Field Investigation of Sub-Isokinetic Sampling by the US D-96-Type Suspended-Sediment Sampler and its Effect on Suspended-Sediment Measurements

Open-File Report 2022–1077

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

Cover. Downstream view of the Diamond Creek cableway study site at the Colorado River above Diamond Creek near Peach Springs, Arizona, 09404200 gaging station.

Field Investigation of Sub-Isokinetic Sampling by the US D-96-Type Suspended-Sediment Sampler and its Effect on Suspended-Sediment Measurements

By Thomas A. Sabol, David J. Topping, Ronald E. Griffiths, and Guillaume Dramais

Open-File Report 2022–1077

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

U.S. Geological Survey, Reston, Virginia: 2022

For more information on the USGS—the Federal source for science about the Earth,
its natural and living resources, natural hazards, and the environment—visit
https://www.usgs.gov/ or call 1–888–ASK–USGS (1–888–275–8747).

For an overview of USGS information products, including maps, imagery, and publications,
visit https://store.usgs.gov/.

Suggested citation:
Sabol, T.A., Topping, D.J., Griffiths, R.E., and Dramais, G., 2022, Field investigation of sub-isokinetic sampling by the US D-96-type suspended-sediment sampler and its effect on suspended-sediment measurements: U.S. Geological Survey Open-File Report 2022–1077, 14 p., https://doi.org/10.3133/ofr20221077.

ISSN 2331-1258 (online)

Contents

Figures

Tables

Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Volume	
pint (pt)	0.4732	liter (L)
cubic inch (in^3)	0.01639	liter (L)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram (kg)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
	Volume	
liter (L)	0.01639	cubic inch (in^3)
liter (L)	2.113	pint (pt)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)
	Density	
kilogram per liter (kg/L)	62.4220	pound per cubic foot (lb/ft^3)

Supplemental Information

Concentration of sediment in water is given in milligrams per liter (mg/L).

Abbreviations

ADCP	acoustic-Doppler current profiler
FISP	Federal Interagency Sedimentation Project
IE	intake efficiency
MST	mountain standard time
USGS	U.S. Geological Survey

Field Investigation of Sub-Isokinetic Sampling by the US D-96-Type Suspended-Sediment Sampler and its Effect on Suspended-Sediment Measurements

By Thomas A. Sabol,[1] David J. Topping,[1] Ronald E. Griffiths,[1] and Guillaume Dramais[2]

Abstract

Collection of accurate suspended-sediment data using depth-integrating samplers requires that they operate isokinetically, that is, that they sample at the local stream velocity unaffected by the presence of the suspended-sediment sampler. Sub-isokinetic suspended-sediment sampling causes grain-size dependent positive biases in the suspended-sediment concentration measured by the suspended-sediment sampler. Collapsible bag suspended-sediment samplers like the US D-96 and the lighter US D-96-A1 depth-integrating samplers have shown a tendency to sample sub-isokinetically under low stream velocities (below ~3.5 feet per second), colder water temperatures, and longer sampling durations. Previous work concluded that the time-dependent decrease in the intake efficiency of the US D-96-type sampler could be partially overcome by increasing the venting of water from the sampler cavity by shortening the sampler tray. The standard-length sampler tray partially blocks the rear vent hole; shortening the sampler tray effectively increases the area of the sampler-cavity rear vent hole. This previous work showed that removing the partial blockage of the rear vent hole caused by the sampler tray resulted in both an increase in intake efficiency and a decrease in the positive bias in measured suspended-sand concentration.

Herein, a series of tests were conducted on the Colorado River in Arizona using different modifications to a US D-96-A1 sampler to see if physical enlargement of the rear vent hole would produce further improvements in intake efficiency. Results from these tests show that physical enlargement of the rear vent hole, beyond that already effectively achieved by shortening the sampler tray, did not result in any further improvement in intake efficiency. However, these tests also indicated that physically increasing the area of the rear vent hole did not affect the suspended-sediment data collected by the US D-96-A1 sampler. Furthermore, comparisons of suspended-sediment data collected using the US D-96-A1 sampler and the isokinetic US P-61-A1 point-integrating sampler show that the suspended-sediment data collected by the US D-96-type sampler can be accurate in certain circumstances despite the tendency of this sampler to sample sub-isokinetically over the entire depth of a sampling vertical. We surmise that this result could arise from the US D-96-A1 sampler collecting sample isokinetically when the water-sediment mixture enters the nozzle, but that the water-sediment mixture only enters the nozzle intermittently while the sampler transits a sampling vertical.

Introduction

Accurate measurement of suspended-sediment concentrations and grain-size distributions using suspended-sediment samplers with nozzles oriented into the flow requires that the water-sediment mixture enters these nozzles at the local stream velocity, a condition known as isokinetic sampling (Federal Interagency Sedimentation Project [FISP], 1941; Edwards and Glysson, 1999; Sabol and Topping, 2013). During isokinetic sampling, the water-sediment mixture enters the sampler nozzle at the velocity that would be present at the location of the intake to the nozzle if the flow were not disturbed by the presence of the sampler (Sabol and Topping, 2013). Intake efficiency (IE), the measure of isokinetic sampling, is defined as

$$\mathrm{IE} = \frac{V_{\mathrm{n}}}{V}, \tag{1}$$

where

V_{n} is the instantaneous velocity of the water-sediment mixture moving through the nozzle into the sample container (that is, the nozzle velocity), and

V is the stream velocity at the nozzle intake unaffected by the presence of the sampler (that is, the stream velocity).

The nozzle velocity is calculated by using the collected sample volume, nozzle cross-sectional area, and sample duration. FISP suspended-sediment samplers are deemed isokinetic when IE = 1.0 ± 0.10 (Davis, 2001; Gray and others, 2008; Sabol and Topping, 2013). Non-isokinetic sampling causes positive or negative biases in suspended-sediment concentrations that are correlated with grain size (FISP, 1941; Edwards and

[1]U.S. Geological Survey.

[2]INRAE, Centre Lyon-Grenoble Auvergne-Rhône-Alpes, Villeurbanne, France.

Glysson, 1999; Sabol and Topping, 2013). Although super-isokinetic sampling (IE > 1.1) causes relatively small negative biases in measured suspended-sediment concentration, sub-isokinetic sampling (IE < 0.9) causes much larger positive biases in measured suspended-sediment concentration (FISP, 1941). The absolute values of these biases increase with increasing grain size.

Previous evaluations by Sabol and Topping (2013) found that the US D-96-type collapsible-bag sampler was typically sub-isokinetic, with time-dependent intake efficiencies that decreased as sampling duration increased. Sabol and Topping (2013) concluded that the most likely explanation for this behavior was the improper venting of the sampler cavity as the bag filled with the sampled water-sediment mixture. In essence, the water in the flooded sampler cavity produces "backpressure" on the filling bag that must be overcome for isokinetic sampling to occur (Sabol and Topping, 2013, eq. 13). Water is vented from the sampler cavity in US D-96-type samplers at three locations as the bag fills with the sampled water-sediment mixture: vent holes located at the top and bottom of the widest part of the sampler body, and a rear vent hole on the bottom of the tail (Davis, 2001). The US D-96-type sampler was designed to utilize Bernoulli's principle so that the reduction in pressure caused by the acceleration of the flow around the sampler body would help purge the water from the flooded sampler cavity through the top and bottom vent holes (Davis, 2001; Sabol and Topping, 2013). In essence, the sampler body acts as half of a Venturi tube. Ideally, water is drawn out of the sampler cavity by this Venturi effect at the proper rate for isokinetic sampling, that is, there is no "backpressure" on the bag as it fills with the sampled water-sediment mixture. Unfortunately, the filling bag progressively blocks these holes, thus requiring the filling bag to "push" more of the water out of the sampler cavity through the rear vent hole over time (Sabol and Topping, 2013). The sampler tray blocks most of the rear vent hole in the standard design of the US D-96-type sampler (Davis, 2001). Sabol and Topping (2013) found in river tests that although the intake efficiency still decreased over time as the bag filled, the intake efficiency was higher when the rear vent hole was effectively enlarged by shortening the sampler tray. Although this improvement in intake efficiency resulted in isokinetic sampling over shorter sampling durations at higher stream velocity, the intake efficiency remained sub-isokinetic at all sampling durations at lower stream velocity (less than ~3.5 feet per second [ft/s]) (Davis, 2001; Sabol and Topping, 2013, fig. 26).

Sabol and Topping (2013) found that, when sub-isokinetic, the US D-96-type sampler oversampled sand in a manner consistent with measurements made during early laboratory experiments used to design isokinetic suspended-sediment samplers (FISP, 1941). Suspended-sand concentrations measured by a US D-96-A1 collapsible-bag sampler were higher than those measured by "rigid-bottle" depth-integrating samplers that were confirmed to be isokinetic, with this positive concentration bias increasing as a function of grain size among the different sand size classes (Sabol and Topping, 2013, fig. 27). Although this positive bias in suspended-sand concentration was not removed, it was reduced by 30 to 60 percent when the intake efficiency of the US D-96-A1 sampler was increased by shortening the sampler tray, thereby effectively enlarging the rear vent hole (Sabol and Topping, 2013).

