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Managing Water in the West

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

Research and Development Office
Science and Technology Program
(Final Report) ST-2018-1893-01

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14. ABSTRACT The US Army Corps of Engineers (USACE) performs an annual sediment flushing exercise of the main outlet gates at Cherry Creek Reservoir in Denver, CO. The purpose of the flushing exercise is to scour sediment from the area immediately upstream of the radial gates, thereby preventing detrimental buildup and maintaining operability. During the 2017 and 2018 flushing event, a LISST-ABS (Sequoia Scientific, Inc.) instrument was used to estimate suspended sediment concentration using acoustic backscatter as a surrogate. The results are compared with sediment measurements collected by USGS field technicians using a FISP (Federal Interagency Sedimentation Project)-approved DH-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 2017 and 2018 flushing events in order to evaluate the effectiveness of sluicing operations and proficiency of instrumentation in capturing the dynamics of the event.

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Executive Summary

The US Army Corps of Engineers (USACE) performs an annual sediment flushing exercise of the main outlet gates at Cherry Creek Reservoir in Denver, CO. Completed in 1950, Cherry Creek Dam and Reservoir are operated by the USACE to provide flood protection to the Denver Region from floodwaters. The purpose of the flushing exercise is to scour sediment from the area immediately upstream of the radial gates, thereby preventing detrimental buildup and maintaining operability. In 2017 and 2018, USACE, USGS, and Bureau of Reclamation (BOR) crews collected hydraulic, sediment, and bathymetric data necessary to verify gate discharge curves, develop sediment discharge relationships, and measure the volume of sediment removed from the reservoir during the annual flush. Physical measurements of the hydraulic and sediment dynamics are used to improve empirical predictive relationships and inform numerical models used to improve flushing efficiency.

During the 2017 and 2018 flushing event, a LISST-ABS (Sequoia Scientific, Inc.) instrument was used to estimate suspended sediment concentration using acoustic backscatter as a surrogate. The results are compared with sediment measurements collected by USGS field technicians using a FISP (Federal Interagency Sedimentation Project)-approved DH-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 2017 and 2018 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 BOR'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?

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 BOR; 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 project implementation benefited greatly from collaboration between USACE, USGS, and BOR engineers and technicians, which resulted in a mutually beneficial study through shared planning and resources. Plans are underway to continue the study coincident with the 2019 Cherry Creek sediment flushing exercise; 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 BOR facilities. It is anticipated that the techniques will be implemented at project sites in 2019 and thereafter.

Contents

Figures

Site

The study was conducted at the Kennedy Golf Course (10500 E Hampden Ave, Denver, CO), immediately downstream of the Cherry Creek Dam (Figure 1). Cherry Creek flows through the golf course and continues to its confluence with the South Platte River approximately 12 miles downstream of the dam. During the 2017 Cherry Creek flushing event, sediment sampling was performed from a small golf cart bridge (Figure 2) approximately ½ mile downstream of the dam outlet. The larger magnitude 2018 flushing event promised to inundate the bridge that was used in the 2017 study; consequently, a larger bridge (Figure 3) was chosen for the 2018 study, located about ¼ mile downstream of the dam outlet.

