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Taihoro Nukurangi

Review of suspended sediment measurement techniques

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Prepared by:
Arman Haddadchi

For any information regarding this report please contact:

Arman Haddadchi
Sediment transport scientist
Sediment Processes
+64-4-343 7896
arman.haddadchi@niwa.co.nz

National Institute of Water & Atmospheric Research Ltd
PO Box 8602
Riccarton
Christchurch 8011

Phone +64 3 348 8987

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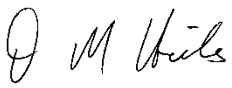	Reviewed by:	Murray Hicks
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Executive summary

This report responds to a request from Tasman District Council to provide a brief review of methodologies and equipment deployed by the United States Geological Survey for the measurement of suspended sediment in rivers. The output of this report will be used to underpin the National Environmental Monitoring Standard (NEMS) for suspended sediment monitoring in New Zealand that is currently in preparation.

To obtain consistent sediment data, the Federal Inter-Agency Sedimentation Project (FISP) was established in the United States to standardize the sediment data-collection equipment, methods, and analytical techniques. The techniques for suspended sediment measurement used by the United States Geological Survey (USGS) and other federal agencies follow the instructions and the guidelines developed by the FISP.

This report provides a description of well-established and more recent techniques for collection and measurement of suspended sediment data including:

- Isokinetic suspended sediment samplers including depth-integrating and point-integrating sampling techniques. This report reviews a full list of samplers developed by the FISP from the earlier designed depth-integrated samplers such as the US D-49 to the more recently developed collapsible bag-type samplers such as US D-96 and US DH-2 samplers.
- Non-isokinetic samplers including open-mouth, thief, single-stage, and automatic pumping water samplers.
- Surrogate technologies used by the United States Geological Survey including turbidity (bulk optics), acoustic backscatter, laser diffraction, and pressure differences.

Where appropriate, the theory behind the development of the equipment and guidelines for its use are presented.

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1 Introduction

The United States Geological Survey (USGS) defines fluvial sediment as “fragmentary material that originates mostly from weathering of rocks and is transported by, suspended in, or deposited by water” (Federal Inter-Agency Sedimentation Project 1963).

Streams usually transport sediments by maintaining the finer particles in suspension with turbulent fluctuations in the flow (suspended load) and by sliding, rolling or skipping the coarser particles along the streambed (bed load). Generally, suspended sediments move downstream at about the same velocity as the water, whereas bed load transport may occur only occasionally during high-flow events (Haddadchi, Omid et al. 2013).

Estimates of sediment transport rate are needed to:

- Determine the annual sediment load.
- Calculate sediment budgets.
- Estimate quantities of gravel extraction or augmentation.
- Assess stream response to changes in water and sediment supply (e.g., landslides, land use change, or reservoir flushing).
- Determine the impact of sediment supply changes on receiving waters.
- Predict channel change based on the rates of sediment transport.

This project responds to a request from Tasman District Council to provide a brief review of methodologies and equipment deployed by the United States Geological Survey for the measurement of suspended sediment in rivers. The output of this report will be used to underpin the National Environmental Monitoring Standard (NEMS) for suspended sediment monitoring in New Zealand that is currently in preparation.

This report focuses on collection and measurement of suspended sediment data. It includes descriptions of manual suspended sediment samplers and methods for their deployment developed by the Federal Interagency Sedimentation Project (FISP) and the USGS and also a summary of surrogate technologies being used or tested for suspended sediment measurements by the FISP, USGS and other researchers.

2 Suspended sediment samplers and sampling methods

The purpose of a suspended sediment sampler is to collect a representative sample of the water-sediment mixture moving in the stream near the sampler intake. There are two main categories of the suspended sediment samplers: isokinetic samplers and non-isokinetic samplers.

Isokinetic samplers include depth-integrated and point-integrated suspended sediment samplers. Non-isokinetic samplers include open-mouth, thief, single-stage and automatic water samplers.

2.1 Isokinetic samplers

It has been found that a deviation in intake velocity of the sampler nozzle from the stream velocity causes an error in the sediment concentration of the sample, especially for coarser (sand-sized) particles (Federal Inter-Agency Sedimentation Project 1941). In order to collect a sample representative of the mean discharge-weighted sediment concentration, the intake velocity within the sampler nozzle must be equal to the stream velocity approaching the sampler. Therefore, appropriate nozzles as designed for a particular series of suspended samplers must be used (Davis 2005). A complete list of isokinetic samplers developed by the FISP are given in Figure 2-1.