Purpose and Scope

The purpose and scope of this study were twofold. First, we evaluated whether further enlargement of the rear vent hole would increase the intake efficiency of the US D-96-type sampler and result in isokinetic sampling over a wider range of flow conditions and for longer sampling durations than observed by Sabol and Topping (2013). Second, we compared single-vertical US D-96-A1 samples with depth-averaged, velocity-weighted point samples collected using the isokinetic US P-61-A1 point-integrating sampler. This comparison was conducted to build on the US D-96-A1, US D-74, and US D-77 suspended-sediment data comparisons in Sabol and Topping (2013) to further evaluate the magnitudes of the concentration and grain-size biases in suspended-sediment measurements made using the sub-isokinetic US D-96-type sampler. The purpose and scope of this report is to present the results from these two field investigations.

Study Sites

Sampler tests were conducted on the Colorado River in Arizona, at three locations chosen for the differences between their velocity and sediment characteristics (fig. 1). These locations were (1) the cableway at the Colorado River at Lees Ferry, Arizona, 09380000 gaging station, herein referred to as the "Lees Ferry cableway;" (2) a temporary tagline located 0.5 mile (mi) downstream from Fall Creek and 2.3 mi upstream from the Lees Ferry cableway, herein referred to as the "Fall Creek tagline;" and (3) the cableway at the Colorado River above Diamond Creek near Peach Springs, Arizona, 09404200 gaging station, herein referred to as the "Diamond Creek cableway."

Methods

The US D-96-type collapsible-bag sampler is manufactured by the FISP in two models that differ only in weight. The US D-96 sampler is the heavier 130-pound (lb) version (Davis, 2001), and the US D-96-A1 sampler is the lighter 80-lb version (FISP, 2003). This weight difference was achieved by changing the metals used to construct the various parts of the sampler without changing the geometry of any part of the sampler; thus, the US D-96 and US D-96-A1 samplers are dimensionally identical (FISP, 2003). Although the drift angle is much greater for the lighter US D-96-A1 sampler (FISP, 2003), the US D-96 and US D-96-A1 samplers both collect suspended-sediment samples in an identical manner. We therefore carried out our field investigations using the lighter and easier-to-deploy US D-96-A1 sampler within its 2- to 6-ft/s permitted range in stream velocity (FISP, 2003). To build

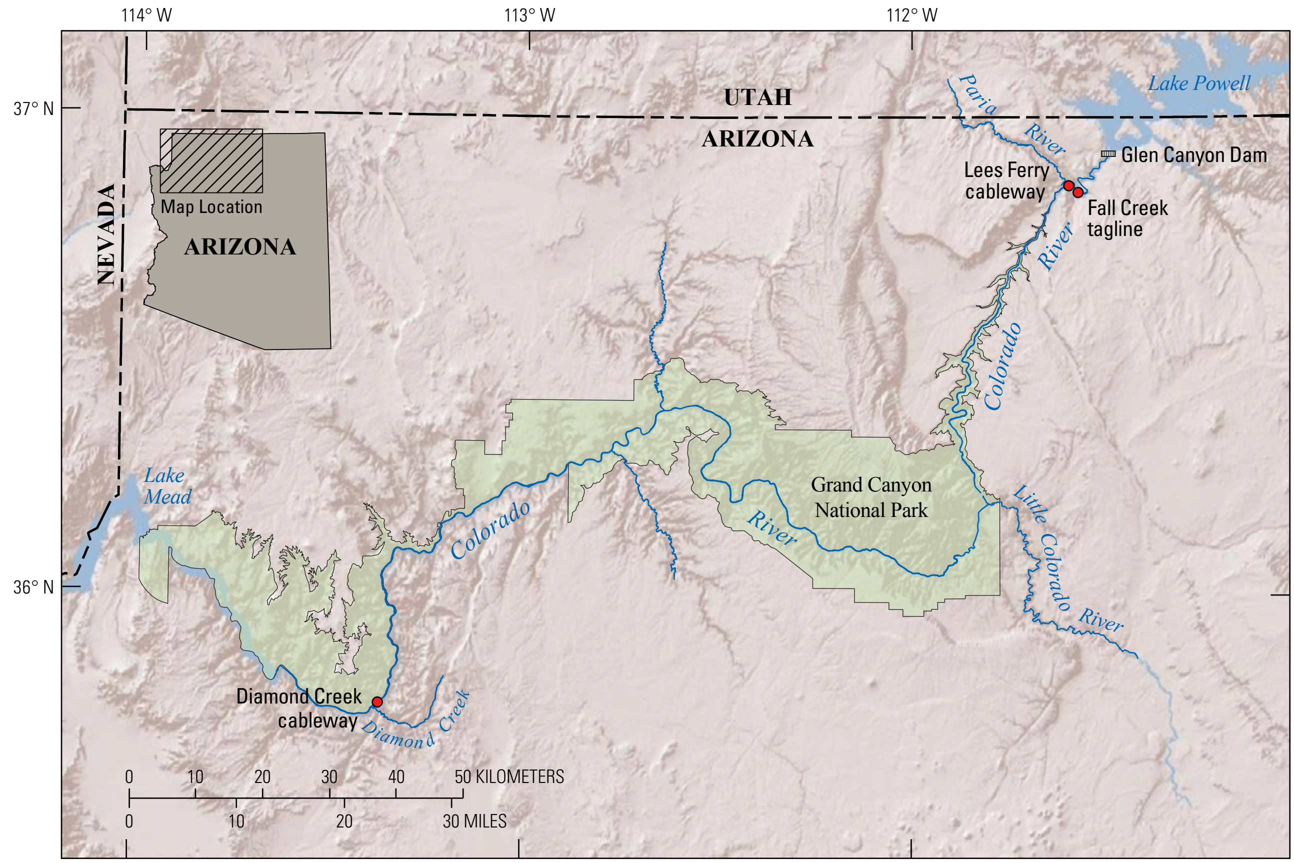

Figure 1. Map showing the locations of the three study sites on the Colorado River in Arizona: (1) Lees Ferry cableway; (2) Fall Creek tagline, and (3) Diamond Creek cableway.

on the earlier results of Sabol and Topping (2013), all tests were carried out using a sampler tray 4 centimeters (cm) (1.6 inches [in.]) shorter than the standard sampler tray that largely blocks the rear vent hole. Standard 3-liter (L) (183.1 cubic inch [in^3]) US D-96 sampler bags were used in all tests. The same nozzle holder and 1/4-in. diameter white plastic (not Teflon) nozzle were used in all tests to avoid variations in intake efficiency arising from small variations in the nozzle and nozzle holder during the manufacturing process (Davis, 2001). Two US D-96-A1 samplers were used: a "control sampler" that was not modified, and a "test sampler" that was modified by incrementally enlarging the rear vent hole. Baseline intake efficiencies were measured for each sampler before modifications were made to the rear vent hole in the test sampler. The control and the test samplers were paired with their own nose and sampler-tray assembly; these pairings remained consistent throughout the study. Because the intake efficiency of the US D-96-A1 sampler decreases as sampling duration and sample volume increases (Sabol and Topping, 2013), we collected similar sample volumes (over similar durations) among each series of tests to avoid this complication.

Measurements of depth- and time-averaged stream velocity were made concurrent with the operation of the US D-96-A1 control and test samplers using a Teledyne RD Instruments Workhorse Rio Grande 600 kilohertz (kHz) acoustic-Doppler current profiler (ADCP) (https://www.comm-tec.com/Prods/mfgs/RDI/brochures/rio_grande_ds_lr.pdf). Standard ADCP instrument configurations were used, and standard pre-measurement tests were conducted at the beginning of each ADCP deployment (Mueller and others, 2013). A manual input command of two bottom track pings per ensemble (BP2) was maintained throughout. Moving-bed tests were conducted prior to collecting stream velocity data with the ADCP to ensure that the measured stream velocities were accurate. The ADCP collected approximately one velocity data ensemble for every second the US D-96-A1 sampler was deployed. The ADCP was mounted to the gunwale of a 15-ft-long motorized V-hull aluminum boat approximately 4 ft off the centerline (Sabol and Topping, 2013, fig. 6). By this geometry, the ADCP velocity measurements were made 4 ft to the side and slightly downstream from the measurements made with the US D-96-A1 sampler. Previous work at other tagline cross sections on the Colorado River using this same boat setup, with the addition of positional data collected by a Global Positioning System, demonstrated that this method of positioning produces small variations in boat motion within ±3 to 6 ft, with total distances traveled of less than 3 ft. This method of positioning, relative to a fixed reference point along a tagline or cableway, is not likely to cause bias in the velocity measurements collected with boat-mounted ADCPs (Gartner and Ganju, 2007; Sabol and others, 2010; Sabol and Topping, 2013).