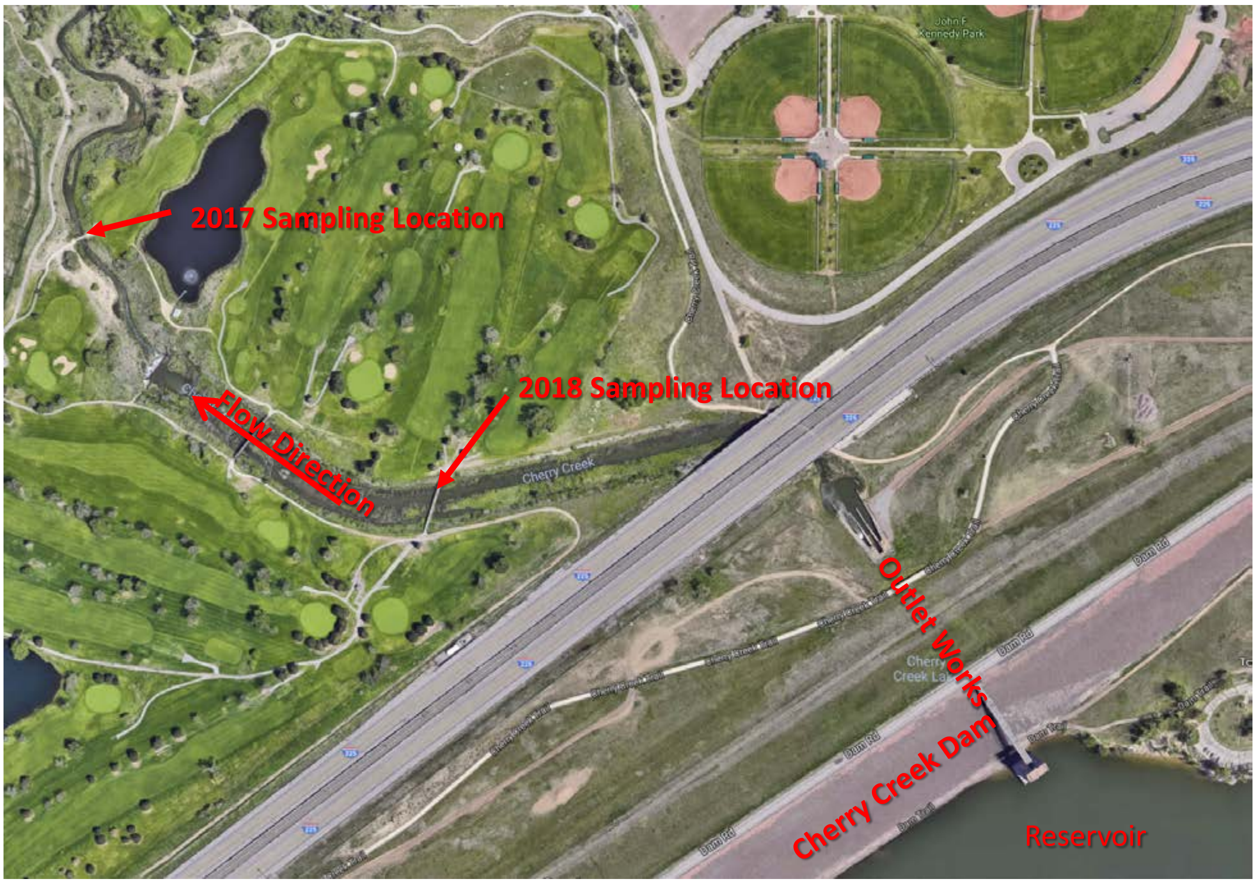

Figure 1. Aerial imagery of site with indication of 2017 and 2018 sediment sampling locations. The 2017 sampling location could not be used during the 2018 flushing event because the higher flows were overtopping the bridge creating an unsafe environment for staff and equipment.

Figure 2. Sediment sampling from bridge at Kennedy Golf Course during the 2017 Cherry Creek flushing exercise.

Figure 3. Sediment sampling from bridge at Kennedy Golf Course during the 2018 Cherry Creek flushing exercise.

Hydraulics

The annual Cherry Creek flushing exercise is conducted by systematically operating each of the five radial gates. The result is an oscillating hydrograph; the entire release schedule is contained within several hours. Further, the magnitude of the peak release from each gate is varied from year-to-year. Presented in Figure 1 is the scheduled 2017 and 2018 releases at the outlet structure of Cherry Creek Dam.

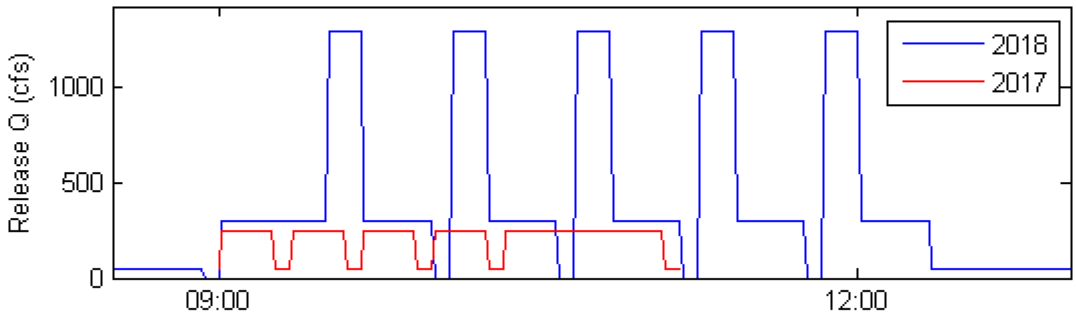

Figure 4. Release hydrograph as scheduled in 2017 (red) and 2018 (blue) at the Cherry Creek Dam outlet structure. Each peak in the hydrograph represents the independent operation of one of the radial gates.

Methods

USGS technicians used a FISP-approved DH-95 sampler to make measurements of depth-averaged suspended sediment concentration in 2017 and 2018. According to FISP specifications, the DH-95 can be used in stream depths up to 15 ft and velocities ranging from 1.7 to 7.4 ft/s. USACE labs processed the samples collected in 2017 and 2018 for sediment concentration and particle size distribution. In 2017, 33 1L bottles were processed for determining sediment concentration, and in 2018, 44 1L bottles were processed.

BOR engineers used a submersible acoustic backscatter sediment sensor (LISST-ABS) to estimate suspended sediment concentration. The instrument is advertised as a low-cost sensor designed specifically for measuring suspended sediment concentration at a point. The manufacturer (https://www.sequoiasci.com/product/lisst-abs/) states:

- The 8MHz acoustic sensor 'sees' all size grains, and unlike turbidity, it sees coarse grains very well.
- The LISST-ABS calibration is far less sensitive to grain size changes than turbidity sensors, changing only ~ ± 30% over 30-400 microns
- The instrument operates over a >4-decade working range in concentration!
- The sensor tolerates fouling.

