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Hydrometry — Methods of measurement of bedload discharge

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National foreword

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TECHNICAL REPORT

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Hydrometry — Methods of measurement of bedload discharge

Hydrométrie — Méthodes de mesurage du débit des matériaux charriés sur le fond

Reference number
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Foreword

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For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the WTO principles in the Technical Barriers to Trade (TBT) see the following URL: Foreword - Supplementary information.

The committee responsible for this document is ISO/TC 113, *Hydrometry*, Subcommittee SC 6, *Sediment transport*.

This third edition cancels and replaces the second edition (ISO/TR 9212:2006), which has been technically revised.

Introduction

The knowledge of the rate of sediment transport in a stream is essential in the solution of practically all problems associated with the flow in alluvial channels. The problems include river management, such as design and operation of flood control works, navigation channels and harbours, irrigation reservoirs and canals, and hydroelectric installations. The bedload and suspended load broadly constitute total sediment load. The bedload is the material transported on or near the bed by rolling or sliding (contact load) and the material bouncing along the bed, or moving directly or indirectly by the impact of bouncing particles (saltation load). Knowledge of the bedload-transport rate is necessary in designing reservoir capacity because virtually 100 % of all bedload entering a reservoir accumulates there. Bedload should not enter canals and distributaries and diversion structures should be designed to minimize the transfer of bedload from rivers to canals.

The bedload-transport rate can be measured either as mass per unit time or volume per unit time. Volume measurements should be converted to a mass rate. Measurements of mass rate of movement are made during short time periods (seconds, minutes), whereas measurements of volume rates of movement are measured over longer periods of time (hours, days). Regardless of whether the mass or volume rate is measured, the average particle-size distribution of moving material should be determined. Knowledge of particle-size distribution is needed to estimate the volume that the bedload material will occupy after it has been deposited. Knowledge of particle-size distribution also assists in the estimation of bedload-transport rates in other rivers transporting sediment.

The movement of bedload material is seldom uniform across the bed of a river. Depending upon the river, hydraulic, and sediment properties (size and gradation), the bedload may move in various forms, such as ripples, dunes, or narrow ribbons. Its downstream rate of movement is also extremely variable. It is difficult to actually sample the rate of movement in a river cross-section or to determine and verify theoretical methods of estimation.

Hydrometry — Methods of measurement of bedload discharge

1 Scope

This Technical Report reviews the current status of direct and indirect bedload-measurement techniques. The methods are mainly based on grain size distribution of the bedload, channel width, depth, and velocity of flow. This Technical Report outlines and explains several methods for direct and indirect measurement of bedload in streams, including various types of sampling devices.

The purposes of measuring bedload-transport rates are to

a) increase the accuracy of estimating total sediment load in rivers and deposition in reservoirs,

b) gain knowledge of bedload transport that cannot be completely measured by conventional suspended-sediment collection methods,

c) provide data to calibrate or verify theoretical transport models, and

d) provide information needed in the design of river diversion and entrainment structures.

NOTE The units of measurement used in this Technical Report are SI units.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 772, *Hydrometry — Vocabulary and symbols*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 772 apply.

4 Measurement of bedload

4.1 General

Bedload can be measured by direct measuring bedload samplers or by indirect methods.

4.2 Direct measurement methods

a) Bedload samplers

In this method, a mechanical device or sampler is required for measuring the bedload-transport rate. The bedload sampler is designed so that it can be placed directly on the channel bed in the flow, to collect a sample of the bedload over a specific time interval. A sample thus obtained represents a time-averaged mass per unit width per unit time.

b) Bedload trap

The best measurement of bedload would occur when all of the bedload moving through the river cross was measured. Slot or pit samplers or traps meet this goal with near 100 % efficiencies.

4.3 Indirect measurement methods

All other methods of bedload measurement in which no mechanical device or bedload sampler is used, are indirect methods. These include differential measurements of total and suspended-sediment loads, periodic volumetric measurements of accumulated sediment depositions, dune tracking, tracers, remote sensing, and acoustic measurements of moving sediment.

5 Design and strategy of measurement of bedload discharge

Measurement of bedload is difficult because it is highly variable in both space and time. Bedload generally varies greatly both longitudinally along the channel and transversely across a cross section. These variations are caused by several factors and are difficult to predict. The design of bedload sampling needs to account for the spatial and temporal variability inherent in the processes of bedload transport.

Pit, vortex-tube, or other samplers that sample for long periods of time and encompass a significant portion of the width of a stream cross section integrate the fluctuations in bedload-transport rate in a cross section. In many instances, time, monetary constraints, or logistics precludes the use of these types of samplers.

The use of portable samplers that essentially only collect samples at a point for short periods of time is often the only practical way to collect samples of bedload. To effectively use portable samplers, the number and location of the samples collected shall be carefully designed. Sufficient information about the temporal and spatial variability is collected. To accomplish this task, information on the scales of spatial and temporal variability is needed. To design an adequate sampling strategy, these time and length scales shall be known at least approximately before the sampling procedure is defined.

Flow in many streams and rivers are not steady for periods of hours to days. For streams in which variable flow is the norm, portable samplers will not be practical unless many flow events can be sampled. No single sampling design can be used at all stations. A sampling design should be derived for each site where bedload is to be sampled. Initial samples collected can provide information to serve as a basis for developing the sampling plan.

6 Site selection

a) Depending upon the method of measurement, the site for conducting bedload measurements can be either a river reach or a cross-section. The site should be relatively close to the geographical location where bedload-transport rate information is needed. There should be no inflow or outflow from the river between the measuring site and the site where bedload transport estimates will be used.

b) When using a method such as dune-tracking, a straight reach where the channel width and depth are fairly uniform throughout the reach is desirable. Flow through the reach should be uniform and steady during the bedload-measurement period (see 9.4).

c) A single cross-section site should be selected if the method of measurement is by bedload sampler. The channel width and mean depth of the cross-section site should be representative of the average channel width and depth upstream and downstream. Ideally, a cross-section used for bedload measurement by bedload sampler should be at the centre of a straight reach selected for measurement of bedload by the dune-tracking method.

d) If it is not possible to place the cross-section site in the centre of an ideal straight, uniform reach, then the cross-section should be located at least 10 to 20 channel widths downstream from any bend in the channel. It should not be located at an excessively narrow section, such as might be present at a bridge site, or at an excessively wide section.

7 Bedload samplers and traps

7.1 Bedload samplers

7.1.1 Requirements of an ideal bedload sampler

In order that the samples taken are truly representative of the bedload material of a river at the point of sampling, the ideal bedload sampler should fulfil the following technical requirements.

a) It should be calibrated for bedload-sampler efficiency of specific sediment particle sizes.

b) It should be designed to minimize disturbances to normal bedload movement. In particular, local erosion near the sampler mouth should be avoided so as to not form scour holes.

c) The lower edge of the sampler and nozzle should be in contact with the river bed.

d) The velocity of inflow at the mouth of the sampler should be as close as possible to the ambient velocity of the stream at the sampling point, irrespective of what this velocity may be. This aspect is very important if large sampling errors are to be avoided.

e) The mouth of the sampler should always face into the current and the sample should be taken parallel to flow direction at the sampling point, into a specially designed chamber.

f) The mouth of the sampler should be outside the zone of the disturbances of the flow set up by the body of the sampler and its operating gear and the flow lines should be as little disturbed as possible, especially near the mouth.

g) The sampler should be able to collect only those particles moving as bedload, without contamination by suspended sediment.

h) The sampler should be portable, yet sufficiently heavy to minimize deflection of the supporting cable from the vertical due to current drag. A separate anchor is recommended for the sampler, wherever possible.

i) The sampler should be simple in design and robust in construction and should require minimum maintenance and care in operation.

j) It should be capable of collecting representative bedload samples under varying bed configurations.

k) The sampler should be designed for easy removal of the sampled material into a container for transfer to a laboratory.

l) The volume of the sample collected should be sufficient for the determination of mass and particle-size distribution.

m) The efficiency of the sampler should be independent of length of sampling over a reasonable time.

n) The efficiency of the sampler should be independent of the size of bedload particles and flow velocity.

