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DHV CONSULTANTS & DELFT HYDRAULICS with HALCROW, TAHAL, CES, ORG & JPS

VOLUME 5
SEDIMENT TRANSPORT MEASUREMENTS

DESIGN MANUAL

Table of Contents

1 GENERAL

1.1 INTRODUCTION

Knowledge of sediment passing in a stream is essential in the solution of variety of problems associated with flow in rivers. Existing theories and empirical formulae for computation of transport give values that are unverified for areas for which they have to be applied. These can be continued where specific data for verification is not available, due to various constraints. Actual data gathering will help in better verification, and will lead to better problem solving and designs of water use facilities.

The quantity of sediment passing a section can be determined either directly or indirectly. The direct method aims at determining the weight or volume of sediment passing a section in a period of time. Indirect methods aim at measuring the concentration of sediment flowing in the moving water. This approach needs the measurement of sediment concentrations, the cross sections areas and velocities. This will also need looking at the sediment being transported as wash load, and bed load. Bed load measurement though very important for unstable river channels may not have same relevance for peninsular rivers. The use of empirical methods for bed load estimation may remain within desired accuracy ranges. Suspended particle load is amenable for practicing alongside quantity measurements and is not too demanding in terms of extra financial and manpower requirements. Another important information needed in respect of sediment is particle size distributions for design of sediment exclusion arrangements etc,

Briefly the objectives of sediment measurements are listed below:

a) Estimation of sediment inflow into reservoirs at the planning and design stage - by estimating the suspended load and bed loads separately
b) Studies for river training and river regimes – data may have to be gathered by mounting intensive gathering drill for short periods.
c) Evaluation of catchment erosion and identifying conservation measures
d) Estimation of regime widths and scour depths for barrages bridges from bed material analysis.

Sediment is fragmented material derived from the physical and chemical disintegration of rocks present on earth's crust. Such particles may range from boulders to particles of colloidal sizes. Their shapes influenced by constituent minerals may range from angular to rounded.

Once particles are detached from their resting-place they may be transported by gravity, wind, water or by a combination of these agents. Where the transporting agent is water the transported material is 'Fluvial sediment' and the process of detaching the particles and setting them in motion is called 'Erosion'. Erosion may be sheet erosion where the finer grains are detached and moved by rain drops, splash and sheet flow. Further transport is in water flowing in channels.

Because of the lie of the land (topography of the catchment) sheet flow does not occur continue over large areas, but quickly concentrates into small rills or channels and streams which grow in size as each joins the other. Within the channels the flowing water erodes the material in the bank or in the bed till the stream is 'loaded'.

Sediment measurements are rightly considered difficult to make and data collected in many parts of the world are doubtful. For reasons earlier outlined sediment observations follow the direct measurement of concentrations of sediment at observation stations of the network stations identified. The sediment observations consisting of obtaining representative samples and analysing them for their concentrations or for particle size distribution is described in this Volume 5 "Sediment transport and sediment data". This volume includes **how** observations are made by sampling and analysis, with **what** equipment, **where** and **when**. Volume 5 consists of three parts:

1. **Design Manual**, in which the basic principles and procedures are put in context
2. **Reference Manual**, for details on specific topics and background information
3. **Field Manual**, dealing with sampling at site and analysis in the laboratory

This part of Volume 5 covers the **Design Manual: "Sediment Transport and Sediment Data".** It is set up as follows:

- Chapter 1 deals with definitions used in sediment transport measurements and sediment data collection.
- Chapter 2 gives an overview of physical processes inherent in sediment transport.
- Chapter 3 discusses network design aspects with special reference to sediment transport measurements.
- Chapter 4 includes site selection criteria for sediment observations.
- Chapter 5 the observation frequency to be applied for sediment observations is dealt with.
- Chapter 6 deals with sediment observation techniques relevant to the Hydrological Information System (HIS).
- Chapter 7 contains remarks on the sediment sampling equipment and sediment field laboratory equipment.
- In Chapter 8 comments are made on hydrometric-station design when sediment data have to emanate from the station.

Field measurements and field laboratory practices are dealt with in the Field Manual. The Field Manual also deals with the topics of equipment maintenance and calibration, in respect of samplers and laboratory items.

Notes

The content of this part of the manual deals with sediment transport and sediment data in the states in peninsular India. The equipment discussed is either used or considered appropriate for use in HIS. Hence, the manual does not provide a complete review of all techniques and equipment applied elsewhere.

The procedures dealt in this manual are conforming to BIS and ISO standards. It is essential that procedures described in this manual be closely followed to guarantee a standard approach in the entire operation of the HIS.

1.2 DEFINITIONS

In rivers, sediment particles are moved by the flow:

- remaining in suspension for a long time before settling on the river bed,
- remaining rolling or sliding on the bed,
- rolling or sliding on the bed before being put again into suspension,
- settling on the bed before resting on it and possibly being buried under new deposits,
- settling on the bed that becomes dry when flow recedes and then being eroded by the wind,
- eroded from the bed to be put in motion again.

The traditional classification as per ISO-standard (ISO 4363: 1993) is:

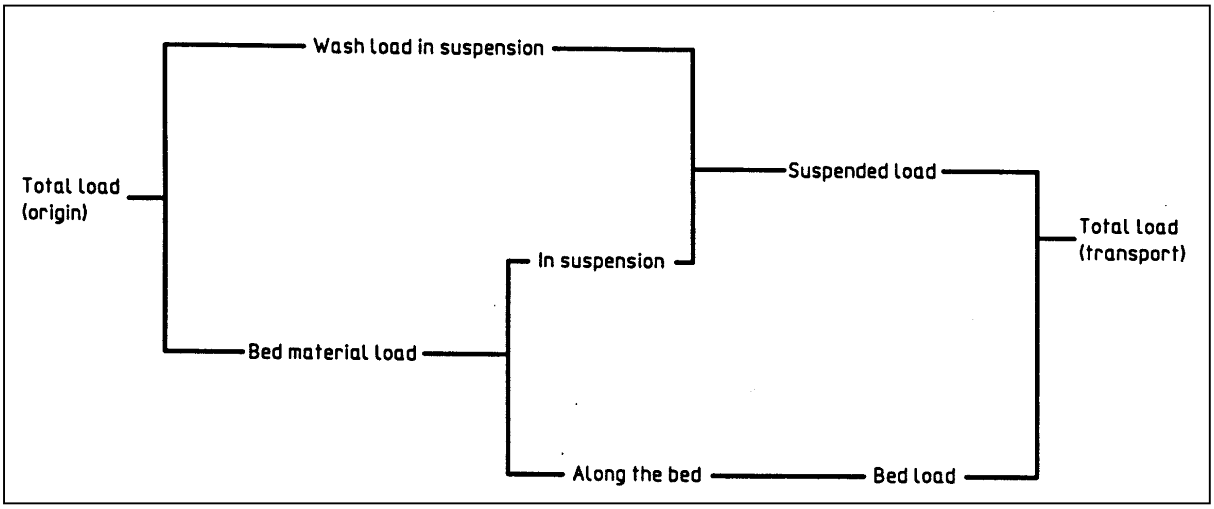

Figure 1.1: Diagram of definitions of sediment load and transport (ISO 4363: 1993)

The definitions of the ISO standard (ISO 772: 1988) are:

SEDIMENT TRANSPORT: Movement of solids transported in any way by a flowing liquid. From the aspect of transport it is the sum of the suspended load transported and the bed load transported. From the aspect of origin it is the sum of the bed material load and the wash load.