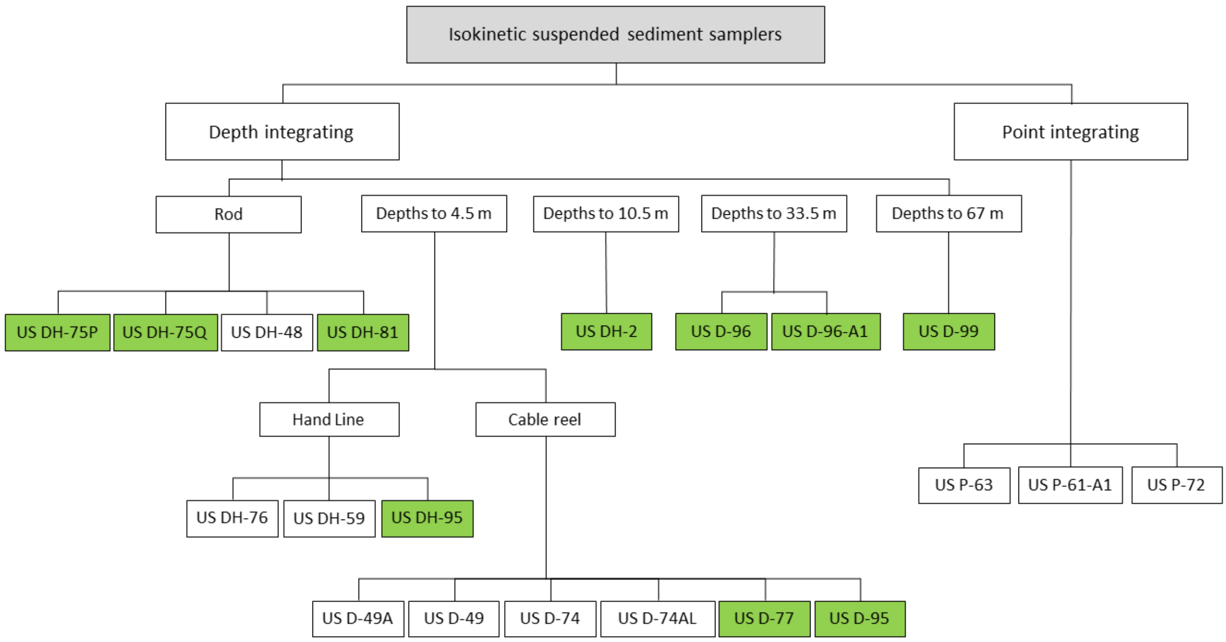

Figure 2-1: Isokinetic suspended samplers categorized based on the effective sampling depth and the type of suspension system. Green coloured boxes indicate the samplers that can be used for water quality sampling as well as suspended sediment measurements.

Generally, for collection of an isokinetic sample, the minimum stream velocity must be greater than 0.46 m/s for the rigid bottle depth-integrating samplers, or 0.61 m/s for the bag-type depth-integrating samplers such as US D-96 or US D-99 (Wilde, Radtke et al. 1998).

Finer particles are uniformly distributed throughout the vertical depth, and coarser particles are concentrated near the streambed (Leopold, Wolman et al. 1964). To obtain representative samples with the range of particle sizes similar to suspended sediment transported in streams, the sampler nozzle must reach to a point as close to the streambed as physically possible. Depending on the type of sampler, nozzle distance from the bottom of the river varies between 7.62 to 17.78 centimetres, as listed in **Error! Reference source not found.**.

The depth-integrated and point-integrated suspended samplers developed by the FISP are designated by the following codes:

- US: United States standard sampler (this code will appear in the initial reference).
- D: depth integrating.
- P: point integrating.
- H: hand-held by rod or line.
- PS or CS: pumping-type samplers.
- Year: last two digits of the year in which the sampler was developed.

Table 2-1: A complete list of isokinetic samplers and their characteristics developed by FISP.

Sampler type	Weight, kg (lbs)	Suspension type	Shape/type of container (bottle)	Intake nozzle size (inch)	Maximum Depth, m (ft)	Velocity range, m/s	Nozzle distance from streambed, cm (in)	Sampler container size in litre	Water Quality
US DH-2	13 (29)	Handline	Quart/flexible bag	5/16	4 (13)	0.6-1.8 (2-6)	8.9 (3.5)	1	Yes
				1/4	6.1 (20				
				3/16	10.5 (30)				
US DH-48	1.6 (3.5)	Rod	Pint/rigid	1/4	2.8 (8.9)	0.46 -2.7 (1.5-8.9)	9 (3.5)	0.47	No
US D-49	28 (62)	Reel and cable	Round/glass	1/8	4.6 (15)	0.46-2 (1.5-6.6)	10.2 (4)	0.47	No
				3/16	4.6 (15)				
				1/4	9				
US D-49A	19 (42)	Reel and cable	Round/glass	1/8	4.6 (15)	0.46-2 (1.5-6.6)	10.2 (4)	0.47	No
				3/16	4.6 (15)				
				1/4	9				
US DH-59	10.9 (24)	Handline	Round	1/8	4.6 (15)	0.46-1.53 (1.5-5)	11.5 (4.5)		No
				3/16					
				1/4					
US D-74	28 (62)	Reel and cable	Round or quart/glass	1/8	4.6 (15)	0.46-2 (1.5-6.6)	10.4 (4.1)	0.47	No
				3/16					
				1/4					
US D-74AL	19 (42)	Reel and cable	Round or quart/glass	1/8	4.6 (15)	0.46-2 (1.5-6.6)	10.9 (4.3)	0.47	No
				3/16					

				1/4					
US DH-75P	0.7 (1.5)	Rod	Pint/plastic	3/16	4.6 (15)	0.46-2 (1.5-6.6)	8.3 (3.3 in)		Yes
US DH-75Q	0.7 (1.5)	Rod	Quart/plastic	3/16	4.6 (15)	0.46-2 (1.5-6.6)	11.4 (4.4)		Yes
US DH-76	11.3 (25)	Handline	Quart	1/8	4.6 (15)	0.46-1.53 (1.5-5)	9 (4)		No
				3/16					
				1/4					
US D-77	34 (75)	Reel and cable	Round/plastic	5/16	5.2	0.31-2.13 (1-7)	17.8 (7)		Yes
US DH-81	0.23 (0.5)	Rod	Pint	3/16	4.6 (15)	0.6-1.89 (2.0-6.2)	Depend on bottle size		Yes
				1/4		0.46-2.3 (1.5-7.6)			
				5/16		0.6-2.1 (2.0-7.0)			
US DH-95	13.1 (29)	handline	Teflon	3/16	4.6 (15)	0.52-2.26 (1.7-7.4)	12.2 (4.8)	0.8	Yes
				1/4					
				5/16					
US D-95	29 (64)	Reel and cable	Quart and pint/flexible bag	3/16	4.6 (15)	0.52 -2.25 (1.7-7.4)	12.2 (4.8)	0.8	Yes
				1/4	4.6 (15)				
				5/16	4 (13.3)				
US D-96	60 (132)	Reel and cable	Toothpaste tube type/plastic	3/16	33.5 (110)	0.61-3.8 (2-12.5)	10.2 (4)	3	Yes
				1/4	18.3 (60)				
				5/16	11.9 (39)				
US D-96-A1	37.2 (82)	Reel and cable	Toothpaste tube type/plastic	3/16	33.5 (110)	0.61-1.83 (2-6)	10.2 (4)	3	Yes
				1/4	18.3(60)				
				5/16	11.9 (39)				
US D-99	124.7 (275)	Reel and cable		3/16	67 (220)	0.91-4.6 (3-15)	24.1 (9.5)	6	Yes
				1/4	36.6 (120)				

