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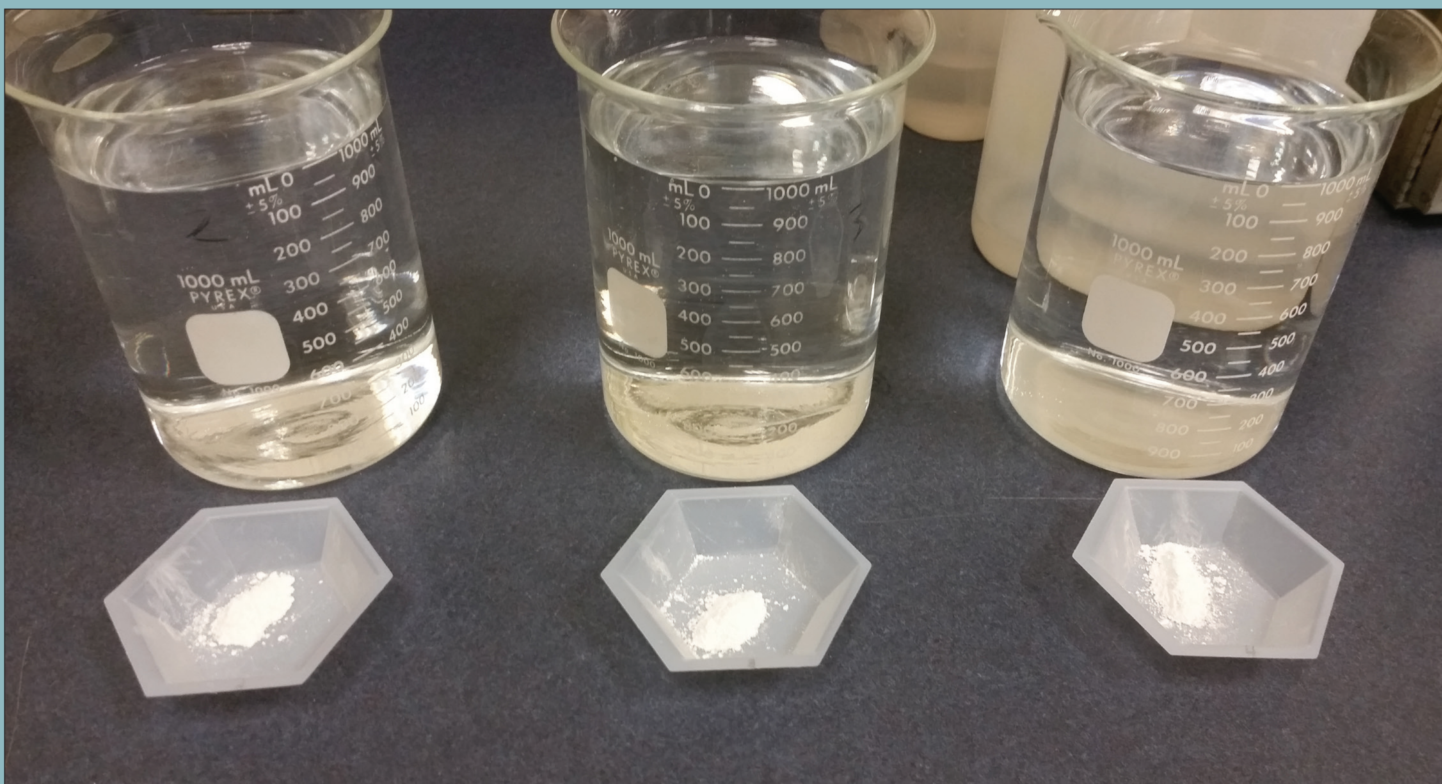
Evaluation of Whole-Water Churn Splitters for Suspended-Sediment Sample Collection and Analysis



Scientific Investigations Report 2018–5126

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

Cover. Three weighted, dry sediment masses and 3 liters of water that were combined to make a set of “slurries,” which were used to analyze bias in five types of U.S. Geological Survey churn splitters.

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By Miya N. Barr

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U.S. Geological Survey
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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
	Volume	
liter (L)	33.82	ounce, fluid (fl. oz)
liter (L)	2.113	pint (pt)
liter (L)	1.057	quart (qt)
liter (L)	0.2642	gallon (gal)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)

Supplemental Information

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

Abbreviations

ASTM	ASTM International (formerly known as American Society of Testing and Materials)
EDI	equal-discharge increment
EWI	equal-width increment
NWIS	National Water Information System
QWDATA	Water-quality database
USGS	U.S. Geological Survey

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By Miya N. Barr

Abstract

The U.S. Geological Survey (USGS) collects a wide range of whole-water samples to test for the many physical and chemical constituents that represent stream conditions at the time of sampling to assess the quality of the Nation's waters. During sampling efforts, in which a suspended-sediment concentration is one result among a broader suite of constituents, a sample is sometimes composited into a churn splitter and then subdivided for analysis. Five churn splitters—comprising three sizes and two different materials—used by the USGS were tested for single-withdrawal accuracy from one-half of full capacity and for multiple-withdrawal accuracy at varied volumes of fullness to see if churn splitters introduce bias during the collection of sediment samples. Both tests were similar to previously conducted tests for consistency, but the tests conducted in this report also attempted to answer questions that arose during previous evaluations of churn splitters. The purpose of this report is to inform sediment analysts about the capabilities and limitations of all available churn-splitter sizes and materials used by the USGS for the analysis of suspended sediment.

The results indicate that suspended-sediment samples and constituents absorbed into suspended sediment may have substantial bias errors when withdrawn from churn splitters. Results were affected by the settling velocity of sediment particles relative to the resuspension velocities induced by the churning, the effects of prior withdrawals of the water-sediment mixture, and the remaining volume in a churn splitter after samples were withdrawn.

Introduction

The U.S. Geological Survey (USGS) collects a wide range of whole-water samples to test for many physical and chemical constituents—including suspended sediment—to assess the quality of the Nation's waters. Typically, the USGS collects suspended sediment using the methods defined in Edwards and Glysson (1999) and the U.S. Geological Survey (2006), all of which require multiple vertical collections of surface water with isokinetic depth-integrated samples using either an equal-width increment (EWI) or equal-discharge increment (EDI) sampling method. The EWI and EDI methods usually yield a composite sample representing discharge-weighted concentrations of the stream reach sampled, and the entire water sample is submitted for analysis. Using the preferred methods for sample collection, in which suspended sediment is a primary component, can provide results that represent stream conditions at the time of sampling. However, during efforts where a suspended-sediment concentration is one result among many, a composite sample is sometimes divided into subsamples for analysis. Each subsample should have equal suspended and dissolved concentrations of specified constituents (Wilde and others, 2014). A churn splitter is used to ensure that subsamples accurately represent a composite sample. Three churn-splitter sizes are currently used: 4-, 8-, and 14-liters (L), in two material and spigot types. Churn splitters—or churns—are used to mix a composited sample and simultaneously dispense it into bottles for laboratory analysis. Comparative data on churn splitters are described in Capel and Larson (1996), Horowitz and others (2001), and Office of Water Quality Technical Memorandum 97.06 (U.S. Geological Survey, Office of Water Quality, 1997); the advantages and limitations of each are found in Wilde and others (2014).

Previous studies (Capel and Larson, 1996; Horowitz and others, 2001) compared the efficiency of various churn sizes and material types, but the studies were limited and did not include all available churn sizes and materials. Capel and Larson (1996) summarized and evaluated available information for churn and cone splitters, and concluded that more work was needed to characterize and quantify the limitations and usefulness of churn splitters. It was noted in Capel and Larson (1996) that no previous studies evaluated the efficiency of the 8-L churn splitter, and only extrapolations from the results of 14-L churn tests have been used and with low confidence. The conclusions in their report stated that both churn sizes at that time were not useful in obtaining representative splits of sand-sized particles. Information on previous tests documented in Capel and Larson (1996) are limited and show only targeted suspended-sediment concentrations at 20,000 milligrams per liter (mg/L) with low sand percentages (5 percent) and high sand percentages (30 percent), but no information on the specific sand-size diameters used was provided, other than data indicating that the particles were greater than 0.063 millimeter (mm). Tests by Horowitz and others (2001) focused on a prototype of the 14-L fluorocarbon churn splitter and only analyzed samples with suspended-sediment concentrations of 50, 100, 300, and 1,000 mg/L. Also, no information about the efficiency of the 4-L churn is available. A need exists to reevaluate the efficiency of the 14-L churn and to better define the efficiency of the 8-L and 4-L churns for suspended-sediment concentration and particle-size analyses.

The USGS collected discrete suspended-sediment data at more than 2,600 sites and analyzed about 25,000 samples per year for the last 7 years (U.S. Geological Survey, 2015). These data are collected using various methods and techniques and are often part of a surface-water-quality sampling effort where chemical constituents other than suspended sediment are analyzed. It is difficult to know which suspended-sediment concentration data in the National Water Information System (NWIS) water-quality database (QWDATA) are part of a water-quality sampling effort because metadata on compositing and subsampling practices are not always available. However, documentation on churn-splitter use during field processing is available from NWIS for about 4,000 suspended-sediment concentration results (U.S. Geological Survey, 2018), indicating a need for more information on the efficiency of churn splitters in suspended-sediment collection and how the churn splitters may affect the traditional analysis of sediment.

Purpose and Scope

The purpose of this report is to describe an evaluation of whole-water churn splitters for suspended-sediment sample collection and inform churn-splitter users about the capabilities and limitations of the churn-splitter sizes and materials used by the USGS to analyze suspended sediment. The efficiency of a churn was determined by measuring how consistently and accurately a suspended-sediment concentration value was reported after repeated withdrawals. This report provides information to assist in study design, field sampling, and the interpretation of sediment data from whole-water samples processed using a churn splitter in a suite of other water-quality parameters but not when suspended sediment is the only concern.

The sampling approach used to determine churn efficiency was twofold: the churns were tested for (1) single-withdrawal accuracy and (2) multiple-withdrawal accuracy from different fill volumes within each churn type. The two tests were performed like those in previous studies (Capel and Larson, 1996; Horowitz and others, 2001) for consistency but were extended to answer questions that arose from those studies.

Methods and Materials

Five churns (Wilde and others, 2014; fig. 1) were used for the single-withdrawal tests: a 4-L polyethylene churn with a cooler-type spigot, an 8-L polyethylene churn with an (all-plastic) cubitainer-style spigot, an 8-L fluorocarbon-polymer churn with a fluorocarbon-polymer spigot, a 14-L polyethylene churn with a cubitainer-style spigot, and a 14-L fluorocarbon-polymer churn with a fluorocarbon-polymer spigot.

Figure 1. Photograph showing all churn splitters used in the study from left to right: 4-liter polyethylene with cooler-type spigot, 8-liter polyethylene with (all-plastic) cubitainer-style spigot, 8-liter fluorocarbon polymer with fluorocarbon-polymer spigot, 14-liter polyethylene with cubitainer-style spigot, and 14-liter fluorocarbon polymer with fluorocarbon-polymer spigot.

Polyethylene churn splitters in this report are referred to as "poly churn," and fluorocarbon-polymer churn splitters are referred to as "polymer churn." Each type of churn splitter has a slightly different geometry because of its size, material type, and the types of spigots it uses. It was essential to evaluate each material type and size to determine if the differences among churns affected efficiency. The poly churns also have agitator paddles made of polyethylene. These paddles weigh less than the polymer churn paddles. Depending on the size of its associated churn, the diameter of the agitator disc at the end of the paddle can affect the weight of the paddle. The 4-L poly churn has a smaller diameter-to-height ratio than the 8- and 14-L poly churns. The churns used for this study were in good to excellent condition, with little to no field use or wear.