TOTAL LOAD: From the aspect of transport of sediment, the total load comprises bed load and suspended load, the latter including wash load. From the aspect of origin of the sediment, the total load comprises the bed material load (including the suspended portion) and the wash load.

BED MATERIAL: Material, the particles of which are found in appreciable quantities in that part of the bed affected by transport.

BED MATERIAL LOAD: Part of the total sediment transported which consists of the bed material and whose rate of movement is governed by the transporting capacity of the channel.

SUSPENDED LOAD: That part of the total sediment transported which is maintained in suspension by turbulence in the flowing water for considerable periods of time without contact with the stream bed. It moves with practically the same velocity as that of the flowing water. It is generally expressed in mass or volume per unit of time.

BED LOAD: Sediment in almost continuous contact with the bed, carried forward by rolling, sliding or hopping.

WASH LOAD: The part of the suspended load that is composed of particle sizes smaller than those found in appreciable quantities in the bed material. It is near permanent suspension and, therefore, is transported through the stream without deposition. The discharge of the wash load through a reach depends only on the rate with which the particles become available in the catchment and not to the transport capacity of the flow. It is generally expressed in mass or volume of the suspension.

SEDIMENT CONCENTRATION: Ratio of the mass or volume of dry sediment in a water-sediment mixture to the total mass or volume of the suspension.

Suspended concentration is determined routinely for three size classes:

Coarse Fraction:	D > 2 mm
Medium Fraction:	2 mm ≥ D > 0.075 mm
Fine Fraction:	0.075 mm ≥ D

Complete sediment size analysis is performed only on bed material samples by sieving. The sediment sizes range from boulders to colloids, through cobbles, pebbles, gravel, sand, silt and clay.

Class Name	Millimetres	Micrometers
Boulders	> 256	
Cobbles	256 – 64	
Gravel	64 – 2	
Very coarse sand	2.0 - 1.0	2,000 - 1,000
Coarse sand	1.0 - 0.50	1,000 - 500
Medium sand	0.50 - 0.25	500 - 250
Fine sand	0.25 - 0.125	250 - 125
Very fine sand	0.125 - 0.062	125 - 62
Coarse silt	0.062 - 0.031	62 - 31
Medium silt	0.031 - 0.016	31 - 16
Fine silt	0.016 - 0.008	16 - 8
Very fine silt	0.008 - 0.004	8 - 4
Coarse clay	0.004 - 0.0020	4 - 2
Medium clay	0.0020 - 0.0010	2 - 1
Fine clay	0.0010 - 0.0005	1 - 0.5
Very fine clay	0.0005 - 0.00024	0.5 - 0.24
Colloids	< 0.00024	< 0.24

Table 1.1: Scales of grain size by the American Geophysical Union

The relative concentration of the fine and medium fractions is determined by settling method, thus using the fall velocity of the particles. This is related to the size obtained by sieving. However, this method may produce errors, as the fall velocity is not solely determined by the size as obtained from the sieving.

The mineralogical composition of the sediment particles is not determined.

2 ORIGIN AND TRANSPORT OF SEDIMENTS

2.1 GENERAL

Sediment is fragmental material transported by, suspended in, or deposited by water or air, or accumulated in the beds by other natural agents; any detritus accumulation, such as loess. Generally sediment does not include, ice, logs of wood or organic material floating on the surface of water.

The surface of earth is solid and uneven. All the relief features on the earth such as fold mountains, block mountains, rift valleys and plateau's are formed by movement of earth's crust. In nature a slow process is always taking place, which tends to reduce difference in level between high and low areas, and thus level the earth surface. This process is called as gradation. Degradation and aggradation are two stages of gradation.

Degradation is the process by which rocks are broken down and load produced is carried away, while aggradation involves the deposition of the removed load at another place which is usually a low lying area.

In nature, gradation takes place because of Sun's heat, rain, changes in temperature, chemical reactions etc. Weathering of earth's surface takes place due to these agents. Gradation is also brought about by different agents like running water, wind and waves (mainly in coastal areas) involved in erosion. They not only act on earth's surface and produce load but also transport it and deposit elsewhere. Erosion, Transportation and Deposition are the different processes involved in gradation.

Erosion: It is a process in which detachment of rock or soil particles takes place under the forces of the eroding agents. In this process the agent of erosion acts on earth's surface resulting in the wearing down of the surface. Flowing water also causes erosion.

Transportation: In transportation agents of erosion carry the load away. During transportation further erosion takes place due to the collision of the particles and frictional forces between earth surface and moving particles.

Deposition: In this process the agents of erosion finally deposit the load carried, at some place raising level at that place

The process of gradation is continuous and unending. The three processes involved in it are always active all the times on earth's surface except in areas covered by thick layers of snow or are under the seas.

2.2 WEATHERING OF ROCKS

The earth surface especially rocks, when exposed to atmosphere decay. This rock decay is called weathering. This is a physical or chemical changes brought about in rocks or at near the surface by atmospheric agencies. The size, shape, texture density etc. of the sediment formed depends on the nature of the parent rock. Weathering takes place in three ways namely

- Chemical weathering
- Mechanical weathering
- Organic weathering

Chemical weathering: chemical weathering cause decomposition of rocks in which chemical composition of the original rock is changed. Water vapour, oxygen and carbon dioxide mainly bring about decomposition. During its descent through the atmosphere rainwater dissolves carbon dioxide and oxygen. This rainwater does not decompose ail minerals equally easily but this water through the process of oxidation, hydration, carbonation and solution decomposes nearly all minerals of the igneous and metamorphic rocks. This process loosens the rocks of the land surface and converts them to easily erodable material. The total effect of decomposition produces large volume of insoluble material like clay, carbonates of alkali elements, free silica and secondary minerals. In very cold places and extremely dry places chemical weathering is absent.

