NEW INFORMATION AND GUIDANCE FOR COLLAPSIBLE BAG-TYPE SEDIMENT SAMPLERS

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INTRODUCTION

Answers for many critical water-related issues require solid-phase water-quality data that are representative, accurate, and consistent. Collection of suspended sediment samples for subsequent analyses of solid-phase constituents that represent water-column sediment concentrations requires use of appropriate isokinetic samplers and sampling techniques (Davis, 2005a). Recent review of field and laboratory data indicates that the Federal Interagency Sedimentation Project (FISP) collapsible bag-type sediment samplers may not function isokinetically under certain low velocity and/or low temperature conditions. Updated guidance and operational limits for FISP bag-type samplers were issued in FISP Memorandum 2013.01 (2013). This paper describes new information and guidance for operation of FISP bag-type samplers and ongoing efforts to further characterize the factors that influence bag-type sampler efficiency.

Suspended sediment concentration (SSC) and sediment-associated water-quality constituent concentrations can be highly variable in stream cross sections, particularly when sand-size particles (≥ 0.0625 millimeters (mm)) are suspended in appreciable quantities. Consequently, samples representative of the flow throughout the cross section must be collected using depth- and width-integrated methods and isokinetic samplers (Edwards and Glysson, 1999; Nolan et al., 2005; Gray et al., 2008). Isokinetic sampling means that water enters the nozzle of a sampler without accelerating or decelerating relative to streamflow velocity (ambient velocity) at the locus of the sampler nozzle opening. The measure of isokinetic sampling is the intake efficiency (IE), which is defined as the ratio of the velocity through the nozzle entrance (Vn) to the ambient stream velocity (V); IE = Vn/V, where Vn and V are averaged over the sample collection time and depth for each specific sample. Before a bag sampler is released for field use, the IE is confirmed to be within 0.9<IE<1.1 at velocities of 3–4 feet per second (ft/s) at laboratory water temperature by flume tests conducted at the U.S. Geological Survey Hydrologic Instrumentation Facility (HIF), Stennis Space Center, Mississippi.

The importance of isokinetic sampler function on sampled SSC is illustrated in Figure 1 (Gray et al., 2008). The study on SSC bias with IE was performed in early FISP research using empirical methods and reported in FISP Report No. 5 (1941). These early FISP findings have been validated in preliminary results from new FISP-sponsored research in 2014-15 using computational fluid dynamic modeling. If flow decelerates as it enters the nozzle (IE < 1, sub-isokinetic), the sample SSC will tend to be biased high; conversely, if flow accelerates as it enters the nozzle, and the sample SSC will be biased low. The bias in SSC for the coarsest grade of sand (0.45mm) shown in Figure 1 is approximately +10% for IE=0.75, at a velocity of 5 ft/s. For a theoretical suspended-sediment sample made up of 25% of each of the size classes shown

in Figure 1 (0.01mm, 0.06mm, 0.15mm, 0.45mm) collected in a stream velocity of 5 ft/s, the overall bias for an IE 0.80, 0.75, and 0.50 is 3.5%, 4.9%, and 13.1%, respectively. The errors associated with SSC measurements due to measurement plus analytical error sources vary with concentration and grain-size distribution as well as site conditions at the time of sample collection. However, based on replicate samples, at concentrations above 20 milligrams per liter, differences of +/- 10% are common (Horowitz 2008, Edwards and Glysson, 1999). Although bias error due to non-isokinetic sampling conditions should always be considered and minimized, overall bias errors of less than 5% are much less than the typical SSC uncertainty. Under some field and deployment conditions it may not be possible to collect a sample with 0.75<IE<1.25; in which case it is particularly important to document the IE so that potential bias in sand SSCs can be considered by users of the reported data. For particles finer than sand size (≥ 0.0625 mm) the bias is less than 10%, even at extreme non-isokinetic conditions (see purple– and blue–dashed lines in figure 1). Thus, it is acceptable to sample under non-isokinetic conditions if the sand percentage of SSC has been shown to be negligible in prior analyses of samples collected at that site under similar conditions. In any case, Vn and V should be recorded and the IE calculated with each environmental sampling effort.