				5/16	23.8 (78)			
US P-61-A1	47.6 (105)	Reel and cable	Quart	3/16	36.6 (120) quart	0.46-3.05 (1.5-10)	10.9 (4.29)	Yes
			Pint		54.9 (180) pint			
US P-63	90.7 (200)	Reel and cable	Quart	3/16	36.6 (120) quart	0.46-4.6 (1.5-15)	15 (5.91)	Yes
			Pint		54.9 (180) pint			
US P-72	18.6 (41)	Reel and cable	Quart	3/16	15.5 (51) quart	0.46-1.61 (1.5-5.3)	10.9 (4.29)	Yes
			Pint		21.9 (72) pint			

2.1.1 Depth-integrating samplers

Depth integrating samplers are designed to isokinetically and continuously accumulate a representative sample from a stream vertical (Federal Inter-Agency Sedimentation Project 1952). Depth-integrating samplers collect a discharge-weighted sample as they are lowered at a uniform rate from the water surface to the streambed, instantly reversed, and then raised up the vertical again to the water surface.

US DH-2

The US DH-2 is a handline suspended sediment sampler capable of collecting a one litre sample to a maximum depth of 10.5 m (using a 3/16 inch internal diameter nozzle). It also can be used for water quality sampling. The sampler works in stream velocities ranging from 0.6 to 1.83 m/s.

The DH-2 has a collapsible bag. During depth integration sampling, a collapsible bottle or bag would be the ideal arrangement to eliminate the problem of depth limitation due to the size of the sample container (Federal Inter-Agency Sedimentation Project 2013a). Depth-integrating samplers incorporating a collapsible bottle concept were more recently developed by the FISP and used throughout the Water Resources Division of the USGS.

US DH-48

The US DH-48 was one of the first samplers designed by the FISP. The US DH-48 is a lightweight hand-held depth-integrating sampler used for the collection of suspended sediment samples in wadable streams. This instrument is calibrated with an intake nozzle of 1/4 inch in diameter. The un-sampled zone using the US DH-48 is 9 cm. The sampler can be used in velocities that range from 0.46 to 2.7 m/s.

A standard 1/2 inch diameter wading rod is threaded into the top of the sampler body for suspending the sampler. To sample to depths greater than can be waded, wading rod extensions in 0.3- and 0.9-metre lengths can be added to the sampler. With the extensions, the sampler can be deployed from a low bridge or boat.

US D-49 and US D-49A

The US D-49 and US D-49A are older versions of the D-74 and D-77 samplers and were used for depth-integrated sediment sampling when streams cannot be waded, but are shallower than about 4.6 m. These samplers are no longer manufactured by the FISP but are mentioned in this report because many of these earlier designed instruments are still used at some locations around the world and in New Zealand.

The head of the sampler is drilled and tapped to receive a 1/4 inch, 3/16 inch or 1/8 inch intake nozzle which points into the current for collecting the sample. The US D-49 sampler, weighing 28 kg with a cast bronze streamlined body, is heavier than the D-49A model which is cast from aluminium (19 kg). A round or square pint-bottle sample container is enclosed for both samplers. The US D-49 is suitable for depth integration of streams with velocities less than 2 m/s. The D-49 replaced the D-43 sampler for general use.

US DH-59

The US DH-59 is a medium-weight hand-line suspended sediment sampler. This sampler is designed for the use in shallow but unwadable streams with velocities ranging from 0.46 m/s to 1.5 m/s. It can be used in stream depths up to 4.6 m. Sediment can be collected to within 11.5 cm of the stream bed. Intake nozzles of l/8 inch, 3/16 inch, and l/4 inch diameters are calibrated for use with these samplers and may be interchanged as necessary when varying flow conditions are encountered.

US D-74

The US D-74 is a 28 kg cable-suspended sediment sampler. The sampler is a more recent version of the D-49 sampler. The only differences between the D-74 and D-49 samplers are the shape and size of their sample container. The D-49 uses a 470 ml round bottle, but the D-74 will accommodate either round or squared pint-bottle containers.

The D-74 sampler is lowered and raised from a bridge crane or cableway by means of a standard hanger bar and reel and cable suspension system. The sampler can be used in stream depths up to 4.6 m and in stream velocities ranging from 0.46 to 2 m/s. Distance between nozzle intake and streambed is 10.4 cm. Intake nozzles of 1/8, 3/16 and 1/4 inch internal diameters are available to project into the stream current for collecting samples.

US D-74AL

The US D-74AL sampler is a lighter version (19 kg) of the D-74 with aluminium casting. Similar to the D-74, intake nozzles with three different diameters are available for use with the D-74AL sampler and can be interchanged as varying flow conditions dictate. The head of both D-74 and D-74AL samplers are hinged at the bottom and swings downward to provide access to the sample container chamber and change the container bottles during the normal sampling routine.

US DH-75

The US DH-75 series are lightweight, freeze-resistant samplers for collection of samples where a wading-rod suspension system is required. They were designed for use in sub-freezing winter conditions and use under ice cover. The open sheet-metal body of this sampler provides easier removal of the sampler container when ice forms over the sampler as it leaves the stream. Their low mass also defrosts more rapidly than the similar light-weight handheld samplers such as the US DH-48.

Two versions of the sampler, the DH-75P and DH-75Q accept plastic containers of pint and quart type, respectively. The sampler only works with the 3/16 inch nozzle. The DH-75Q sampler is a modification of the DH-75P allowing it to tilt to a vertical position to permit use through a 15 cm ice hole to obtain the suspended sediment samples. The sampler weighs 0.4 kg excluding the sample container. The instrument can sample to 8.3 cm and 11.4 cm of the stream bed using pint and quart containers, respectively.

US DH-76

The US DH-76 is a more recent version of the DH-59 sampler which designed to take a quart glass bottle sample container for additional sample volume. The tail assembly extends below the body of the casting to ensure sampler alignment parallel to the flow direction with the intake nozzle. Similar to its lighter version (i.e., DH-59), the sampler uses 1/8 inch, 3/16 inch, and 1/4 inch internal diameter nozzles.