The cooler-type spigot often used with a 4-L poly churn can hinder flow because of a spring mechanism inside the spigot that allows it to open and release water from the churn. If the spring rusts or becomes embedded with dirt and debris, the valve may not fully open, hindering the sample stream from the churn and possibly contaminating water-quality samples. Due to these mechanical issues, the 8- and 14-L poly churns are usually operated with an all-plastic, cubitainer-style spigot. This spigot style has no inner springs and allows maximum flow from the churn when fully opened. The 8- and 14-L polymer churns are heavier than equivalently sized poly churns due to material density. The agitation paddles and spigots are molded from fluorocarbon polymer, are heavier than the polyethylene paddles, and include fewer creases and bonded corners. The polymer churn spigots dispense at a 60-degree angle from the opening on the churn, whereas the cubitainer-style spigot dispenses at a 90-degree angle. Both types of 8-L churn splitters have the same dimensions, and both types of the 14-L churn splitter have the same dimensions. The ratio of diameter to height between the 8- and 14-L churns is nearly equal, making the 14-L churn almost twice as large as the 8-L churn.

A modified plastic spigot was used with the 8- and 14-L poly churn splitters. At the beginning of the study, only one originally manufactured length of spigot opening was available. This spigot extended past the bottom of both the 8- and 14-L churns, which necessitated the churn being placed on the edge of a surface to keep the entire weight of the churn from being borne by the spigot. Most users modify the spigot length in the field to avoid damage to the churn and contamination of the spigot opening. A user-modified plastic spigot was in place for all 8-L poly-churn withdrawals except for the multiple-withdrawal tests at the targeted concentration of 3,000 mg/L. Before completion of the sampling portion of the study, a modified spigot became available for purchase through the USGS Hydrologic Instrumentation Facility, Stennis Space Center, Mississippi, and was used for the multiple-withdrawal tests. The new spigot was used for all 14-L poly-churn single and multiple withdrawals and the 8-L poly-churn multiple withdrawals at the targeted 3,000 mg/L concentration. During sampling, it was noted that after about 120 sample withdrawals the newly modified spigot leaked a measurably minimal loss (approximately 200 mL over a 4-day period). Therefore, users should maintain a supply of new spigots for replacement once 100 samples are processed. This finding could be useful for logistical planning to avoid sample loss or contamination when the new, modified spigot is in place for long-term use.

Preparation of Samples With Targeted Concentrations

Targeted concentrations for each churn ranged from 50 to 10,000 mg/L for single-withdrawal analysis. Multiple-withdrawal tests were performed at a 1,000-mg/L targeted concentration for all churn sizes and at 3,000 mg/L for all churn sizes except the 4-L churn. The decision to limit the range of concentrations for the 4-L churn was based on the idea that a smaller churn volume was not ideal for sampling conditions in which higher suspended-sediment concentrations were likely. Also, the 4-L churn is unsuitable for preparing subsamples for multiple or large-volume constituents, which would require a larger churn splitter to process.

Targeted concentrations in the study were determined by previous studies and suspended-sediment concentrations documented in NWIS as part of a sampling suite composited into a churn splitter during the field-sampling process. Concentration targets selected as evaluation levels for the churn splitters were those commonly measured in rivers and streams throughout the United States and those used to evaluate the churns at larger concentrations, all of which were collected between October 2005 and September 2015.

A ball-milled silica flour manufactured by U.S. Silica Holdings, Inc. was used for the fine material—hereafter referred to as "fines"—portion of all samples. The silica sands used as test samples were clean quarry-sands from Ottawa, Illinois, also manufactured by U.S. Silica. All sand and fine sediment were washed with deionized water, dried, and sieved into five categories: 0.5, 0.25, 0.125, and 0.063 mm, and residual. Materials captured on each sieve were dry-stored in separate containers until used to create known masses. For targeted concentrations of 50, 100, 250, and 500 mg/L, sand classified as very fine sand (table 1; having a grain diameter ranging from <0.125 to 0.063 mm) was used in combination with fines measuring <0.063 mm. The three targeted sand-grain distributions for 1,000 and 3,000 mg/L concentration samples were <0.5 to 0.25 mm to represent medium sand, <0.25 to 0.125 mm to represent fine sand, and <0.125 to 0.063 mm to represent very fine sand. Targeted concentrations of 5,000 and 10,000 mg/L contained equally mixed sand portions, by mass, ranging from <0.5 to 0.063 mm to represent natural environments with higher concentrations of suspended sediment. The ratio of sands and fine sediment used to create each sample of dry mass was 20 percent sand and 80 percent fines, which represented the median percentages historically found among discrete suspended-sediment samples collected by the USGS throughout the United States (U.S. Geological Survey, 2015).

Table 1. Sand-sized sediment classification.

[Modified from Guy (1969); mm, millimeter; <, less than]

Class name	Metric unit (mm)
Very coarse sand	<2 – 1.0
Coarse sand	<1 – 0.50
Medium sand	<0.5 – 0.25
Fine sand	<0.25 – 0.125
Very fine sand	<0.125 – 0.063

Dried materials were weighed on a Fisher Scientific XA-250 analytical balance. The calibration of the balance was verified daily using a set of ASTM International (ASTM) Class 1 calibration weights that weighed 1, 2, 5, 10, 20, 50, and 100 grams (g). If the 50-g weight check was greater than ±0.0005 g, the balance was recalibrated to 50.0000 g and rechecked with weights bracketing the targeted masses to be weighed. All balance checks, calibrations, and dates of annual professional calibration services by Thermo Fisher Scientific were recorded in a designated balance logbook stored with the balance and calibration weights in the USGS Central Midwest Water Science Center's water quality laboratory, located in the Rolla, Missouri, office. The balance used for dry material weighing processes had the following specifications: capacity 250 g; repeatability ±0.0001 g; and readability 0.0001 g. An analytical tray was placed on the balance, the balance was tared to a weight of zero to account for the weight of the tray, and then the fines were weighed to within ±0.0005 g of the computed mass needed for a designated churn volume. The sand portion was weighed on the same tray, also to within ±0.0005 g of the computed mass. One analyst created each dry mass to ensure consistency in measurements, which are shown in table 2.

For the single-withdrawal analysis, five samples of each targeted concentration were created for each churn used in the study. The dry mass of sand and fine sediment for each sample was added to 1 L of deionized water to create a slurry and stirred in a borosilicate glass, double graduated, 1-L beaker with a ±5 percent tolerance for at least 5 minutes on a stir plate to ensure the material was fully wetted. This process simulated the suspension of sediment present during a sample collection from a stream. The churn was filled to 1 L less than full capacity using a large-capacity (3 L, 5 L, or a combination of the two, depending on churn volume), graduated, polypropylene beaker with a handle and a ±5 percent tolerance. The slurry was added and fully rinsed from the glass beaker into the churn using deionized water. The churn was agitated using a paddle at a rate of 9 inches per second, not breaking the upper water surface and touching the bottom for 10 strokes, as indicated in Wilde and others (2004). After the proper pre-agitation time, agitation with the paddle continued, the spigot was opened, and the churn was drained to one-half of full-churn capacity. Next, a single 1-L sample was withdrawn from the churn as the water in the churn was agitated with the paddle. The sample was given a unique sample identifier and sent to the USGS Central Midwest Water Science Center's Missouri Sediment Laboratory for analysis. One analyst processed each sample, through each churn, to ensure consistent churning rates and sample withdrawals. A total of 185 single-withdrawal samples were processed through all churn splitters in the test.

A consistent sand-grain size category of very fine sand (<0.125 to 0.063 mm) was used for all targeted concentrations from 50 to 3,000 mg/L, and these sands formed 20 percent of the total mass for each targeted concentration. For targeted concentrations of 5,000 and 10,000 mg/L, an equal mix (by mass) of sands in three grain-size categories, from <0.5 to 0.063 mm, represented common grain-size distributions of larger suspended-sediment concentrations sampled by the USGS, with sands comprising 20 percent of the total sample mass. Three samples were removed from the datasets due to either a dry-mass measurement error or a laboratory error, as described in the "Single-Withdrawal Test Results" section.

A study by Capel and Larson (1996) analyzed sand-grain sizes in relation to churn-splitting efficiencies and advised that churn splitters only be used for samples with a particle size ≤0.25 mm and for suspended-sediment concentrations of 1,000 mg/L or less. The study noted that the 8- and 14-L churns were not useful in replicating split sampling or sand-grain-sized particles. Horowitz and others (2001) recommended limiting churn-splitter use to environmental samples with a maximum sand-grain size of 0.25 mm but only used the 14-L polymer churn to determine the limitation. This report extrapolated previous analyses and performed further tests to better define the limitations of each churn splitter available for USGS use. This report also isolated targeted concentrations and sand-grain-size distributions and evaluated how efficiently a churn could replicate results from three different volumes.

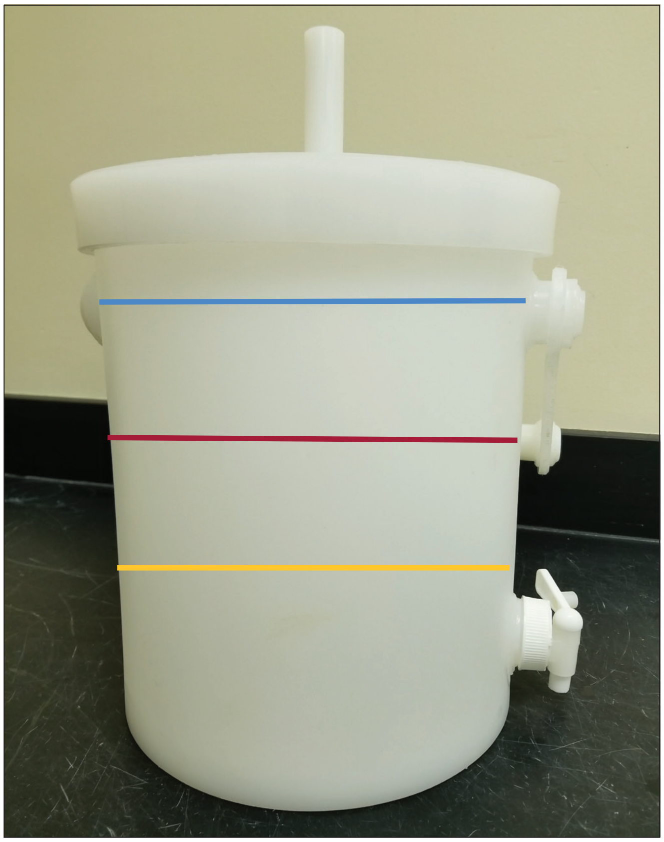
During the multiple-withdrawal analysis, five samples of each targeted concentration and sand-grain-size distribution were created for each churn. Preparation of the dry mass weighing, sediment slurry, and the churn-filling procedures followed the same methods and techniques used for the single-withdrawal tests. The churn was filled to 1 L less

Table 2. Percent and dry weight of sand and fine-sediment mass used for creating all targeted concentrations for each churn splitter used in the study.