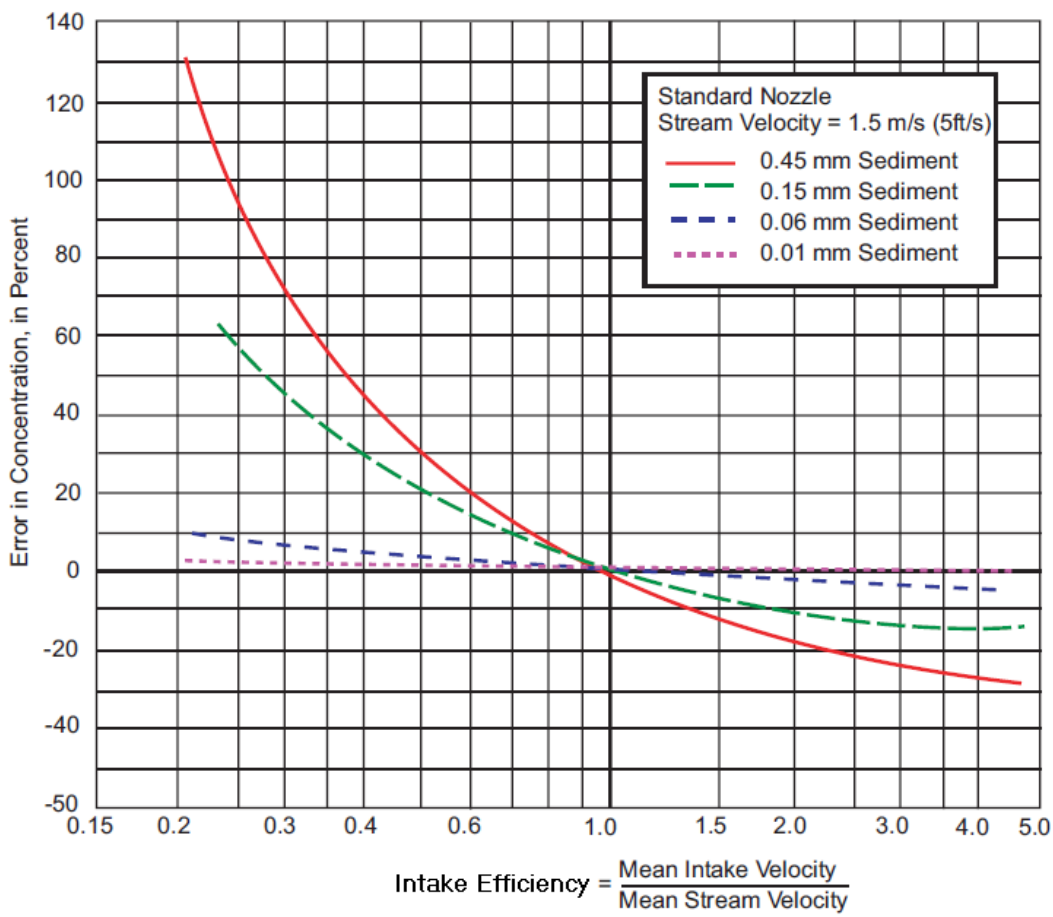

Figure 1 Errors in SSC under variable non-isokinetic sampling conditions for four sediment sizes (0.01mm, 0.06mm, 0.15mm, 0.45mm). Mean velocity of flow in the flume of 5 ft/s was maintained during data collection. Figure from Gray et al. (2008), based on data from FISP Report No. 5 (1941).

Factors that affect the IE of isokinetic samplers include sampler type and nozzle size, ambient stream velocity, water temperature, sampler orientation relative to the flow, and the volume of water collected relative to that of the sample container. IE in bag-type samplers tends to decrease rapidly as stream velocities decrease from about 4 to 2 ft/s, depending on the type of sampler, nozzle size, and stream temperature (Davis, 2001; McGregor 2006; Sabol and Topping, 2013). Because bag-type samplers require ambient velocity in order to fill, the effects of all other IE-related factors tend to increase as velocities approach the minimum recommended operating velocities. Substantial concentrations of sand are not typically in suspension for velocities less than the minimum operational limits of bag-type samplers, and this may mitigate the influence of non-isokinetic sampling on the accuracy of SSCs and sediment-associated water-quality constituent concentrations. Sample volumes should never exceed maximum sample container capacities or IE will decline very rapidly as described by Szalona (1982). Sampling up to full bag capacity did not affect IE in tests conducted in extensive laboratory tests at warm temperatures and in limited field tests in larger rivers (Davis, 2001).