Both US D-96-A1 depth-integrating and US P-61-A1 point-integrating samplers were used in this study (FISP, 2003; Edwards and Glysson, 1999). All suspended-sediment samplers were deployed following the general operating instructions outlined by the FISP (Davis, 2001; FISP, 2007, 2015) and subsequent recommendations made both by Sabol and Topping (2013), as well as in the U.S. Geological Survey (USGS) Office of Surface Water Technical Memorandum 2013.03 (USGS, 2013). Depending on the study site, the suspended-sediment samplers used in these tests were deployed from either the boat or from a cableway. The suspended-sediment samplers were deployed from the boat using a B-56 sounding reel attached to a bow-mounted crane or from a cableway using a B-56 reel mounted to a cable car. At each study site, the location of the sampling vertical for these tests was chosen at a point along the tagline or cableway cross section where the flow was oriented downstream, relatively uniform, and had normal levels of turbulence (Rantz and others, 1982; Mueller and others, 2013). Each sampling vertical was marked by a weighted target suspended from the tagline or cableway, approximately 8 ft above the water surface. During data collection, the tip of the crane boom was positioned under the suspended target to maintain precise stationary boat position throughout the duration of each individual test.

The ADCP model used in this study was standard and had four beams that diverged from nadir at an angle of 20 degrees. ADCPs use the Doppler effect to measure the velocity along each beam and then trigonometry to estimate the time-averaged stream velocity in cells of finite dimension (not at points) at different depths directly below the ADCP; they do not directly measure stream velocity at points along the nadir (Mueller and others, 2013). Owing to turbulence, substantial fluctuations in velocity occur at all points in the flow over sub-minute timescales. Because standard ADCPs do not measure all components of the instantaneous velocity at a point, they cannot be used to measure stream velocities at the points sampled by point samplers over the sub-minute timescales typically sampled by point samplers (Topping and others, 2011). ADCPs do, however, provide a means of making accurate depth- and time-averaged measurements of stream velocity within the "cone" defined by the four diverging beams. Therefore, ADCPs can easily be used to evaluate the intake efficiency of depth-integrating samplers but not point-integrating samplers. Therefore, we used the ADCP measurements to measure only the depth-averaged stream velocity over the duration sampled by the US D-96-A1 sampler. Because the lateral spatial change in depth- and time-averaged stream velocity at our study sites was typically negligible over distances much less than 10 ft, the small lateral offset between the sampling vertical and the ADCP required by our boat geometry did not introduce a substantial bias in our results.

Lees Ferry Cableway

Testing at the Lees Ferry cableway and Fall Creek tagline study sites was for US D-96-A1 intake efficiency only; suspended-sediment data were not collected at these sites. The procedure used at both study sites was as follows: each single-vertical intake-efficiency test with the control and modified test versions of the US D-96-A1 sampler consisted of lowering the sampler to the bed of the river at a constant transit rate and then, without pausing at the bed, raising the sampler back to the surface at the same transit rate. For each test (1) the depth was recorded from the depth indicator on the B-56 reel; (2) the transit time was recorded with a stopwatch to the tenth of a second; (3) the transit rate was kept consistent using the audio US VTP-99 vertical transit-rate pacer (https://water.usgs.gov/fisp/products/4110032.html); (4) the mass of each sample was measured using a digital scale accurate to 0.5 grams (g), and recorded masses were converted to volume using the standard density of fresh water (1 kilogram per liter [kg/L]); (5) the sampled volume of the water-sediment mixture, the cross-sectional area of the nozzle, and the transit time were together used to calculate the depth-averaged nozzle velocity; and (6) the depth-averaged nozzle velocity was divided by the concurrent ADCP-measured depth-averaged stream velocity to determine the sampler intake efficiency (eq. 1).

The sampling vertical at Lees Ferry cableway was located approximately 215 ft from the left edge of water in the 410-ft-wide cross section; by convention, left and right edges of water are referenced to an observer looking downstream. On March 20, 2019, we carried out an initial baseline comparison between the control sampler and the test sampler before it was modified. This baseline comparison consisted of a sequence of 10 intake-efficiency tests with the unmodified test sampler followed by 10 tests using the control sampler.

Testing using the incrementally modified test sampler occurred on March 21, 2019. With the aid of a jig to allow consistent and repeatable cuts along the conical tail of the test sampler, the area of the sampler-cavity rear vent hole was incrementally enlarged. During this process, the depth and width of the vent hole was measured using a digital caliper with a resolution of 0.0005 in. and an accuracy of ±0.001 in. The initial depth of the factory-manufactured vent hole was 0.295 in., and the width was 0.528 in. (fig. 2). For the first three modifications made to the test sampler, the goal was to increase the depth of the vent hole while keeping the width nearly constant. These conditions were achieved by using a router with a 1/2-in.-diameter straight bit to increase the depth of the vent hole; note that the width of the vent hole did increase slightly between the second- and third-modification versions of the sampler (table 1). After each modification, a series of 3 to 7 single-vertical sampler tests were conducted to measure the effect the change in vent-hole area had on sampler intake efficiency. Over the course of three testing iterations, the depth was incrementally increased to 1.057 in., and the width increased slightly to 0.536 in. For the fourth, and final, modification made to the test sampler, the area of the rear vent hole was increased by increasing both the depth and width of the vent hole. This final modification was achieved by using a 3/4-in.-diameter straight bit, producing a cut to a depth of 1.162 in., with a width of 0.756 in. (fig. 2, table 1).

Fall Creek Tagline

The Fall Creek tagline was selected as a study site auxiliary to the Lees Ferry cableway for testing sampler intake efficiency because the stream velocity at the Fall Creek location was over two times greater than at the Lees Ferry cableway. The sampling vertical at the Fall Creek tagline was located ~50 ft from the right edge of water in the 320-ft-wide cross section. On May 9, 2019, a series of 5 single-vertical intake-efficiency tests were conducted using the control sampler, followed by a series of 5 single-vertical intake-efficiency tests using the final fourth-modification version of the test sampler.

Diamond Creek Cableway

Intake-efficiency and suspended-sediment data were collected at the Diamond Creek cableway on three sampling trips (December 19, 2018; April 2, 2019; and May 24, 2019). The sampling vertical was located at the 105-ft cableway station on both December 19, 2018, and May 24, 2019, and the sampling vertical was located at the 125-ft cableway station on April 2, 2019; stations at this site are measured from the left-bank endpoint of the cableway. Water discharge varied only slightly during the three sampling tests: (1) increasing from 13,500 to 14,100 cubic feet per second (ft^3/s) during sample collection on December 19, 2018; (2) increasing from 13,200 to 13,700 ft^3/s during sample collection on April 2, 2019; and (3) staying nearly constant (varying between 14,500 and 14,700 ft^3/s) during sample collection on May 24, 2019. All suspended-sediment data collected at the Diamond

Table 1. Summary of modifications to the rear vent hole in the US D-96-A1 test sampler at the Lees Ferry cableway.

[Date in month/day/year format. in., inch; in^2, square inch]

Date	Test-sampler modification	Depth of rear vent hole (in.)	Width of rear vent hole (in.)	Area of rear vent hole (in^2)	Percent increase in area of rear vent hole
3/21/2019	Unmodified	0.295	0.528	0.156	0.0
3/21/2019	1	0.427	0.528	0.225	44.2
3/21/2019	2	0.687	0.528	0.363	133
3/21/2019	3	1.057	0.536	0.567	263
3/21/2019	4	1.162	0.756	0.878	463