Mechanical weathering: in this process rock is broken down in smaller and smaller fragments without change in the chemical properties. Chemical reactions of decomposition are accelerated by presence of water and high atmospheric temperatures. Therefore, in the regions where either or both are lacking the scope of decomposition is limited. In this process rock undergoes physical disintegration.

In very hot areas rocks are exposed to extreme heat during day causing expansion. During night there is heat loss causing contraction. This continuous expansion and contraction of rocks cause layers in the rocks to peel off. Finally, the rock crumbles and breaks down. This process is called as exfoliation.

In regions where temperatures fall below the freezing point during night, the water present in the cracks of rocks during daytime, freezes at night. While freezing it expands and widens the cracks and the rock to break down into angular fragments.

Organic weathering: in organic weathering roots of the plants that grow in to the cracks or burrowing animals cause disintegration in rocks.

2.3 EROSION

Wind erosion

Wind is effective agent of erosion in and around areas where it is strong and blows throughout the year. Wind erosion takes place in three ways.

Deflation: In this process wind blowing over deserts and ploughed fields carries away fine sand and dust particles which are loose.

Abrasion: In abrasion, the particles of load carried by the wind, rub against the rock surfaces and wears them away.

Attrition: In this way, particles of load rub against each other and wear each other down. This reduces the size of the particles.

The relief features caused by wind erosion are deflation hollows, hamadas, rock pedestals and yardangs.

Erosion by water

When drop of rain reaches ground it transfers its energy to the material on which it falls. If the particles of the material are loosely bound, they get free from each other and thus erosion takes place. The erosion due to rainfall is most effective when it takes place on uncovered soil. Vegetative covers provide shield to the soil absorbing the energy of the raindrop failing on it.

Water after reaching soil surface starts moving down under gravity. When the top layer is saturated it prevents further rainfall from infiltrating. Then, overland flow starts. Higher rainfall intensities and depths produce more erosion. Time distribution of rainfall over storm duration plays an important role in erosion. High magnitude rainfalls for short duration produce large runoff resulting in more soil erosion.

Rainwater (precipitation) that reaches ground, after saturating the soil surface starts flowing on the surface as overland flow called ‘sheet flow’. Concentrated overland flow causes rills. As water flows through the rills, it erodes the soil surface. During a storm, large overland runoff takes place developing innumerable rills causing erosion. During this process a soil sheet more or less as an even layer is removed. This has known as ‘sheet erosion’. When water starts flowing through rills, development of relatively deep and steep sided channels called ‘gullies’ take place. The removal of sediment by widening and deepening ‘gullies’ is called ‘gully erosion’. Thus overland flow concentrates into rills, gullies and then small streams which grow in size as they join each other to form a stream channel. Within these channels the water erodes the available material in the banks or riverbeds and 'loads' the stream.

Erodability of a particular soil material varies inversely with particle size. Fine sandy soil erodes more rapidly than tough clay.

The total sediment outflow from a watershed or drainage basin measurable at a given place in specified period of time is called 'sediment yield'. It is expressed in terms of tonnes/km^2/ year. The rate at which erosion takes place from a given area is called 'rate of erosion'. A measure of diminution of sediment by deposition as they move from point of erosion to any designated downstream location is called 'sediment delivery ratio'. It is also expressed as a percentage of on site eroded material that reaches a given measuring point.

2.4 FACTORS AFFECTING EROSION AND SEDIMENT YIELD

Catchment erosion and the quantity of eroded material that may reach the outlet of a catchment depend upon several factors viz. hydro-meteorology, topography, land use and lithology. Their effect on the catchment erosion and sediment yield has been summarised below.

2.4.1 NATURAL FACTORS

Climate

Rainfall, runoff and temperature are the main climatic factors affecting catchment erosion and sediment yield. The splash capacity of raindrop increases with drop size, rainfall intensity and presence of overland flow. The temperature plays an important role in process of weathering which leads to disintegration of rocks.

Topography

Catchment area, its average slope and drainage density are some of the factors related to the catchment topography, which are found to influence the erosion and sediment yield. Velocity of the overland flow and hence the shear stress on the land surface and transport capacity increases with the increase in catchment slope.

Land Use

Vegetation or plant cover reduces the soil erosion, its effectiveness depending upon the height and continuity of canopy, density of ground cover and root density. If canopy is near the ground, it dissipates the kinetic energy of rain; canopy on the ground increases roughness and reduces the velocity of flow. Roots play an important role in reducing erosion by binding the soil mass to increase its resistance to flow. These also increase percolation and reduce runoff. Generally forests are most effective in reducing erosion because of their canopy; dense grass is equally effective.

Geology

Geology is also an important factor that controls upland erosion and channel erosion phases of sediment yield. The inter dependence among climatic conditions, land use and geology makes it difficult to detect the specific role-played by geology on sediment yield production. The landslides, related to the geology of the area, enhance erosion in the catchment.

2.4.2 HUMAN ACTIVITIES

Agricultural activity

Opening of new lands for agricultural purposes necessarily disturbs the natural conditions. Many times forests are removed by axe and fire, native grassland are burnt, overgrazed and broken by plough.

Deforestation

Forests are cut down for agriculture (by tribal people.), timbre, industrial developments, construction etc. Deforestation removes vegetative canopy exposing land to the climatic changes.

Urbanisation

Urbanised area when fully developed, is actually low sediment producing areas but during development erosion rates are high due to construction activity.

Roads and Highway Construction

Serious erosion takes place during the construction of roads and highways as protective vegetative cover is removed and steep sloping cuts and fills are left unprotected. Such erosion can create local problems and spurt in downstream sediment loads.

Mining Operations

Mining activities introduce large quantity of sediment directly into the streams. Tailing dumps and spoil banks, which are left ungraded and unvegetated, often continue to erode by natural rainfall for years.

2.5 EFFECTS OF EROSION AND SEDIMENTATION

Land erosion and soil conservation

Rainfall causes surface runoff. If the drag force of the surface runoff is sufficiently large, soil particles are dislodged and transported along with water. Soil can be eroded by strong winds over the soil surface. When land is brought under cultivation, soil mass is exposed to abrasive action of water and air and accelerated soil erosion takes place. The quantity of fertile soil lost in this way is very large. Several practices of soil conservation are followed to check this accelerated soil erosion.

Floods and meandering

When heavy rainfall occurs river rises above the banks and spills to the low-lying areas, which are usually fertile. The top fine layer of soil is eroded during traversing of a flood wave. Rivers flowing through loose alluvial material 'meander' or follow zigzag paths. These rivers erode the outer bank depositing material on the inner bank increasing meandering. This leads to the development of steep river cliffs in the outer banks of the river.