RECENT STUDIES

Recent field studies have indicated problems with intake efficiencies of the US D-96 bag-type sampler. Sabol and Topping (2013) conducted an extensive study of sampling efficiencies of the US D-96 and US D-77 bag-type samplers in the Colorado River within Grand Canyon National Park. The US D-77 bag-type sampler was removed from the list of recommended samplers in 2002 (USGS OWQ Technical Memorandum 2002.09); however the US D-77 bag-type sampler results of Sabol and Topping (2013) are useful in evaluating historical sample data. Selected primary findings of Sabol and Topping (2013, page 64) are:

- Although both the US D-77 and US D-96 bag-type samplers have been proven to sample isokinetically in flumes, typically both sampled sub-isokinetically in field tests on the Colorado River.
- The US D-96 sampler performed closer to isokinetic conditions than the US D-77 bag-type sampler.
- Water temperatures in the field test environment are colder than in FISP laboratory test environment, and affect the sub-isokinetic performance of the samplers; but this is not the dominant effect.
- Intake efficiencies of the US D-77 and US D-96 bag-type samplers are time dependent. IEs decrease over time as sampling duration (and thus sample volume) increases. Intake efficiencies of rigid-container samplers in this environment were found to be constant with time, when recommended procedures were used.
- Analyses of paired, concurrent samples collected in the Colorado River using the US D-96 sampler and two rigid-container samples (tested to be isokinetic) indicate that the US D-96 samples have a positive bias error of +5 to +6 percent in the concentration of particles ≥ 0.0625mm, and this observed bias error is consistent with the observed sub-efficiency of the sampler according to the results from FISP Report No. 5 results shown in Figure 1.

Sabol and Topping (2013) hypothesized that the "most likely physical mechanism responsible for the large time-dependent decreases in intake efficiency observed in the Colorado River tests of both the US D-77 bag-type and US D-96-type samplers is the improper venting of the rear of the sampler cavity." They experimented with increasing the sampler venting by modifying the sampler tray from the standard FISP tray length (16.75 inches (in) long) to a shorter tray length (15.5 in long) and found slight but significant improvements in the US D-96 IE when the shorter tray length was used. In late-February 2013, the FISP tested the standard and shortened trays on a new US D-96 sampler and on a US D-96-A1 sampler that had been used in the field study of Sabol and Topping. The D-96-A1 is dimensionally identical to, but weighs 52 pounds less than, the D-96. The tests were conducted in a 6-foot (ft.) wide by 3-ft. deep, 250-ft. long tilting flume at a stream velocity of 3.31 ft/s (+/- 2%) and water temperatures of 20-22 °C (68-72 °F) at the USGS HIF hydraulics laboratory. A 3-liter (L) sample bag was used in the field and lab studies. While the FISP lab study indicates decreasing IE with increasing sample duration and volume, the IE is within the range of 0.9 to 1.15 for the 5/16 and ¼ in. nozzle sizes; and within 0.85 to 1.0 for the 3/16 in. nozzle size (Figure 2). Comparing the shortened versus the standard tray length, there was no notable difference for the 5/16 in. and ¼ in. nozzle sizes and slight improvement was noted with the shorter tray for the 3/16 in. nozzle (Figure 2). Moreover, the 2013 FISP test results agreed very closely with those from the FISP US D-96 sampler development data (Davis, 2001). Thus, the results of Sabol and Topping (2013) appear to be associated with field conditions that are not being replicated in the laboratory flume environment and may or may not be due to sample cavity venting in those conditions.