7.1.2 Basket or box type sampler

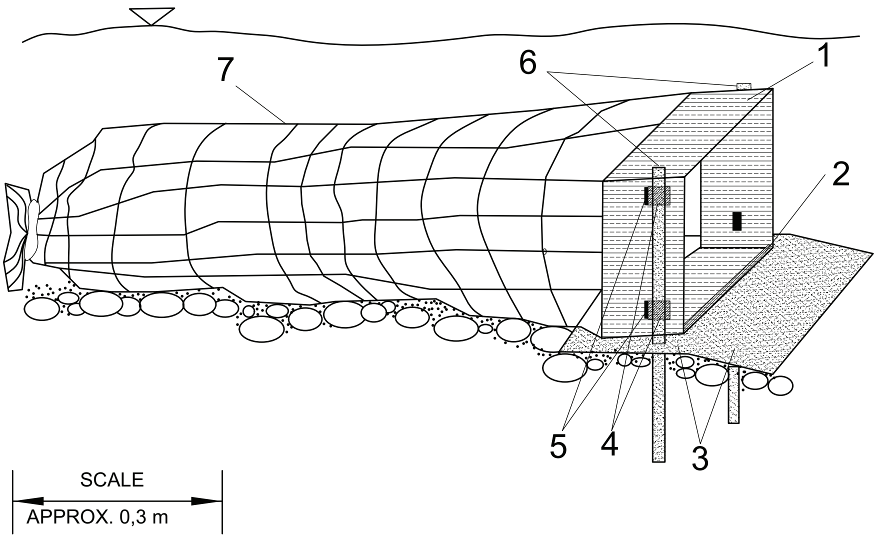
This type of sampler consists of a basket or box, usually made of mesh material on all sides except the front and bottom. The bottom may be solid or of loosely woven iron rings or steel mesh, to enable it to conform to the irregular shape of the stream bed. The sampler is placed on the channel bed with the help of a supporting frame and cables. A steering fin or vane(s) attached to the basket ensures positioning of the instrument in the direction of the flow. The sediment is collected in the basket by causing a reduction of the flow velocity and/or screening the sediment from flow for a measured time period.

Since a part of the bedload is dropped in front of the sampler, the efficiency of basket type samplers is only about 45 %, for average sediment sizes varying from 10 mm to 50 mm. However, due to their large capacity, basket type samplers are well suited for measuring of transport rate of large-sized sediment [7].

7.1.3 Frame and net sampler

These are portable samplers consisting of a steel or aluminium frame and a trailing net for collecting the sediment. The samplers can be used in small wadable streams. The samplers are anchored to the streambed with steel rods driven through the frames. These samplers can be deployed for 1 h or more, depending on the transport rate, so they can average out short-term temporal variations in transport rates.

The sampler shown in Figure 1 was designed for use in small mountain streams. The frame, which was fabricated from aluminium, 0,3 m wide, 0,2 m high, and 0,1 m deep. The netting, which extends about 1 m downstream from the frame, is sturdy nylon mesh with 3,5 mm openings. The sampler is able to trap gravel particles as small as 4 mm and cobbles particles as large as 128 mm.



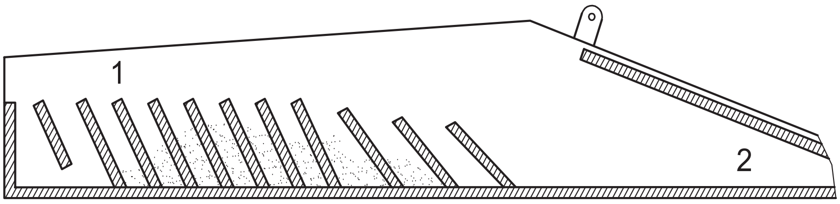
Key

1 aluminium frame
2 bottom piece, bevelled
3 aluminium ground plate, inclined in front, with holes
4 adjustable nylon straps
5 slits at top and bottom on each side of the frame
6 smooth stakes, rolled steel
7 nylon netting

Figure 1 — Schematic diagram of a portable frame and net sampler[2]

7.1.4 Pressure-difference sampler

This type of sampler is designed so that the velocity of water entering the sampler and the stream velocity is approximately equal. Equalization of velocity is accomplished through creation of a pressure drop at the exit due to a diverging configuration between the entrance and the exit. These are flow-through samplers that trap coarse material behind baffles or in a mesh bag attached to the exit side or in a specially designed chamber. The Scientific Research Institute of Hydrotechnics (SRIH) and Sphinx samplers (see Figure 2 and Figure 5) are examples of samplers with internal baffles. The Arnhem, Helley-Smith, US BLH-84, and US BL-84 are examples of mesh bag samplers (see Figure 3, Figure 4, Figure 6, and Figure 7)



Key

1 transverse partitions

2 entrance

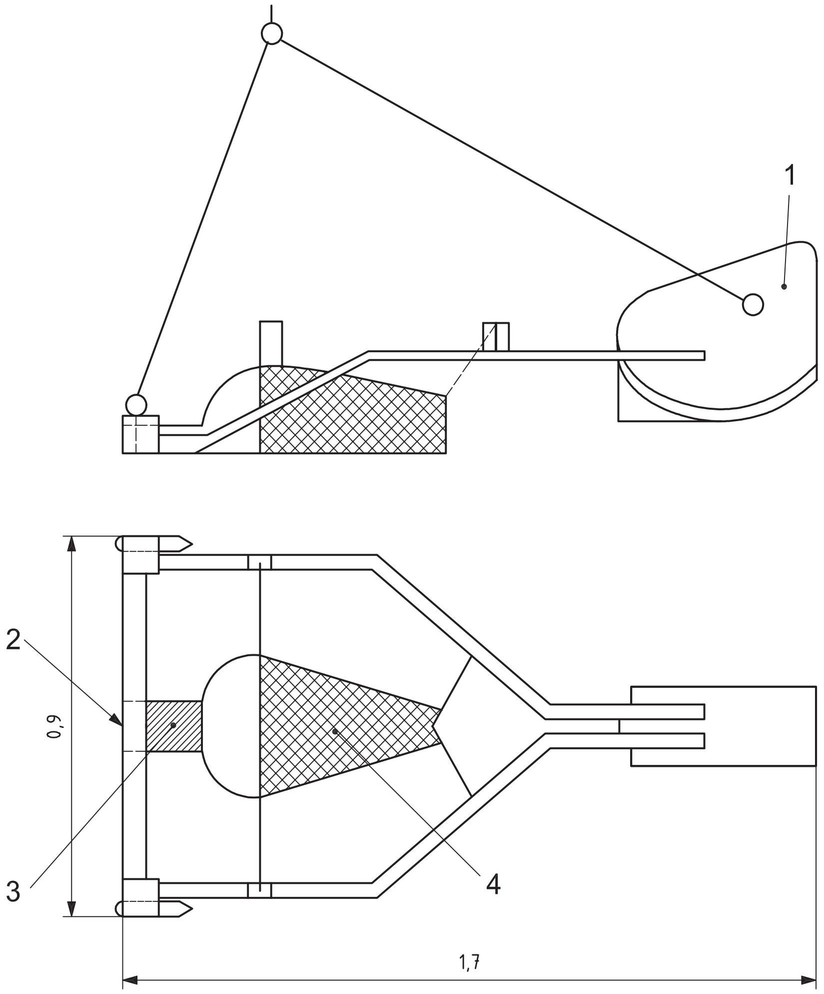
NOTE This is a pressure-difference bedload sampler. The SRIH sampler was the first of this type to be developed. Such samplers can sample particles as small as fine sand to as large as 200 mm. Efficiencies are extremely variable.