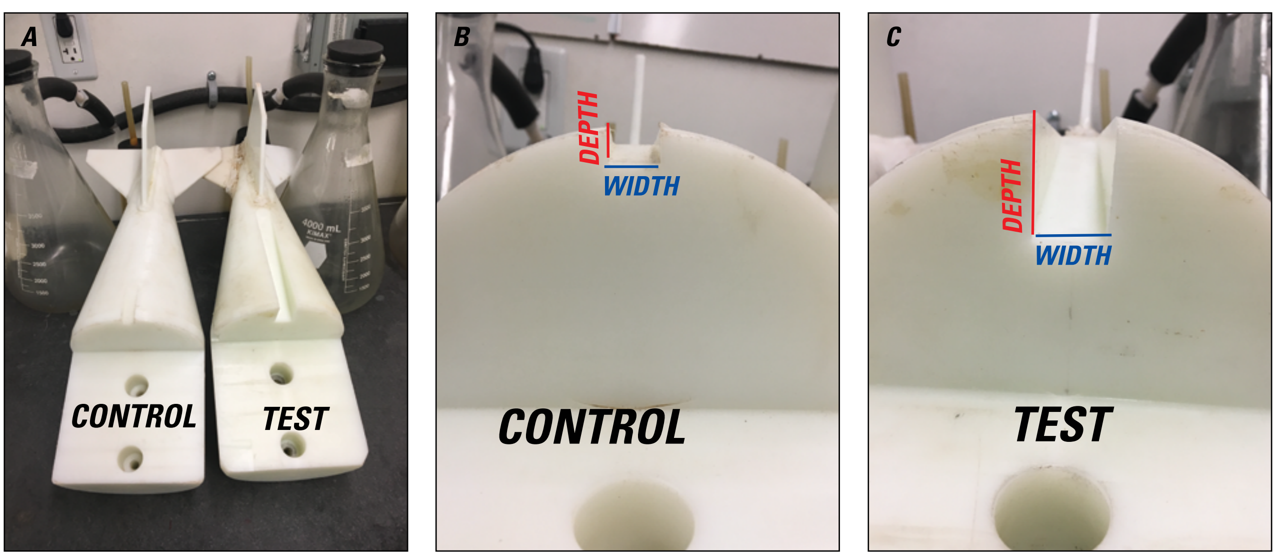

Figure 2. Photographs of the polyethylene tails from the US D-96-A1 control and test samplers. *A*, Polyethylene (HDPE) tails from the control sampler and the final fourth-modification version of the test sampler. *B*, *C*, Close-up cross-sectional views of the control (*B*) and test (*C*) sampler tails in *A* show how the area of the rear vent hole was enlarged in the test sampler.

Creek cableway for this study are available from the USGS at https://www.gcmrc.gov/discharge_qw_sediment/station/GCDAMP/09404200.

On May 24, 2019, intake-efficiency tests were carried out to determine whether the differences and (or) similarities observed in the intake efficiencies between the control and final fourth-modification version of the test sampler at the Lees Ferry cableway and Fall Creek tagline also occurred at the Diamond Creek cableway. These tests consisted of 5 single-vertical samples collected using the final version (modification 4) of the test sampler followed by 5 single-vertical samples collected using the control sampler. Because they were collected under similar flow conditions at the same sampling vertical, these 10 samples were analyzed in combination with the 2 single-vertical samples collected using the control sampler on December 19, 2018. In addition to being used to compute intake efficiencies, these samples were analyzed for suspended-sediment concentration and grain size to determine whether there were any differences in the suspended-sediment data collected using these two versions of the US D-96-A1 sampler. To facilitate the intake-efficiency tests, concurrent ADCP velocity measurements were made from the boat as the samples were collected from the cableway.

Earlier tests at other gaging stations on the Colorado River indicated that the sub-isokinetic US D-96-A1 sampler oversampled sand relative to other depth-integrating samplers that were confirmed to be isokinetic at these stations (Sabol and Topping, 2013). Furthermore, the US D-96-A1 sampler oversampled sand relative to these isokinetic samplers in the manner expected based on the FISP (1941) laboratory experiments, that is, the oversampling of sand increased with grain size (Sabol and Topping, 2013, fig. 27). These earlier tests were carried out with both standard-length-tray and shorter-tray versions of the US D-96-A1 sampler, and US D-74 and US D-77 rigid-bottle depth-integrating samplers. These tests showed that use of the shorter-tray version of the US D-96-A1 sampler reduced the sand oversampling by ~50 percent, that is, from about +6 to +3 percent; the shorter-tray version of the US D-96-A1 sampler used in these earlier tests is the control version of the US D-96-A1 sampler used in the present study. We carried out new tests for this study at the Diamond Creek cableway on December 19, 2018, and April 2, 2019, to further evaluate the suspended-sediment sampling behavior of the US D-96-A1 sampler. These new tests used the control version of the US D-96-A1 sampler and the isokinetic US P-61-A1 point-integrating sampler. On each day of these tests, 18 total US P-61-A1 point samples were collected at 6 discrete depths (that is, 3 at each depth) immediately bracketed by 2 single-vertical depth-integrated US D-96-A1 samples. ADCP velocity measurements from the boat were used to determine the intake efficiency of the control version of the US D-96-A1 sampler on December 19, 2018, but not on April 2, 2019.

ADCP measurements were not made to confirm whether the US P-61-A1 point-integrating sampler sampled isokinetically owing to the following: (1) the previously described impossibility of using an ADCP to measure the velocity at the exact point and time sampled by a point-integrating sampler, and (2) the underlying design of the US P-61-A1 sampler having been proven to sample isokinetically. Extensive tests conducted on the precursor of the US P-61-A1 sampler, the functionally identical US P-46 point-integrating sampler, indicate that the design of the US P-61-A1 sampler is isokinetic (FISP, 1951). In particular, the mean intake efficiency of the US P-46 sampler using the standard 3/16-in.-diameter nozzle was found to be 0.98 among 56 current-meter tests conducted at points distributed throughout the entire flow depth in the Colorado River between May 30 and June 6, 1947 (FISP, 1951). In these tests, the nozzle velocities at a point differed from the stream velocities measured by current meters at the same point within ~1 hour within a range of only −10.0 to +4.2 percent (FISP, 1951). Subsequent comparisons in the Colorado River in 1996 between nozzle and current-meter measurements of velocity provide further confirmation that the design of the US P-61-A1 point-integrating sampler is isokinetic (Topping and others, 2007); these tests used a US P-61 point-integrating sampler (the pint-bottle version of the quart-bottle US P-61-A1 sampler). In both the 1947 and 1996 comparisons, the larger scatter in the nozzle velocity measurements arose because only the current-meter velocity measurements were made over durations longer than the timescales of the turbulent velocity fluctuations (Topping and others, 2011).

To allow direct comparison with the velocity-weighted suspended-sediment data collected by the US D-96-A1 sampler, the data collected using the US P-61-A1 sampler were converted to depth-averaged velocity-weighted values using a 4-step process: (1) the stream velocity associated with each US P-61-A1 point sample was calculated by assuming isokinetic sampling and using the sampled volume of the water-sediment mixture, the cross-sectional area of the nozzle, and the sampling duration; (2) the velocity-weighted silt-and-clay and sand concentrations in each point sample were then calculated by multiplying the measured concentrations by the velocities from step one and dividing by the depth-averaged velocity calculated among the 18 US P-61-A1 samples collected at the sampling vertical; (3) the velocity-weighted concentrations were averaged among the 3 point samples collected at each of the 6 elevations in the flow; and (4) these average values were integrated over the depth range that was sampled (from ~1.6 ft above the bed to ~1.1 ft below the surface) and then divided by this depth range. The depth-averaged velocity-weighted suspended-sand grain-size distribution was calculated for each set of 18 US P-61-A1 samples by using the above 4-step process in each 1/4-ϕ sand size class (after Krumbein, 1934). D_{16}, D_{50}, and D_{84} values were then extracted from this velocity-weighted grain-size distribution. By standard convention, D is the grain diameter in millimeters, and the subscripts on D indicate the cumulative percentage in the grain-size distribution of a given grain-size D in a coarsening sense.

Results

US D-96-A1 Baseline Intake-Efficiency Tests Conducted Prior to Test Sampler Modification—Lees Ferry Cableway

Baseline tests of the US D-96-A1 control and unmodified test samplers show that both samplers sampled identically and sub-isokinetically, with mean intake efficiencies of 0.67 and 0.66 respectively (table 2). Previous work has shown a progressive decrease in the intake efficiency of collapsible-bag depth-integrating suspended-sediment samplers when velocities drop below ~3.5 ft/s (Davis, 2001; Sabol and Topping, 2013). Given the relatively low velocity conditions at the Lees Ferry cableway, the sub-isokinetic performance of both versions of the US D-96-A1 sampler is expected; the mean depth-averaged stream velocity among these tests was only 2.43 ft/s (table 2). Variance-ratio F-tests using the methods of Griffiths (1967, p. 453–455) were conducted to determine if there was a significant difference in the relation between depth-averaged stream velocity and nozzle velocity between the control and unmodified test samplers. To remove intercorrelation between the dependent and independent variables, nozzle velocity was used as the dependent variable instead of intake efficiency. These F-tests determine the level of significance (p) at which the variance about multiple linear regressions is less than the variance about a single linear regression, thus indicating the level of significance at which multiple relations fit the data better than a single relation. These tests were also used to determine the significance at which multiple relations better fit the nozzle-velocity measurements rather than a single relation in the following "Iterative Intake-Efficiency Tests of the Incrementally Modified US D-96-A1 Test Sampler—Lees Ferry Cableway" section of this report. Variance-ratio F-tests yielding values of $p>0.05$ thus indicate no significant difference in the relations between depth-averaged stream and nozzle velocity, and thus no significant difference in the intake efficiencies, between the samplers with different rear-vent-hole areas. No significant difference in the relations between stream and nozzle velocity for the control and unmodified test sampler was

Table 2. Results from baseline intake-efficiency tests of the US D-96-A1 control sampler and the unmodified test sampler at the Lees Ferry cableway.