For the 2017 flushing event, the LISST-ABS was mounted to a 50 lb USGS sounding weight suspended from a bridge board using a USGS A-Reel (Figure 2). Due to the higher flow rates anticipated for the 2018 flushing event, the LISST-ABS was mounted to a 75 lb USGS sounding weight suspended from a Type-A 4-wheel crane using a USGS A-Reel (Figure 3).

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. This was especially true during the early part of the 2018 flushing event, when the high stage brought large amounts of floating debris downstream. 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 (2017 exercise only)

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 DH-95 sampler is operated.

Results

Particle Size Analysis

Sediment size distribution as reported from the processing of data collected using the DH-95 sampler is presented in Figure 5 (2017) and Figure 6 (2018). A Malvern laser diffraction analyzer was used to measure particle size. Outliers are observable in both the 2017 and 2018 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 likely a function of the higher peak discharge (Figure 4) 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.

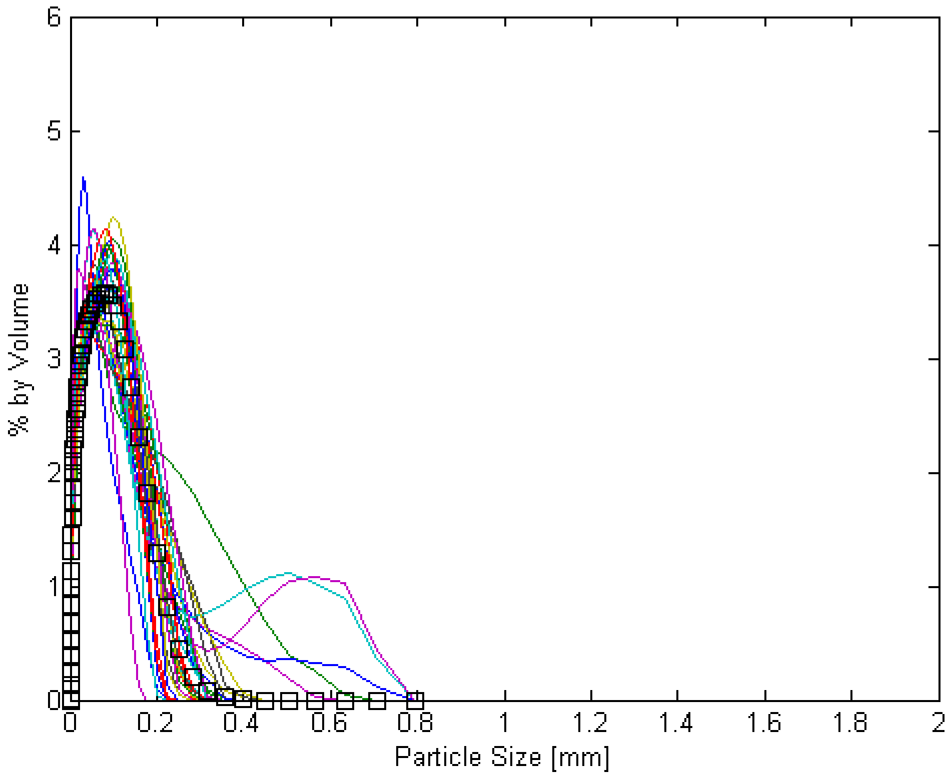

Figure 5. Sediment size distribution reported from samples acquired using the DH-95 sampler during the 2017 Cherry Creek flushing event. Black squares indicate mean with outliers removed. According to the manufacturer, the calibration range of the LISST-ABS sensor over 0.03 – 0.4 mm range is flat to within +/- 30%.