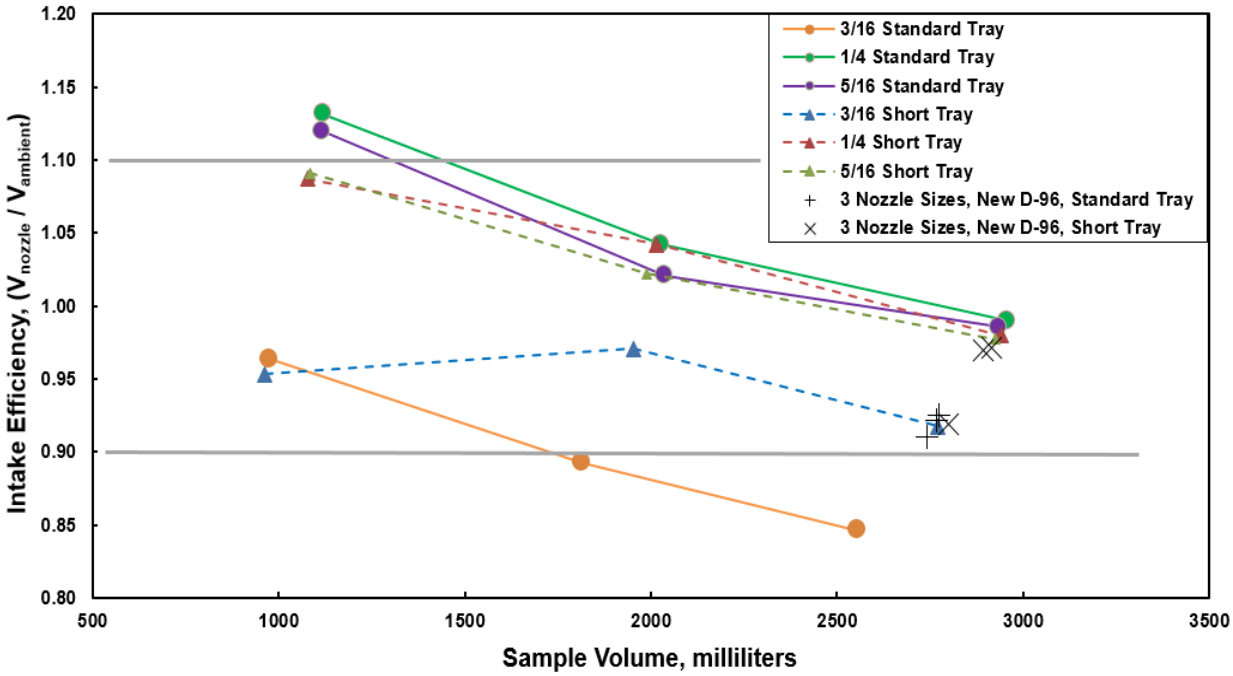

Figure 2 Intake efficiency results for US D-96 bag-type sampler conducted during February, 2013 in the tilting flume located at the USGS Hydrologic Instrumentation Facility. Tests run using standard FISP tray (16.75 in. long) and shortened tray (15.5 in. long) and available nozzle sizes (in inch fractions). For all tests the water velocity is 3.31 ft/s and the temperature is 20-22 C. Each point represents an mean of 5 to 10 measurements.

Additional field studies are being conducted to evaluate the IE of FISP bag-type samplers. An extensive study of depth-integrated sampling methods was conducted by the USGS Mississippi Water Science Center (Heather Welch, Mike Manning, and Claire Rose, personal communication). Over 240 samples, including replicates for each sampling vertical, were collected on the Mississippi River at Vicksburg, MS during 8 field trips from April 2013 to August 2013, at water temperatures ranging from 13 to 28 ^{o}C (55 to 82 ^{o}F). Velocity was measured concurrently with sample collection using an acoustic Doppler current profiler along with high-accuracy marine GPS technology to control boat movement during sampling. Velocities during normal flows in the sampled reach of the Mississippi River can surge by 1-2 ft/s within a range of 3-9 ft/s over the duration of a sample. The ADCP velocity data, concurrent with each sample, were extensively examined to obtain as accurate a concurrent sample velocity as possible. Both ¼ and 3/16 in. nozzle sizes were used. The mean IE from this data set of 240 samples was 0.81 with a standard deviation of 0.12 and IE was not significantly correlated with sample duration or volume, nozzle size, nor with stream velocity.