Figure 2 — Scientific Research Institute of Hydrotechnics (SRIH) sampler[10]

7.1.5 Advantages and disadvantages

Portable samplers are generally inexpensive to acquire, but can be expensive to operate and suffer from uncertain calibrations.

Dimensions in metres



Key

1 steering fin

2 entrance

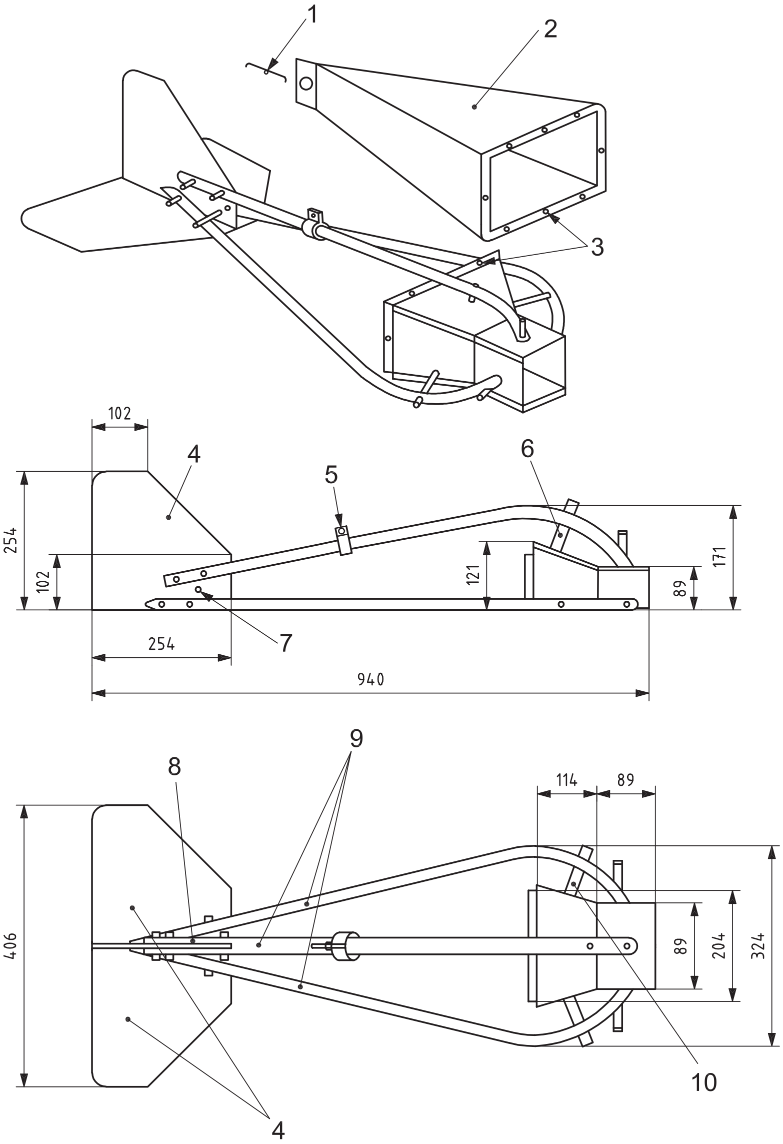
3 rubber connection

4 mesh bag

NOTE This is a pressure-difference bedload sampler. The Arnhem or Dutch sampler comprises a rigid rectangular entrance connected by a diverging rubber-neck to a basket of 0,2 mm to 0,3 mm mesh. Efficiencies are variable, but generally about 70 % [13]. It is suitable for collection of fine bedload material. The fine net of the sampler can get clogged leading to a drop in efficiency of the sampler.

Figure 3 — Arnhem sampler[14]

Dimensions in millimetres



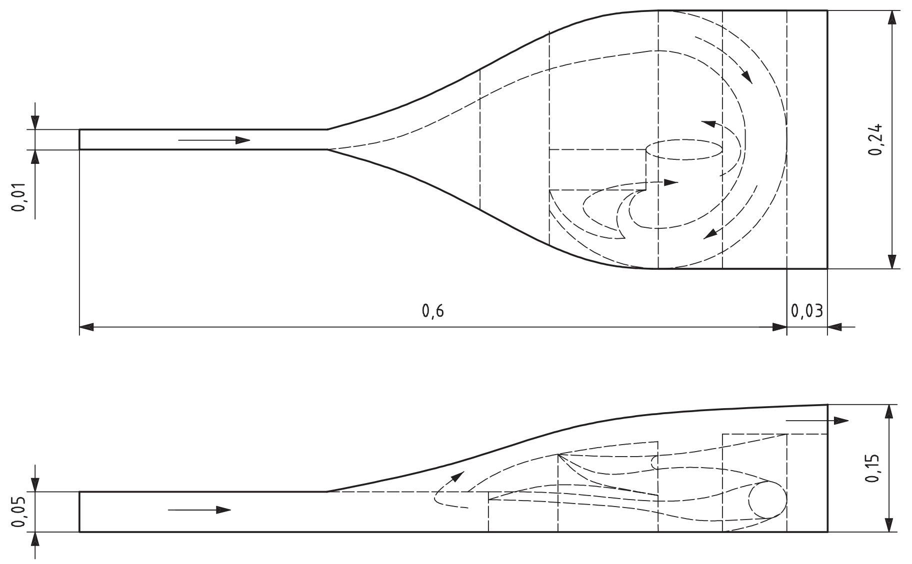
Key

1	bag to tail attachment spring	6	rail attachment bolt
2	mesh polyester monofilament, 0,2 mm	7	hole for bag attachment spring
3	dot fastener	8	slot top rail to fit tail
4	aluminium alloy weld tail pieces except where side rails join tail	9	aluminium tubing filled with lead after farming
5	sliding collar	10	tubing spacers, where necessary

NOTE This is a pressure-difference bedload sampler with a 76-mm square entrance nozzle and an area expansion ratio of 3,22[9]. Field experiments indicate a nearly 100 % sampling efficiency for sizes from about 0,5 mm to 16 mm[6]. Laboratory studies indicate that sampling efficiencies vary widely with particle size and transport rate, ranging from 150 % for sand and small gravel and close to 100 % for coarse gravel[11].