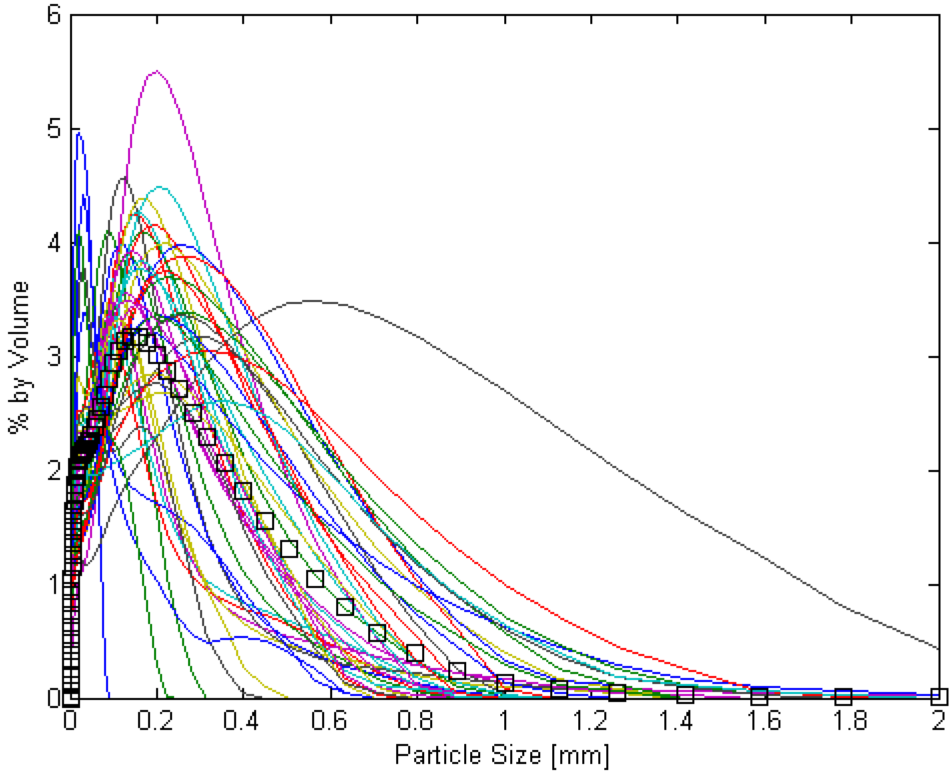

Figure 6. Sediment size distribution reported from samples acquired using the DH-95 sampler during the 2018 Cherry Creek flushing event. Black squares indicate mean with outliers removed. According to the manufacturer, the calibration range of the LISST-ABS sensor over 0.03 – 0.4 mm range is flat to within +/- 30%.

Cherry Creek Flush Results

A compilation of the discharge, stage, and suspended sediment concentration data for the 2017 and 2018 Cherry Creek flushing events are presented in Figure 7 and Figure 8, respectively. In each figure, the top panel compares the scheduled discharge to what was actually released from the gates due to inherent variability in operation. The second panel provides the record of pressure head (a surrogate for stage) as measured by the HOBO logger at the sediment sampling location. In 2017 (Figure 7), 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 DH-95 sampler. The bottom panel shows mean (with errorbars indicating one standard deviation) record of sediment concentration measurements from the LISST-ABS compared to data collected using the DH-95 sampler. The mean LISST-ABS values represent approximately 5-min average intervals, although individual vertical transects are averaged into a single value despite shorter record length. In the third panel of Figure 7 and Figure 8, the vertically oriented distributions of points from the LISST-ABS represent collection of a vertical profile of concentration measurements through the water column. Thus the wide range of values observed is indicative of vertical stratification of suspended sediment. To better indicate the distribution of suspended sediment observed, Figure 9 and Figure 10 each show a snapshot of the overall record of LISST-ABS values reported for the 2017 and 2018 flushing events, respectively. 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 (Figure 9). 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 was likely 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. Vertical profiles of suspended sediment concentration collected with the LISST-ABS during the 2018 flushing event (Figure 10) 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. The difference in vertical sediment concentration distributions between the 2017 and 2018 events is consistent with the particle size analysis results (Figure 5 and Figure 6); 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.