Field studies were conducted by the USGS, Arizona Water Science Center (Jessica Anderson and Corey Sannes, personal communication) in Water Year 2014 using US D-96-A1 (3 liter bag), and DH-2 (1 liter bag) samplers on the Colorado River at Lees Ferry, AZ. This study evaluated methods to increase the accuracy of the IE test results by limiting possible errors introduced in the field measurements. A Price-AA meter was mounted atop a D-96A1 sampler and velocity was measured concurrently with an ADCP mounted on a boat next to the sampler for the duration that the sampler was under the water surface. Two of the questions posed in the study design were: (1) Does the method by which the velocity is measured affect the intake efficiency results? and (2) Is there a directional bias either by the meter or the sampler when performing a depth-integrated sample? Tests conducted with the US D-96A1 sampler transiting through the vertical (depth-integrated samples) resulted in a mean IE of 0.70 for nine tests using a Price-AA meter; and a mean IE of 0.63 for thirty-two tests performed using an ADCP to measure velocity. Tests conducted holding the sampler at fixed locations at 2- and 10-foot depths with a ¼ in. nozzle resulted in a mean IE of 0.69 for nineteen tests using a Price-AA meter and an IE of 0.78 for nineteen tests using an ADCP to measure velocity. Tests conducted holding the D-96-A1 sampler at fixed locations at 2- and 10-foot depths with a 5/16 in. nozzle resulted in a mean IE of 0.62 for nine tests using a Price-AA meter and an IE of 0.69 for eleven tests using an ADCP to measure velocity. Velocities measured using the Price-AA (presumed to be more representative of ambient velocity at the locus of the sample nozzle) resulted in lower IE values for these tests; but sample durations did not have a significant effect on the IE results. The DH-2 had a mean IE of 0.89 with a 3/16 in. nozzle and a mean IE of 0.88 with a 1/4 in. nozzle. From all of the tests performed at this site, it was determined that the major variables that seem to affect the IE results in the field are the sampler type and nozzle size. More data needs to be collected with both samplers and with each nozzle size to determine if there is directional bias.

IE is determined, in the field or the laboratory, from measurements of ambient stream velocity (ideally at the locus of the sampler nozzle) and nozzle velocity determined from known nozzle intake area and measured sample volume and duration of sample collection. Any component measurement errors translate directly to errors in the computed IE. In the laboratory these factors

are measured with high accuracy. In field studies, the greatest source of measurement error typically is the stream velocity; and this can be more difficult when measuring from a boat. However, velocity measurement errors are not the likely cause of indicated IE in these field studies because they used detailed and careful evaluation of the velocity measurements and other measured factors. It is also noteworthy that field testing in large rivers and towed-sampler IE tests conducted during development FISP bag-type samplers do not indicate sub-isokinetic performance. The reaches of the Colorado River sampled in the above sited studies are much steeper than those in the large river test areas and in the Mississippi River, resulting in greater shear stress, turbulence, and velocity gradients. These are the likely environmental conditions, in addition to colder temperatures, that result in the sub-isokinetic performance of the bag-type samplers tested, as stated by Sabol and Topping (2013). The sub-isokinetic performance in the above noted studies appear to be due to conditions that do not occur in laboratory testing nor in all riverine conditions.