Degradation, aggradation and local scour

A certain length of alluvial stream is said to be in equilibrium when amount of sediment coming into the reach is equal to the sediment going out from the same. Therefore, the stream bed elevation will not change over long periods of time. However if the incoming and outgoing sediment loads are different, the bed levels will either rise or fall. A rise in the bed level is called as aggradation, while a fall is called degradation. Aggradation causes rise in bed level and change in river cross section, reducing flow area. When an obstruction is introduced in the flowing river, the water goes round the obstruction resulting in scour. Scour around spurs, groins, bridge piers and abutments are some examples where this phenomenon is important.

Silting of reservoirs

Dams are constructed across rivers to create large water storage used for agriculture, generation of hydropower, flood management, and water supply etc. After construction of dams the entire bed load and a part of suspended load is deposited in the pool of water of the reservoir. This reduces the storage capacity of the reservoir. To have a given storage it increases the water-spread area and thus evaporation loss.

Navigation

Water transport is treated as cheaper than surface transport. If the navigation channels are fed with silt-laden waters, deposition of sediment will occur. To maintain required drafts and channel navigable dredging will be required. Dredging activity will both be obstructive for navigation and also expensive.

2.6 SEDIMENT TRANSPORT

2.6.1 FALL VELOCITY

The fall velocity of a sediment particle in stagnant water is derived from equilibrium between the gravitational force and the drag force due to a difference W in velocity between particle and water, equal to the fall velocity, see Figure 2.1:

$$\frac{1}{6}\pi(\rho_s - \rho)gD^3 = C_D.\frac{1}{2}\rho W^2.\frac{1}{4}\pi D^2$$

So:

$$W = \left(\frac{4}{3C_D}\Delta gD\right)^{1/2} \text{ with} :\Delta = \frac{\rho_s - \rho}{\rho} \approx 1.65 \qquad (2.1)$$

where:
- W = fall velocity [m/s]
- C_D = drag coefficient [-]
- D = relative density [-]
- ρ_s = sediment density [kg/m^3]
- ρ = density water [kg/m^3]
- g = acceleration of gravity [m/s^2]
- D = particle diameter [m]

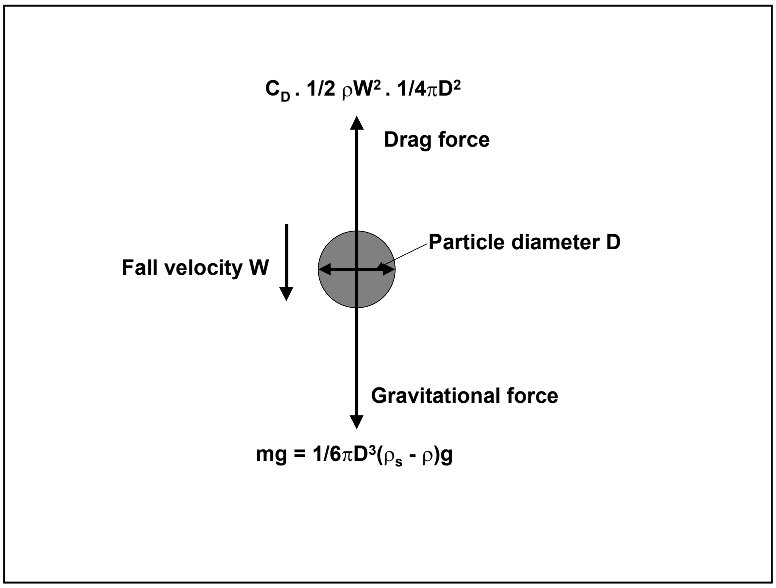

Figure 2.1: Definition sketch of fall velocity

Dependent on the **particle Reynold number** Re = WD/ν, where ν is kinematic viscosity coefficient of water [m^2/s] the drag coefficient C_D is inversely proportional to D or independent of D, as follows:

for Re < 1, Stokes law is applicable: $C_D = 24/Re$, so:

$$W = \frac{1}{18}\frac{\Delta g}{\nu}D^2$$

for Re > 150, Newton's law is applicable: $C_D \approx$ constant

$W :: \sqrt{g\Delta D}$ So, generally for any particle Reynolds number:

$$W :: D^{\alpha}, \quad \text{with: } \tfrac{1}{2} \leq \alpha \leq 2 \qquad (2.2)$$

In general the fall velocity is a function of:

1. particle diameter D
2. relative density Δ, for quarts Δ = 1.65
3. temperature (in viscosity): the fall velocity increases with temperature
4. sediment concentration: the fall velocity reduces when the sediment concentration increases
5. shape factor, defined by $c/\sqrt{(a.b)}$, where c is the smallest of the 3 of the mutually perpendicular dimensions of the particle. For sand and gravel $c/\sqrt{(a.b)} = 0.7$. The drag coefficient C_D varies between 0.3 and 2.3 for shape factors ranging from 1 to 0.3 respectively.
6. turbulence of the flow.

Reference is made to van Rijn (1993) for an overview.

2.6.2 INITIATION OF MOTION

The initiation of particle motion is determined by 3 forces:

- the force exerted by the flow on the particles, which is a resulting force due shear and lift caused by the curvature of streamlines around the particle

- the gravitational force on the particle
- reaction force delivered by surrounding particles.

Particle movement will occur if the moment of the force resulting from lift and shear taken from the point of contact exceeds the stabilizing moment of the submerged weight of the particle, as shown in Figure 2.2.

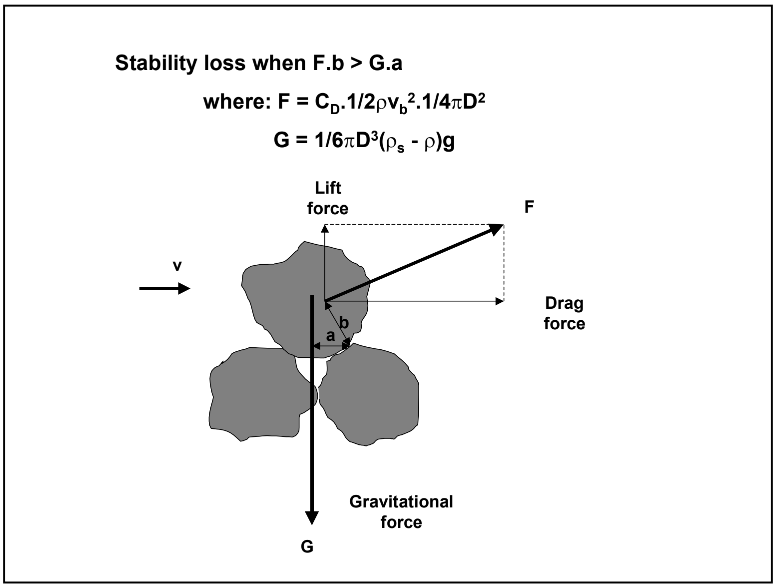

Figure 2.2:
Definition sketch for initiation of motion

The condition for particle movement reads:

$$F.b > G.a$$

This implies:

$$C_D.\frac{1}{2}\rho v_b^2.\frac{1}{4}\pi D^2.b > \frac{1}{6}\pi D^3(\rho_s - \rho)g.a$$

Since the velocity near the bottom v_b is proportional to the shear velocity u_* the condition for mobility of the particles can be formulated as:

$$\frac{u_*^2}{g\Delta D} > \frac{\alpha}{C_D}$$

where α as well as C_D are coefficients dependent a.o. on the shape factor of the particles and the Reynolds number $Re_* = u_* D/\nu$. Since $u_*^2 = \tau_0/\rho = \rho ghS/\rho = ghS$, by substitution in the above expression one obtains on the left hand side the Shields parameter θ. The right hand side represents the critical shear stress parameter θ_{cr}.