[mg/L, milligram per liter; L, liter; %, percent; g, gram]

Targeted concentration, mg/L	Churn volume, L	Total sediment dry mass, g	Sand portion (20%), g	Fines portion (80%), g
50	4	0.20	0.04	0.16
	8	0.40	0.08	0.32
	14	0.70	0.14	0.56
100	4	0.40	0.08	0.32
	8	0.80	0.16	0.64
	14	1.40	0.28	1.12
250	4	1.00	0.20	0.80
	8	2.00	0.40	1.60
	14	3.50	0.70	2.80
500	4	2.00	0.40	1.60
	8	4.00	0.80	3.20
	14	7.00	1.40	5.60
1,000	4	4.00	0.80	3.20
	8	8.00	1.60	6.40
	14	14.00	2.80	11.20
3,000	4	12.00	2.40	9.60
	8	23.60	4.72	18.88
	14	42.00	8.40	33.60
5,000	4	20.00	4.00	16.00
	8	40.00	8.00	32.00
	14	70.00	14.00	56.00
10,000	4	40.00	8.00	32.00
	8	80.00	16.00	64.00
	14	140.00	28.00	112.00

than full capacity, the slurry was added, and the churn was agitated 10 times at a constant rate of 9 inches per second, as described in Wilde and others (2004). Amidst continuous agitation, 1 L was withdrawn from the churn and then discarded. While agitation with the churn paddle continued, the subsequent “top” 1-L sample was withdrawn to 2 L less than full capacity. The churn was then drained to one-half of full capacity before a “middle” 1-L sample was withdrawn at an appropriate agitation speed, then agitated and drained until the required minimum 2 L of volume remained—approximately 2 inches above the spigot—at which point the final, “bottom” 1-L sample was withdrawn (fig. 2). The three samples were given unique identifiers, which indicated a top, middle, and bottom withdrawal location, and sent to the USGS Central Midwest Water Science Center’s Missouri Sediment Laboratory for analysis. Each sample was approximately 1 L in volume and captured in a standard, 1-L polyethylene sample bottle commonly used for both sediment and water-quality sampling. A single analyst processed all samples to ensure the sampled volumes and churn rates were consistent throughout the study. A slight variation was made for the multiple-withdrawal analysis of the 4-L churn splitter because only 4 L of water were available when the churn was filled to capacity. The “top” 1-L sample was collected from full churn capacity with no prewithdrawal volume discarded. The churn was then drained to one-half of full capacity for the “middle” 1-L sample, and the “bottom” 1-L sample was collected immediately after. The 4-L churn was agitated during the entire withdrawal process. A total of 425 multiple-withdrawal samples were processed through all churn splitters in the test.



EXPLANATION

Top (1 liter less than full capacity when sample withdrawn, except for the 4-liter churn splitter, which was collected at full capacity)

Middle (one-half of full capacity when sample withdrawn)

Bottom (2 liters remaining when sample withdrawn)

Figure 2. Photograph marked with lines showing the location of the top, middle, and bottom sample volumes in a churn splitter.

Laboratory Analysis

Samples were received at the laboratory and logged into the laboratory database using the identification on each bottle. A designated laboratory number was assigned to each sample container for tracking through the laboratory, and each container was weighed to obtain a gross weight in grams. A tare weight was recorded on each bottle and entered into the database so that a net sample weight in grams could be computed. All sample container weights were measured using an A&D GF-6000 precision balance. The balance calibration was verified with ASTM Class 1 calibration weights weighing 1,000, 500, and 200 g before daily use, as per laboratory requirements, and recorded in a designated logbook for the balance. Also included in the logbook are dates of annual professional services and calibrations performed by Thermo Fisher Scientific. The maximum weighing capacity of the balance is 6,100 g, with a minimum weighing value of 0.1 g and a repeatability of 0.1 g.

All samples were analyzed by the sediment laboratory for suspended-sediment concentration in milligrams per liter using the filtration method described in Guy (1969). In addition to the suspended-sediment concentration, the multiple-withdrawal samples were analyzed for a particle-size distribution commonly known as a percent of sediments finer than 0.063 mm, which is the size-break between the sands and the fine sediments analyzed in the wet-sieve, sand-break laboratory process, and the process was performed using a filtration method (Guy, 1969). The sand-break results aided in determining the capacity of the churn to accurately deliver different sand-grain sizes and to determine if the volume of the sample that remained in the churn at the time of withdrawal affected grain-size delivery. One laboratory analyst processed all samples for the study.

Dried-mass weighing, after the filtration processes for both suspended-sediment concentration and sand-break, was performed on a Denver Instruments A250 analytical balance. The balance was used for all samples processed by the sediment laboratory during this study. The balance was checked for calibration daily, or twice per day when the balance was used for more than 1 hour a day, with 20- and 50-g ASTM Class 1 calibration weights. If the balance was ±0.0005 g from the 50-g calibration weight, the balance was recalibrated and reverified with the 20-g weight. Calibration checks, recalibrations, and annual professional services and calibrations performed by Thermo Fisher Scientific are recorded in a designated logbook stored with the analytical balance in the sediment laboratory. The balance specifications include a maximum capacity of 250 g and a readability of 0.0001 g.

Final laboratory results were archived in the laboratory database and submitted to the author for inclusion in the report. Suspended-sediment concentration results were reported in milligrams per liter. The particle-size distribution from the sand-break analysis was reported as percent finer than 0.063 mm. All values were reported to three significant figures.

Quality Assurance and Quality Control

Quality control was applied across the study to reduce bias in the results. The churns used in the study were in good to excellent condition with little to no field use, reducing possible loss of sediment withdrawals due to mechanical issues or sediment retention within the churn in damaged areas or surfaces. Samples were withdrawn from churns by one analyst to maintain a consistent agitation speed with the churn paddle and allow consistent measurements of sampling volumes. Sample slurries, as well as volumes of deionized water added to churns for each test, were measured in clean, manufacturer-etched, graduated beakers. All samples withdrawn from the churn splitters were targeted at 1 L using the same bottle type for all samples. Bottles were washed in a commercial dishwasher with low-phosphorus detergent and marked with a tare (empty and dry) weight to the nearest 0.1 g before use with the same balance. All samples were labeled with a unique identifier to avoid confusion about which test was performed or which churn was used. Samples were created in small batches so laboratory results could be reviewed and new samples created if errors were detected in the dry weight measurements or the churn procedures. Dry mass weights were measured to the nearest 0.0005 g of the targeted mass needed for each concentration set to minimize bias between samples in a set. Churns were cleaned between each single-withdrawal sample and between each multiple-withdrawal set for each targeted concentration. In the interest of time and available resources, the procedure for the field cleaning of churn splitters (Wilde, 2004) was used between sample sets. When all sampling was complete for a churn splitter, the procedure for laboratory cleaning outlined in Wilde (2004) was used.

Blind samples of known concentrations were sent to the laboratory during the testing period to ensure laboratory procedures were not a source of bias in the results (table 3). The blind samples were made by one person, who weighed an exact mass of sands and fines, which were then added to a sampling container with 1 L of deionized water. Some concentrations consisted of a specific sand-grain size distribution to mimic the multiple-withdrawal tests, and these instances are noted in table 3.

Laboratory quality control was applied to ensure minimal effects on the results from laboratory procedures. Bottle gross and tare weights were measured by the sediment laboratory using the same balance for consistency. Laboratory blanks of decanted water from random sand-break samples were processed to measure losses of mass. The tare and gross weights of the crucibles used to process samples were reweighed to ensure the balances were accurate. In addition, blanks were processed with deionized water in cleaned sample containers to determine if all material was removed during the analysis. Laboratory methods used to process the concentration and sand-break analyses for the test samples are documented in Guy (1969).

Evaluation From Experimental Results

The churn-test results were affected by the settling velocity of sediment particles relative to the resuspension velocities induced by the churning and the effects of prior withdrawals of the water-sediment mixture. The settling velocity of sediment particles, as defined by Stokes' Law (Rumble, 2017), depends on opposing gravitational and drag forces on the sediment particle because they are related to particle characteristics (size, density, and shape) and fluid characteristics (viscosity). The manual churning process and rate are intended to keep particles in suspension; however, larger particles settle even while churning, as indicated in the results described in this report. Particles classified as sands (particles larger than 0.063 mm) have substantial settling velocities in fluvial systems. Because of these characteristics, increases in negative bias are expected for larger sediment-sized particles.

Table 3. Laboratory-reported results of blind samples.

[mg/L, milligram per liter; %, percent; mm, millimeter; —, not available; <, less than]

Known concentration, mg/L	Concentration reported by laboratory, mg/L	Bias in concentration result, %	Sand-grain size distribution, mm	Known % of sand in sample	Reported % sand by laboratory	Bias in sand recovery, %
4.3	4.0	–7.0	—	—	—	—
10.0	12.0	20	—	—	—	—
26.9	27.0	0.4	—	—	—	—
52.0	48.0	–7.7	—	—	—	—
100	98.0	–2.0	—	—	—	—
253	256	1.2	—	—	—	—
499	512	2.6	—	—	—	—
1,000	1,003	0.3	<0.125 – 0.063	30	32	7.3
1,000	1,040	4.0	<0.250 – 0.125	30	35	15.7
1,000	1,012	1.2	<0.500 – 0.125	30	33	9.3
3,005	2,953	–1.7	<0.500 – 0.063	30	33	9.7
5,008	5,039	0.6	<0.500 – 0.063	30	32	6.0
10,487	10,176	–3.0	<0.500 – 0.063	30	33	11.0

At the beginning of every test, each churn was filled with a sample of a selected target concentration. When the water-sediment mixture was removed to reach the churn volume level for each withdrawal test, the concentration that remained in the churn changed relative to the initial target concentration because the withdrawn water was biased, as indicated in all test results. This result also affected the withdrawn-sample concentration relative to the initial target concentration.

In addition to the effects of particle-settling velocity and the previous withdrawals, the results were affected by a loss of sediment mass in the sample handling and transferal process; in this case, the lost sediment included fine sediment (size <0.063 mm). This loss was usually a small absolute mass, but it could be a substantial, relative percentage of the total mass for low concentrations, particularly for concentrations <20 mg/L. As noted in the previous investigations summarized by Capel and Larson (1996), potential errors in suspended-sediment concentration measurements can come from both field errors (collection and processing) and laboratory analytical errors. Other findings suggest that the natural variability of suspended sediments, sand-sized particles in particular, can be large and should be considered when reviewing the error associated with churn-splitter efficiency.

Single-Withdrawal Test Results

Basic statistical computations were used to help determine the capabilities of each churn used in the single-withdrawal tests. A previous study by Capel and Larson (1996) observed variability in suspended-sediment analyses from both natural field-sampling conditions and laboratory-produced samples. In that report, Capel and Larson (1996) noted the natural variability in replicating suspended-sediment concentrations was about 10 percent for sands and about 3 percent for fine sediment (<0.063 mm). For consistency, the same thresholds determined by Capel and Larson (1996) were used in this report.

For this report, the analysis of each churn splitter for single-withdrawal samples at targeted concentrations is shown in table 4. The standard deviation and percentage of relative standard deviation for each targeted-concentration dataset were computed to show the accuracy among the five samples in each set. A mean value and a percentage of bias were computed from the five sample results to show variability and efficiency among the churn splitters and targeted concentrations and are visually demonstrated in figure 3.