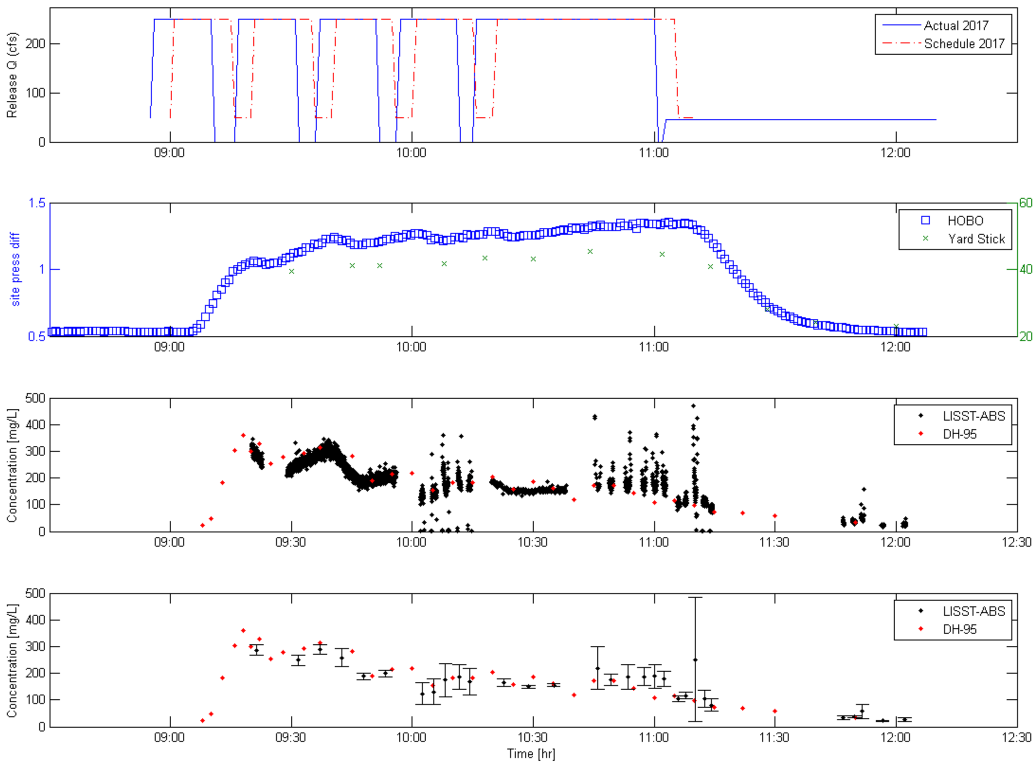

Figure 7. Compilation of results from the 2017 Cherry Creek flushing event. Panels from top to bottom correspond to: (1) scheduled and actual flow release from Cherry Creek Dam outlet works, (2) Pressure and hydraulic head reported from HOBO pressure transducer logger and stage, (3) Continuous record of LISST-ABS measurements compared to DH-95 measurements, (4) mean values of LISST-ABS measurements compared to DH-95 measurements.

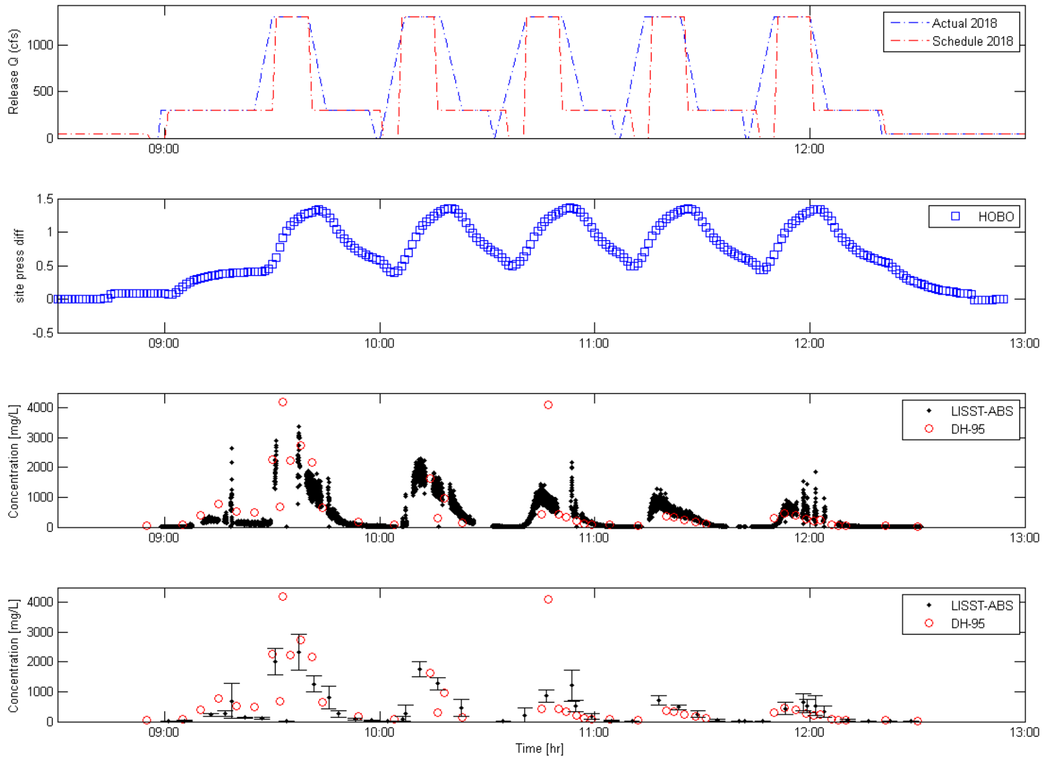

Figure 8. Compilation of results from the 2018 Cherry Creek flushing event. Panels from top to bottom correspond to: (1) scheduled and actual flow release from Cherry Creek Dam outlet works, (2) Pressure and head reported from HOBO pressure transducer logger, (3) Continuous record of LISST-ABS measurements compared to DH-95 measurements, (4) mean values of LISST-ABS measurements compared to DH-95 measurements.

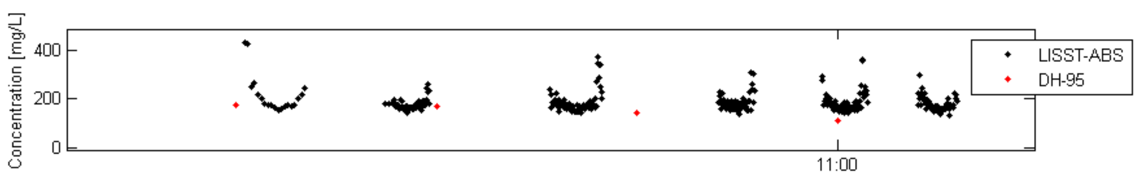

Figure 9. Record of sediment concentration measurements from LISST-ABS collected during the 2017 Cherry Creek flushing event over the period approximately 10:40 am – 11:05 am. Each grouping of points represents a vertical profile through the water column. The valley shape of the profiles indicates that suspended sediment concentration was higher near the water surface and lower near the bed.