Hence, the mobility of sediment can be studied by means of the **Shields-parameter** θ. This is a dimensionless measure for the bottom shear stress, which brings the particles in motion:

$$\theta = \frac{hS}{\Delta D} = \frac{v^2}{C^2\Delta D} \qquad (2.3)$$

where: h = flow depth
S = energy slope (= bed slope for steady uniform flow)
v = depth average velocity
C = Chezy rugosity coefficient

If θ exceeds a critical value θ_{cr} then particles start moving. The experimental range for θ_{cr} as a function of Re_* is:

$\theta_{cr} \geq 0.035$	for	$Re_* \leq 5$, hydraulically smooth regime
$0.03 \leq \theta_{cr} \leq 0.04$	for	$5 \leq Re_* \leq 70$, transitional regime
$0.04 < \theta_{cr} \leq 0.06$	for	$Re_* \geq 70$, hydraulic rough regime

The value of θ_{cr} can also be expressed as a function of D_*, with:

$$D_* = \left(\frac{\Delta g}{\nu^2}\right)^{1/3} D_{50} \qquad \text{with:} \quad \nu = \frac{4x10^{-5}}{20 + t_c} \tag{2.4}$$

where: t_c = temperature in °C. The relation between D_* and θ_{cr} is presented in Table 2.1. Note that the Shields curve refers to the situation that a large number of particles are put in motion.

D_*-range	θ_{cr}
$D_* \leq 4$	$0.24\ D_*^{-1}$
$4 < D_* \leq 10$	$0.14\ D_*^{-0.64}$
$10 < D_* \leq 20$	$0.04\ D_*^{-0.1}$
$20 < D_* \leq 150$	$0.013\ D_*^{0.29}$
$D_* > 150$	0.055

Table 2.1:
Shields curve as function of D_*

The Shields curve is shown in Figure 2.3:

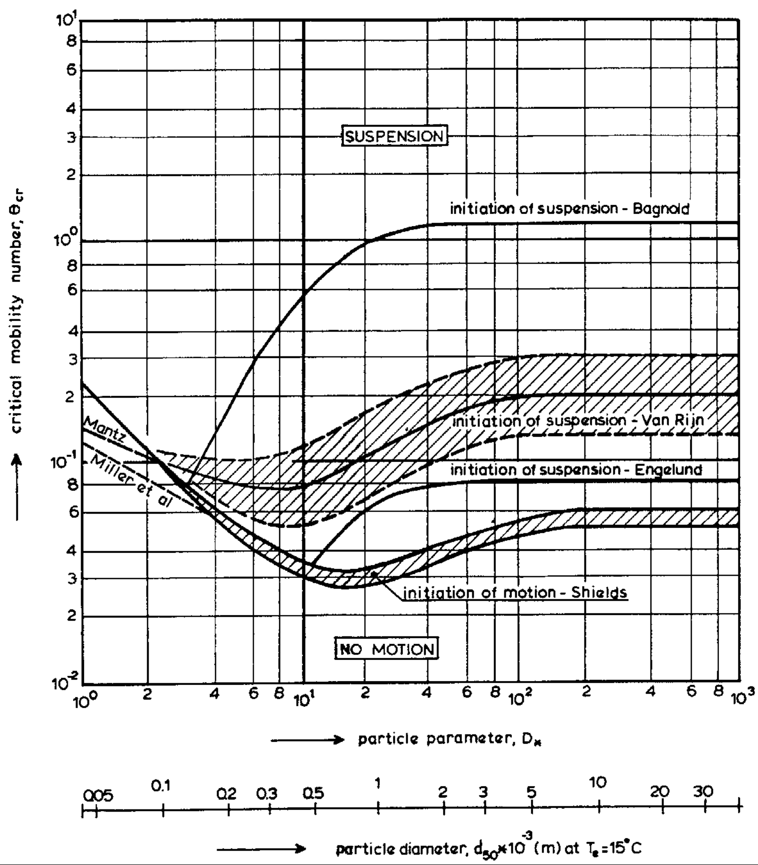

Figure 2.3:
Shields curve as a function of the dimensionless particle diameter D_*

2.6.3 VERTICAL SEDIMENT CONCENTRATION DISTRIBUTION

The sediment concentration in a stream as a function of the position in the vertical is given by (Vanoni, 1946):

$$\frac{c(y)}{c(a)} = \left(\frac{a}{h-a}\frac{h-y}{y}\right)^Z \text{ with : } Z = \frac{W}{\kappa u_*} \text{ and : } u_* = \sqrt{\frac{\tau}{\rho}} = \sqrt{ghS} \qquad (2.5)$$

where:
- $c(y)$ = sediment concentration at depth y from the bed
- $c(a)$ = known sediment concentration at depth 'a', with $0 < a < h$
- h = flow depth
- Z = parameter, which determines character of the sediment transport, see below.
- W = fall velocity
- ν = kinematic viscosity
- u_* = bottom shear velocity
- κ = von Karman constant
- τ = shear stress
- S = energy slope

(Note that κ for a sediment laden flow deviates somewhat from 0.4; it depends on the average concentration in the vertical and the concentration at the bed, see e.g. Jansen et.al. 1979)).

Equation (2.5) gives an appropriate picture of the sediment concentration for uniform flow, provided that $c << 1$. Generally, measured concentration verticals show a more uniform distribution of the concentration than the computed ones. To apply (2.5), the sediment concentration has to be known at a particular depth 'a' to be able to determine the concentration at depth 'y'. The parameter Z or equivalently u_*/W determine the character of the sediment transport as indicated in the following table.