These medium-weight handline samplers (i.e., DH-76 and DH-59) are the most commonly used for sediment sampling during normal flow in small and, perhaps, intermediate-sized streams. Because they are small, light, durable, and adaptable, they are preferred by hired observers and field people on routine or reconnaissance measurement trips.

US D-77

The US D-77 sampler can be used in most streams with low to moderate velocities from 0.31 to 2.13 m/s and at depths to about 5.2 m. The nozzle of 5/16 inch diameter are recommended for use with this sampler. The distance between the nozzle and the sampler bottom is 17.8 cm.

The design of this sampler is different from the D-74 and its predecessors (i.e., D-49 and D-43). This sampler is constructed without a head assembly to cover the mouth of the container. Instead, a cap, nozzle, and air-exhaust assembly, which are made from autoclavable plastic, are screwed onto the mouth of the sample container at the front of the sampler.

The sample bottle is made of autoclavable plastic to make it possible to collect a depth-integrated sample for water quality (bacteriological) analyses. The large three litre bottle makes collection of a large volume of water easier and faster than with any other available depth-integrating sampler.

US DH-81

The US DH-81 is a sediment and water quality sampler fabricated using parts from other FISP samplers, including the DH-81A adaptor and the cap and nozzle of the D-77 sampler.

The US DH-81 sampler will collect samples at an acceptable inflow efficiency in stream velocities ranging from 0.6 to 1.89 m/s with a 3/16 inch nozzle, 0.46 to 2.3 m/s with a 1/4 inch nozzle, and 0.6 to 2.1 m/s with a 5/16 inch nozzle. The sampler will collect samples to a maximum depth of 3.66 m using a 800 ml bottle. Also, by collecting up to 1 litre of sample, it can be used to a depth of 4.6 m.

The height of the unmeasured zone will vary depending on the size of bottle used. Similar to the DH-75, the DH-81 sampler is useful for sampling in cold weather conditions.

US DH-95

The US D-77 sampler is difficult to use properly because the transit rates at which the sampler is raised and lowered are very low (United States Geological Survey 1998). Therefore, the US DH-95 sampler was developed to meet the requirement for a faster transit rate and make the sampler easier to use properly. The sampler is capable of collecting non-contaminated samples for trace-element analysis (Wilde, Radtke et al. 1998). The sampler weighs approximately 13.1 kg. The DH-95 sampler collects water-sediment samples at acceptable inflow efficiencies and remains stable in stream velocities ranging from 0.52 to 2.26 m/s. The sampler can be used in stream depths up to 4.6 m. The distance between the centreline of the nozzle and the streambed, is 12.2 cm. Three nozzles are available including 3/16, 1/4, and 5/16 inch. The recommended sample volume to be collected with the US DH-95 sampler is 800 ml.

US D-95

The US D-95 is used to collect water samples where flowing water should not be waded. The sampler is lowered and raised by means of a suspension system such as a reel and crane or bridge board. Depending on the nozzle diameters used, the sampler operates properly in flow velocities exceeding 0.52 m/s but no greater than 2.25 m/s.

The sampler should be used in water less than 4 to 4.6 m deep, depending on the nozzle (i.e., nozzles with 3/16, 1/4, and 5/16 inch internal diameter) used and altitude at the site for an isokinetic, depth-integrated sample. The sampler weighs 64 pounds and the recommended sample volume to be collected with the US D-95 sampler is 800 ml. The unsampled zone using the US D-95 is 12.2 cm.

US D-96

The US D-96 is a collapsible-bag sampler capable of collecting a 3 litre sample. Like the handheld DH-81 and DH-95 samplers, this sampler can be used for collecting inorganic and organic samples (water quality sampling).

The US D-96 sampler, weighing 60 kg, will collect acceptable flow-weighted samples in velocities exceeding 0.61 m/s but no greater than 3.8 m/s. It can be used in water with a maximum depth of 11.9 m with a 5/16 inch internal diameter nozzle, 18.3 m with a 1/4 inch internal diameter nozzle, and 33.5 m with a 3/16 inch internal diameter nozzle. The unsampled zone using the US D-96 sampler is 10.2 cm. Water temperature must be at or greater than 4°C. However, the sampler performs sub-isokinetically at temperatures less than about 10°C at velocities less than about 1.13 m/s. (Federal Inter-Agency Sedimentation Project 2013a).

US D-96-A1

The US D-96-A1 is a lighter (37.2 kg) version of the D-96 sampler with similar dimension, design and casting materials (i.e., fabricated from aluminium and bronze castings with a high-density polyethylene tail). The main difference is that the D-96-A1 sampler works to a maximum velocity of 1.83 m/s, while the maximum flow velocity for the D-96 sampler is 3.8 m/s. The US D-96-A1 sampler is theoretically capable of sampling to depths similar to the D-96 sampler using different nozzles. However, in streams with high velocities, the obtainable sampling depths will likely be less than theoretical depth due to the large drift angle created by the sampler in high stream velocities (Federal Inter-Agency Sedimentation Project 2013a).

US D-99

The US D-99 is the heaviest (124.7 kg) depth integrated suspended sediment/water quality sampler, with a collapsible bag capable of collecting a 6 litre sample. The sampler will collect samples in stream velocities ranging from 0.91 to 4.6 m/sec. However, extreme care should be practiced when deploying the sampler at stream velocities above 3.05 m/s. The sampler works properly to a maximum depth of 23.8 m with a 5/16 inch internal diameter nozzle, 36.6 m with a 1/4 inch internal diameter nozzle, and 67 m with a 3/16 inch internal diameter nozzle. Because the US D-99 uses a large 6 litre perfluoroalkoxy (PFA) or polyethylene bag that is placed in a chamber behind the nozzle, through an access door, the distance of the nozzle from the riverbed increases to 24.1 cm. Similar to the D-96 series sampler, water temperature must be at or greater than 4°C (Wilde, Radtke et al. 1998).