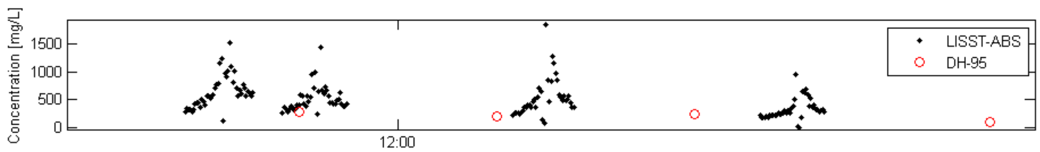

Figure 10. Record of sediment concentration measurements from LISST-ABS collected during the 2018 Cherry Creek flushing event over the period approximately 11:55 am – 12:05 pm. Each grouping of points represents a vertical profile through the water column. The peaked shape of the profiles indicates that suspended sediment concentration was lower near the water surface and higher near the bed.

Discussion

In gauging the effective differences imparted on the hydraulic and sediment dynamics as a function of the gate operations at Cherry Creek Dam, it is instructive to plot 2017 and 2018 results in the same figure panels (Figure 11). The panels in the figure indicate how the greater peak discharges of the 2018 event mobilize significantly greater sediment concentrations into the water column than observed in the 2017 event. Further, the signature of the gate operations is much more apparent in the results from the 2018 event, both in the pressure readings from the HOBO logger (panel 2) and the sediment concentration measurements (panels 3 & 4). The larger magnitude of peak flows released in the 2018 event partially account for the variation in stage and sediment concentrations observable at the sampling site. However, in 2017, the sampling site was further downstream from the bottom of the outlet structure (about 0.5 mi) than in 2018 (about 0.25 mi), which imparts greater longitudinal mixing and dispersion of the wave signal as it advects in the downstream direction from the dam outlet structure.

From examining the 2018 sediment concentration measurements, it is apparent that several peak concentration values reported from the DH-95 sampler were not replicated by the readings from the LISST-ABS. While it is certainly possible that the difference in high concentration readings is due to a systematic bias in the LISST-ABS instrument, it is also likely that high concentration pulses of sediment were not captured by the LISST-ABS simply due to the high spatial and temporal variability of the hydraulic and sediment dynamics in the system, especially as compared to the 2017 event. Because the spatial and temporal gradients in concentration were apparently much smaller during the 2017 event than the 2018 event, the agreement in sediment concentration results between the DH-95 sampler and LISST-ABS sensor were likely less sensitive to coincidence of sampling in time and space. Particle size in suspension may have also influenced the results. In 2018, the size distribution indicates a broader range of particle sizes which may be outside the optimum range of sensitivity of the LISST-ABS.

To further illustrate the differences observed in results from the 2017 and 2018 events between the DH-95 sampler and LISST-ABS sensor, Figure 12 and Figure 13 present the computed sediment transport rate and cumulative mass transport, respectively. The total cumulative mass transport will be used in further mass balance studies aimed at gauging the effectiveness of reservoir flushing operations at Cherry Creek. The sediment transport rate, computed by assuming uniform suspended sediment concentration and multiplying by the discharge, reveals several points where the LISST-ABS results significantly underestimate results from the DH-95 samples. Because the points of significant disagreement in concentration measurement coincide with peaks in the discharge hydrograph, the effect on the differential computed sediment transport rate is nonlinearly large. As mentioned previously, the differences between the LISST-ABS readings and DH-95 samples may be either related to systematic instrument bias or unpredictable spatial and temporal variation in the sediment pulses advecting down the channel. Integrating the sediment rate over the duration of the release produces an estimate of the cumulative sediment mass transported through the system (Figure 13). The significant difference between computed mass transported from LISST-ABS measurements and DH-95 samples is dominated by the points of nonlinearly large differences in estimated transport rate shown in Figure 12.