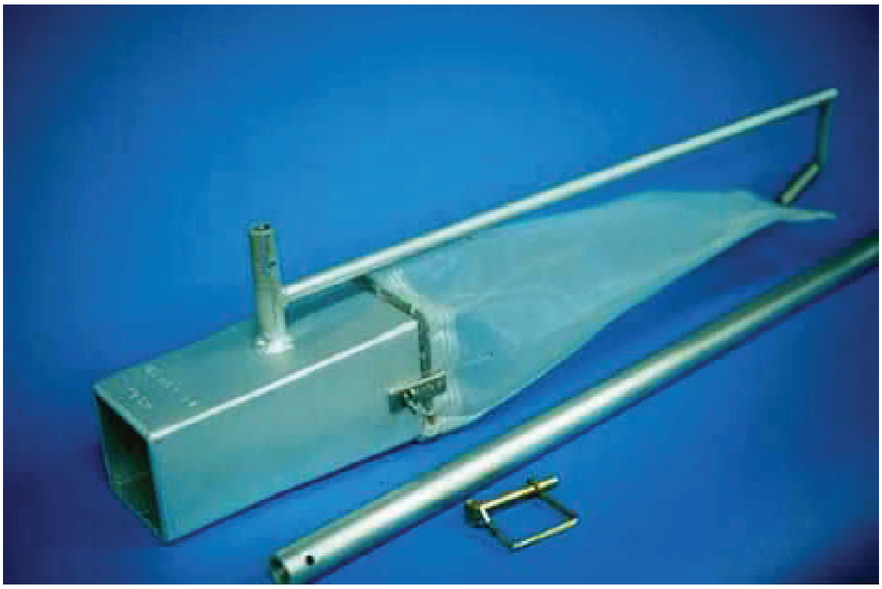
Figure 4 — Helley-Smith bedload sampler[9]

Dimensions in metres



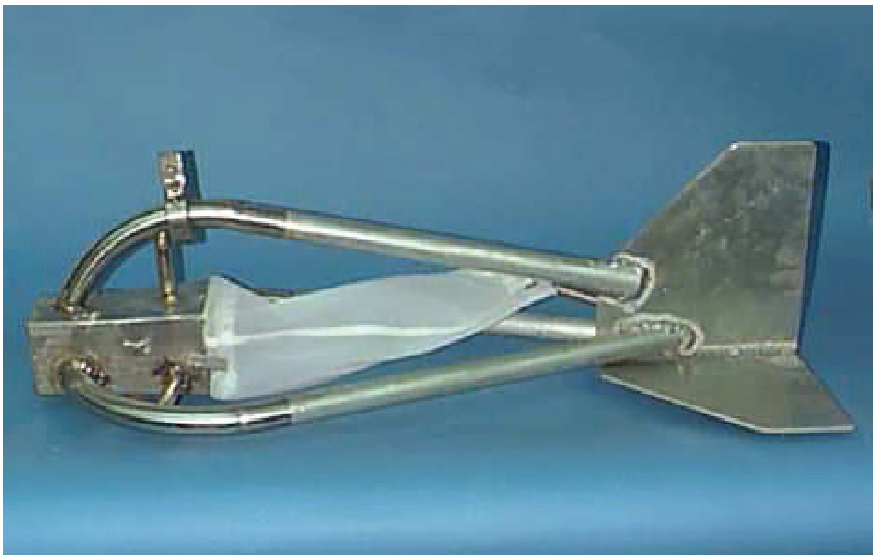
NOTE This is a direct measurement sampler developed by Vinckers, Bijker and Schijft (see Reference [22]). The hydraulic efficiency varies from about 1,09 for clear flow to about 1,0 for extreme conditions. Sampling efficiency varies from about 93 % for particle sizes finer than 0,2 mm to about 85 % for sizes finer than about 0,09 mm.

Figure 5 — Sphinx sampler[22]



NOTE The US BLH-84 is a hand-held 4,5 kg, wading type sampler used to collect bedload samples from a stream of wading depth. The sampler consists of an expanding nozzle, a sampler bag, and a wading rod assembly. Particle sizes less than 38 mm at mean velocities up to 3 m/s can be measured with this sampler. It was developed by Reference [21]. Size of sampler: length: 711 mm, width: 140 mm, mass: 4,5 kg.

Figure 6 — US BLH-84 Wading type bedload sampler[5]



NOTE The US BL-84 is a cable suspended 14,4 kg, sampler to collect bedload samples from a stream of any depth. The sampler consists of an expanding nozzle mated to a frame, and a sampler bag. Particle sizes less than 38 mm at mean velocities up to 3 m/s can be measured with this sampler. It was developed by Reference [21]. Size of sampler: length: 921 mm, width: 381 mm, mass: 14,4 kg.

Figure 7 — US BL-84 Cable suspended bedload sampler[21]

7.1.6 Characteristics of bedload samplers

Since the sampling conditions encountered in streams vary widely, a single sampler for all conditions cannot be recommended. Factors such as cost, availability, and specific requirements of the sampling also influence the choice of the sampler to a great extent. Table 1, which summarizes the characteristics of some commonly used samplers, can assist in the selection of a sampler in given conditions.

As the data obtained is affected by the sampling action and the mechanism of the sampler, any change in the sampler would itself introduce a variable. Therefore, the results obtained from different samplers might not be comparable.

Table 1 — Samplers commonly used for bedload measurement

Type	Description	Disturbance of flow characteristics	Hydraulic stability	Sampler efficiency	Acceptability to various field conditions
Frame and net	Portable bedload trap with 0,3 m by 0,2 m opening and trailing nylon net with 3,5 mm openings.	Near-bottom flow velocity increases by about 30 %.	Anchored to streambed.	Variable from −50 to +20 %	Suitable for sampling coarse particles (greater than 4 mm) in streams that are wadable at high flow.
SRIH	This is a pressure difference bedload sampler.			Efficiencies extremely variable	The sampler design to measure particles as small as fine sand or as large as 200 mm.