2.1.2 Point-integrating samplers

The point-integrating samplers are designed to collect through time a sample at a given point in the stream vertical, as well as to integrate over a range in depth. As suggested by the FISP, point-integrating samplers can be used for depth integration sampling of “streams too deep in a continuous round-trip integration by starting the sampling at any depth and proceed either upward or downward from that initial point through a maximum vertical distance of 10 m” (Federal Inter-Agency Sedimentation Project 1963).

A remotely operated rotary valve opens and closes the sampler. During the sampling period, the valve is opened and the air escapes the sampler at a nozzle intake velocity nearly equal to the local stream velocity. All point-integrating samplers listed in this report can be used for collecting trace-element samples. Testing indicates that these samplers contaminate samples with measurable concentrations of trace elements (Wilde, Radtke et al. 1998)

US P-61-A1

The US P-61-A1, weighing 47.6 kg, is a point-integrating suspended sediment sampler with an electrically operated valve for starting and stopping the collection of a sample. The sampler can be used for depth integration as well as point integration to the maximum recommended depth for different container types. The sampler uses a 3/16 inch internal diameter nozzle and can be used in stream velocities ranging from 0.46-3.05 m/s. The maximum sampling depth is about 36.6 m using the quart container and 54.9 m with the pint container.

US P-63

The US P-63 differs from the P-61 mainly in size and weight. The P-63 is a 90.7 kg point-integrating sampler and is better adapted to high velocities. The maximum sampling depth is the same as for the P-61, about 54.9 m with a pint sample container and about 36.6 m with a quart container. The sampler uses a 3/16 inch internal diameter nozzle and can be used in stream velocities ranging from 0.46-4.6 m/s.

US P-72

The US P-72 is a light version of the P-61 weighing 18.6 kg. The sampler uses a 3/16 inch internal diameter nozzle and the range of velocities at which the P-72 is recommended for use is 0.46-1.61 m/s. It can be used to a depth of 21.9 m with a pint container and 15.5 m with a quart container. These maximum depths are less than one-half of the maximum usable depths for the P-61 with the same container sizes.

2.1.3 Sampling methods

Commonly, sediment samples collected by isokinetic suspended sediment samplers will be used to determine the instantaneous mean discharge-weighted suspended sediment concentration at a cross section. Sediment concentrations derived from the samplers together with the water discharge measurements will be used to compute suspended sediment discharge.

The International Standard Organization (ISO) (1993) lists three methods for suspended sediment data collection in a cross section including the equal-discharge-increment, equal-width-increment, and equal-area-increment methods. In this report, the first two methods are described in following subsections as the third method (i.e., equal-area-increment) has been rarely used by the USGS or other researchers.

2.1.4 The Equal-Discharge-Increment (EDI) method

With the equal-discharge-increment method, samples are obtained from the locations representing equal increments of discharge. The first step in the EDI method is to derive the distribution of discharge in the cross section prior to selecting sampling intervals. The distribution of streamflow can be derived from immediate discharge measurement or, if the channel is relatively stable, from a long period of discharge record.

The mean discharge-weighted suspended sediment concentration for the whole cross section using the EDI method (C_m) equals the arithmetic mean of the concentrations of the vertical samples:

$$C_m = \frac{1}{n}\sum_{i=1}^{n} C_i$$

Where n is the number of verticals used in the EDI method and C_i is the concentration in the vertical *i* (i.e., concentration of each sample).

The standard deviation of the sediment concentration (s_c), to indicate the cross-channel variation in concentration, is calculated as:

$$s_c = \left(\sum_{i=1}^{n} (C_i - C_m)^2 \Big/ (n-1) \right)^{0.5}$$

The EDI method requires a minimum of four and maximum of nine verticals. More sampling verticals are required in the cross sections with the greater potential heterogeneity in the distribution of suspended sediment concentrations and particle size distributions. The field person can estimate the locations of sampling verticals by plotting the cumulative discharge against sample-station widths. The descending and ascending transit rates need not be equal in both directions, but the rates must remain constant during each phase.

The USGS (1998) considers the EDI sampling technique as the most universally applicable and useful discharge-weighted sampling method.

2.1.5 The equal width increment method

A cross-sectional suspended sediment sample obtained by the equal-width-increment (EWI) method requires a sample volume proportional to the amount of flow at each of equally spaced verticals in the cross section (Edwards and Glysson 1999).

The mean discharge-weighted suspended sediment concentration in a cross section using the EWI method is found by summing the total mass of sediment and total volume of sample:

$$C_m = \sum_{i=1}^{n} M_i \Big/ \sum_{i=1}^{n} V_i$$

Where M is the mass and V is the volume of each individual sample (i). Note that where samples are bulked, C_m equals the concentration of the bulked sample.

The number of verticals (n) required for an EWI sediment discharge measurement depends on:

- The distribution of sediment concentrations in the cross section at the time of sampling.
- The distribution of water discharge in the cross section at the time of sampling.
- The desired accuracy of the results.

The distance between verticals is determined by dividing the stream width by the number of verticals needed to collect a discharge-weighted suspended sediment sample representative of the sediment concentration of the streamflow in the cross section. The locations of the two left- and right- channel bank verticals are at a distance of one-half of the total width divided by the number of verticals. The locations of the middle verticals are separated from bank verticals by a distance of the total width divided by the number of verticals.

2.1.6 Point-integrated sampling methods

If point samples are collected to define the mean concentration in a vertical, 5 to 10 samples should be collected from the vertical. The sampling time for each sample (i.e., the elapsed time that the nozzle is open) must be equal. This result will ensure that the sample volumes collected are proportional to the flow at the point of collection. These samples may be composited for a single laboratory analysis. If the EDI method is used to define the location of the verticals within the cross-section, the sampling time may be varied among the verticals. If the EWI method is used, a constant time for collecting samples from all verticals must be used (Edwards and Glysson 1999).

2.2 Non-isokinetic sampler

Non-isokinetic samplers are devices in which the sample enters the device at a velocity that differs from the ambient stream velocity.

2.2.1 Open-mouth samplers

Open-mouth samplers used for the collection of water-sediment mixture samples include the hand-held bottle, the weighted-bottle sampler, the biochemical oxygen demand (BOD) sampler, and the volatile organic compound (VOC) sampler.

