends field calibration using "the specific type and size of sediment being measured".

The variability in calibration factors over the range of concentrations tested present considerable difficulty in establishing reasonable confidence for these instruments to provide relevant data in assessing field operational performance at IDD. It is apparent that the variability in calibration factors observed during this testing is largest for concentrations below about 1,000 mg/L. In that case, the calibration factors decrease with increasing Ck. Above 1,000 mg/L the calibration factors are more consistent. As such, and recognizing that absolute concentrations are not necessary for the purposes of field deployment in the case of IDD since concentration ratios will be used as primary indicators of operational performance, two approaches may be considered:

1. Acquisition of sensors data during field deployment with calibration factors of 1.0 followed by post–correction of the data using calibration factors obtained during this laboratory testing.

2. Acquisition of sensors data during field deployment using the average calibration factors obtained during this testing for concentrations ≥ 1000 mg/L.

The second approach is recommended. Calibration factors of 0.632 for SN 6166 and 0.341 for SN 6218 should provide reasonably consistent concentration ratio results for a range of field sediment concentrations between 800–2,000 mg/L at IDD. This of course assumes no long–term drift will occur during sensors deployment and that the sensors remain clean and free of biofouling. The only reasonable possibility to resolve the issue of drift would be to periodically (every 3–6 months) retrieve the instruments for calibration checks.

Figure A–1.—ABS calibration test setup.

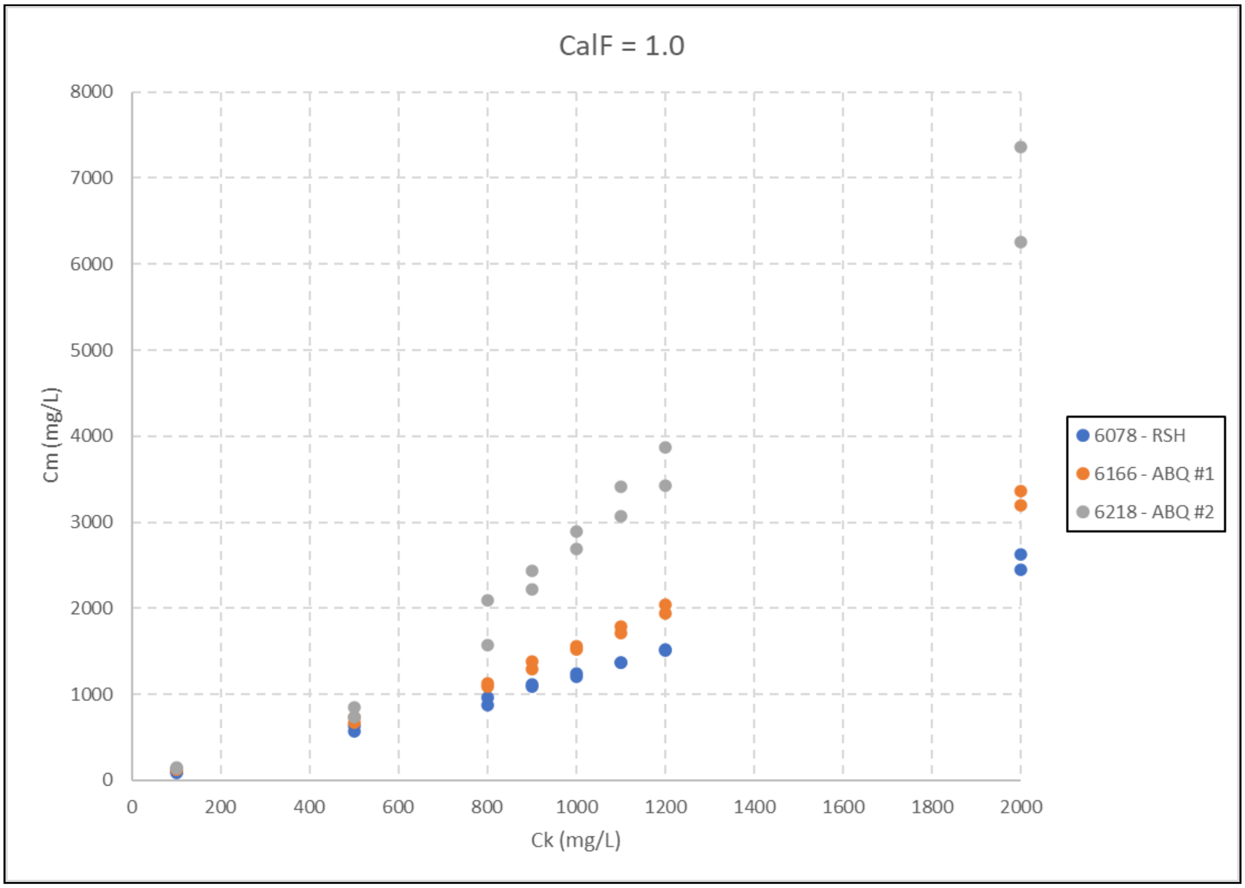

Figure A–2.—Test results showing measured concentration Cm versus known concentration Ck for each ABS sensor tested using field sediment (calibrations factors set to 1.0). Solid black line reflects 1:1 ratio between Cm and Ck.