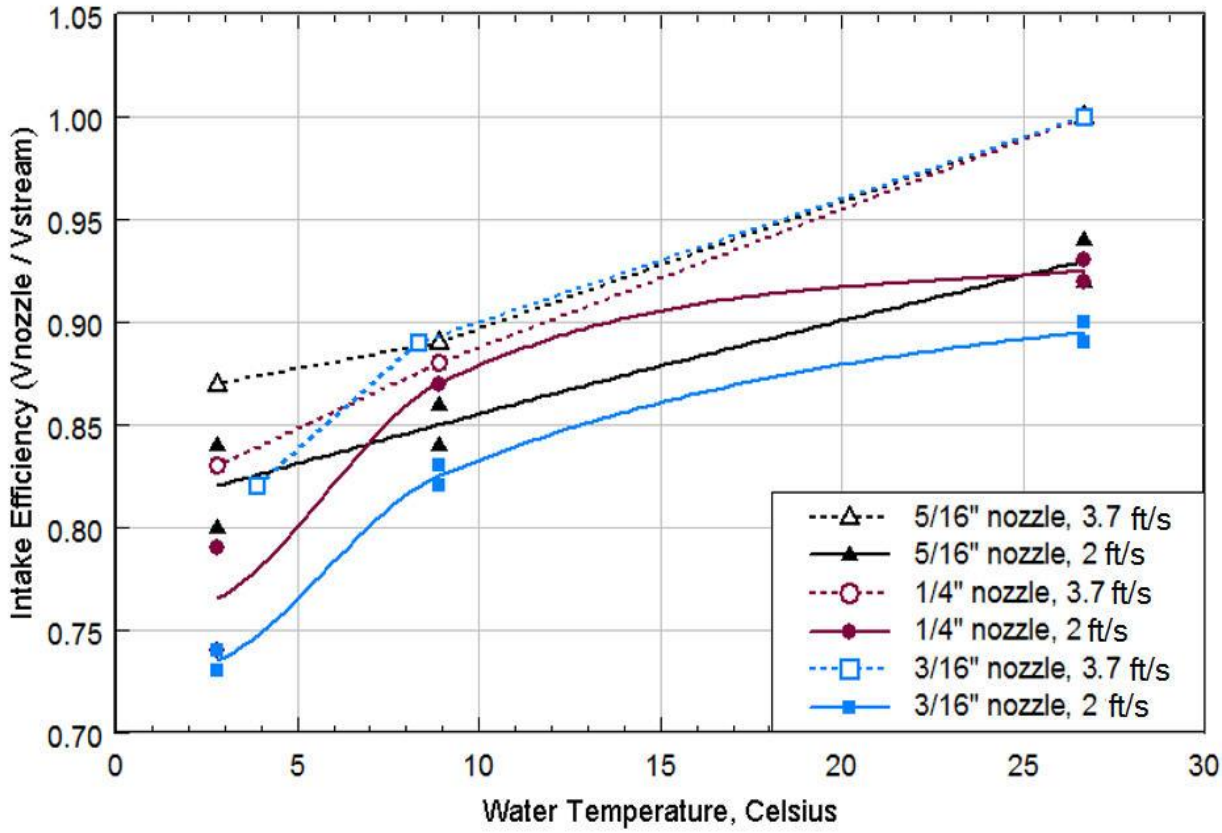

Figure 3 Changes in IE (intake efficiency) with temperature and fitted curves for the FISP US D-96 bag-type sampler at three water temperatures, and nozzle sizes, and two velocities, from data in Davis, 2001.

TEMPERATURE EFFECTS

Decreasing stream temperatures tend to cause decreasing sampler IEs because friction losses increase through the sampler nozzle as fluid viscosity increases. This effect becomes more

pronounced at lower velocities as shown in Figure 3 (from data in Davis, 2001). Tests of FISP samplers are typically conducted at water temperatures between about 24ºC–29ºC (75º–85ºF), in the warmer range of most field sampling conditions. Cold–water tests indicate that the US D-96 functions sub-isokinetically (IE < 0.9) at temperatures less than about 10ºC (50°F) at velocities less than about 3.7 ft/s for all nozzle sizes (Davis, 2001). A theoretical and empirical evaluation of temperature effects also was conducted by Sabol and Topping (2013) for US D-96 bag-type samplers in the Colorado River in Arizona. These data and subsequent review of FISP bag-sampler calibration data prompted revision by FISP of previous temperature-indexed minimum operational velocity limits; the revised limits are shown in Table 1.

RECOMMENDATIONS AND SUMMARY

FISP Memorandum 2013.01 (2013) supplements the FISP reports and operation manuals for the FISP US-series DH-2, D-96, D-96A1, and D-99 bag-type samplers (Davis 2001 and 2005a and b; McGregor, 2006) with the following recommendations to users of FISP bag-type samplers:

- Obtain quality-assurance field measurements of IE before each set of samples is collected during site visits using care to measure the stream velocity at the sample location as concurrently as possible.
- Incorporate the revised, temperature-indexed minimum stream velocities (Table 1) for bag-type samplers into data-collection practices where possible.
- If measured IE clearly indicates sub-isokinetic performance, evaluate potential bias in reported concentrations, based on percent of sand-sized material (≥ 0.0625 mm) in the sample using the chart in Figure 1 and evaluate the significance of this bias to the overall sample concentration accuracy and the purpose of the sampling effort.