- The hand-held open-mouth bottle sampler is the simplest type of suspended sediment sampling technique. In this method, a bottle will be dipped into a stream with depth and velocity of less than minimum requirements for depth-integrated sampling.
- The weighted-bottle sampler can be used to collect water sediment mixtures in streams with low flow velocities (i.e., less than minimum required for isokinetic sampling) where flow is too deep to wade. The US WBH-96 sampler is a weighted bottle sampler designated by the FISP. The sampler has a stainless steel metal housing which used to secure a bottle for sampling. The metal housing has holes drilled near the top for a rope line that is used to secure the bottle and deploy the sampler. Sampling depth is restricted by the capacity of the bottle and the rate of filling.
- The biochemical oxygen demand (BOD) sampler is a type of open-mouth sampler designed to collect non-aerated samples for dissolved-oxygen determination. The 400 ml chamber of the sampler contains a 300 ml glass BOD bottle and is deployed in the closed position to the specified depth (see Delzer,McKenzie (2003) for biochemical oxygen demand sampling recommendation).
- The volatile organic compound (VOC) sampler is designed to collect samples for analysis of volatile organic compounds at a single point in the stream. The stainless-steel sampler holds four 40 ml vials. Four small inlet tubes with 1/16 inch inside diameter are extended into the sample vials. The sampler weighs 5 kg and can be suspended, by hand, from a short rope or chain while wading a stream (see Zogorski, Carter et al. (2006) for field recommendation for collecting VOC samples).

2.2.2 Thief samplers

Thief samplers are used to collect instantaneous discrete samples from lakes, reservoirs and estuaries as well as from flowing surface water. The samplers are constructed in various type of materials and are available in various sizes and mechanical configurations. For descriptions of additional thief samplers, see related USGS technical note by Wilde, Sandstrom et al. (2014).

2.2.3 Single-stage samplers

Single-stage samplers are simple containers equipped with intake and exhaust tubes. The US U-59 and US U-73 samplers are two type of single-stage samplers designed by the FISP to obtain suspended sediment samples from streams at remote sites or at streams where rapid changes in stage makes it impractical to use a conventional isokinetic, depth-integrating sampler.

A sample is collected when a rising stage first submerges a sampler. Samples are obtained with respect to gage height and not to time. Because of restrictions on intake and exhaust components, a single-stage sampler is not an isokinetic sampler.

Single-stage samplers can be mounted above each other to collect samples from various elevations or times as streamflow increases and the hydrograph rises.

The US U-59 series single-stage samplers designed and tested by the FISP consist of a 0.45 litre milk bottle, the air vent, and 3/16 inch or 1/4 inch inside diameter intake. There are four models of US U-59 samplers. The US U-59A sampler is designed for collection of silt- and clay-size sediments in less than about 0.7 m/s stream velocities. The US U-59B, US U-59C, and US U-59D are for collection of sand-size and finer material in stream velocities less than 1, 1.6, and 2.1 m/s, respectively.

The US U-59 series of samplers obtain a sample on the rising phase of the hydrograph from a point near the water surface, while the US U-73 is a more sophisticated single-stage sampling device which can be used to sample water during either the rising or falling stage of hydrograph.

2.2.4 Automatic pumping water samplers

Automatic samplers are useful for collecting suspended sediment samples during periods of rapid discharge changes from storm-runoff and in reducing the need for manual measurements associated with intensive sediment-collection programs (Skinner and Beverage 1981). Automatic pumping samplers with fixed-depth intake (e.g., Sigma, ISCO, Manning) have tubes going into the water and a pump to pull water through the tubes into the sampling bottles. It is programmed to take a sample at intervals during a storm when the river is at first rising and again later, where it's falling. Samples from automatic sampler are considered to be point samples. These samplers can be set to collect one sample per bottle or to composite more than one sample into each bottle (composite sampling).

To allow for isokinetic sample collection using automatic pumping samplers, stream velocity and sampler intake velocity should be equal (Bent, Gray et al. 2001). To yield the most reliable and representative sediment samples, the intake should be placed at the point where the concentration and particle-size distribution are most representative of the mean sediment concentration for the cross section over the full range of flows. Generalised guidelines provided in the USGS reports for placing a sampler intake in the streamflow at any given cross section (Edwards and Glysson 1999; Bent, Gray et al. 2001).

3 Surrogate non-sampling techniques for suspended sediment measurement

The suspended sediment sampling methods described in previous sections do have some limitations as they can be are labour intensive, expensive and may be of unknown accuracy due to the large spatial and temporal variability associated with the transport of suspended sediment. In addition, sampling techniques for quantifying suspended sediment concentration lack sufficient temporal frequency to capture daily, weekly and monthly fluctuations in these concentrations and fluxes.

Sediment-surrogate technologies are required to continuously measuring high-quality suspended sediment data. Surrogate techniques are capable of measuring selected characteristics of suspended sediment, in a more timely and cost effective way than using traditional methods. This section lists the most commonly used non-sampling techniques for measuring suspended sediment concentration (SSC) including instruments operating on bulk optic (turbidity), laser diffraction, pressure difference, and acoustic backscatter principles. Other surrogate technologies for estimating suspended sediment concentration such as focused beam reflection, digital optical, vibrating tube, nuclear technique and impact sampler have been developed, but the robustness of these techniques must be more fully evaluated.

3.1.1 Turbidity (bulk optics)

Turbidity is an optical measurement of the transparency of a solution due to the scattering, reflecting and attenuation of light by the suspended particles and dissolved materials (Ziegler 2002). Continuous turbidity measurements have been shown to provide reliable estimates of suspended sediment concentration with a quantifiable uncertainty.

Turbidity has been well established as a surrogate measure of suspended sediment concentration in rivers throughout the world and is the most common surrogate used for measuring suspended sediment concentration in the United States. The technology has been shown to provide reliable data at a large number of USGS monitoring sites (e.g., Gray, Glysson et al. 2000; Ziegler 2002; Gray, Melis et al. 2003; Schoellhamer and Wright 2003; Uhrich and Bragg 2003; Rasmussen, Ziegler et al. 2005).