[Date given in month/day/year format. MST, mountain standard time (24-hour format); in^2, square inch; ft/s, foot per second; s, second; in^3, cubic inch; ft, foot; in., inch]

Time on 3/20/2019 (MST)	Sampler type	Area of rear vent hole (in^2)	Depth-averaged stream velocity (ft/s)	Sample duration (s)	Sample volume (in^3)	Maximum depth sampled (ft)	Nozzle diameter (in.)	Depth-averaged nozzle velocity (ft/s)	Intake efficiency
15:02	control	0.156	2.42	33.4	32.8	18.5	1/4	1.67	0.69
15:06	control	0.156	2.48	33.6	31.2	18.5	1/4	1.58	0.63
15:09	control	0.156	2.30	34.0	34.2	18.5	1/4	1.71	0.74
15:11	control	0.156	2.32	32.6	31.1	18.5	1/4	1.62	0.70
15:14	control	0.156	2.43	32.8	32.7	18.5	1/4	1.69	0.70
15:16	control	0.156	2.30	33.6	31.0	18.5	1/4	1.57	0.68
15:19	control	0.156	2.16	32.4	26.0	18.5	1/4	1.36	0.63
15:22	control	0.156	2.34	35.2	29.9	18.5	1/4	1.44	0.62
15:25	control	0.156	2.35	33.5	30.7	18.5	1/4	1.56	0.66
15:28	control	0.156	2.24	33.3	30.9	18.5	1/4	1.58	0.70
	Mean depth-averaged stream velocity		**2.33**				**Mean intake efficiency**		**0.67**
14:23	test	0.156	2.81	32.5	37.1	18.5	1/4	1.94	0.69
14:27	test	0.156	2.39	33.0	35.4	18.5	1/4	1.82	0.76
14:30	test	0.156	2.40	33.3	32.4	18.5	1/4	1.65	0.69
14:33	test	0.156	2.44	34.8	29.2	18.5	1/4	1.43	0.59
14:35	test	0.156	2.45	32.9	31.7	18.5	1/4	1.63	0.67
14:38	test	0.156	2.64	31.5	32.2	18.5	1/4	1.74	0.66
14:42	test	0.156	2.77	31.8	32.7	18.5	1/4	1.75	0.63
14:44	test	0.156	2.51	32.8	32.6	18.5	1/4	1.69	0.67
14:47	test	0.156	2.43	33.6	33.2	18.5	1/4	1.68	0.69
14:50	test	0.156	2.43	32.8	28.1	18.5	1/4	1.45	0.60
	Mean depth-averaged stream velocity		**2.53**				**Mean intake efficiency**		**0.66**
	Mean depth-averaged stream velocity (control and test samplers)		**2.43**						

found among the data collected on March 20, 2019, at the Lees Ferry cableway ($F_{1,16}$=0.071, p=0.79, fig. 3). The subscripts 1 and 16 on F indicate the degrees of freedom in the numerator and denominator of the F ratio, respectively. This result indicates that US D-96-A1 samplers using the shorter-tray design but different "off the shelf" tails from the FISP should sample identically.

Iterative Intake-Efficiency Tests of the Incrementally Modified US D-96-A1 Test Sampler—Lees Ferry Cableway

Results from the iterative intake-efficiency tests at the Lees Ferry cableway indicate that the incremental physical enlargement of the rear vent hole in the US D-96-A1 test sampler produced no detectable improvement in intake efficiency (table 3). No improvement occurred despite that, by after the fourth and final modification, the area of the rear vent hole had ultimately been enlarged by 463 percent (table 1). The mean intake efficiency among each of the four modified versions of the test sampler varied from only 0.62 to 0.69, with an overall mean of 0.66 among the 17 individual tests, statistically indistinguishable by Student's t-test (p=0.92) from the 0.66 mean intake efficiency of the unmodified test sampler (table 2). These intake efficiencies are directly comparable because the mean depth-averaged stream velocities were similar among the data collected with the unmodified test sampler on March 20, 2019 (that is, 2.53 ft/s, table 2), and among the data collected during the incremental modifications to this sampler on March 21, 2019 (that is, 2.58 ft/s, table 3). As in the case of the baseline tests in the previous section, variance-ratio F-tests indicate that regressions of nozzle velocity on stream velocity for each of the 4 modifications (4 individual relations) did not result in significantly less variance than a common regression fit to the data among all 17 modification tests ($F_{3,9}$=2.3, p=0.15).

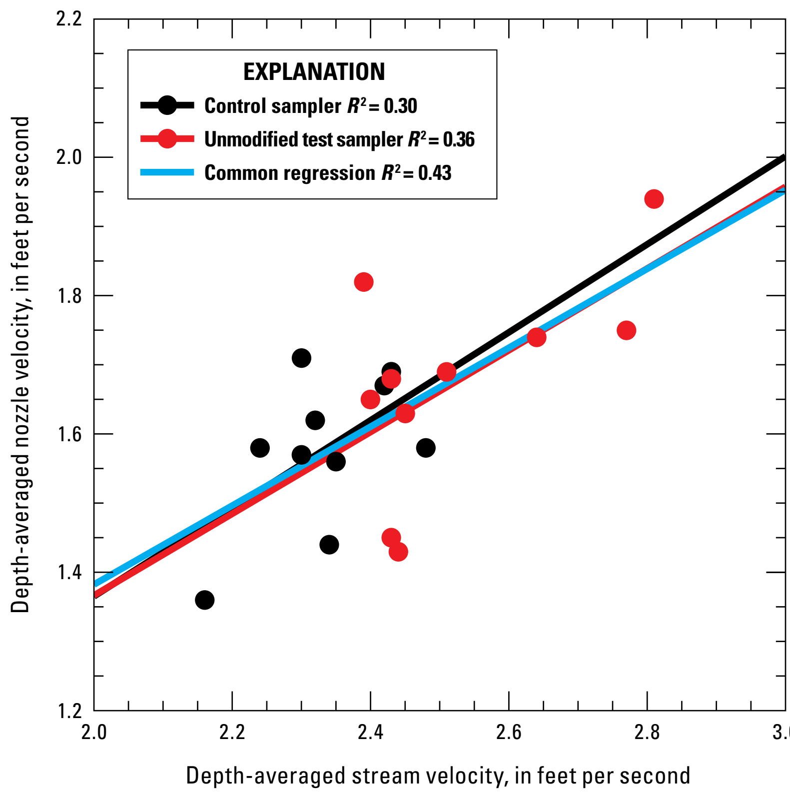

Figure 3. Depth-averaged nozzle velocities for the US D-96-A1 control sampler and unmodified test sampler plotted as a function of depth-averaged stream velocity; measurements made at the Lees Ferry cableway, on March 20, 2019. Shown with their respective R^2 values (their coefficients of determination) are the least-squares linear regressions fit to the control-sampler nozzle velocities, unmodified-test-sampler nozzle velocities, and the common regression line fit to both the control-sampler and unmodified-test-sampler nozzle velocities. Variance-ratio F-tests indicate that a common regression fits the data better than two different regressions fit to the control and unmodified-test sampler nozzle velocities. Velocities associated with the unmodified test sampler are, on average, higher than those associated with the control sampler because discharge was decreasing in the river during data collection, and the test-sampler data were collected before the control-sampler data (table 2).

Table 3. Results from the iterative intake-efficiency tests of the incrementally modified US D-96-A1 test sampler at the Lees Ferry cableway.