The memorandum gives step-by-step instructions for field measurement and computation of IE, and provides a spreadsheet template to facilitate the computations for user-specified nozzle sizes. Revised minimum operational velocities for FISP bag-type samplers where sand-size (≥0.0625 mm) material may be in suspension are shown in Table 1. The new minimum velocity guidance is indexed to water temperature for specific nozzle sizes. The minimum-velocity requirement remains unchanged for temperatures greater than 27ºC (80°F) for all nozzle sizes, and for temperatures greater than 10ºC (50°F) for ¼- and 5/16-in. nozzle sizes. Field tests of IE are particularly important when sampling near these operational limits. Recent studies have demonstrated that the samplers do not operate isokinetically in some riverine environments, even within these limits.

In summary, recent, detailed studies have found that the FISP US D-96 and D-96A1 bag-type samplers operates sub-isokinetically (IE<0.9) in some field conditions. FISP test results in a laboratory tilting flume have not replicated these field results; and have confirmed the original results from sampler development and sampler operational guidance. Moreover, field IE testing does not uniformly indicate sub-isokinetic sampler performance. Colder water temperatures are a known cause of lower IE and revised, temperature-indexed minimum velocity guidance has been issued by the FISP in view of this effect. Colder water temperatures cannot, however, explain the magnitude of observed sub-isokinetic performance in the some of the recent studies; and the actual contributing causes and their relative influence on low IE remains uncertain. It is likely

that the effects of turbulence (at different scales) and transit through relatively high velocity gradients are important factors, as stated by Sabol and Topping (2013). FISP now recommends field IE measurements during each sampling effort and recording of this quality-assurance data with sample analytical data. If any non-isokinetic sample performance is documented, then the potential concentration bias should be evaluated based on the results of FISP Report No. 5 (1941) summarized in Figure 1. While it is essential to recognize and evaluate any source of potential bias in sample results; the bias effect should not be overstated. The significance of any IE-caused bias should be evaluated based on particle size distribution of the sediment, the significance of the bias to specific particle size classes, the overall accuracy of the analyzed sample concentration, and the accuracy needed to address the purposes of the sampling effort.

Table 1 Characteristics and operational ranges for FISP bag-type samplers.

FISP Sampler	Con-tainer type and capa-city	Wei ght, pou -nds	Mode of Suspen-sion	Un-samp-led Zone, in	Max Velo-city [1], ft/s	Nozzle Inner Dia-meter [2], in.	Maxi-mum Depth [3], ft	Minimum Isokinetic Velocity [4], ft/s for Temperature (T) °C		
								T <10°	10< T <27°	T >27°
US DH-2	Flexible 1-L bag	30	Handline or Cable Reel	3.5	6	3/16	35	3.7	3.7	2
						1/4	20	3.7	2	2
						5/16	13	3.7	2	2
US D-96	Flexible 3-L bag	132	Cable Reel	4.0	12	3/16	110	3.7	3.7	2
						1/4	60	3.7	2	2
						5/16	39	3.7	2	2
US D-96-A1	Flexible 3-L bag	80			6	3/16	110	3.7	3.7	2
						1/4	60	3.7	2	2
						5/16	39	3.7	2	2
US D-99	Flexible 3-L or 6-L bag	285	Cable Reel, Heavy	9.5	15	3/16	220	4	4	4
						1/4	120	3.7	3	3
						5/16	78	3.7	3	3

[1]The maximum recommended velocity for bag-type sampler deployment is based on maximum drift angle of the suspension cable (25–30 degrees). Actual maximum velocity should be determined based on this maximum drift angle and field safety considerations.

[2] The 3/16 in. nozzle is more sensitive to velocity and temperature effects and should only be used when necessary to sample maximum depths.

[3] The maximum theoretical depth is based on a maximum transit rate of 0.4 times the mean flow velocity in the sampled vertical and the sample bag capacity (6 L for the US D-99 sampler).

[4]Test results are not available for temperatures <10ºC (50°F). In colder water it is particularly important to test and record intake efficiency with each sample data set.

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