Table 4. Total suspended-sediment concentration results of single-withdrawal samples for all churn splitters used in the study.—Continued

[<, less than; —, no result]

Sample number	Total suspended-sediment concentration, in milligrams per liter							
	50	100	250	500	1,000	3,000	5,000	10,000
	Sand-grain size range used for samples, in millimeters							
	<0.125 to 0.063						<0.500 to 0.063	
4-liter polypropylene churn splitter								
1	38	77	234	474	856	—	—	—
2	43	94	224	460	778	—	—	—
3	43	94	244	487	793	—	—	—
4	40	104	234	494	791	—	—	—
5	45	90	256	489	791	—	—	—
Mean	42	92	238	481	802	—	—	—
Standard deviation	2.5	8.7	11	12	28	—	—	—
Percent relative standard deviation	5.9	9.5	4.5	2.6	3.4	—	—	—
Percent bias	–16	–8.2	–4.6	–3.8	–20	—	—	—
8-liter polypropylene churn splitter								
1	42	93	241	448	970	2,789	4,070	7,789
2	45	92	233	486	990	2,711	4,377	7,684
3	44	94	233	484	948	2,823	4,487	7,239
4	47	97	234	469	981	2,754	4,539	7,120
5	48	94	238	480	974	2,703	4,523	7,121
Mean	45	94	236	473	973	2,756	4,399	7,391
Standard deviation	2.1	1.7	3.2	14	14	46	174	288
Percent relative standard deviation	4.7	1.8	1.4	3.0	1.4	1.7	4.0	3.9
Percent bias	–9.6	–6.0	–5.7	–5.3	–2.7	–8.1	–12	–26

Table 4. Total suspended-sediment concentration results of single-withdrawal samples for all churn splitters used in the study.—Continued

[<, less than; —, no result]

Sample number	Total suspended-sediment concentration, in milligrams per liter							
	50	100	250	500	1,000	3,000	5,000	10,000
	Sand-grain size range used for samples, in millimeters							
	<0.125 to 0.063						<0.500 to 0.063	
8-liter fluorocarbon polymer churn splitter								
1	46	94	231	465	964	2,498	4,502	8,931
2	46	92	235	466	958	2,799	4,976	8,746
3	48	92	241	455	916	2,646	4,581	9,431
4	48	94	233	468	990	2,794	4,793	8,808
5	45	92	229	468	953	2,772	4,464	8,429
Mean	47	93	234	464	956	2,702	4,663	8,869
Standard deviation	1.2	0.98	4.1	4.8	24	116	193	326
Percent relative standard deviation	2.6	1.1	1.8	1.0	2.5	4.3	4.1	3.7
Percent bias	–6.8	–7.2	–6.5	–7.1	–4.4	–9.9	–6.7	–11
14-liter polyethylene churn splitter								
1	48	91	247	466	971	3,005	4,612	9,153
2	45	95	244	485	968	2,913	4,356	8,121
3	48	98	238	—[a]	—[b]	2,985	4,619	9,419
4	47	96	239	481	972	2,876	4,469	9,226
5	47	95	240	488	982	2,935	4,512	9,561
Mean	47	95	242	480	973	2,943	4,514	9,096
Standard deviation	1.1	2.3	3.4	8.5	5.3	47	98	508
Percent relative standard deviation	2.3	2.4	1.4	1.8	0.5	1.6	2.2	5.6
Percent bias	–6.0	–5.0	–3.4	–4.0	–2.7	–1.9	–10	–9.0
14-liter fluorocarbon polymer churn splitter								
1	46	94	238	485	966	2,791	5,597	10,019
2	47	90	—[a]	451	929	2,838	4,996	9,713
3	39	93	239	466	988	2,901	4,783	9,771
4	44	95	236	481	992	2,952	4,876	9,380
5	44	95	198	479	998	3,014	4,947	8,946
Mean	44	93	228	472	975	2,899	5,040	9,566
Standard deviation	2.8	1.9	17	12	25	79	288	371
Percent relative standard deviation	6.3	2.0	7.6	2.6	2.6	2.7	5.7	3.9
Percent bias	–12	–6.6	–8.9	–5.5	–2.5	–3.4	0.8	–4.3

[a]Dry sample weight was computed incorrectly, sample not used.

[b]Laboratory sampling error, sample not used.

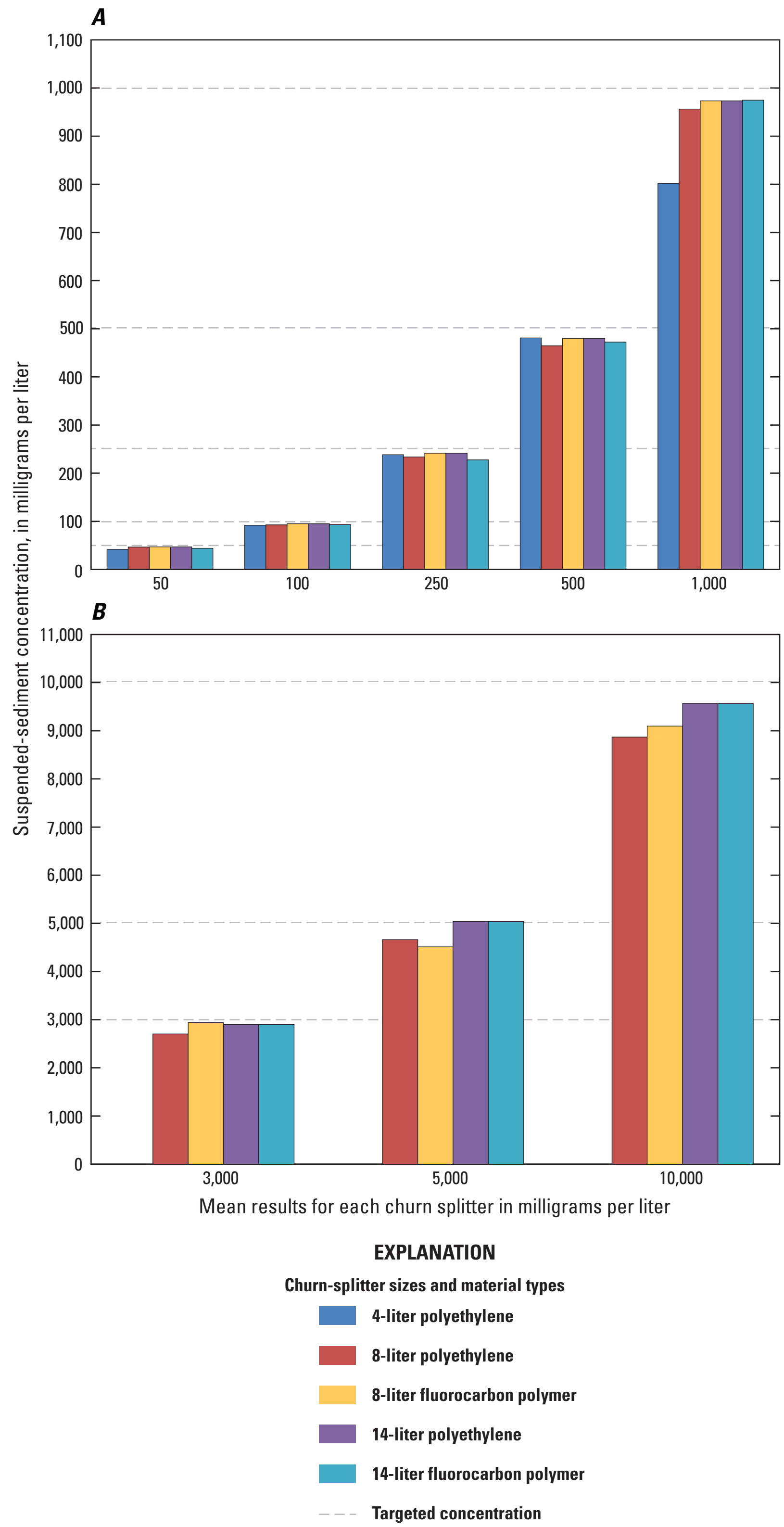


Figure 3. Combination graphs showing the mean of five suspended-sediment concentration results for single withdrawals at one-half of full capacity (*A*) at a range of 0–1,000 milligrams per liter for all churn splitters used in the study and (*B*) at a range of 3,000–10,000 milligrams per liter for all churn splitters used in the study, excluding the 4-liter polyethylene churn splitter. In both cases, the results were in relation to the targeted suspended-sediment concentrations.

The difference in the mean bias of the 8-L poly and polymer churns was small relative to the sampling variability and is not statistically significant at a 5-percent significance from a two-sample, parametric t-test (Helsel and Hirsch, 2002). Likewise, the difference in the mean bias of the 14-L poly and polymer churns is small relative to the sampling variability (except for one outlier at the 10,000 mg/L test, which was kept in the analysis; table 4) and is not statistically significant at a 5-percent significance test. A significant difference was not expected in sediment concentrations withdrawn from the poly churns versus the polymer churns because sediment was not expected to adhere to, or otherwise behave differently with, the two materials.

The single-withdrawal results indicate significant differences based on churn volume. As indicated in figure 4, the 8-L results had a greater negative bias than the 14-L results for most tests, although there is considerable scatter among the results. A comparison of the mean bias results for the 4-L churn indicates a greater negative bias for three of the five targeted concentrations in the test (–16, –8.2, and –20 percent for 50, 100, and 1,000 mg/L, respectively; table 4; fig. 4). For statistical comparison of the 8- and 14-L volumes, the 8-L results from the poly- and polymer-material churns at each of the eight concentrations were combined for a total of 16 sample results. This comparison was also made for the 14-L results. The difference in the mean bias of the 8-L versus the 14-L churn results is statistically significant at a 5-percent threshold (p-value = 0.02). Statistical comparisons were not made for the 4-L results because of the small sample size. The results from the 8- and 14-L comparisons can be reasonably extrapolated to demonstrate that the 4-L churn volume would have a greater negative bias than either the 8- or 14-L churns.

Multiple-Withdrawal Test Results

The results for all multiple withdrawals for each churn and sand-grain size distribution show the variability in targeted concentrations and the percentage of sand recovered from different sampled volumes within a churn (table 5; fig. 5). The results are also organized by separate sample runs or numbers (table 6) to identify how effectively each churn could replicate a targeted concentration from three split samples per sand-grain size.