The characteristics of sediment particles, including size, shape, and composition as well as water colour can affect turbidity measurements and their corresponding relationship to suspended sediment concentration. Therefore, site-specific empirical calibrations are required to convert turbidity measurements to reliable cross-sectional suspended sediment concentration estimates.

Commercially available turbidity instruments operate on one of two basic bulk-optic (turbidity) principles:

- Transmissometers employ a light source beamed directly at a light detector. The instrument measures the fraction of visible light, typically at about 660 nm, from a collimated light source that reaches the detector. The fraction of light reaching the detector is converted to a beam attenuation coefficient, which is related to suspended sediment concentration.
- Nephelometry is the measurement of light scattering usually with a light detector at 90° from the incident light in visible or infrared spectra.

Lewis, Eads et al. (2007) and Rymszewicz, O'Sullivan et al. (2017) quantified differences and determined the magnitude of the potential errors among several turbidity measurement devices. However, Rymszewicz, O'Sullivan et al. (2017) found that "regardless of the differences in raw turbidity readings from the different sensors, the final calculated sediment loads for the flood events, based on the specific turbidity - SSC relationships, were similar. Thus, sensor differences are potentially problematic when turbidity is the property of interest, but these differences are not important when turbidity is used as a surrogate for determining sediment flux from established turbidity - SSC relationships." Table 3-1 summarizes the advantages and disadvantages of using turbidity instruments.

Table 3-1: Advantages and limitations of turbidity technology. From Gray and Gartner (2009).

Advantages	Disadvantages
Large number of field settings are available for evaluation of turbidity measurements	Point measurement technique which should be calibrated to mean suspended sediment concentration throughout the river cross section
The technology is reliable and highly developed	Saturation of the turbidimeter signal resulting in erroneous SSC values
Less expensive than other sediment surrogate technologies	Biological fouling of sensor optical windows
Straightforward calibration technique	Additional calibrations required in rivers with highly variable sediment characteristics (e.g., grain size, shape, mineral composition)

3.1.2 Acoustic backscatter

Acoustic instruments were originally developed to measure stream velocities. However, these instruments are capable of providing information on acoustic return signal strength, which in turn has been shown to be useful as a surrogate parameter for estimating suspended sediment concentration and fluxes (Gartner and Cheng 2001a).

Short bursts of high frequency sound emitted from a transducer are directed towards the measurement volume. Sediment in suspension will direct a portion of this sound back to the transducer. Suspended sediment concentration is then computed based on site-specific relations established between measured SSC values and information provided by the acoustic instrument.

The USGS researchers found high correlation between measured and estimated suspended sediment concentration using different type of acoustic instruments. Wall, Nystrom et al. (2006) developed an empirical model that related sediment concentration measured by point-integrating isokinetic samplers to measurements made using a boat-mounted acoustic-Doppler current profilers (ADCP) on the Hudson River in New York. They found high correlation between measured and estimated sediment concentration. Topping, Wright et al. (2016) tested side-looking acoustic-Doppler profilers (ADPs) at multiple frequencies at 14 stations in the Colorado River and Rio Grande catchment to measure suspended sediment concentration of different grain sizes. Byrne, Patino (2001) used data from streams in south Florida to generate a time series of sediment concentration using acoustic velocity meter (AVM), and the newer acoustic Doppler velocity meter (ADVM) systems. Gartner and

Cheng (2001b) estimated sediment concentrations in San Francisco Bay by using two different frequencies of ADCPs.

The main limitation of the acoustic technique is the fact that errors in estimates of suspended sediment concentration will increase if a significant fraction of the suspended material includes particles that are too large or too small for a given frequency. For these reasons, acoustic instruments that utilize more than one frequency are preferable to single-frequency methods (Gray and Gartner 2009). Table 3-2 summarizes the advantages and disadvantages of using acoustic backscatter techniques and instruments.

Table 3-2: Advantages and limitations of acoustic backscatter technology. From Gray and Gartner (2009).

Advantages	Disadvantages
Unlike point measurements techniques, acoustic backscatter measurements can cover a substantial part of the water depth or river cross section.	Single frequency source cannot differentiate between changes in particle size distributions and changes in suspended sediment concentrations without calibration
Sediment fluxes in the beam can be computed and empirically indexed to the mean cross-sectional SSC value.	Narrow frequency range for a given particle size range
Biological fouling is not a problem	Complex software requirement for the analysis of the acoustic signals.
Monitoring high range of suspended sediment concentration (for silt and clay: 0.01 – 20 g/l, for sand: 0.01 – 3 g/l)	Expensive

3.1.3 Laser diffraction

From the last three decades, field-deployable, laser-diffraction instruments have been used in several investigations in marine and estuarine environments (e.g., Agrawal and Pottsmith 1994; Gartner, Cheng et al. 2001; Mikkelsen and Pejrup 2001). More recently, these instruments have provided high temporal and spatial resolution measurements of volumetric suspended sediment concentration (SSCV) and volumetric particle-size distribution (PSDV) in fluvial environments (Agrawal and Pottsmith 2006; Williams, Walling et al. 2007; Guo and He 2011; Landers and Sturm 2013; Haun, Rüther et al. 2015). FISP-sponsored researches found excellent correlations between calibrated volumetric suspended sediment concentration and traditional mass suspended sediment concentration (see Federal Inter-Agency Sedimentation Project 2013b).

The Laser In-Situ Scattering and Tranmissometry (LISST) series of instruments developed by Sequoia Scientific, Inc. for field use are the first such instruments to be commercially available. A fixed-location, laser-diffraction instrument provides real-time, high temporal resolution data, while a user-deployed, laser-diffraction instrument can -typically during brief deployments- provide at-a-point high temporal- and spatial-resolution data in real time. The LISST-SL is a streamlined version of the LISST-100 adapted for fluvial environments for deployment from a suspension cable. Recent applications of LISST instruments by the USGS for measurements of suspended sediment concentration in rivers are summarised in Table 3-3.

Table 3-3: Review of recent United States Geological Survey studies on application of Laser In Situ Scattering and Tranmissometry (LISST) instruments in rivers.