Type of sediment transport	$Z=W/(\kappa u_*)$	u_*/W
Intensive bed load transport	10	0.25
Suspension in lower half of vertical	2.5	1
Particles reach water surface	0.8	3
Well developed suspended transport	0.1	20
Homogeneous suspension	0.01	200

Table 2.2: Effect of Z and u_*/W on sediment transport

From Table 2.2 and Figure 2.4 it is observed that for particle diameters for which $u_*/W < 1$ or $Z > 2.5$ hardly any suspended transport takes place. For low values of u_*/W it matters much where to measure the sediment concentration as the variation with depth is very large.

To determine the total load with the aid of (2.5) the following integration has to be carried out (see Figure 2.5):

$$s = \int_0^h v(y)c(y)dy \qquad (2.6)$$

2.6.4 SEDIMENT TRANSPORT EQUATIONS (TOTAL LOAD)

One of the objectives of sediment transport measurements is to calibrate a sediment transport formulae to be used in investigations or for design. It is noted that all sediment transport formulae are empirical equations with limited validity. Generally, these formulae give a relation between the transport parameter ϕ and the parameter θ, discussed above:

$$\phi = f(\theta, \theta_{cr}, \dots) \quad \text{where:} \quad \phi = \frac{s}{\sqrt{g\Delta D^3}} \quad \text{and:} \quad \theta = \frac{hS}{\Delta D} \tag{2.7}$$

where: s = sediment transport per unit width ($m^3/s/m$)

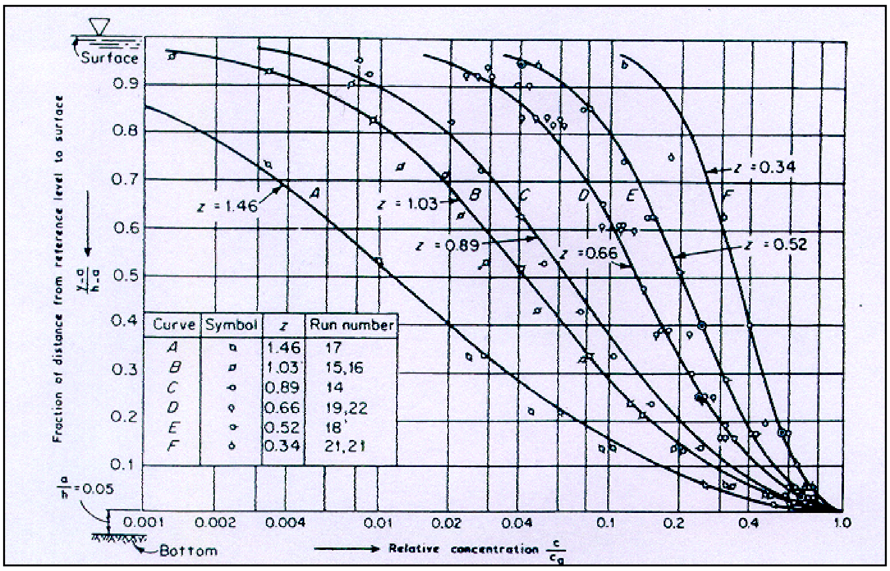

Figure 2.4:
Sediment concentration verticals measured and computed according to Vanoni (1946)

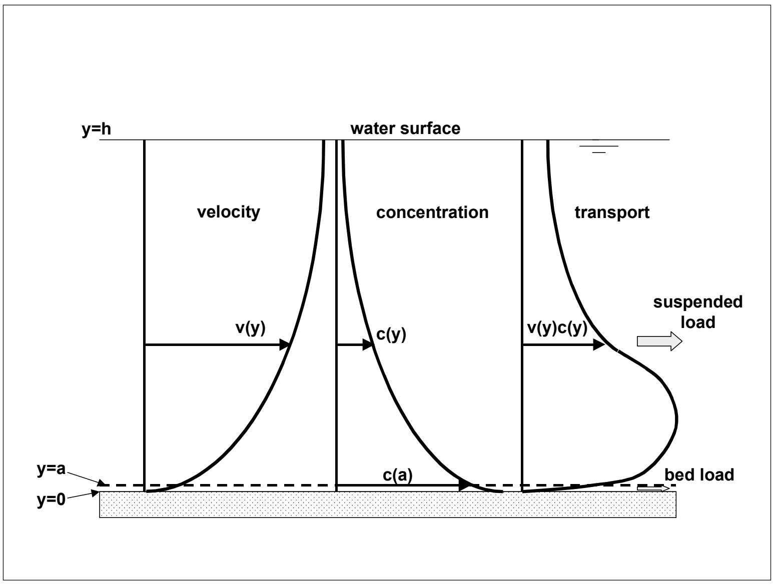

Figure 2.5:
Definition sketch suspended load transport

The parameter θ is generally accompanied by a ripple factor μ, to allow for the fact that only a part of the shear stress is used for transport. An example is the Meyer-Peter and Müller (1948) formula often used for coarse material:

$$s = c_1 \sqrt{g\Delta D_m^3} \left(\mu\theta - c_2\right)^{3/2} \tag{2.8}$$

where: c_1 and c_2 = regression coefficients for which M-PM found respectively 13.3 and 0.047, but the coefficients should be calibrated for a particular river

μ = ripple factor: $(C/C_{90})^{3/2}$

Another equation is by Engelund-Hansen (1967) suitable for finer sediments:

$$s = c_3 \sqrt{g \Delta D_{50}^3} \mu \theta^{5/2} \quad \text{with:} \quad \mu = \frac{C^2}{g} \quad \text{and characteristic grain size} \quad D_{50} \qquad (2.9)$$

Generally, the transport equations are of the form:

$$s = av^b \qquad (2.10)$$

where: a = coefficient
b = exponent (3 for MPM and 5 for EH)

2.6.5 BED LOAD TRANSPORT

In case of coarse bed material, sediment transport uniquely takes place in a thin layer above the bed. Then the sediment transport can be derived from the migration of bed forms. If c_b is the celerity of a dune, then from continuity principles for the local transport it follows; see also Figure 2.6:

$$s_b(x) = c_b \, y_b(x) \qquad (2.11)$$

where: $y_b(x)$ = local height of bed relative to trough level, with $y_b(max)$ = H (the height of a dune).