The multiple-withdrawal test results contain more information than the single-withdrawal tests. The remaining volume (or withdrawal location) in a churn splitter strongly influences the sand concentration of withdrawn samples (fig. 5). The mean sand-concentration bias in the top, middle, and bottom withdrawals is +34 percent, –13 percent, and –47 percent, respectively, for the combined multiple-withdrawal churn tests (table 5; fig. 6). There was no statistically significant difference in sand-bias results between the combined 8- and 14-L churns. The reason for the positive bias in the top-level sample is that sand particles settle more rapidly than they are resuspended; therefore, sand concentrations increase over the depth of the churn, and higher concentrations are near the churn spigot. Capel and Larson (1996) documented similar results, noting that a study by Meade (1985) observed that sand grains were not distributed evenly because the stirring action could not overcome the tendency of sand grains to settle, causing a gradient where sand was more concentrated near the bottom where the spigot is located. This is true for any sand concentration in the churns at any level. Positive bias—relative to the initial target concentration—in withdrawn, suspended sediment in the top

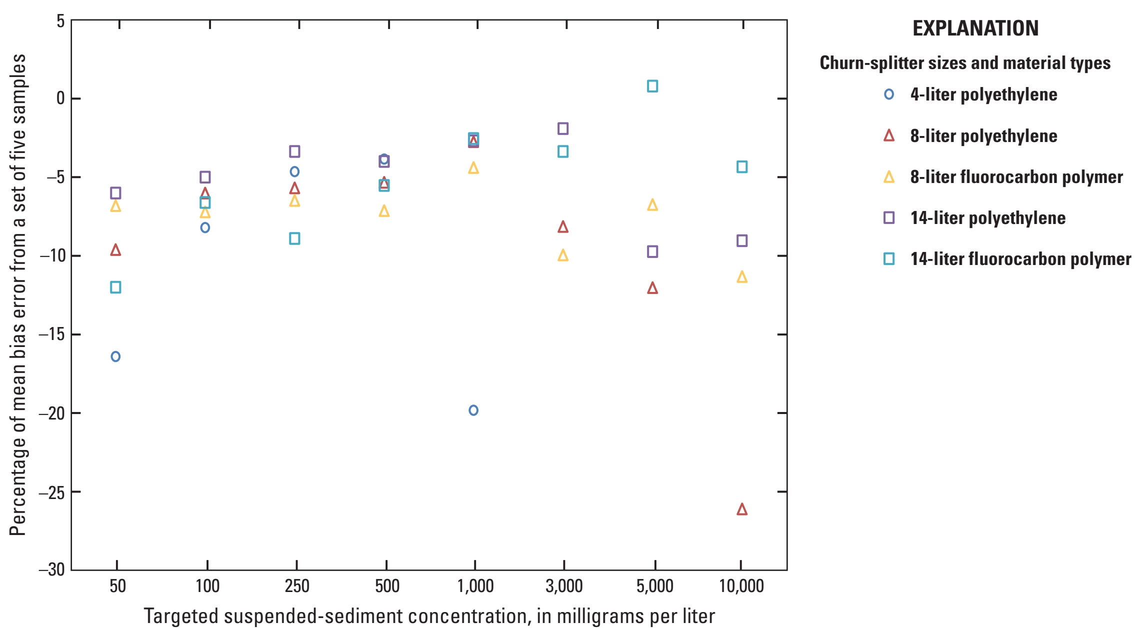


Figure 4. Symbol graph showing the percentage of mean bias error, from a set of five samples of single withdrawal at one-half of full capacity, for all churn splitters used in the study.

Table 5. Total suspended-sediment concentration results from multiple-withdrawal analysis at targeted concentrations of 1,000 and 3,000 milligrams per liter for all churn splitters.

[mm, millimeter; top, 1 liter less than full churn capacity; middle, one-half of full churn capacity; bottom, 2 liters remaining in churn; mg/L, milligram per liter; %, percent; <, less than; —, not used]

Churn size and material type	Sand-grain size distribution, mm	Churn-splitter volume sampled											
		Top		Middle		Bottom		Top		Middle		Bottom	
		Total suspended-sediment concentration, in milligrams per liter (percent of sand)											
		1,000 (20)						3,000 (20)					
4-liter polyethylene	<0.50 to 0.250	761	(21)	630	(8)	634	(9)	—	—	—	—	—	—
		775	(16)	698	(11)	658	(8)	—	—	—	—	—	—
		782	(17)	694	(10)	751	(7)	—	—	—	—	—	—
		756	(26)	768	(18)	658	(8)	—	—	—	—	—	—
		810	(22)	719	(14)	689	(12)	—	—	—	—	—	—
	Mean	777	(20)	702	(12)	678	(9)	—	—	—	—	—	—
	Standard deviation	19	(4)	45	(4)	40	(2)	—	—	—	—	—	—
	Bias in fines	–23%	—	–23%	—	–23%	—	—	—	—	—	—	—
	Bias in sands	–20%	—	–57%	—	–70%	—	—	—	—	—	—	—
	<0.250 to 0.125	862	(26)	781	(21)	684	(11)	—	—	—	—	—	—
		841	(25)	742	(18)	664	(11)	—	—	—	—	—	—
		802	(22)	761	(20)	705	(15)	—	—	—	—	—	—
		901	(28)	733	(17)	699	(14)	—	—	—	—	—	—
		894	(31)	702	(14)	686	(13)	—	—	—	—	—	—
	Mean	860	(27)	744	(18)	688	(13)	—	—	—	—	—	—
	Standard deviation	36	(3)	27	(2)	14	(2)	—	—	—	—	—	—
	Bias in fines	–21%	—	–24%	—	–25%	—	—	—	—	—	—	—
	Bias in sands	15%	—	–33%	—	–56%	—	—	—	—	—	—	—
	<0.125 to 0.063	1,003	(27)	856	(16)	791	(15)	—	—	—	—	—	—
		889	(28)	778	(21)	711	(17)	—	—	—	—	—	—
		892	(28)	793	(22)	752	(19)	—	—	—	—	—	—
		868	(28)	791	(22)	736	(18)	—	—	—	—	—	—
		884	(28)	791	(23)	744	(19)	—	—	—	—	—	—
	Mean	907	(28)	802	(21)	747	(17)	—	—	—	—	—	—
	Standard deviation	49	(1)	28	(2)	26	(2)	—	—	—	—	—	—
	Bias in fines	–18%	—	–21%	—	–23%	—	—	—	—	—	—	—
	Bias in sands	26%	—	–16%	—	–35%	—	—	—	—	—	—	—
	Average fines bias	–21%	—	–23%	—	–24%	—	—	—	—	—	—	—
	Average sands bias	7%	—	–35%	—	–54%	—	—	—	—	—	—	—

Table 5. Total suspended-sediment concentration results from multiple-withdrawal analysis at targeted concentrations of 1,000 and 3,000 milligrams per liter for all churn splitters.—Continued

[mm, millimeter; top, 1 liter less than full churn capacity; middle, one-half of full churn capacity; bottom, 2 liters remaining in churn; mg/L, milligram per liter; %, percent; <, less than; —, not used]

Churn size and material type	Sand-grain size distribution, mm	Churn-splitter volume sampled											
		Top		Middle		Bottom		Top		Middle		Bottom	
		Total suspended-sediment concentration, in milligrams per liter (percent of sand)											
		1,000 (20)						3,000 (20)					
8-liter polyethylene	<0.50 to 0.250	1,119	(30)	923	(18)	800	(8)	2,852	(22)	2,525	(13)	2,106	(6)
		1,017	(25)	932	(19)	766	(7)	2,842	(22)	2,575	(16)	2,017	(5)
		1,079	(29)	916	(18)	787	(8)	2,828	(21)	2,642	(19)	2,074	(8)
		1,067	(26)	928	(18)	790	(8)	2,735	(20)	2,497	(17)	2,038	(5)
		1,031	(24)	952	(20)	822	(11)	3,257	(30)	2,689	(19)	2,248	(9)
	Mean	1,063	(27)	930	(19)	793	(8)	2,903	(23)	2,586	(17)	2,097	(7)
	Standard deviation	36	(2)	12	(1)	18	(1)	182	(3)	71	(2)	82	(2)
	Bias in fines	–3%	—	–6%	—	–9%	—	–7%	—	–11%	—	–18%	—
	Bias in sands	43%	—	–13%	—	–67%	—	11%	—	–26%	—	–77%	—
	–0.250 to 0.125	1,035	(26)	962	(21)	730	(6)	2,904	(25)	2,574	(18)	2,277	(12)
		1,141	(29)	935	(17)	771	(7)	3,025	(28)	2,609	(20)	2,249	(12)
		972	(22)	909	(19)	776	(9)	3,043	(27)	2,802	(23)	2,129	(8)
		1,023	(27)	903	(20)	848	(16)	2,797	(21)	2,445	(13)	2,074	(6)
		1,020	(25)	982	(22)	826	(12)	2,839	(22)	2,447	(12)	2,571	(16)
	Mean	1,038	(26)	938	(20)	790	(10)	2,922	(25)	2,575	(17)	2,260	(11)
	Standard deviation	56	(2)	30	(2)	42	(4)	98	(3)	131	(4)	173	(3)
	Bias in fines	–4%	—	–6%	—	–11%	—	–8%	—	–11%	—	–16%	—
	Bias in sands	34%	—	–6%	—	–61%	—	20%	—	–27%	—	–59%	—
	<0.125 to 0.063	1,021	(26)	970	(24)	850	(17)	2,942	(25)	2,789	(22)	2,031	(9)
		1,061	(27)	990	(23)	867	(16)	2,956	(28)	2,711	(22)	2,218	(14)
		1,023	(27)	948	(24)	885	(18)	2,916	(27)	2,823	(23)	2,099	(10)
		1,030	(26)	981	(24)	852	(16)	3,082	(27)	2,754	(23)	2,149	(11)
		1,063	(27)	974	(22)	843	(14)	3,126	(30)	2,703	(22)	2,362	(17)
	Mean	1,040	(26)	973	(23)	859	(16)	3,004	(28)	2,756	(22)	2,172	(12)
	Standard deviation	19	(0)	14	(1)	15	(1)	83	(2)	46	(0)	113	(3)
	Bias in fines	–4%	—	–7%	—	–10%	—	–9%	—	–11%	—	–21%	—
	Bias in sands	38%	—	13%	—	–30%	—	38%	—	3%	—	–56%	—
	Average fines bias	–4%	—	–6%	—	–10%	—	–8%	—	–11%	—	–18%	—
	Average sands bias	38%	—	–2%	—	–53%	—	23%	—	–17%	—	–64%	—

Table 5. Total suspended-sediment concentration results from multiple-withdrawal analysis at targeted concentrations of 1,000 and 3,000 milligrams per liter for all churn splitters.—Continued

[mm, millimeter; top, 1 liter less than full churn capacity; middle, one-half of full churn capacity; bottom, 2 liters remaining in churn; mg/L, milligram per liter; %, percent; <, less than; —, not used]

Churn size and material type	Sand-grain size distribution, mm	Churn-splitter volume sampled											
		Top		Middle		Bottom		Top		Middle		Bottom	
		Total suspended-sediment concentration, in milligrams per liter (percent of sand)											
		1,000 (20)						3,000 (20)					
8-liter fluorocarbon polymer	<0.50 to 0.250	1,075	(27)	949	(17)	839	(10)	3,467	(37)	2,504	(16)	2,604	(20)
		1,056	(26)	898	(16)	851	(14)	2,949	(23)	2,478	(11)	2,504	(12)
		1,163	(33)	896	(15)	859	(12)	3,159	(28)	2,513	(13)	2,417	(11)
		1,081	(28)	901	(15)	839	(10)	2,996	(27)	2,556	(16)	2,430	(13)
		1,185	(33)	827	(8)	841	(12)	3,180	(28)	2,727	(18)	2,495	(12)
	Mean	1,112	(29)	894	(14)	846	(12)	3,150	(28)	2,556	(15)	2,490	(14)
	Standard deviation	52	(3)	39	(3)	8	(1)	182	(5)	89	(2)	67	(3)
	Bias in fines	–2%	—	–4%	—	–7%	—	–6%	—	–9%	—	–11%	—
	Bias in sands	63%	—	–35%	—	–51%	—	49%	—	–37%	—	–43%	—
	<0.250 to 0.125	1,045	(28)	916	(19)	839	(14)	3,017	(25)	2,555	(14)	2,580	(16)
		1,087	(29)	926	(19)	847	(14)	3,080	(27)	2,583	(15)	2,531	(15)
		1,178	(35)	964	(23)	858	(15)	3,259	(29)	2,670	(17)	2,580	(15)
		1,172	(34)	919	(19)	884	(16)	2,969	(25)	2,673	(18)	2,459	(13)
		1,098	(32)	881	(18)	858	(16)	2,947	(24)	2,585	(17)	2,510	(14)
	Mean	1,116	(32)	921	(19)	857	(15)	3,054	(26)	2,613	(16)	2,532	(15)
	Standard deviation	51	(2)	26	(2)	15	(1)	112	(2)	49	(1)	46	(1)
	Bias in fines	–5%	—	–7%	—	–9%	—	–6%	—	–9%	—	–10%	—
	Bias in sands	76%	—	–11%	—	–36%	—	32%	—	–30%	—	–37%	—
	<0.125 to 0.063	1,083	(27)	964	(21)	895	(16)	3,234	(27)	2,498	(19)	2,765	(15)
		1,031	(25)	958	(22)	916	(18)	3,247	(28)	2,799	(20)	2,624	(17)
		1,018	(25)	916	(20)	882	(17)	3,010	(27)	2,646	(20)	2,508	(18)
		1,056	(27)	990	(22)	953	(20)	3,205	(28)	2,794	(20)	2,609	(18)
		1,062	(28)	953	(22)	912	(20)	3,147	(27)	2,772	(20)	2,654	(18)
	Mean	1,050	(26)	956	(21)	912	(18)	3,169	(28)	2,702	(20)	2,632	(17)
	Standard deviation	23	(1)	24	(1)	24	(1)	86	(0)	116	(1)	83	(1)
	Bias in fines	–4%	—	–6%	—	–7%	—	–4%	—	–10%	—	–9%	—
	Bias in sands	39%	—	2%	—	–16%	—	46%	—	–11%	—	–25%	—
	Average fines bias	–3%	—	–6%	—	–7%	—	–5%	—	–9%	—	–10%	—
	Average sands bias	60%	—	-15%	—	–34%	—	42%	—	–26%	—	–35%	—