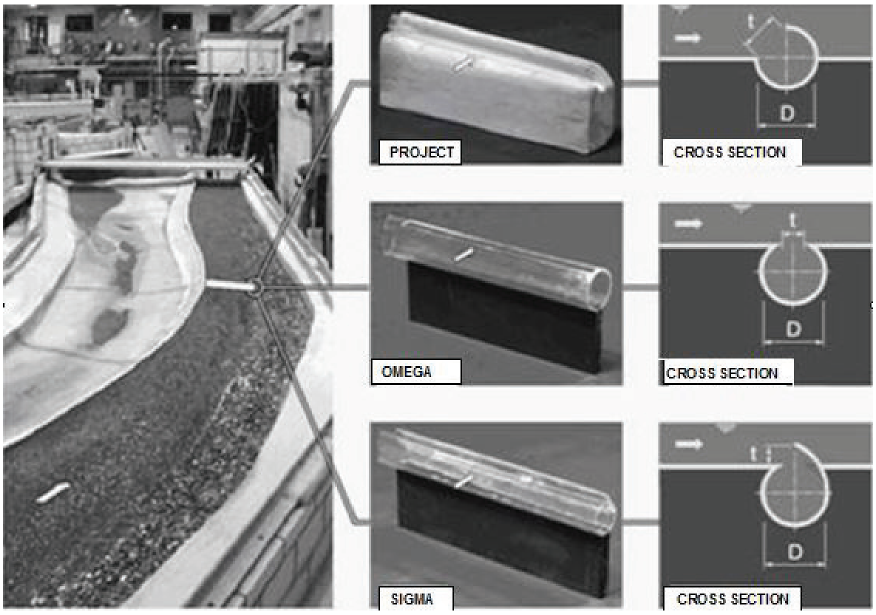
Table 1 *(continued)*

Type	Description	Disturbance of flow characteristics	Hydraulic stability	Sampler efficiency	Acceptability to various field conditions
Arnhem	Consists of a rigid rectangular entrance connected by a diverging rubber neck to a basket of 0,2 mm to 0,3 mm mesh fixed to a large framework by springs in such a way that the entrance is in contact with the bottom when the sampler is lowered onto the bed.	Variable	Variable	About 70 %	Generally restricted to collection of fine bedload material (2 mm); portable.
Helley - Smith	Tear-drop shaped, aluminium tubing frame connecting expanding brass entrance to aluminium tailfins; aluminium tubing filled with lead for mass (weight); bedload particles are trapped in a polyester mesh bag attached to exit.	Intake velocities are consistently higher than ambient velocities.	Stable in velocities up to 3 m/s.	Variable from about 100 % for gravel to more than 150 % for sand	Varying sizes, from hand-held wading sampler to heavy sampler suspended from cables; fairly streamlined; portable.
Sphinx	In this sampler the flow enters through a rectangular nozzle that gradually becomes circular, then through a series of settling chambers, and then out a wide exit at the rear.	The hydraulic efficiency varies from about 1,09 for clear flow, to about 1,0 for extreme conditions		Sampling efficiency varies from about 93 % for particle sizes finer than 0,2 mm to about 85 % for sizes finer than about 0,09 mm	
US BLH-84 wading type sampler	The sampler is constructed of aluminium and is 711 mm long. Consists of an expanding nozzle, a sampler bag, and a wading rod assembly. The sampler has a 76-mm square entrance nozzle, and nozzle and an area expansion ratio (ratio of nozzle exit area to entrance area) of 1:40. A polyester mesh bag with mesh openings of 0,25 mm is attached to the rear of the nozzle assembly with a rubber "O" ring.		Mean velocities up to 3 m/s (this velocity is higher than safe wading velocities).	Variable from near 100 % for 11 mm to 32 mm particles to 125 % to 160% for finer particles[10][11]	The sampler design enables collection of particle sizes less than 38 mm at mean velocities up to 3 m/s.
US BL-84 cable suspended sampler	The sampler consists of an expanding nozzle mated to a frame, and a sampler bag. The sampler has a 76-mm square entrance nozzle and an area expansion ratio of 1,40. The US BL-84 is constructed of stainless steel and aluminium, is equipped with tail fins, and is 921 mm long by 381 mm wide. The sampler should be supported by a steel cable and reel to be lowered into a river or stream for taking a bedload sample.		Mean velocities up to 3 m/s.	Variable from near 100 % for 11 mm to 32 mm particles to 125 % to 160% for finer particles[10][11]	The sampler design enables collection of particle sizes up to 38 mm at mean velocities up to 3 m/s.

7.2 Measurement using bedload trap

7.2.1 Vortex tube bedload trap

The samplers consist of a 45 % diagonal slot in a concrete broad crested weir constructed across the channel at the measurement site. A vortex is generated in the diagonal slot and from 5 % to 15 % of the flow carries the bedload sediment to a trap on the side of the channel. The sediment is then weighed and sampled and returned to the stream downstream of the weir (Robinson, 1962[18]; Milhous, 1973[15]; Tacconi and Billi, 1987[20]).



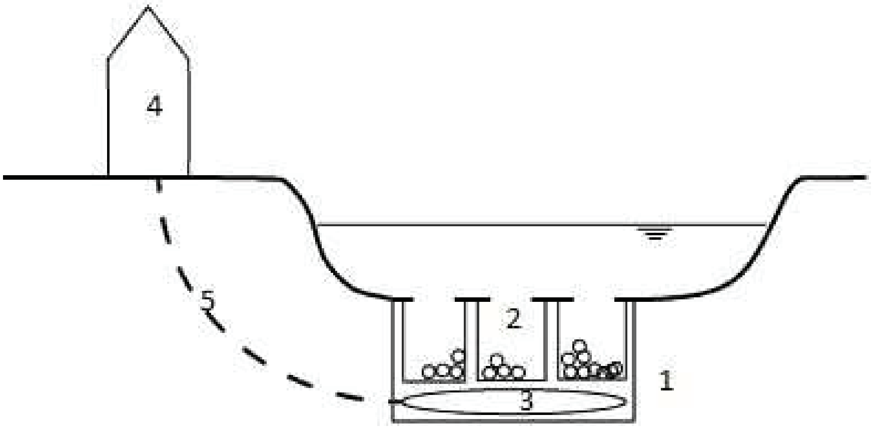
NOTE 1 This is a vortex tube bedload sampler designed by the Swiss Federal Institute of Technology Zurich. The hydraulic tests showed that the principle of vortex tubes is suited for the extraction of transported sediment. The results demonstrated extracting rates over 95 % under appropriate hydraulic conditions. The tube geometry is dependent on sediment size, channel width, and economical aspects.

NOTE 2 Left: headrace channel (right) and residual flow reach (left), middle: types of the investigated vortex tubes, right side: vortex tube cross-sections, arrows indicate the direction of flow.

Figure 8 — Vortex tube bedload trap

7.2.2 Pit and Trough trap

These samplers are used on small flashy streams where the bedload moves during a flood event. The samplers are installed in the bed of the channel by burying the sampler so that the top is flush with the surface of the bed. They consist of small containers that catch and retain all bedload sediment that is transported to the sampler[10]. The bedload is either removed and weighed after a flood event or weighed continuously by a pressure pillow in the bottom of the trap[13][16]. Another pit-type trap uses a continuous conveyor belt, which carries the bedload to a weighing station on the stream bank[6].



Key

1 reinforced concrete outer box
2 steel inner box with slotted covers
3 pressure pillow
4 shelter for bubbler system
5 tubes from bubbler system to pillow

Figure 9 — Example of a pit and trough sediment trap that captures and weighs the sediment transported as bedload during the measurement period (adapted from Reference [13] and Reference [16])

7.2.3 Advantages and disadvantages

The bedload trap operates reliably on relatively small gravel-bed stream, but they are not portable and the initial construction cost is high.

8 Procedures for measurement of bedload discharge using bedload samplers

8.1 General

Many problems in determining bedload discharge over the wide range of sediment and hydraulic conditions found in nature have yet to be resolved. Among these problems, it should be noted that

a) quantification of physical relations is not complete enough to estimate the bedload discharge,

b) quantitative measurements are applicable only to specific site studies at the time of measurement, and

c) direct measurement devices are useful for only a very limited range of sediment size and hydraulic conditions.

As a result, no single apparatus or procedure has been universally accepted as completely adequate for the determination of the bedload discharge over the wide range of sediment and hydraulic conditions found in nature.

The type of sampler and the technique of sampling used will depend on a large number of factors namely, stream velocity, depth, width, particle size, transport rate, channel stability, and bed configuration. The transport rate of bedload not only changes from point to point in a cross-section but also exhibits widely variable short-term and long-term fluctuations at a fixed point. These variations in the measurement of bedload discharge mean that short-term measurements at a point are very likely to be non-representative of the mean bedload discharge at that point. Therefore, each sampling point should be sampled many times over an adequately long period in order to achieve any reasonable accuracy. The number of sampling points in a cross-section is usually dependent on funding and manpower available. However, it should be noted that the more points are sampled, the greater is the degree of accuracy.

The sampling time interval will be determined by the volume of bedload material in transport and the capacity of the sampler used. Generally, the quantity of material collected should not exceed two-thirds of the sampler capacity.

Among the potential problems inherent in the manual deployment of bedload samplers is the orientation of the deployed bedload sampler with respect to flow direction, deployed sampler movement, and inadvertent collection of bed material. A bedload sampler orientation other than directly upstream may collect bedload from a stream section that is less than the nozzle's width resulting in a systematic negative bias in the capture of bedload.