[Date given in month/day/year format. MST, mountain standard time (24-hour format); in^2, square inch; ft/s, foot per second; s, second; in^3, cubic inch; ft, foot; in., inch. See table 1 for a summary of rear-vent-hole modifications]

Time on 3/21/2019 (MST)	Sampler modification	Area of rear vent hole (in^2)	Depth-averaged stream velocity (ft/s)	Sample duration (s)	Sample volume (in^3)	Maximum depth sampled (ft)	Nozzle diameter (in.)	Depth-averaged nozzle velocity (ft/s)	Intake efficiency
14:08	1	0.225	2.54	36.2	35.6	18.5	1/4	1.67	0.66
14:11	1	0.225	2.58	37.0	39.7	18.5	1/4	1.82	0.71
14:14	1	0.225	2.67	36.9	43.8	18.5	1/4	2.01	0.75
14:17	1	0.225	2.71	36.8	40.9	18.5	1/4	1.89	0.70
14:20	1	0.225	2.79	37.8	42.0	18.5	1/4	1.89	0.68
14:24	1	0.225	2.78	37.6	40.8	18.5	1/4	1.84	0.66
14:26	1	0.225	2.64	36.8	39.1	18.5	1/4	1.80	0.68
							Mean intake efficiency		**0.69**
15:24	2	0.363	2.51	36.7	36.9	18.5	1/4	1.71	0.68
15:27	2	0.363	2.51	37.1	33.0	18.5	1/4	1.51	0.60
15:30	2	0.363	2.54	37.9	39.1	18.5	1/4	1.75	0.69
15:33	2	0.363	2.52	37.6	37.1	18.5	1/4	1.68	0.67
							Mean intake efficiency		**0.66**
16:32	3	0.567	2.52	37.5	37.0	18.5	1/4	1.68	0.67
16:35	3	0.567	2.40	37.4	29.3	18.5	1/4	1.33	0.55
16:37	3	0.567	2.44	37.2	33.6	18.5	1/4	1.53	0.63
							Mean intake efficiency		**0.62**
17:31	4	0.878	2.55	37.3	34.6	18.5	1/4	1.57	0.62
17:34	4	0.878	2.59	37.1	37.2	18.5	1/4	1.70	0.66
17:36	4	0.878	2.53	37.5	37.4	18.5	1/4	1.69	0.67
							Mean intake efficiency		**0.65**
	Mean depth-averaged stream velocity among all 17 tests		**2.58**				**Mean intake efficiency among all 17 tests**		**0.66**

Intake-Efficiency Tests of the US D-96-A1 Control and Modified Test Samplers—Fall Creek Tagline

Unfortunately, results from intake-efficiency tests at the Fall Creek tagline indicate that the physical enlargement of the rear vent hole in the US D-96-A1 test sampler actually caused a decrease in intake efficiency at this higher-velocity study site (table 4). Mean depth-averaged stream velocity during the Fall Creek testing on May 9, 2019, was 5.68 ft/s (table 4), over twice that measured during the testing at Lees Ferry on March 20 and March 21, 2019 (table 3). The test sampler used at the Fall Creek tagline site was the final fourth-modification version of the test sampler that was used at the Lees Ferry cableway site (table 1, fig. 2). As expected on the basis of the higher stream velocities at Fall Creek, compared to the extremely low stream velocities at Lees Ferry (after Davis, 2011; Sabol and Topping, 2013), the average intake efficiencies for both the control sampler (0.87) and fourth-modification version of the test sampler (0.80) were higher than the 0.66 mean intake efficiency observed among all US D-96-A1 sampler configurations at Lees Ferry (control and modification versions). Because the tests at the Fall Creek tagline were all conducted at similar stream velocities, it was inappropriate to use the variance-ratio F-tests used in the previous sections to evaluate differences in nozzle velocity between the different sampler configurations. We therefore simply used a Student's t-test to evaluate whether the intake efficiency of the fourth-modification version of the test sampler was different than the intake efficiency of the control sampler at this study site. This test yielded a p-value of 0.0090 and therefore indicated that the intake efficiency of the fourth-modification version of the test sampler (0.80) was significantly worse than that of the control sampler (0.87) at the $p=0.05$ critical level. Thus, as in the tests at Lees Ferry, the tests at the Fall Creek tagline do not indicate any improvement in intake efficiency resulting from a physical increase in the area of the rear vent hole beyond the improvement in intake efficiency arising from the effective increase in rear-vent-hole area achieved through use of the shorter tray in the US D-96-A1 sampler (Sabol and Topping, 2013, fig. 26).

Table 4. Results from intake-efficiency tests of the US D-96-A1 control sampler and final fourth-modification version of the US D-96-A1 test sampler at the Fall Creek tagline.

[Date given in month/day/year format. MST, mountain standard time (24-hour format); test mod. 4, final fourth-modification version (see table 1); in^2, square inch; ft/s, foot per second; s, second; in^3, cubic inch; ft, foot; in., inch]

Time on 5/9/2019 (MST)	Sampler type	Area of rear vent hole (in^2)	Depth-averaged stream velocity (ft/s)	Sample duration (s)	Sample volume (in^3)	Maximum depth sampled (ft)	Nozzle diameter (in.)	Depth-averaged nozzle velocity (ft/s)	Intake efficiency
13:35	control	0.156	5.59	27.9	78.7	15.5	1/4	4.79	0.86
13:43	control	0.156	5.58	25.1	72.9	14.0	1/4	4.93	0.88
13:46	control	0.156	5.79	25.2	75.1	14.0	1/4	5.06	0.87
13:49	control	0.156	5.55	25.1	75.7	14.0	1/4	5.12	0.92
13:52	control	0.156	5.77	25.8	72.9	14.0	1/4	4.80	0.83
							Mean intake efficiency		**0.87**
14:21	test mod. 4	0.878	5.62	25.8	67.4	14.0	1/4	4.44	0.79
14:25	test mod. 4	0.878	5.76	25.2	72.1	14.0	1/4	4.85	0.84
14:28	test mod. 4	0.878	5.64	29.3	73.5	15.7	1/4	4.26	0.76
14:32	test mod. 4	0.878	5.69	25.1	69.6	14.0	1/4	4.70	0.83
14:35	test mod. 4	0.878	5.84	26.0	70.5	14.0	1/4	4.60	0.79
							Mean intake efficiency		**0.80**
	Mean depth-averaged stream velocity among all 10 tests		**5.68**						

Intake-Efficiency Tests of the US D-96-A1 Control and Modified Test Samplers—Diamond Creek Cableway

As with the tests conducted at the Lees Ferry cableway and Fall Creek tagline sites, results from intake-efficiency tests at the Diamond Creek cableway study site also indicate that physical enlargement of the rear vent hole in the US D-96-A1 test sampler did not produce improvement in intake efficiency beyond that arising from use of the shorter sampler tray (Sabol and Topping, 2013) (table 5). As at the Fall Creek tagline, the test sampler used at the Diamond Creek cableway was the same test sampler, that is, the final fourth-modification version, used at the Lees Ferry cableway (table 1, fig. 2). Because the tests at the Diamond Creek cableway were all conducted at similar stream velocities (also as at the Fall Creek tagline), it was inappropriate to use the

Table 5. Results from intake-efficiency tests of the US D-96-A1 control sampler and final fourth-modification version of the US D-96-A1 test sampler at the Diamond Creek cableway.

[Date given in month/day/year format. MST, mountain standard time (24-hour format); test mod. 4, final fourth-modification version (see table 1); in^2, square inch; ft/s, foot per second; s, second; in^3, cubic inch; ft, foot; in., inch]

Date and time (MST)	Sampler type	Area of rear vent hole (in^2)	Depth-averaged stream velocity (ft/s)	Sample duration (s)	Sample volume (in^3)	Maximum depth sampled (ft)	Nozzle diameter (in.)	Depth-averaged nozzle velocity (ft/s)	Intake efficiency
12/19/2018; 12:05	control	0.156	4.06	71.3	126.0	27.9	1/4	2.99	0.74
12/19/2018; 13:55	control	0.156	4.42	60.3	137.0	28.8	1/4	3.86	0.87
5/24/2019; 15:12	control	0.156	4.15	58.8	102.6	31.8	1/4	2.96	0.71
5/24/2019; 15:19	control	0.156	4.18	58.9	121.0	31.8	1/4	3.49	0.83
5/24/2019; 15:24	control	0.156	4.14	57.1	121.8	31.8	1/4	3.62	0.88
5/24/2019; 15:29	control	0.156	4.33	57.7	119.8	31.8	1/4	3.53	0.81
5/24/2019; 15:34	control	0.156	4.23	57.0	105.0	31.8	1/4	3.13	0.74
							Mean intake efficiency		**0.80**
5/24/2019; 14:42	test mod. 4	0.878	4.39	54.0	108.4	31.8	1/4	3.41	0.78
5/24/2019; 14:47	test mod. 4	0.878	4.28	56.4	111.0	31.8	1/4	3.34	0.78
5/24/2019; 14:52	test mod. 4	0.878	4.25	58.3	123.4	31.8	1/4	3.59	0.85
5/24/2019; 14:56	test mod. 4	0.878	4.15	57.2	114.2	31.8	1/4	3.39	0.82
5/24/2019; 15:01	test mod. 4	0.878	4.19	56.8	120.4	31.8	1/4	3.60	0.86
							Mean intake efficiency		**0.82**

variance-ratio F-tests used at the Lees Ferry cableway to evaluate differences in nozzle velocity between the different sampler configurations. We therefore used Student's t-tests to evaluate whether the intake efficiency of the fourth-modification version of the test sampler was different than the intake efficiency of the control sampler at this study site. These tests yielded a p-value of 0.51 when only the 10 samples collected on May 24, 2019, were included and yielded a p-value of 0.55 when all 12 samples were included. Thus, the intake efficiency of the fourth-modification version of the test sampler (0.82) was not significantly different than that of the control sampler (0.80) at the $p=0.05$ critical level at the Diamond Creek cableway.