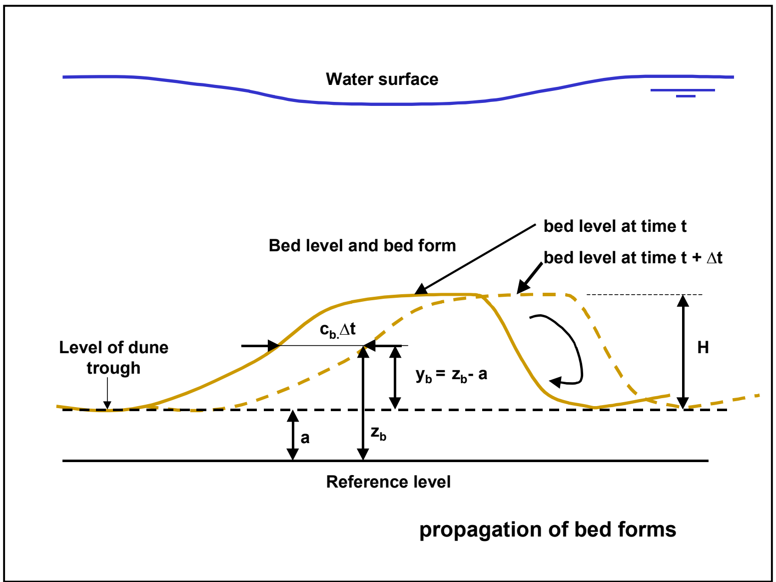

Figure 2.6: Dune propagation

For the average bed load transport one gets:

$$\bar{s}_b \approx (0.5 \text{ to } 0.6)\, c_b H \qquad (2.12)$$

The value of 0.5 refers to triangular dunes; in nature dunes do have a more rounded streamward face so 0.6 is a better approximation. Above method forms the basis for the determination of bed load transport by means of dune tracking. The problem however is that some saltation transport is missed, so the procedure will lead to a slight underestimation of the bed load transport.

Bed load may also be measured; details are presented in the Reference Manual.

3 NETWORK DESIGN

3.1 THE NEED FOR SEDIMENT DATA

Routine sediment measurements at stations are usually restricted to sampling the suspended load at flow gauging stations. In this sense, sediment is looked at as a "quality" parameter of the water. Although the present need for sediment data may be satisfied with the existing network, new needs could emerge in relation to various kind of projects or studies, e.g. hydraulic structures, reservoirs, quality aspects.

3.2 GENERAL CRITERIA FOR NETWORK DESIGN

For the hydrological network, priority is given to the need for streamflow data and the guidelines set out in the corresponding section of the manual on streamflow apply. For possible supplementary stations in which emphasis is given on sediment, the following general principles should be followed:

- assess the existing conditions within the watershed;
- define clearly the monitoring objectives and the data needs;
- establish the required time table, the frequency and periods of observation;
- make a thorough evaluation of the geomorphic setting in the reaches where useful measurement stations were selected.

Obviously, the site selection will be a compromise between many and different criteria; it will be the responsibility of the network designer to make a careful choice, bearing in mind the need to use the available resources in an optimal way.

In case supplementary stations are to be established for sediment measurements, they will be integrated in the existing network taking into account the specific data needs. This would be done project-wise or in collaboration with the data users.

3.3 SEDIMENT MEASUREMENT NETWORK

A sediment-measuring network is a system of flow and sediment gauging stations in a river basin that provides data needed for the planning, design and management of the water resources in the catchment from the point of view of the sediment. Most often, the number of hydrological stations with sediment monitoring is only a part of the entire network. From the sediment viewpoint, the network requirement for flow and sediment stations is largely influenced by a number of factors, including:

- the geomorphic characteristics in the basin catchment;
- the purposes for which the data are required;
- existing and potential water resources projects or environmental considerations;
- the type of sediment data needed;
- the availability of financial, manpower and other resources.

Specific criteria for selecting sites for sediment measurements can not be found in ISO in the standard on methods for measurement of suspended sediment (ISO 4363: 1993, "Measurements of liquid flow in open channels - Methods for measurements of suspended sediment"). The site selection is further discussed in Section 4.2.6 of this manual on Sediment and Sediment Transport Data. They are mainly based on the general assessment of the geomorphic situation and on local conditions of flow and sediment.

3.4 CLASSIFICATION OF SEDIMENT MEASUREMENTS SITES

The three categories defined in the general classification of streamflow measurements, as presented in the corresponding section of the manual on streamflow, also apply to the stations where sediment is gauged together with the flow. Most often, no particular categories are made for sediment measurements. However, specific categories may be useful to define specific sediment gauging strategies based on the particular sedimentology of each. There are no such requirements as density per unit area, rather a network adapted to the specificity of the catchment in terms of geomorphology and sediment production, transport and deposition.

This additional classification (or differentiation) of measurement sites may be made in different ways (see also the Sediment Measurements). One considers the kind of the sediment moving through the considered reach:

1. suspended load mainly wash load, composed of clay or fine silt, with little sand content; negligible bed load;
2. suspended load mainly containing bed material load with significant proportions of sand; limited bed load;
3. suspended load mainly containing bed material load with high proportions of coarse sediment; significant bed load.

Besides the classification based on the composition of the transported sediment load, the composition of the bed material is important as well as the degree of degradation or aggradation of the bed in the considered reach:

1. stable bed with negligible bed erosion/scour: hard rock or sedimentary bed material;
2. unstable bed composed of the same material transported by the flow, degrading or aggrading;
3. unstable bed composed of a different material as the one transported by the flow, degrading or aggrading.

The sites may thus be classified under nine main categories as shown in Table 3.1.

Type of sediment load	Fine suspended load	High	Medium	Low
	Coarse suspended load	Low	Significant	High
	Bed load	Negligible	Limited	Significant
Type of channel	Stable bed, rock or poised	**A**	**B**	**C**
	Unstable bed, bed material suspended	**D**	**E**	**F**
	Unstable bed, bed material suspended but different	**G**	**H**	**I**

Table 3.1: Classification of measurement sites for selecting the appropriate measurement strategy

However, differentiation can also be made according to the flow regime, e.g. torrential or tranquil regime, or depending on the position in relation to particular reaches or structures, e.g. stations immediately upstream or downstream from reservoirs.

3.5 SOME NETWORK DESIGN CONSIDERATIONS

Little has been done in terms of international standards for establishing sediment measurement networks. The routine networks, operated by governmental organisations are usually part of streamflow networks. Specific networks are often designed for particular projects and the duration of operation depends on the objectives, e.g. permanent stations in relation to monitoring reservoir sedimentation. However, designers of hydraulic structures such as headworks for water diversion find themselves with a lack of data or with data of too short observation period. This situation has led to wrong assessment of the design data and failures in design and operation.