Additionally, a bedload sampler that swings upstream as it is lowered to the bed can gouge into a bedform and collect bed material that may be spuriously included in bedload. These problems tend to be most prevalent in cable deployments. Use of a stayline and tetherline assembly[4] minimizes or eliminates the above-mentioned problems. This assembly enables the bedload sampler to be lowered vertically to the bed and to be restrained from further movement.

Regardless of the method for deploying manual bedload samplers, without observing the bedload sampler as it is deployed, one cannot be certain of the orientation or movement of the sampler once on the bed, nor could one confirm or refute that the sampler collected bed material by gouging the bed. When the deployed bedload sampler cannot be directly observed, affixing a video camera and light source above and behind the bedload-sampler nozzle to provide video of bedload approaching the nozzle can enable the operator to qualitatively assess of the reliability of the sample bedload collected.

8.2 Sample identification

In order to properly evaluate the bedload samples, the following items should be recorded on the individual sampler container:

a) river name and location;

b) date of collection;

c) start time of collection;

d) cross-section location;

e) stationing on the cross section;

f) length of sampling time;

g) depth of water;

h) water temperature;

i) water discharge;

j) type of sampler used.

8.3 Calculations

The computation of bedload discharge from measurements made by direct methods employs the Formula (1) which is applicable for all conditions for determining the total sediment discharge of a given particle-size range:

$$T = \left(D / e\right) + Q_{\text{sM}} + Q_{\text{usM1}} - FQ_{\text{sM}} + \left(1 - E / e\right) Q_{\text{ts2}} \tag{1}$$

where

T is the total sediment discharge of the size range considered;

D is the discharge of the size range as measured with the bedload sampler; if the sampler measures more than the bedload discharge, D includes some of the suspended-sediment discharge; if the sampler measures only the bedload discharge, $D = B$ (B being the bedload-transport rate);

e is the efficiency of the bedload sampler in measuring the bedload discharge of the size range;

Q_{sM} is the measured suspended-sediment discharge of the size range. It equals the product of the total water discharge, a units-conversion constant, and the velocity-weighted mean concentration in the sampled zone;

Q_{usM1} is the unmeasured suspended-sediment discharge of the size range at the depth between the lowest point measured by the suspended-sediment sampler and the highest point measured by the bedload sampler. It equals the product of the water discharge at this depth, a units-conversion constant, and the difference between the velocity-weighted mean concentrations in the sampled zone and at this depth;

F is the fraction of flow at the depth measured by the bedload sampler with respect to total flow;

E is the efficiency of the bedload sampler in measuring the suspended-sediment discharge of the size range that passes at the depth measured by the sampler;

Q_{ts2} is the total suspended-sediment discharge of the size range that passes at the depth measured by the bedload sampler.

Simplifications of Formula (1) can be made for different combinations of particle-size ranges (expressed as bedload or suspended load), vertical distribution of the suspended-sediment concentration, and type of bedload measuring apparatus. Table 2 shows the simplified formula for each combination of relevant parameters.

Table 2 — Formulae for computing the total sediment discharge of a size range

Particle size range transported as[a]	Type of bedload measuring apparatus[b]	Equivalent					Simplified formula
		D/e	Q_{sM}	Q_{usM1}	F	Q_{ts2}	
s	W	0	Q_{sM}	0	0	0	$T = Q_{sM}$
s	Y	$(E/e)\ Q_{ts2}$	Q_{sM}	0	F	FQ_{sM}	$T = Q_{sM}$
s	Z	$(E/e)\ Q_{ts2}$	Q_{sM}	0	F	FQ_{sM}	$T = Q_{sM}$
σ	W	0	Q_{sM}	Q_{usM1}	0	0	$T = Q_{sM} + Q_{usM1}$
σ	Y	$(E/e)\ Q_{ts2}$	Q_{sM}	0	F	Q_{ts2}	$T = (D/e) + Q_{sM} - FQ_{sM} + (1 - E/e)\ Q_{ts2}$[c]
σ	Z	$(E/e)\ Q_{ts2}$	Q_{sM}	Q_{usM1}	F	Q_{ts2}	$T = (D/e) + Q_{sM} + Q_{usM1} - FQ_{sM} + (1 - E/e)\ Q_{ts2}$[c]
β	W	B/e	0	0	0	0	$T = (D/e)$
β	Y	B/e	0	0	F	0	$T = (D/e)$
β	Z	B/e	0	0	F	0	$T = (D/e)$
β, s	W	B/e	Q_{sM}	0	0	0	$T = (D/e) + Q_{sM}$
β, s	Y	$(B/e) + (E/e)\ Q_{ts2}$	Q_{sM}	0	F	FQ_{sM}	$T = (D/e) + Q_{sM} - (E/e)\ Q_{ts2}$
β, s	Z	$(B/e) + (E/e)\ Q_{ts2}$	Q_{sM}	0	F	FQ_{sM}	$T = (D/e) + Q_{sM} - (E/e)\ Q_{ts2}$
β, σ	W	B/e	Q_{sM}	Q_{usM1}	0	0	$T = (D/e) + Q_{sM} + Q_{usM1}$
β, σ	Y	$(B/e) + (E/e)\ Q_{ts2}$	Q_{sM}	0	F	Q_{ts2}	$T = (D/e) + Q_{sM} - FQ_{sM} + (1 - E/e)\ Q_{ts2}$
β, σ	Z	$(B/e) + (E/e)\ Q_{ts2}$	Q_{sM}	Q_{usM1}	F	Q_{ts2}	$T = (D/e) + Q_{sM} + Q_{usM1} - FQ_{sM} + (1 - E/e)\ Q_{ts2}$

[a] β: bedload; s: suspended sediment having a uniform vertical distribution; σ: suspended sediment having a non-uniform vertical distribution.

[b] W: measures only bedload; Y: measures bedload plus suspended sediment in all of unsampled depth; Z: measures bedload plus suspended sediment in part of unsampled depth.

[c] Or $Q_{sM} + Q_{usM}$ where Q_{usM} is the unmeasured suspended-sediment discharge in unsampled depth.

8.4 Errors

Bedload discharge is especially important during periods of extremely high discharge and in landscapes of large topographical relief, where the river gradient is steep (such as in mountains). Measurement of bedload is extremely difficult. Most bedload movement occurs during periods of high discharge on steep gradients when the water level is high and the flow is extremely turbulent. Such conditions also cause problems when making field measurements.

Despite many years of experimentation, sediment-monitoring agencies have so far been unable to devise a standard sampler that can be used without elaborate field calibration or that can be used under a wide range of bedload conditions.

Even with calibration, the measurement error can be very large because of the inherent hydraulic characteristics of the samplers and the immense difficulty with representative sampling of the range of sizes of particles in transit as bedload in many rivers.

Unless bedload is likely to be a major engineering concern (as in the filling of reservoirs), agencies should not attempt to measure it as part of a routine sediment-monitoring programme. Where engineering works demand knowledge of bedload, agencies shall acquire the specialized expertise that is essential to develop realistic field programmes and to understand the errors associated with bedload measurement.

The errors in the bedload-transport rate measured in a stream are caused by many factors namely, variable bedload movement, efficiency of the bedload sampler, and the restricted number of verticals sampled in a cross-section, as well as operator error.

9 Indirect measurement of bedload

9.1 General

Some methods (based on collection of samples) do not involve the measurement of the mass rate of transport of bedload. They mostly measure related parameters from which estimates of the rate of movement of bedload can be made. The one exception is the differential measurement method which can be utilized at some sites if the bedload material consists mostly of particles finer than about 2 mm.

A table edited by Gray, Laronne and Marr (see Reference [8]) about surrogate monitoring technologies of bedload is given in Table A.1.