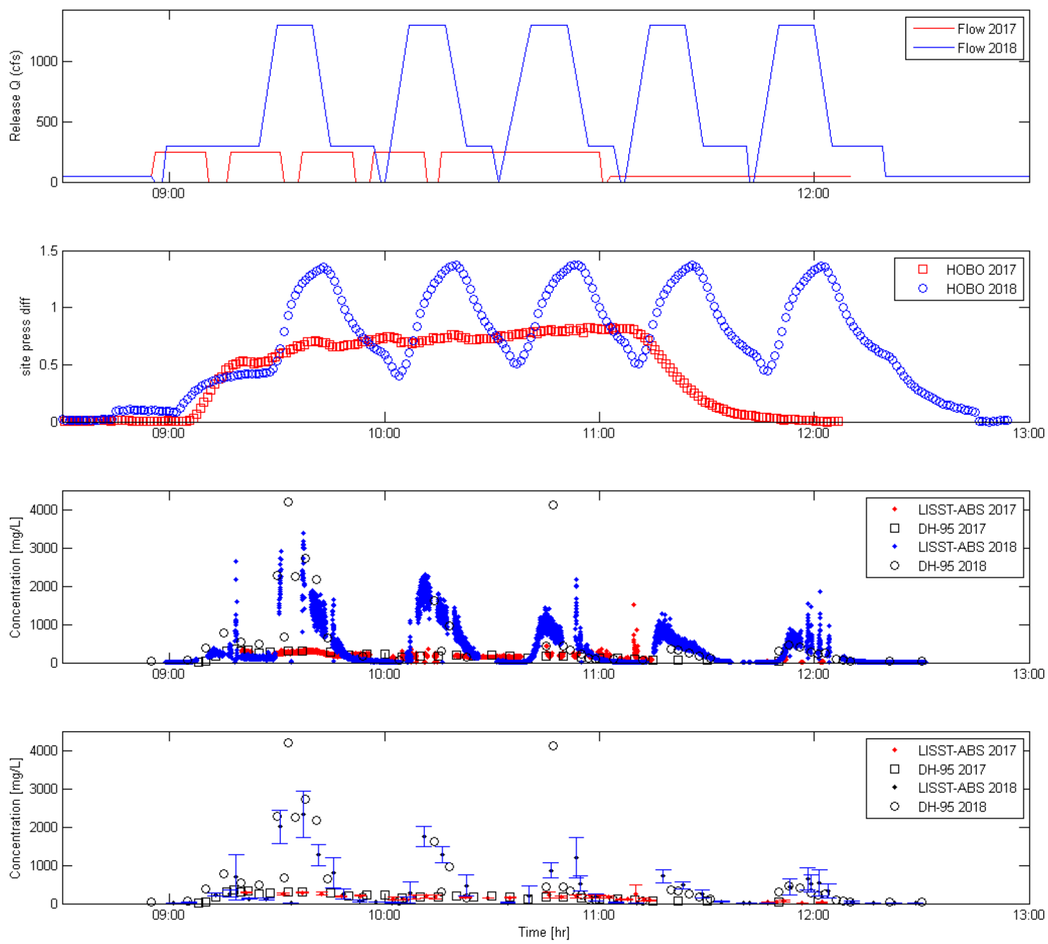

Figure 11. Comparison of results from the 2017 and 2018 Cherry Creek flushing event. Panels from top to bottom correspond to: (1) actual flow release from Cherry Creek Dam outlet works, (2) Pressure head reported from HOBO pressure transducer logger, (3) Continuous record of LISST-ABS measurements compared to DH-95 measurements, (4) mean values of LISST-ABS measurements compared to DH-95 measurements.