Comparisons of Suspended-Sediment Data Collected Using the US D-96-A1 Control Sampler, US D-96-A1 Modified Test Sampler, and US P-61-A1 Sampler—Diamond Creek Cableway

Suspended-sediment data collected at the Diamond Creek cableway on December 18, 2018, and April 2, 2019, indicate that, despite the sub-isokinetic sampling behavior of the US D-96-A1 sampler, the shorter-tray version of this sampler collected suspended-sediment data that were equivalent to depth-averaged velocity-weighted suspended-sediment data collected using the isokinetic US P-61-A1 sampler (table 6). Among the comparisons between the US D-96-A1 control sampler and US P-61-A1 sampler, the depth-averaged velocity-weighted suspended-silt-and-clay concentrations measured by the US D-96-A1 sampler varied from −6 to +2 percent of those measured by the US P-61-A1 sampler, with a mean difference in measured silt-and-clay concentration between the samplers of only −2 percent. The depth-averaged velocity-weighted suspended-sand concentrations measured by the US D-96-A1 sampler varied from −7 to +9 percent of those measured by the US P-61-A1 sampler, with a mean difference in measured sand concentration between the samplers of only −1 percent. In addition, the suspended-sand grain-size distributions measured by these two samplers were indistinguishable, as indicated by the almost identical values of sand D_{16}, D_{50}, and D_{84} between the paired US D-96-A1 and US P-61-A1 measurements in table 6. This minimal variation in suspended-silt-and-clay and suspended-sand concentration and in the suspended-sand grain-size distribution is well within the natural variability in the suspended sediment in the Colorado River over the hourly timescales required to make these paired measurements with the two samplers (for example, Topping and others, 2011, 2021; Rubin and others, 2020).

These results differ slightly from the results of Sabol and Topping (2013). They found that, despite the shorter-tray version of the US D-96-A1 sampler being closer to isokinetic than the standard-length-tray version of this sampler, the shorter-tray version of the US D-96-A1 still oversampled sand by ~3 percent at an intake efficiency of 0.89 and by ~4 percent at an intake efficiency of 0.74. In addition, they

Table 6. Depth-integrated suspended-silt-and-clay concentration, suspended-sand concentration, and suspended-sand D_{16}, D_{50}, and D_{84} in samples collected using the sub-isokinetic US D-96-A1 control and modified test samplers and isokinetic US P-61-A1 sampler.

[Date given in month/day/year format; MST, mountain standard time (24-hour format); ft, foot; test mod. 4, final fourth-modification version; conc., concentration; mg/L, milligrams per liter; D, grain diameter; mm, millimeter. The subscripts on D indicate the cumulative percentage in the grain-size distribution of a given grain-size D in a coarsening sense]

Date and time (MST)	Cableway station (ft)	Sampler type	Silt and clay conc. (mg/L)	Sand conc. (mg/L)	Sand D_{16} (mm)	Sand D_{50} (mm)	Sand D_{84} (mm)
12/19/2018; 12:05	105	US D-96-A1 control	28.2	86.4	0.080	0.134	0.250
12/19/2018; 12:26–13:18	105	US P-61-A1	29.6	79.3	0.079	0.128	0.219
12/19/2018; 13:55	105	US D-96-A1 control	29.9	76.0	0.078	0.127	0.223
4/02/2019; 08:56	125	US D-96-A1 control	158	60.0	0.074	0.114	0.184
4/02/2019; 09:19–10:29	125	US P-61-A1	168	64.5	0.076	0.119	0.190
4/02/2019; 10:43	125	US D-96-A1 control	171	62.7	0.073	0.110	0.170
5/24/2019; 14:42	105	US D-96-A1 test mod. 4	31.5	61.5	0.079	0.135	0.229
5/24/2019; 14:47	105	US D-96-A1 test mod. 4	36.8	74.3	0.081	0.135	0.221
5/24/2019; 14:52	105	US D-96-A1 test mod. 4	34.8	64.5	0.081	0.137	0.237
5/24/2019; 14:56	105	US D-96-A1 test mod. 4	36.3	88.5	0.084	0.141	0.237
5/24/2019; 15:01	105	US D-96-A1 test mod. 4	30.7	64.2	0.080	0.135	0.245
Median values among the 5 samples collected using the modified test (test mod. 4) sampler			**34.8**	**64.5**	**0.081**	**0.135**	**0.237**
5/24/2019; 15:12	105	US D-96-A1 control	36.5	58.9	0.078	0.124	0.203
5/24/2019; 15:18	105	US D-96-A1 control	33.8	55.9	0.079	0.135	0.266
5/24/2019; 15:24	105	US D-96-A1 control	35.2	70.1	0.083	0.139	0.237
5/24/2019; 15:29	105	US D-96-A1 control	34.1	65.1	0.080	0.133	0.227
5/24/2019; 15:34	105	US D-96-A1 control	34.1	64.5	0.081	0.138	0.244
Median values among the 5 samples collected using the control sampler			**34.1**	**64.5**	**0.080**	**0.135**	**0.237**

found that this oversampling of sand was associated with preferential oversampling of coarser sand, as expected based on FISP (1941). The mean intake efficiencies of the shorter-tray, control version of the US D-96-A1 sampler at the Diamond Creek cableway were 0.81 during the tests on December 18, 2018, and ~0.86 during the tests on April 2, 2019. These intake efficiencies were calculated using the depth-averaged ADCP velocity measurements made concurrently with the US D-96-A1 samples on December 18, 2018, and using the depth-averaged velocity calculated from the US P-61-A1 samples collected on April 2, 2019, because no ADCP measurements were made on that date.[1] Thus, the shorter-tray version of the US D-96-A1 can, but does not always, collect unbiased suspended-sediment data at sub-isokinetic intake efficiencies between ~0.8 and ~0.9.

The most plausible explanation for the nearly identical suspended-sediment data collected by the sub-isokinetic US D-96-A1 sampler and the isokinetic US P-61-A1 sampler is that the US D-96-A1 sampler may sample isokinetically when the water-sediment mixture enters the nozzle, but that the water-sediment mixture only enters the nozzle of the US D-96-A1 sampler intermittently while the sampler transits a sampling vertical. By this explanation, there would be short periods where no sample enters the US D-96-A1 sampler nozzle, thus giving rise to the apparent sub-isokinetic efficiencies calculated using the entire time the sampler is transiting a sampling vertical. These short periods of zero sample collection as the sampler moves through the water column could arise from backpressure in the sampler cavity on the filling bag and (or) the bag temporarily blocking the sampler-cavity vent holes as the bag fills with sample. The shortcoming of this explanation, however, is that it does not explain the slight oversampling of sand by the US D-96-A1 sampler observed by Sabol and Topping (2013) in tests against isokinetic rigid-bottle depth-integrating samplers.

In addition to the US D-96-A1 control sampler collecting data equivalent to those collected by the isokinetic US P-61-A1 sampler at the Diamond Creek cableway, the final fourth-modification version of the US D-96-A1 test sampler collected suspended-sediment data that were equivalent to the suspended-sediment data collected by the US D-96-A1 control sampler (table 6). Thus, not only did the physical enlargement of the rear vent hole not improve the intake efficiency of the shorter-tray version of the US D-96-A1 sampler, it also did not change the sediment-sampling behavior of this sampler. Although some variability was present between the 5 samples collected using the control sampler and the 5 samples collected using the final fourth-modification version of the test sampler, the median values of the silt-and-clay concentration, sand-concentration, sand D_{16}, sand D_{50}, and sand D_{84} measured by these 2 versions of the US D-96-A1 sampler were all virtually identical.

[1]The intake efficiency of ~0.86 on April 2, 2019, is taken as approximate and less certain than the intake efficiency of 0.81 on December 18, 2018, because the depth-averaged velocity calculated on the basis of the US P-61-A1 samples on April 2, 2019, assumed an intake efficiency of 1.0 for those samples, when it likely varied between 0.9 and 1.04 based on FISP (1951).

Conclusions

Previous work has shown that the intake efficiencies of the US D-96 and US D-96-A1 samplers are generally sub-isokinetic, with intake efficiencies that decrease with (1) decreasing depth-averaged stream velocity below ~3.5 ft/s, (2) decreasing water temperature, and (3) increasing sample volume and (or) duration (Sabol and Topping, 2013). As the result of this sub-isokinetic sampling behavior, Sabol and Topping (2013) found that the US D-96-A1 oversampled suspended sand by ~6 percent at two gaging stations on the Colorado River relative to rigid-bottle depth-integrating samplers confirmed to be isokinetic at these stations. Moreover, they found that the intake efficiency of the US D-96-A1 sampler was increased by shortening the sampler tray by 4 cm, effectively enlarging the rear vent hole, thereby reducing the oversampling of suspended sand to only ~3 percent.