9.2 Differential measurement

The differential method for measuring bedload requires the measurement of suspended-sediment discharge at two cross sections within a river reach. Samples are collected from both a turbulent and normal section by standard suspended-sediment sampling techniques. The difference between the total sediment discharge measured in the turbulent section and the suspended-sediment discharge measured in the normal section should be considered a good estimate of the bedload discharge in the normal section.

The two sites should meet the following criteria:

a) particles no larger than about 2 mm are being transported;

b) short-term time averaged bedload-transport rates are similar at the two sections;

c) upstream section represents a normal cross-section where bedload material is moving along the bed and finer material is moving in suspension;

d) downstream section is one at which the total sediment load is transported in suspension; this can be an artificially constructed section where turbulence is developed and maintained by a system of baffles;

e) representative cross-section samples can be collected at both sites using suspended-sediment samplers.

9.3 Volumetric measurement

Periodic volumetric measurements of changes in shape of deltoid deposits at river mouths may be used to estimate bedload discharge. Periodic volumetric measurements of the accumulation of deposited sediment behind dams or diversion structures may be used to estimate bedload discharge over longer periods of time.

Based on periodic measurement of the increased volume of sediment deposited in ponds, lakes, reservoirs, and delta formations, volumetric measurements can sometimes be used to estimate average rates of bedload movement. These methods involve the use of capacity survey methods. Techniques for the measurement of elevations of the deposited sediments vary from use of sounding weights in small ponds to echo sounders in large lakes, reservoirs, and deltas.

Periodic volumetric measurements of deposited sediments will be indicative of bedload-transport rates if the volume attributable to the sediment deposited from suspension can be determined. Generally, if suspended-sediment loads entering the area of deposition are measured on a continuing basis during the period of study, the deposited volume of the suspended portion of the total load can be estimated.

In order to accurately determine the bedload-transport rate of a river entering a well-defined area of deposition, the following factors should be taken into account.

a) The river being studied should be the major contributor of sediment to the deposition area; if it is not, the relative contributions of all other sources of sediment should be determined.

b) A unit mass of deposited sediment should be determined in order to translate volumetric measurements into mass measurements.

c) The period of time between surveys should be long enough to detect measurable differences in elevations of the deposition area; generally, this means a minimum of 1 year to 5 years between surveys, depending upon the sizes of the retention basin and the drainage basin.

d) The rate of compaction of deposited material between surveys should be estimated.

9.4 Dune-tracking

Dune-tracking is a hydrographic survey method used when the bed forms are dune shaped. This method involves the mapping of a relatively short, straight reach of a channel under steady-flow conditions. The average parameters of the dune shapes are measured and the average velocity of dune movement is determined[17][23]. A variation of this approach is the measurement of the amount of scour from the upstream face of dunes over time[1].

The dune-tracking method involves the monitoring of the rate of movement of dune-shaped forms in the downstream direction. The two techniques that are used are the moving boat method and the *in situ* echo sounder method.

9.4.1 Moving boat

An echo sounder or acoustic Doppler current profiler mounted on a boat makes repetitive passes along well-defined longitudinal lines in a straight reach. The length of reach traversed should be long enough to include 20 to 25 well-defined dune forms.

For the moving-boat technique, a straight reach should be selected. The length of reach can be determined by first making a longitudinal pass along the approximate centreline of the channel to determine the length necessary to include 20 to 25 dune forms. For instance, if the dunes are approximately 3 m long, a 75 m to 100 m reach should be established to ensure inclusion of 20 to 25 dunes. Five to seven longitudinal lines should be established parallel to each other in the active bed zone of the reach. The sounding boat is moved along each line at a slow uniform speed so that the bed profile is accurately recorded on an analog or digital recorder. Each line should be sounded two to four times to determine the mean travel time of each identifiable dune form. Accurate records of times and distances along each line should be maintained. The second run should be maintained within 30 min to 40 min after the initial run to determine the approximate rate of movement of the dunes. The last run should be timed so that the first and last runs include most of the dune forms from crest to trough.

9.4.2 *In situ* echo sounder

An echo sounder is mounted at a point in the cross-section of flow. The time rate of movement of at least 20 to 25 dunes past this point should be monitored.

Similar criteria should be followed if the *in situ* technique is used. The sounder can be placed at 5 to 7 points in the cross-section in order to include a larger number of dune forms. Five to seven separate echo sounders can also be set up to operate simultaneously.

9.4.3 Accuracy of the dune-tracking methods

The accuracy of dune-tracking methods depends on the following:

a) ability of the sounding equipment to record the distance from transducer to the bed;

b) accuracy of the determination of the boat position at any increment of time;

c) accuracy of the recording of all data.

9.5 Tracers

The tracer method is based on the detection of the sediment movement by tracers. This method is feasible for measuring bed material discharge and sediment dispersion. However, there are large variations in the techniques used. Selecting the appropriate technique depends on the study purpose and the river conditions in the measuring reach. The procedures and techniques involved are the selection and labelling of the sediment tracer particles, the method of introducing the tracer into the flow system, and the method of detection.

Field data collection includes tracing the labelled particles, sampling the bed material, and measuring hydraulic elements in the river reach under investigation. The latter two are usually measured using conventional methods. Four labelling methods are available for use with the tracer method.

The fluorescent tracer and stable isotope tracer can all be used in rivers where the bed material is composed of relatively coarse particles such as gravel and sand. Fluorescent and stable isotope tracers have to be detected in laboratories from samples taken in the field.

Magnetic methodologies have also been used. The magnetic properties of sediment can be enhanced (by heating, inserting iron, or using electric coils). The particles are then traced using metal detectors or specially designed detectors. In all cases, the labelled particles should have the same hydraulic behaviour after labelling as before and should resist leaching, abrasion, and decay of their traceability.

The tracer method does not affect the flow, the measurement is direct and the response is fast. The methods may be inappropriate with high mobile fine grained sediment.

9.6 Remote sensing LiDAR

Remote sensing is the acquisition of information about an object or phenomenon, without making physical contact with the object. The term refers to the use of aerial sensor technologies to detect and classify objects on the Earth.

There are two main types of remote sensing: passive remote sensing and active remote sensing. Passive sensors detect natural radiation that is emitted or reflected by the object or surrounding areas. Examples of passive remote sensors include film photography, infrared, charge-coupled devices, and radiometers. Active collection emits energy in order to scan objects and areas whereupon a sensor then detects and measures the radiation that is reflected or backscattered from the target. RADAR and LiDAR are examples of active remote sensing, where the time delay between emission and return is measured, establishing the location, height, speed, and direction of an object. The process of remote sensing is also helpful for the geo-morphological surveying.

Advantages are high levels of accuracy, ability to cover large areas quickly, quick turnaround, and application of data, as well as reasonable cost (considering the resources and time it would take to gather information of similar accuracy using conventional geo-technologies). It can be integrated with traditional aerial photography.