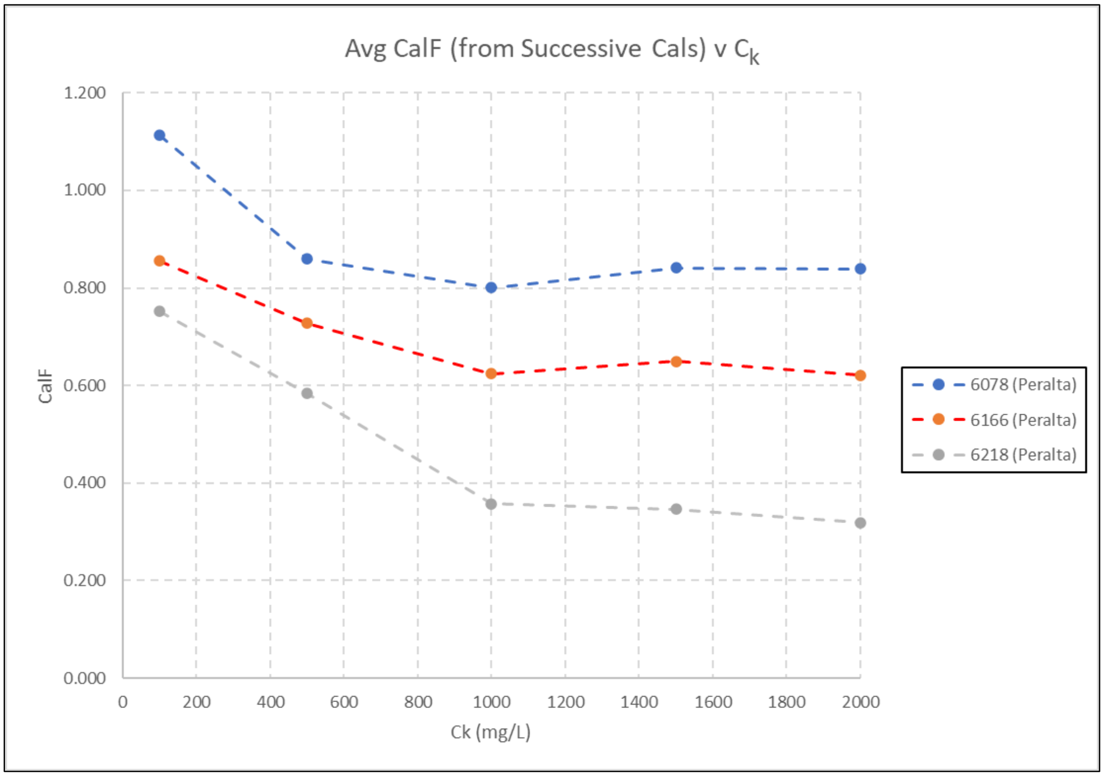

Figure A-3.—Calibration factors obtained for each sensor over range of know concentrations Ck.

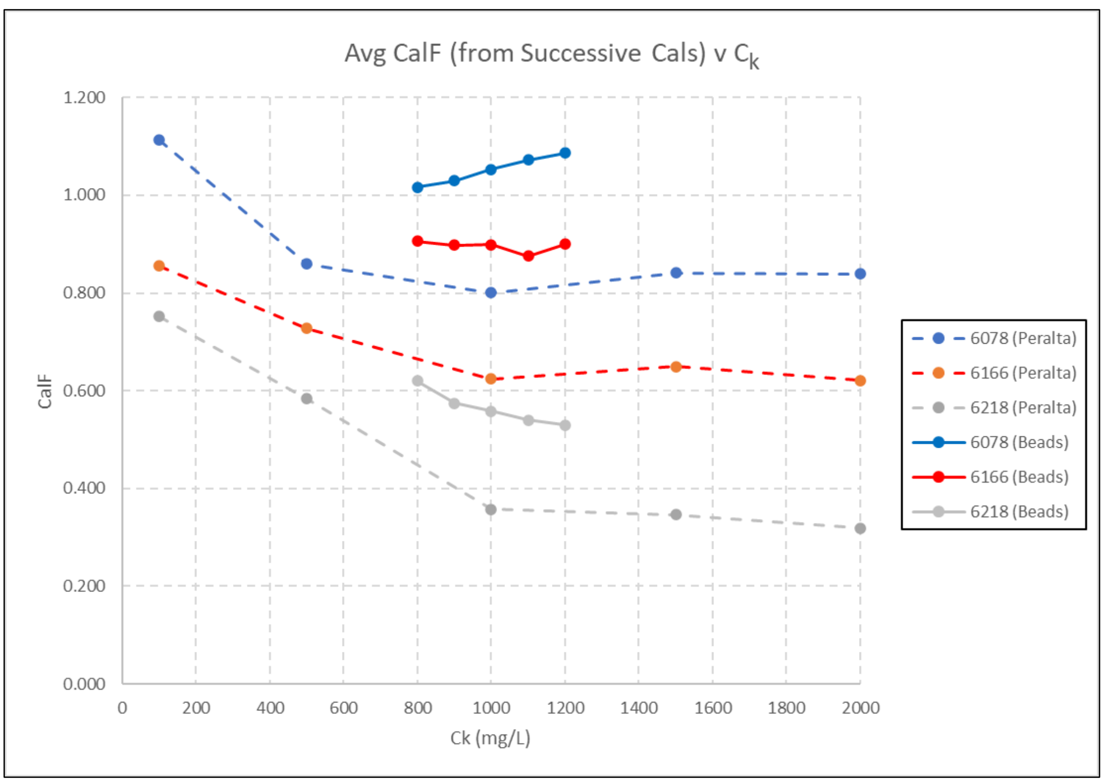

Figure A-4.—Calibrations factors comparison between field sediment and glass beads.