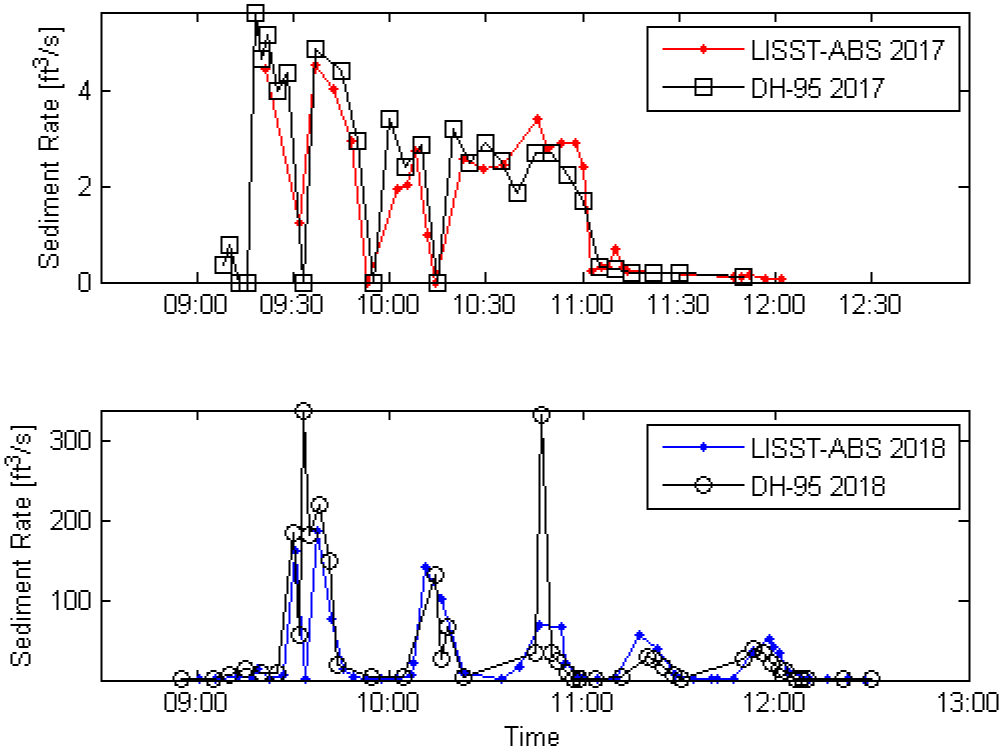

Figure 12. Sediment transport rate, estimated by assuming uniform concentration and multiplying by the discharge hydrograph. The points of large disagreement (2018) between LISST-ABS and DH-95 are nonlinearly large because of the coincidence with discharge peaks. Note the difference in y-axis scaling between the 2017 (upper) and 2018 (lower) results.

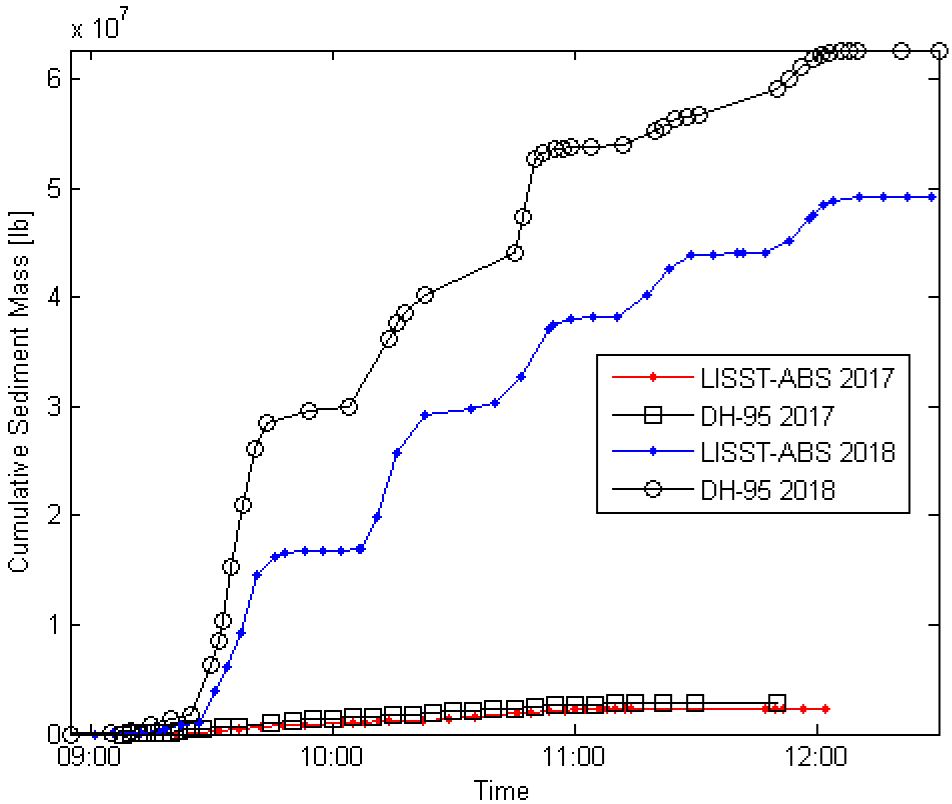

Figure 13. Total sediment mass transported, estimated by integrating the sediment transport rate (Figure 12) over the duration of the record and converting volume to mass.

Conclusions

The study has been useful in demonstrating the utility of the LISST-ABS instrument in estimating suspended sediment concentrations. The factory calibration of the instrument is not generally considered to be valid for all conditions in which sampling may be conducted, primarily due to changing particle size distributions during and between the releases. However, the values reported by the instrument in this study were based on the factory calibration. The agreement between the LISST-ABS measurements and DH-95 samples collected during the 2017 event was quite robust. Although significant differences are observed from comparison of results from the 2018 event, some possible issues with the data collection methodology and variability of dynamics in the system have been identified and may be at least partially responsible.

Moving forward, more is to be learned by continuing the annual sediment data collection activities coincident with the Cherry Creek flushing event. Due to the significant interagency collaboration and close proximity of the site to the Denver Office, the annual event invariably represents a low-cost opportunity to refine collection techniques and enhance user knowledge base. At a project level, it is anticipated that additional benefits of implementing LISST-ABS collection of sediment surrogate information will be realized due to the potential for continuous and autonomous data acquisition which will help increase resolution and decrease costs associated with long-term sampling of sediment dynamics.

In parallel with the activities related to the Cherry Creek flushing event, two proposals for further study of suspended sediment dynamics using acoustic surrogate methods are in development. One proposal is for interagency applied research submitted to the USGS John Wesley Powel Center for Analysis and Synthesis; the other proposal is concerned with monitoring and analysis of sediment dynamics at Isleta Diversion Dam in New Mexico. In each case, the PI would serve in a supporting role. Both project proposals are pending review.