Table 5. Total suspended-sediment concentration results from multiple-withdrawal analysis at targeted concentrations of 1,000 and 3,000 milligrams per liter for all churn splitters.—Continued

[mm, millimeter; top, 1 liter less than full churn capacity; middle, one-half of full churn capacity; bottom, 2 liters remaining in churn; mg/L, milligram per liter; %, percent; <, less than; —, not used]

Churn size and material type	Sand-grain size distribution, mm	Churn-splitter volume sampled											
		Top		Middle		Bottom		Top		Middle		Bottom	
		Total suspended-sediment concentration, in milligrams per liter (percent of sand)											
		1,000 (20)						3,000 (20)					
14-liter polyethylene	<0.50 to 0.250	1,031	(24)	967	(24)	785	(8)	3,247	(27)	2,719	(16)	2,400	(9)
		978	(22)	913	(22)	801	(10)	2,991	(21)	2,692	(15)	2,269	(6)
		960	(21)	903	(21)	718	(4)	3,254	(30)	2,776	(18)	2,326	(8)
		992	(22)	895	(22)	769	(8)	2,848	(20)	2,810	(19)	2,294	(7)
		951	(19)	976	(19)	793	(9)	2,960	(22)	2,665	(14)	2,318	(6)
	Mean	982	(22)	931	(22)	773	(8)	3,060	(24)	2,732	(16)	2,321	(7)
	Standard deviation	28	(2)	34	(2)	30	(2)	163	(4)	53	(2)	44	(1)
	Bias in fines	–4%	—	–9%	—	–11%	—	–3%	—	–5%	—	–10%	—
	Bias in sands	6%	—	0%	—	–70%	—	22%	—	–26%	—	–73%	—
	<0.250 to 0.125	975	(20)	925	(17)	775	(8)	3,214	(27)	2,860	(19)	2,515	(11)
		1,016	(25)	916	(19)	778	(10)	3,158	(26)	2,799	(18)	2,421	(9)
		1,009	(24)	921	(19)	765	(8)	3,155	(26)	2,830	(20)	2,547	(14)
		1,013	(23)	881	(15)	815	(10)	3,254	(28)	2,985	(22)	2,521	(11)
		1,013	(23)	959	(20)	813	(10)	3,038	(24)	2,880	(21)	2,575	(13)
	Mean	1,005	(23)	920	(18)	789	(9)	3,164	(26)	2,871	(20)	2,516	(12)
	Standard deviation	15	(2)	25	(2)	21	(1)	73	(1)	63	(2)	52	(2)
	Bias in fines	–3%	—	–6%	—	–11%	—	–3%	—	–4%	—	–8%	—
	Bias in sands	16%	—	–18%	—	–63%	—	38%	—	–4%	—	–50%	—
	<0.125 to 0.063	1,037	(25)	971	(21)	837	(14)	3,122	(25)	3,005	(22)	2,581	(14)
		1,013	(24)	968	(22)	891	(17)	3,025	(23)	2,913	(21)	2,728	(18)
		1,167	(34)	--	--	875	(18)	3,218	(26)	2,985	(23)	2,656	(16)
		1,014	(25)	972	(22)	849	(16)	2,980	(24)	2,876	(22)	2,656	(18)
		1,031	(24)	982	(23)	895	(17)	3,096	(25)	2,935	(22)	2,735	(17)
	Mean	1,052	(26)	973	(22)	869	(16)	3,088	(25)	2,943	(22)	2,671	(17)
	Standard deviation	58	(4)	5	(1)	23	(1)	82	(1)	47	(1)	56	(1)
	Bias in fines	–3%	—	–5%	—	–9%	—	–3%	—	–4%	—	–7%	—
	Bias in sands	39%	—	6%	—	–29%	—	27%	—	8%	—	–26%	—
	Average fines bias	–3%	—	–6%	—	–10%	—	–3%	—	–4%	—	–8%	—
	Average sands bias	20%	—	–4%	—	–54%	—	29%	—	–7%	—	–49%	—

Table 5. Total suspended-sediment concentration results from multiple-withdrawal analysis at targeted concentrations of 1,000 and 3,000 milligrams per liter for all churn splitters.—Continued

[mm, millimeter; top, 1 liter less than full churn capacity; middle, one-half of full churn capacity; bottom, 2 liters remaining in churn; mg/L, milligram per liter; %, percent; <, less than; —, not used]

Churn size and material type	Sand-grain size distribution, mm	Churn-splitter volume sampled											
		Top		Middle		Bottom		Top		Middle		Bottom	
		Total suspended-sediment concentration, in milligrams per liter (percent of sand)											
		1,000 (20)						3,000 (20)					
14-liter fluorocarbon polymer	<0.50 to 0.250	1,066	(28)	920	(17)	832	(11)	3,288	(29)	2,590	(12)	2,452	(9)
		1,048	(28)	905	(17)	875	(14)	3,016	(26)	2,617	(13)	2,354	(8)
		1,151	(32)	889	(14)	849	(11)	3,255	(29)	2,783	(18)	2,455	(11)
		1,041	(27)	915	(18)	859	(13)	3,503	(33)	2,802	(18)	2,475	(10)
		1,054	(26)	944	(19)	828	(12)	3,005	(25)	2,675	(17)	2,340	(9)
	Mean	1,072	(28)	915	(17)	849	(12)	3,213	(28)	2,693	(16)	2,415	(9)
	Standard deviation	40	(2)	18	(2)	17	(1)	186	(3)	86	(2)	56	(1)
	Bias in fines	–4%	—	–5%	—	–7%	—	–4%	—	–5%	—	–9%	—
	Bias in sands	52%	—	–22%	—	–48%	—	53%	—	–30%	—	–63%	—
	<0.250 to 0.125	978	(24)	930	(20)	899	(17)	2,920	(25)	2,924	(25)	2,415	(13)
		1,063	(27)	1,017	(24)	904	(16)	3,082	(26)	3,047	(25)	2,545	(13)
		1,048	(27)	924	(18)	877	(15)	3,229	(28)	2,780	(20)	2,593	(13)
		1,029	(25)	963	(21)	887	(15)	3,308	(30)	2,898	(21)	2,561	(12)
		1,003	(29)	1,017	(20)	932	(18)	2,999	(24)	2,756	(18)	2,573	(13)
	Mean	1,024	(26)	970	(21)	900	(16)	3,108	(26)	2,881	(22)	2,537	(13)
	Standard deviation	31	(2)	40	(2)	19	(1)	143	(2)	105	(3)	63	(1)
	Bias in fines	–6%	—	–4%	—	–6%	—	–5%	—	–6%	—	–8%	—
	Bias in sands	35%	—	1%	—	–27%	—	36%	—	4%	—	–45%	—
	<0.125 to 0.063	1,054	(27)	966	(23)	848	(17)	3,090	(25)	2,791	(22)	2,772	(21)
		1,123	(29)	929	(18)	826	(13)	2,965	(26)	2,838	(23)	2,578	(18)
		1,011	(25)	988	(23)	869	(19)	3,319	(30)	2,901	(21)	2,795	(19)
		1,058	(26)	992	(22)	945	(20)	3,124	(25)	2,952	(22)	2,658	(18)
		1,027	(25)	998	(22)	950	(20)	3,138	(27)	3,014	(26)	2,589	(17)
	Mean	1,055	(26)	975	(22)	888	(18)	3,127	(26)	2,899	(21)	2,678	(16)
	Standard deviation	38	(2)	25	(2)	51	(3)	114	(2)	79	(2)	90	(1)
	Bias in fines	–3%	—	–5%	—	–9%	—	–4%	—	–4%	—	–7%	—
	Bias in sands	39%	—	6%	—	–21%	—	37%	—	1%	—	–27%	—
	Average fines bias	–4%	—	–5%	—	–7%	—	–4%	—	–5%	—	–8%	—
	Average sands bias	42%	—	–5%	—	–32%	—	42%	—	–8%	—	–45%	—