Herein, we showed that physical enlargement of the rear vent hole resulted in no improvement in the intake efficiency of the US D-96-A1 sampler relative to that already achieved by shortening the sampler tray. However, despite the intake efficiencies of the control and modified-test US D-96-A1 samplers being sub-isokinetic, we found that the suspended-sediment data collected by the sub-isokinetic US D-96-A1 sampler were equivalent to the data collected by the isokinetic US P-61-A1 sampler. We surmise that the best explanation for this result is that the US D-96-A1 sampler may sample isokinetically when the water-sediment mixture enters the nozzle, but that the water-sediment mixture only enters the nozzle of the US D-96-A1 sampler intermittently while the sampler transits a sampling vertical. This condition would give rise to the apparent sub-isokinetic efficiencies calculated using the entire time a US D-96-A1 sampler is transiting a sampling vertical. This explanation is not fully satisfactory, however, in that it does not explain the slight oversampling of sand by the US D-96-A1 sampler observed by Sabol and Topping (2013) in tests against isokinetic rigid-bottle depth-integrating samplers. Thus, we conclude that the shorter-tray version of the US D-96-A1 sampler described in Sabol and Topping (2013) may collect reasonably accurate suspended-sediment data despite its apparent sub-isokinetic sampling behavior. We suggest, however, that further comparisons of suspended-sediment data collected in other rivers using the US D-96-type sampler with data collected by isokinetic samplers may be warranted to fully understand the sampling behavior of US D-96-type suspended-sediment samplers.

References

Davis, B.E., 2001, The US D-96—An isokinetic suspended-sediment/water-quality collapsible-bag sampler: Vicksburg, Miss., Federal Interagency Sedimentation Project [FISP], Waterways Experiment Station, Report PP, 37 p., https://water.usgs.gov/fisp/docs/Report_PP,_US_D–96_011114_.pdf.

Edwards, T.K., and Glysson, G.D., 1999, Field methods for measurement of fluvial sediment: Techniques of Water-Resources Investigations of the U.S. Geological Survey, book 3, chap. C2, 89 p., https://pubs.usgs.gov/twri/twri3-c2/.

Federal Interagency Sedimentation Project [FISP], 1941, Laboratory investigation of suspended-sediment samplers: Iowa City, Iowa, University of Iowa Hydraulic Laboratory, A Study of the Methods Used in Measurement and Analysis of Sediment Loads in Streams, Report 5, 99 p., https://water.usgs.gov/fisp/docs/Report_5.pdf.

Federal Interagency Sedimentation Project [FISP], 1951, Progress report, field tests on suspended sediment samplers Colorado River at Bright Angel Creek near Grand Canyon, Arizona: Minneapolis, Minn., St. Anthony Falls Hydraulic Laboratory, A Study of the Methods Used in Measurement and Analysis of Sediment Loads in Streams, Report F, 119 p., https://water.usgs.gov/fisp/docs/Report_F.pdf.

Federal Interagency Sedimentation Project [FISP], 2003, The US D-96—An isokinetic suspended-sediment/water-quality collapsible-bag sampler, the US D-96-A1—A lightweight version of the US D-96: Vicksburg, Miss., Waterways Experiment Station, Report PP, Addendum II, 4 p., https://water.usgs.gov/fisp/docs/Report_PP-Addendum_II,_US_D-96_030507_.pdf.

Federal Interagency Sedimentation Project [FISP], 2007, Operating instructions for the US D-96-A1 depth-integrating collapsible bag suspended-sediment sampler: Vicksburg, Miss., Waterways Experiment Station, 13 p., https://water.usgs.gov/fisp/docs/Instructions_US_D-96-A1_030507.pdf.

Federal Interagency Sedimentation Project [FISP], 2015, Operator's manual instructions for the US P-61-A1 point-integrating suspended-sediment sampler: Vicksburg, Miss., Waterways Experiment Station, 14 p., https://water.usgs.gov/fisp/docs/Instructions_US_P-61-A1_030115.pdf.

Gartner, J.W., and Ganju, N.K., 2007, Correcting acoustic Doppler current profiler discharge measurement bias from moving-bed conditions without global positioning during the 2004 Glen Canyon Dam controlled flood on the Colorado River: Limnology and Oceanography Methods, v. 5, no. 6, p. 156–162, https://doi.org/10.4319/lom.2007.5.156.

Gray, J., Glysson, J.D., and Edwards, D.T., 2008, Suspended-sediment samplers and sampling methods, *in* Garcia, M., ed., Sedimentation engineering—Processes, measurements, modeling, and practice: American Society of Civil Engineers [ASCE] Manuals and Reports on Engineering Practice no. 110, p. 320–339, https://doi.org/10.1061/9780784408148.

Griffiths, J.C., 1967, Scientific method in analysis of sediments: New York, McGraw-Hill, 508 p.

Krumbein, W.C., 1934, Size frequency distributions of sediments: Society for Sedimentary Geology [SEPM], Journal of Sedimentary Petrology, v. 4, no. 2, p. 65–77, https://doi.org/10.1306/D4268EB9-2B26-11D7-8648000102C1865D.

Mueller, D.S., Wagner, C.R., Rehmel, M.S., Oberg, K.A., and Rainville, F., 2013, Measuring discharge with acoustic Doppler current profilers from a moving boat (ver. 2.0, December 2013): U.S. Geological Survey Techniques and Methods, book 3, chap. A22, 95 p., https://doi.org/10.3133/tm3A22.

Rantz, S.E., and others, 1982, Measurement and computation of streamflow—Volume 1, Measurement of stage and discharge: U.S. Geological Survey Water-Supply Paper 2175, 284 p., https://doi.org/10.3133/wsp2175.

Rubin, D.M., Buscombe, D., Wright, S.A., Topping, D.J., Grams, P.E., Schmidt, J.C., Hazel, J.E., Jr., , Kaplinski, M.A., and Tusso, R., 2020, Causes of variability in suspended-sand concentration evaluated using measurements in the Colorado River in Grand Canyon: Journal of Geophysical Research: Earth Surface, v. 125, no. 9, 23 p., https://doi.org/10.1029/2019JF005226.

Sabol, T.A., and Topping, D.J., 2013, Evaluation of intake efficiencies and associated sediment-concentration errors in US D-77 bag-type and US D-96-type depth-integrating suspended-sediment samplers: U.S. Geological Survey Scientific Investigations Report 2012–5208, 88 p., https://doi.org/10.3133/sir20125208.

Sabol, T.A., Topping, D.J., and Griffiths, R.E., 2010, Field evaluation of sediment-concentration errors arising from non-isokinetic intake efficiency in depth-integrating suspended-sediment bag samplers, Proceedings of the Joint Federal Interagency Conference on Sedimentation and Hydrologic Modeling, June 27–July 1, 2010, Riviera Hotel, Las Vegas, Nev.: Advisory Committee on Water Information [AWCI], https://acwi.gov/sos/pubs/2ndJFIC/Contents/P23_SABOL_02_23_10.pdf.

Topping, D.J., Grams, P.E., Griffiths, R.E., Dean, D.J., Wright, S.A., and Unema, J.A., 2021, Self-limitation of sand storage in a bedrock-canyon river arising from the interaction of flow and grain size: Journal of Geophysical Research: Earth Surface, v. 126, no. 5, https://doi.org/10.1029/2020JF005565.

Topping, D.J., Rubin, D.M., and Melis, T.S., 2007, Coupled changes in sand grain size and sand transport driven by changes in the upstream supply of sand in the Colorado River: Relative importance of changes in bed-sand grain size and bed-sand area: Sedimentary Geology, v. 202, no. 3, p. 538–561, https://doi.org/10.1016/j.sedgeo.2007.03.016.

Topping, D.J., Rubin, D.M., Wright, S.A., and Melis, T.S., 2011, Field evaluation of the error arising from inadequate time averaging in the standard use of depth-integrating suspended-sediment samplers: U.S. Geological Survey Professional Paper 1774, 95 p., https://doi.org/10.3133/pp1774.

U.S. Geological Survey [USGS], 2013, SW2013.03, WQ201302 Guidelines for FISP bag sampler intake efficiency tests and operational velocities: U.S. Geological Survey, Office of Surface Water, Technical Memorandum 2013.03, 9 p., https://water.usgs.gov/admin/memo/QW/qw2013.02.pdf.

Moffett Field Publishing Service Center
Manuscript approved August 15, 2022
Edited by Regan Austin
Illustration support by Katie Sullivan
Layout by Cory Hurd

Sabol and others—**Field Investigation of Sub-Isokinetic Sampling by the US D-96-Type Suspended-Sediment Sampler**—Open-File Report 2022–1077

ISSN 2331-1258 (online)
https://doi.org/10.3133/ofr20221077