Authors	Study sites	Measurement	Results
Czuba, Straub et al. (2015)	16 catchments (USGS stations) at Illinois and Washington, U.S.	Depth= 0.6 – 9.1 m Velocity= 0.2 – 2.3 m/s Instrument: LISST-SL	Comparing measurements of depth-integrated and point-integrated sediment samplers with LISST-SL found computed effective density of 1.24 g/ml provide the best fit to convert VC to SSC with RMSE=143 mg/L and R2= 0.95.
Agrawal,Hanes (2015)	Cowlitz River in Washington, U.S.	Width= 200 m Depth= 3.8 m Instrument: LISST-SL	A consistent ration of 0.88 found in comparing measurements of P-61 point integrated samplers with LISST. This suggests an effective mass density for LISST-SL data of 2.33 g/cm^3.
Landers,Sturm (2013)	Yellow River, U.S.	Flow from Q= 10.4 m^3/s to 2-yr flood: Q=144 m^3/s Instrument: LISST-SL	To investigate hysteresis effect during flood event on relating suspended sediment concentration (SSC in mg/L) to turbidity (FNU) and discharge (m^3/s)

3.1.4 Instrumentation

Table 3-4 summarises some specific features of different LISST instruments which can be used to measure the particle size and concentration in rivers, streams, ports, harbours, coasts and oceans. The LISST-200X is the most recently developed instrument.

Table 3-4: Features of available LISST instruments developed by Sequoia Scientific, Inc.

	LISST-ABS	LISST-200X	LISST-SL	LISST-100X	LISST-STX
Measurements	SSC, PSD	SSC, PSD	SSC, PSD	SSC, PSD	Settling velocity, SSC, PSD
Sediment size (µm)	30 - 400	1 – 500	2.5 - 500	2.5 - 500	2.5 – 500 µm
Sediment concentration (mg L^{-1})**	1 – 70000 (7 micron) 1 - <50000 (200 micron)	0.5 - 700	15-13500	1-800	1 – 750
Size classes***	32	36	32	32	Size distribution: 32 Settling velocity: 8
Max. Depth (m)	100	600	30	300	200 m
Specific features		- Real time monitoring (mean size, total concentration) - Reject ambient light			Settling experiment will be measured by trapping water samples
Weight (kg)	Air Water	0.5 0.22	5.4 1.7	16 7	11 3.6

* SSC= Suspended Sediment Concentration; PSD= Particle Size Distribution
** Concentration range is highly grain-size dependent
*** Log-spaced size classes

Limitations of laser-diffraction measurements of concentration and particle size distribution include:

- Only point measurements are possible.
- Effects of particle shape- mineral composition (especially Mica) can influence the results through the shape of sediment particles (biases from sphere sizes).
- Effects of particle composition (colour)- this affects the refractive index of a particle.
- Absence of information on particle mass density- Laser diffraction measures volume concentration (VC). In order to get mass concentration, VC is multiplied to particle density (ρ_c):

- $SSC = VC \times \rho_c$ (g/ml)
- Several studies using various LISST devices in fluvial environments have found that computed effective density, which merely serves as a correction factor in place of the true effective density, should be used instead of average measured specific gravity (see section 3).
- Errors in particle size distribution results when operating in river systems with strong thermal or density fluctuations.

However, in light of their limitations, the LISST devices' ability to measure the temporal variability of suspended sediment by grain size at-a-point shows great promise for advancing our understanding of suspended sediment transport by rivers (Czuba, Straub et al. 2015).

3.1.5 LISST data calibration using samples collected from physical samplers

A comprehensive study by Czuba, Straub et al. (2015) on US rivers found errors averaging more than 100 per cent could occur if mass sediment concentration (SSC_m) was estimated by multiplying volume concentration (SSC_V) by the average sediment specific gravity of 2.67 g/ml. Several other studies using various LISST devices in fluvial environments have found similar results (Williams, Walling et al. 2007; Andrews, Nover et al. 2011; Guo and He 2011; Landers and Sturm 2013).

Therefore, volumetric particle size distribution (PSD_v) and suspended sediment concentration (SSC_v) measured by LISST devices must be rescaled (calibrated) to mass parameters (i.e., SSC_m and PSD_m) using the measurements from physical samplers (i.e., depth and time -integrated sediment samplers). Czuba, Straub et al. (2015) postulates this reduced apparent density is due to flocculation, shape effects, or unmeasured size fractions. Sassi, Hoitink et al. (2012) computed an effective density between 1.2 and 1.6 g/mL with a best fit to all measurements of 1.37 g/ml for the River Mahakam in Indonesia. Czuba, Straub et al. (2015) obtained best-fit value of 1.24 g/ml to correct the measurements to mass values. Furthermore, on their thorough laboratory analysis, Felix, Albayrak et al. (2013) computed an effective density of 1.73 g/ml for elongated, angular feldspar powder and 0.35 g/ml for flaky, not rounded mica powder.

3.1.6 Pressure differential

Estimation of suspended sediment concentrations from fluid density computed from pressure measurements shows promise for monitoring highly sediment-laden stream flows.

This technique relies on simultaneous measurements from two exceptionally sensitive pressure transducer sensors arrayed at different fixed elevations in a water column (Gray and Gartner 2009). However, changes in temperature gradient, turbulence, and dissolved solids concentration will affect measurements. When corrected for water temperature, the density data are used to estimate sediment concentrations from a density-concentration relation (United States Geological Survey 1993). Table 3-5 lists the advantages and disadvantages of using the pressure differential technique.

Table 3-5: Advantages and limitations of pressure differential technology. from Gray and Gartner (2009).

Advantages	Disadvantages
Inference of sediment concentration in a single vertical (note that this technique may not provide SSC data representative of mean cross-sectional values)	Assumes that the concentration in the vertical profile above the lower pressure sensor is constant to the surface
Biological fouling and signal drift is not a problem	Incapable of measurements in low sediment concentrations, specifically in turbulent flows
Higher accuracy with increasing the sediment concentration	Incapable of measurements when the top orifice is not submerged or the bottom orifice is buried in sediment
Relatively simple and straightforward technology	

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