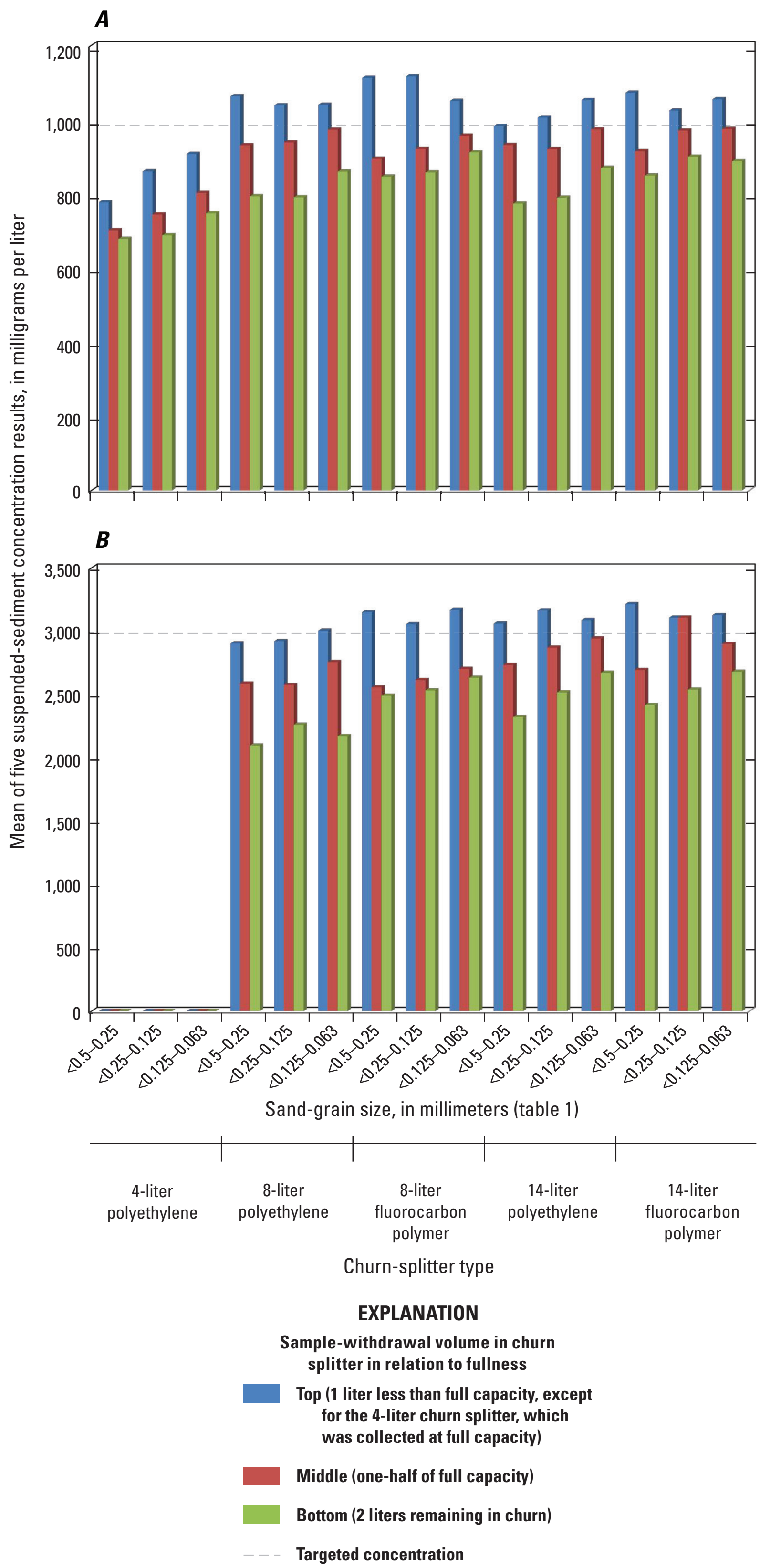


Figure 5. Combination graphs showing the mean of five suspended-sediment concentration results for a targeted concentration of (*A*) 1,000 milligrams per liter and (*B*) 3,000 milligrams per liter, in both cases by sample-withdrawal volume in relation to fullness and sand-grain size by churn-splitter type.

Table 6. Total suspended-sediment concentration results from multiple-withdrawal analysis at targeted concentrations of 1,000 and 3,000 milligrams per liter for all churn splitters by sample set.

[<, less than; top, 1 liter less than full churn capacity; middle, one-half of full churn capacity; bottom, 2 liters remaining in churn]

Set number	Churn splitter volume sampled		Total suspended-sediment concentration, in milligrams per liter					
			1,000			3,000		
			Sand-grain size, in millimeters (table 1)					
			<0.50 to 0.250	<0.250 to 0.125	<0.125 to 0.063	<0.50 to 0.250	<0.250 to 0.125	<0.125 to 0.063
4-liter polyethylene churn splitter								
1	Top		761	862	1,003	—	—	—
	Middle		630	781	856	—	—	—
	Bottom		634	684	791	—	—	—
		Mean	675	776	883	—	—	—
		Standard deviation	61	73	89	—	—	—
2	Top		775	841	889	—	—	—
	Middle		698	742	778	—	—	—
	Bottom		658	664	711	—	—	—
		Mean	710	749	793	—	—	—
		Standard deviation	49	72	73	—	—	—
3	Top		782	802	892	—	—	—
	Middle		694	761	793	—	—	—
	Bottom		751	705	752	—	—	—
		Mean	742	756	812	—	—	—
		Standard deviation	36	40	59	—	—	—
4	Top		756	901	868	—	—	—
	Middle		768	733	791	—	—	—
	Bottom		658	699	736	—	—	—
		Mean	727	778	798	—	—	—
		Standard deviation	49	88	54	—	—	—
5	Top		810	894	884	—	—	—
	Middle		719	702	791	—	—	—
	Bottom		689	686	744	—	—	—
		Mean	739	761	806	—	—	—
		Standard deviation	51	95	58	—	—	—

Table 6. Total suspended-sediment concentration results from multiple-withdrawal analysis at targeted concentrations of 1,000 and 3,000 milligrams per liter for all churn splitters by sample set.—Continued

[<, less than; top, 1 liter less than full churn capacity; middle, one-half of full churn capacity; bottom, 2 liters remaining in churn]

Set number	Churn splitter volume sampled		Total suspended-sediment concentration, in milligrams per liter					
			1,000			3,000		
			Sand-grain size, in millimeters (table 1)					
			<0.50 to 0.250	<0.250 to 0.125	<0.125 to 0.063	<0.50 to 0.250	<0.250 to 0.125	<0.125 to 0.063
8-liter polyethylene churn splitter								
1	Top		1,119	1,035	1,021	2,852	2,904	2,942
	Middle		923	962	970	2,525	2,574	2,789
	Bottom		800	730	850	2,106	2,277	2,031
		Mean	947	909	947	2,494	2,585	2,587
		Standard deviation	131	130	72	305	256	398
2	Top		1,017	1,141	1,061	2,842	3,025	2,956
	Middle		932	935	990	2,575	2,609	2,711
	Bottom		766	771	867	2,017	2,249	2,218
		Mean	905	949	973	2,478	2,628	2,628
		Standard deviation	104	151	80	344	317	307
3	Top		1,079	972	1,023	2,828	3,043	2,916
	Middle		916	909	948	2,642	2,802	2,823
	Bottom		787	776	885	2,074	2,129	2,099
		Mean	927	886	952	2,515	2,658	2,613
		Standard deviation	119	82	56	321	387	365
4	Top		1,067	1,023	1,030	2,735	2,797	3,082
	Middle		928	903	981	2,497	2,445	2,754
	Bottom		790	848	852	2,038	2,074	2,149
		Mean	928	925	954	2,423	2,439	2,662
		Standard deviation	113	73	75	289	295	386
5	Top		1,031	1,020	1,063	3,257	2,839	3,126
	Middle		952	982	974	2,689	2,447	2,703
	Bottom		822	826	843	2,248	2,571	2,362
		Mean	935	943	960	2,731	2,619	2,730
		Standard deviation	86	84	90	413	164	312

Table 6. Total suspended-sediment concentration results from multiple-withdrawal analysis at targeted concentrations of 1,000 and 3,000 milligrams per liter for all churn splitters by sample set.—Continued

[<, less than; top, 1 liter less than full churn capacity; middle, one-half of full churn capacity; bottom, 2 liters remaining in churn]

Set number	Churn splitter volume sampled		Total suspended-sediment concentration, in milligrams per liter					
			1,000			3,000		
			Sand-grain size, in millimeters (table 1)					
			<0.50 to 0.250	<0.250 to 0.125	<0.125 to 0.063	<0.50 to 0.250	<0.250 to 0.125	<0.125 to 0.063
8-liter fluorocarbon polymer churn splitter								
1	Top		1,075	1,045	1,083	3,467	3,017	3,234
	Middle		949	916	964	2,504	2,555	2,498
	Bottom		839	839	895	2,604	2,580	2,765
		Mean	954	933	981	2,858	2,717	2,832
		Standard deviation	96	85	78	432	212	304
2	Top		1,056	1,087	1,031	2,949	3,080	3,247
	Middle		898	926	958	2,478	2,583	2,799
	Bottom		851	847	916	2,504	2,531	2,624
		Mean	935	953	968	2,644	2,731	2,890
		Standard deviation	88	100	48	216	247	262
3	Top		1,163	1,178	1,018	3,159	3,259	3,010
	Middle		896	964	916	2,513	2,670	2,646
	Bottom		859	858	882	2,417	2,580	2,508
		Mean	973	1,000	939	2,696	2,836	2,721
		Standard deviation	135	133	58	329	301	212
4	Top		1,081	1,172	1,056	2,996	2,969	3,205
	Middle		901	919	990	2,556	2,673	2,794
	Bottom		839	884	953	2,430	2,459	2,609
		Mean	940	992	1,000	2,661	2,700	2,869
		Standard deviation	103	128	43	243	209	249
5	Top		1,185	1,098	1,062	3,180	2,947	3,147
	Middle		827	881	953	2,727	2,585	2,772
	Bottom		841	858	912	2,495	2,510	2,654
		Mean	951	946	976	2,801	2,681	2,858
		Standard deviation	166	108	63	284	191	210

Table 6. Total suspended-sediment concentration results from multiple-withdrawal analysis at targeted concentrations of 1,000 and 3,000 milligrams per liter for all churn splitters by sample set.—Continued

[<, less than; top, 1 liter less than full churn capacity; middle, one-half of full churn capacity; bottom, 2 liters remaining in churn]

Set number	Churn splitter volume sampled		1,000: <0.50 to 0.250	1,000: <0.250 to 0.125	1,000: <0.125 to 0.063	3,000: <0.50 to 0.250	3,000: <0.250 to 0.125	3,000: <0.125 to 0.063
			Total suspended-sediment concentration, in milligrams per liter; Sand-grain size, in millimeters (table 1)					
14-liter polyethylene churn splitter								
1	Top		1,031	975	1,037	3,247	3,214	3,122
	Middle		967	925	971	2,719	2,860	3,005
	Bottom		785	775	837	2,400	2,515	2,581
		Mean	928	892	948	2,789	2,863	2,903
		Standard deviation	104	85	83	349	285	232
2	Top		978	1,016	1,013	2,991	3,158	3,025
	Middle		913	916	968	2,692	2,799	2,913
	Bottom		801	778	891	2,269	2,421	2,728
		Mean	897	903	957	2,651	2,793	2,889
		Standard deviation	73	98	50	296	301	122
3	Top		960	1,009	1,167	3,254	3,155	3,218
	Middle		903	921	740	2,776	2,830	2,985
	Bottom		718	765	875	2,326	2,547	2,656
		Mean	860	898	927	2,785	2,844	2,953
		Standard deviation	103	101	178	379	248	231
4	Top		992	1,013	1,014	2,848	3,254	2,980
	Middle		895	881	972	2,810	2,985	2,876
	Bottom		769	815	849	2,294	2,521	2,656
		Mean	885	903	945	2,651	2,920	2,837
		Standard deviation	91	82	70	253	303	135
5	Top		951	1,013	1,031	2,960	3,038	3,096
	Middle		976	959	982	2,665	2,880	2,935
	Bottom		793	813	895	2,318	2,575	2,735
		Mean	907	928	969	2,648	2,831	2,922
		Standard deviation	81	84	56	262	192	148

Table 6. Total suspended-sediment concentration results from multiple-withdrawal analysis at targeted concentrations of 1,000 and 3,000 milligrams per liter for all churn splitters by sample set.—Continued

[<, less than; top, 1 liter less than full churn capacity; middle, one-half of full churn capacity; bottom, 2 liters remaining in churn]