Disadvantages are inability to penetrate heavily canopied forests without breaks, inability to accurately delineate stream channels, shorelines, ridge lines often visible on photographic images (ill-suited for break lines which need to be generated independently or from intensity image), and generated contours not hydrologically corrected

9.7 Acoustic instruments

Sound generated by particle impacts is employed for detecting bedload movement. Non-invasive acoustic systems allow the measurement of spatially integrated bedload-transport rates. The systems consist of acoustic sensors, acoustic Dopplers, hydrophones, and geophones deployed along a reach, with data recorded to disk after signal conversion. The sensors are installed onto the bedrocks near the banks and onto large boulders in the centre of the stream. The sensors record acoustic energy of bedload impact on a plate fixed to the river bad. It is necessary to eliminate signals from fluid turbulence, cavitation, and bubble collapse. The systems should be calibrated using bedload-transport rates observed during a range of flows by conventional techniques. These systems should allow measurement of bedload integrated over a cross-section at very short time intervals. It allows monitoring temporal variations in bedload transport and thereby provides additional information about the transport process. All electronics components have to be mounted in robust and watertight stainless steel housing. The results obtained using this technique are showing a good relation with classical methods. The systems shall be calibrated to direct samples of bedload for each measuring sites. The systems allow monitoring temporal variations in the rate of bedload transport where classical methods fail to capture the episodic high flux rates. The method shows also potential for use in stream channels with gravel beds.

The acoustic method is applicable on sand-bed and in larger gravel bed channel and it does not affect the flow. The logistics of installing these systems and data reduction requirements are complex.

9.8 Acoustic Doppler current profiler

Movement of the bedload sediment layer can be detected by acoustic Doppler type instrumentations by measuring the surface velocity of the bedload layer. Be load discharge values are estimated by using the surface velocity of the bedload layer, the estimated thickness of the bedload layer (estimated by the shear stress, which is estimated by the vertical velocity distribution), and the characteristics of the bed material[24]. An ADCP is deployed by a tethered boat or a manned controlled boat. A stationery measurement is recommended, though a traverse measurement is acceptable if the ADCP or boat has a differential GPS system. The method can be used in most river conditions in terms of bed form, from ripple to the anti-dune, because the equation for estimating the thickness of bedload layer is valid within this range.

Annex A
(informative)

Bedload-surrogate monitoring technologies[8]

Table A.1 — Selected characteristics of bedload-surrogate monitoring technologies

Technology	Technology description	Continuous operation (Yes/no)	Mode of operation	Sediment Types	Stage of development	Ease of use[a]	Durability[b]	Portability[c]	Reliability[d]	Spatial coverage[e]	Cost[f]
ACTIVE SENSORS (all require field calibration)											
Acoustic Doppler Current profiler (ADCP)	Commercially available device that uses sonar and principles of Doppler to determine Vertical Velocity profile. Device also provides information on bedload movement (velocity).	Yes	Stationary ADCP device-sonar.	Sand and gravel	Moderately well developed. In preliminary usage.	2	4	2	1	Point/ cross-section reach	High
Sonar. Backscatter	High-frequency sonar transceiver to measure spatial and temporal fluctuations in sand-sediment concentrations over bedforms.	Yes	Stationary sonar.	Sand	Needs further work to quantify spatial and temporal characteristics of suspended sediment transport. Small-scale applications. Early stage of development.	4	4	2	3	Point/ cross-section	Low
Sonar: Bed differencing	Techniques for computationally differencing temporally distinct bathymetric surveys of a stream/river reach to determine total bedload flux.	No	Boat-mounted multi-frequency sonar and post processing.	Sand	Moderately well developed. Used in large rivers.	4	5	5	1	Reach	High
Radar	Short-pulse electromagnetic waves are transmitted into open-channel flow. The waves are scattered by particles in transport and recorded by receiving antennae.	No	Electro-magnetic wave return produced by presence of grains.	Gravel	Tested in laboratory but not in field. Early stage of development.	4	4	3	4	Reach	Moderate

a Ease of use: 1 easy, 5 difficult.

b Durability:1 durable, 5 fragile.

c Portability: 1 portable, 5 not portable.

d Reliability: 1 low maintenance needs, 5 high maintenance needs.

e Spatial coverage: Point - single point measurement, Cross-section - cross sectional measurement, Reach - measurement of an entire reach.

f Cost: Low - relatively inexpensive, High - relatively expensive.

Table A.1 *(continued)*

Technology	Technology description	Continuous operation (Yes/no)	Mode of operation	Sediment Types	Stage of development	Ease of use[a]	Durability[b]	Portability[c]	Reliability[d]	Spatial coverage[e]	Cost[f]
Smart tracers	Micro-radio-transmitters, radio frequency identification, and other advanced tracers used to track particles through channel or watershed.	Yes	Place tracer in system and monitor location through various techniques.	Gravel	Laboratory and field testing completed. Useful for specific applications. Systems are affordable but can be delicate to operate.	4	3	2	3	Reach	Moderate
PASSIVE SENSOR (all require field calibration)											
Impact pipes	Air-filled pipe installed within riverbed with passive sensor (geophone or hydrophone) recording impacts of grains on pipe.	Yes	Signal produced by impact of grain or pipe.	Gravel >4 mm	Moderately well developed. Testing in both laboratory and field. Requires local calibration.	2	2	4	2	Cross-section	Low
Impact plates	Steel plate installed within riverbed with passive sensor (geophone or hydrophone) recording impacts of grains on plates.	Yes	Signal produced by contact of grain on with plate.	>10 mm	Moderately well developed. Testing in laboratory and field. Requires local calibration.	2	2	4	2	Cross-section	Low
Impact columns	Gravel transport sensor (GTS) – piezoelectric vibration sensor or momentum sensor.	Yes	Signal produced by impact of grain on column.	10 mm to 128 mm	Early development with only laboratory testing to date. Requires local calibration.	3	3	2	2	Cross-section	Moderate
Magnetic tracers: coil log	Tracer technique that uses naturally magnetic or imbedded magnets in natural particles to track flux and trajectory of bedload particles. Parallel “inductors” are placed in the bed of the channel to measure passage of magnetic particles.	Yes	Signal produced by passage of grain over inductor.	Magnetic gravels	Early-to-moderate development. Technology is for specific application and specific sites where magnetic particles are found.	3	3	4	4	Cross-section	Low

[a] Ease of use: 1 easy, 5 difficult.

[b] Durability:1 durable, 5 fragile.

[c] Portability: 1 portable, 5 not portable.

[d] Reliability: 1 low maintenance needs, 5 high maintenance needs.

[e] Spatial coverage: Point - single point measurement, Cross-section - cross sectional measurement, Reach - measurement of an entire reach.

[f] Cost: Low - relatively inexpensive, High - relatively expensive.

Table A.1 *(continued)*

Technology	Technology description	Continuous operation (Yes/no)	Mode of operation	Sediment Types	Stage of development	Ease of use[a]	Durability[b]	Portability[c]	Reliability[d]	Spatial coverage[e]	Cost[f]
Magnetic tracers: bedload movement detector	Tracer technique that uses naturally magnetic or imbedded magnets in natural particles to track flux and trajectory of bedload particles. The bedload Movement Detector has an approximately 1 cm "inductor" that detects movement of magnetic particles.	Yes	Counts/time.	8 mm to 90 mm artificial stones	Early development conducted in the laboratory. Technology is for specific application where magnetic particles are found.	2	2	2	3	Point/ cross-section	Low
Passive hydro-acoustics	Recording natural sound generated by rock-rock collisions during bedload transport in channels using a hydrophone and data acquisition system.	Yes	Signal produced by impact of grains with one another.	Gravel and larger	Needs additional work to be an operational monitoring technique.	2	3	1	3	Reach	Low

[a] Ease of use: 1 easy, 5 difficult.

[b] Durability:1 durable, 5 fragile.

[c] Portability: 1 portable, 5 not portable.

[d] Reliability: 1 low maintenance needs, 5 high maintenance needs.

[e] Spatial coverage: Point - single point measurement, Cross-section - cross sectional measurement, Reach - measurement of an entire reach.

[f] Cost: Low - relatively inexpensive, High - relatively expensive.

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