Set number	Churn splitter volume sampled		Total suspended-sediment concentration, in milligrams per liter					
			1,000			3,000		
			Sand-grain size, in millimeters (table 1)					
			<0.50 to 0.250	<0.250 to 0.125	<0.125 to 0.063	<0.50 to 0.250	<0.250 to 0.125	<0.125 to 0.063
14-liter fluorocarbon polymer churn splitter								
1	Top		1,066	978	1,054	3,288	2,920	3,090
	Middle		920	930	966	2,590	2,924	2,791
	Bottom		832	899	848	2,452	2,415	2,772
		Mean	939	936	956	2,777	2,753	2,884
		Standard deviation	97	32	84	366	239	146
2	Top		1,048	1,063	1,123	3,016	3,082	2,965
	Middle		905	1,017	929	2,617	3,047	2,838
	Bottom		875	904	826	2,354	2,545	2,578
		Mean	943	995	959	2,662	2,891	2,794
		Standard deviation	75	67	123	272	245	161
3	Top		1,151	1,048	1,011	3,255	3,229	3,319
	Middle		889	924	988	2,783	2,780	2,901
	Bottom		849	877	869	2,455	2,593	2,795
		Mean	963	950	956	2,831	2,867	3,005
		Standard deviation	134	72	62	328	267	226
4	Top		1,041	1,029	1,058	3,503	3,308	3,124
	Middle		915	963	992	2,802	2,898	2,952
	Bottom		859	887	945	2,475	2,561	2,658
		Mean	938	960	998	2,927	2,922	2,911
		Standard deviation	76	58	46	429	305	192
5	Top		1,054	1,003	1,027	3,005	2,999	3,138
	Middle		944	1,017	998	2,675	2,756	3,014
	Bottom		828	932	950	2,340	2,573	2,589
		Mean	942	984	992	2,673	2,776	2,914
		Standard deviation	92	37	32	271	174	235

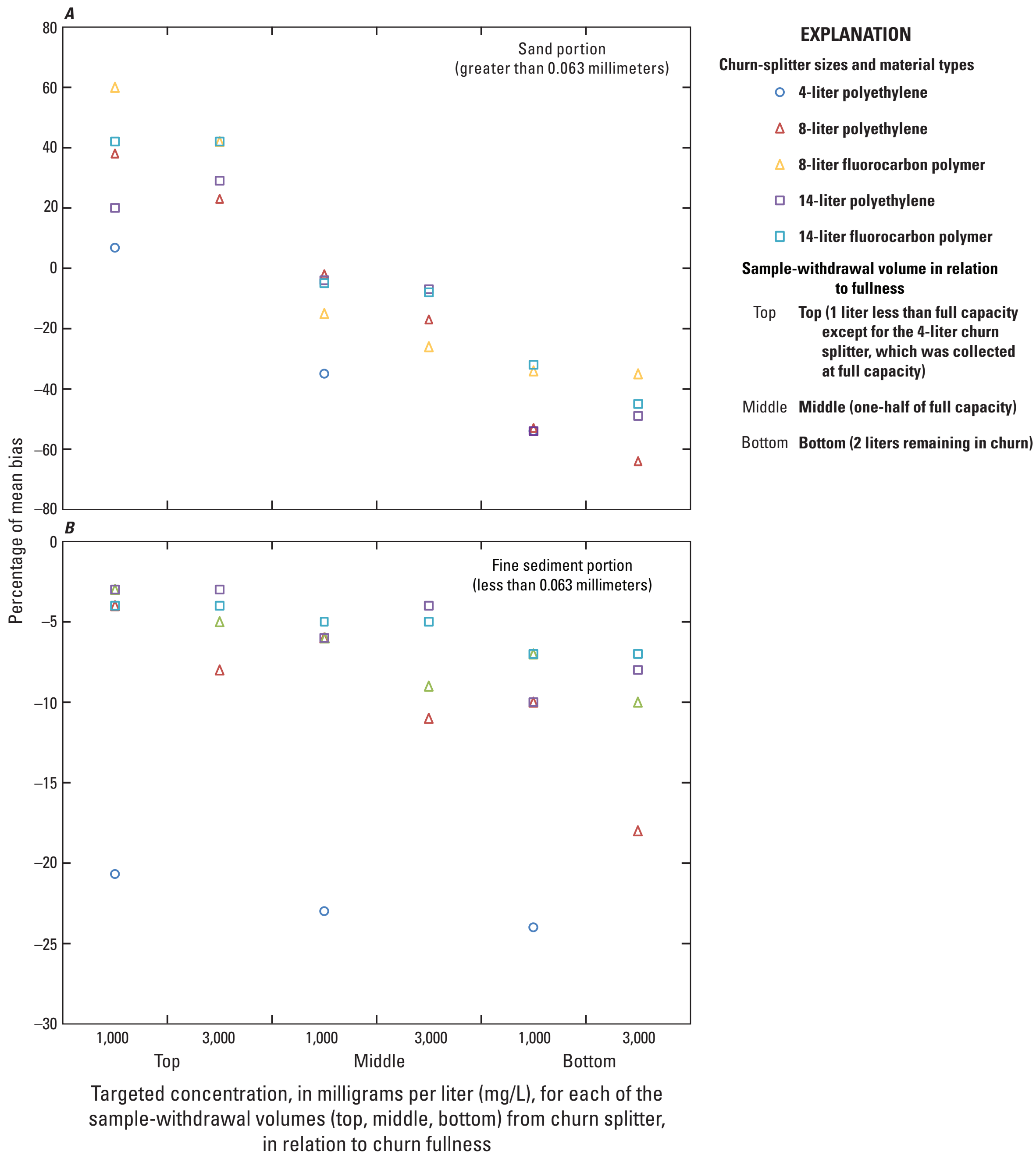


Figure 6. Symbol graphs showing the percentage of mean bias for five (*A*) sand and (*B*) fine-sediment portions. In both cases, the mean bias is shown for targeted suspended-sediment concentrations of 1,000 and 3,000 milligrams per liter for each churn splitter.

liter (from the 8- and 14-L churns), the top-level sample, and the remaining discarded water depletes the sand mass, leaving concentrations in the churns biased low, as indicated in the mid- and bottom-level samples. These results indicate that samples for suspended sediment and constituents absorbed into suspended sediment have extensive bias errors when withdrawn from churn splitters.

The volume of, and withdrawal location on, churn splitters also affects the concentration of fine sediment. The fine concentrations do not have a positive bias for the top withdrawals because material of this size is usually kept in full suspension by the churning process (table 5; fig. 6). The negative bias is partially due to the loss of sediment mass noted in the discussion of single-withdrawal results. The reason for this trend in increasing negative bias, from top to middle to bottom sample location, is uncertain. It is possible that sand, regardless of size, is more difficult to retain in suspension with the churn disk as the water volume in the churn decreases, as defined by Stokes' Law, which states that the force required to move a sphere through a given viscous fluid at a low uniform velocity is directly proportional to the velocity and radius of the sphere (Rumble, 2017). A similar observation was noted in Horowitz and others (2001), where a more accurate concentration was obtained if churns were drained between one-third and one-half capacity before collection of a whole-water sample, yet the grain-size distribution did not represent an overestimation of the fine sediments, and an underestimation of the sands would occur. There is a statistically significant difference in fine-sediment concentration bias results between the combined 8- and 14-L churns at a 5-percent threshold significance (p-value = 0.02) and a strong difference in the 4-L versus the 8- and 14-L churns. The reason for the high negative bias (–22 percent mean; fig. 6) in the fine-sediment concentration for the top, middle, and bottom samples for the 4-L churn is uncertain.

Summary

The U.S. Geological Survey collects numerous suspended-sediment data for many physical and chemical analyses to define stream conditions at the time of sampling. Using the preferred methods for sample collection, in which suspended sediment is a primary component, provide results that better represent stream conditions at the time of sampling. However, during sampling efforts in which a suspended-sediment concentration is one result among a broader suite of constituents, a composited sample is sometimes subdivided into subsamples for analysis. Individual samples are collected along a cross-section in a stream or river and composited inside a churn splitter to obtain a representative sample. Whole-water subsamples drawn from the churn splitter are expected to represent the composite sample with regard to suspended and dissolved concentrations of target analytes that are equal to those in every other subsample. Polyethylene churn splitters (or poly churns) are available in 4-, 8-, or 14-L volumes; fluorocarbon-polymer churns (or polymer churns) are available in 8- and 14-L volumes. Previous studies, although limited, compared the efficiencies of various churn sizes and material types. As sampling protocols progressed over the previous decade, a reevaluation of the efficiency inherent to all churn splitters was needed to determine the accuracy of suspended-sediment concentration and particle-size analysis measurements. Two tests were performed to quantify the capabilities of each churn volume and determine if material types affected churn-splitter performance. The tests used single-withdrawal and multiple-withdrawal analyses. A total of 185 samples were analyzed during the single-withdrawal test, and 425 samples were analyzed during the multiple-withdrawal test.

A single-withdrawal test determined the efficiency of all churns at one-half of full capacity at a range of targeted concentrations: 50, 100, 250, 500, 1,000, 3,000, 5,000, and 10,000 milligrams per liter (mg/L). A consistent sand-grain size distribution of very fine sand (<0.125 to 0.063 millimeter [mm] in diameter) was used for all targeted concentrations from 50 to 3,000 mg/L. For targeted concentrations of 5,000 and 10,000 mg/L, an equal mix of medium to very fine-grained sand (<0.5 to 0.063 mm) was used. For all target concentrations, the sand-sized portion made up 20 percent of the total sample mass.

The churn test results were affected by the settling velocity of sediment particles relative to the resuspension velocities induced by the churning and by the effects of prior withdrawals of the water-sediment mixture. The settling velocity of sediment particles depends on opposing gravitational and drag forces on the sediment particle related to particle and fluid characteristics. In addition to particle settling velocity and previous withdrawals, the results were affected by a loss of sediment mass in the sample handling and transferal process, with the loss being fine-sized sediment (<0.063 mm). This loss was, usually, a small absolute mass, but it could be a substantial, relative percentage of the total mass for low concentrations, particularly at concentrations <20 mg/L.

The single-withdrawal results indicate differences based on churn volume. The 8-L results had a greater negative bias than the 14-L results, but there was a considerable scatter of results. A significant difference in sediment concentrations withdrawn from the poly churns versus the polymer churns was not revealed, as sediments did not behave differently with the two materials. Statistical comparisons were not made for the 4-L results because of the small sample size. However, the results from the 8- and 14-L comparisons can be reasonably extrapolated to show that the 4-L churn volume may have a greater negative bias than either the 8- or 14-L churns.

The multiple-withdrawal test results contain much more information than the single-withdrawal test results. It was noted that the remaining volume (or withdrawal location) in a churn splitter had a great influence on the sand concentration of withdrawn samples. The mean sand-concentration bias in the top, middle, and bottom withdrawals were +34 percent,

–13 percent, and –47 percent, respectively, for the combined multiple-withdrawal churn tests. The reason for the positive bias in the top-level sample is that sand particles settle more rapidly than they are resuspended so that sand concentrations increase across the depth of the churn and higher concentrations are near the churn spigot. Each removal of water-sediment mixtures from the churn splitter—the initial withdrawal, the top sample, and the discarded volume to the proceeding sample withdrawal—depleted the sand mass, leaving concentrations in the churns biased low, as indicated in the middle- and bottom-level samples. These results indicate that samples taken for suspended sediment and constituents absorbed into suspended sediment have extensive bias errors when withdrawn from churn splitters. The volume and the withdrawal location of churn splitters also affected the concentration of fine sediment. The fine-sediment concentrations do not have a positive bias for the top withdrawals because material of this size usually stays in full suspension because of the churning process. The negative bias in the fine-sediment concentrations is partially due to the loss of sediment mass noted in the discussion of single-withdrawal results. The reason for the trend of increasing negative bias from the top to middle to bottom sample location is uncertain. There was a statistically significant difference in fine-sediment concentration bias results between the combined 8- and 14-L churns and a strong difference in the 4-L versus the 8-L and 14-L churns. The reasons for the high negative bias in fine-sediment concentrations for the top, middle, and bottom samples for the 4-L churn are uncertain.

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