1. All primary streamflow stations should have sediment measured together with the flow, if feasible but not necessarily at the same location as the flow gauging section. They should all comprise at least simple suspended load measurement, but the need for more detailed suspended load, near-bed load and bed load has to be evaluated for each individual site, depending on the sedimentological characteristics, geomorphic setting and data needs;
2. The network for sediment measurements other than routine suspended load gauging should consider the geomorphology and sedimentology of the stream catchment and course: changes in sediment load and associated possible sources, sudden changes in sediment transport capacity, changes in physical properties of the sediment (mainly size) etc.;
3. There are no specific requirements in terms of minimum stream basin area, but all the sediment sources of importance for establishing sediment balances should be included in the network;
4. Special requirements apply to specific situations as in deltas or estuaries, or in alluvial fans; they are too specific to be described here;
5. Sediment measurement networks need to be re-evaluated periodically, both their number and location. This upgrading has to be performed together with an evaluation of the streamflow data, but not only based on hydrological criteria;
6. It makes little sense to apply statistical and mathematical optimisation techniques to the sediment measurement networks, mainly because of the complexity of the design and site selection criteria, e.g. the importance of geomorphology, but also because many stations are project oriented;
7. Sediment networks for both suspended load and bed load are expensive to equip and to operate; optimisation is therefore a must, but it should rather be based on sound judgement and economic consideration (cost-effectiveness).

4 SITE SELECTION

4.1 DEFINITION, OBJECTIVES AND CONSTRAINTS

Sediment sampling and measurement is often at streamflow station locations. Criteria for locating such stations places emphasis on flow/discharge measurement with sediment being considered an attribute of flow. This is the situation for streams carrying mainly fine solids over a stable bed (see Table 4.1). For other categories, streamflow stations may not be appropriate for sediment measurements with the given objectives, in which case two options are open: to have the streamflow site moved to a different, more appropriate location, or to have streamflow and sediment measured at different locations. This problem may obviously be solved by a review of the network design, at which stage the issue of the general objectives of the sediment measurements should be addressed.

Eventually, the initial objectives of an existing station may be modified because of new data needs, for example in relation to new projects or requirements, such as a water intake structure for a new irrigation scheme in a stream carrying significant coarse suspended bed material and some bed load. In such a case, near-bed or contact load will be needed in addition to the routine suspended load measurements and the conditions at the site could not be optimal anymore.

Possible questions to be addressed when selecting the sediment measuring site are formulated similarly to those for the flow (see also Chapter 4 of Volume 4, Hydrometry):

1. What is the purpose of the station: e.g. monitoring of reservoir sedimentation, planning and design of structures, setting up sediment balances in river reaches;
2. What are the sediment conditions at the site: i.e. how variable are sediment transport rates in the river reach, are there preferential zones of scour and/or deposition;
3. In what range of flow should the sediment be gauged, and which part of the load: e.g. no bed load during the lean season;
4. What fraction of the sizes are needed: e.g. the wash load not of interest for a problem of river morphology;
5. What level of accuracy should be attempted, for the various transport modes and for the various size fractions?
6. What period of record is required and what frequency of measurement is desirable, possibly in particular phases of the hydrograph: e.g. more frequent sampling during the rising limb of the hydrograph;
7. Who are the possible users and for which kind of data?
8. Are their limitations in terms of access to the site and transport of the samples to the laboratory for analysis?
9. What are the constraints in terms of resources (human and financial)?
10. What are the possible preferences for equipment and methodology: e.g. existing experience with one or another type of instrument; proximity of a research centre that can assist in case of difficulties for implementing the measurements.

In India and especially the peninsular region, all the rivers pass from the boulder stage to the flood plains to the deltas as the rivers approach and confluence with the sea. The measured sediment transport by suspension is converted to a gross estimate of sediment flow into storage’s planned. For adding bed load transport empirical relationships are used with some error being present, due to limitations in availability of finances and manpower for a more accurate estimation. Bed material sampling and analysis is resorted to in estimating regime widths of rivers and planning for possible scour depths.

4.2 SITE SURVEYS

4.2.1 GENERAL

As the site is usually a streamflow station, the surveys should concentrate specifically to gather sufficient information complementary to the one collected about the flow conditions (see in the corresponding section of the manual on streamflow). However, in the case of sediment observations needed for special problem solving, there is the need to go for a better specific evaluation of the geomorphic setting (see the operations manual on Sediment Transport and Sediment data).

4.2.2 DESK TOP STUDY

The site location will be located on the topographic maps - both at a large and a small scale – including for specific studies eventually on hydro-graphic (bathe-metric) chart in the case of large rivers, on geological maps (possibly with soil mechanical and tectonic information), on land-use and vegetation-cover maps. When feasible, the site should be indicated on a longitudinal profile so as to identify the regularity of the average river slope, preferably the bottom and surface slope, at least the valley slope. The site location may be analysed in relation to the valley shape and geological formations.

Depending on the importance of a specific study, and of the objectives, the geomorphic setting may be established. Aerial photographs and satellite images, when available, help identifying specific geomorphic features (topographic, geologic, vegetation in relation with soil properties, etc.).

4.2.3 RECONNAISSANCE SURVEYS

The survey will be additional to the one needed for the streamflow station (see in the corresponding section of the manual on streamflow). However, in particular cases such as larger, unstable alluvial reaches, a bathymetric survey, possibly complemented with surface float tracks, should be made. In the case of significant bed load transport with bed forms, these should be observed to assess their possible use in hydraulic and sedimentological studies. Observation can be made with topographic surveys at low stages, when part of the (remnant) bed forms appear on the dry bed or during higher stages by longitudinal profiling with echo-sounder.

4.2.4 OTHER SURVEYS - BED SAMPLING, FLOAT TRACKS AND SLOPES

A preliminary observation of the sediment present on the riverbed may help identifying peculiar features, such as zones of hard rock, of preferential deposition zones, of sorting due to selective transport or of bed armouring.

Additional water level observations with temporary staff gauges may be useful to interpret these peculiar features, and assess the reliability of water surface slope data for computation of flow resistance.

4.2.5 SITE SURVEY CHECK LIST AND ASSESSMENT FORM

New survey check lists and assessment forms should be prepared on the basis of various kind of site situation, possibly for the categories mentioned above.

4.2.6 SITE SELECTION CRITERIA

1. The measuring site should be in the middle of a channel stretch that should be straight over a distance at least 6 times the width at bankfull flow and be of uniform cross section and slope, so as to avoid abnormal velocity distribution such as helical flow or irregular velocity distribution. When this condition can not be met, the length of the channel with these flow conditions may be reduced, but keeping upstream of the gauging section a length of straight channel at least twice the downstream part. Table 4.1 presents indicative distances for complete mixing as a function of the average stream width and mean depth.
2. In stable channels (poised alluvial bed or rock substratum) flow directions for all points on any vertical across the width should be as much as possible parallel to one another and at right angles to the measurement section, and this at all stages. If this criterion can not be met, the cross-section orientation could be adapted to the changes of flow direction with stage.
3. In large alluvial sand bed rivers with formation of migrating shoals, the cross-section for gauging flow and sediment should be adapted continuously to the changing morphology, possibly also during the flood hydrograph.
4. The bed and margins of the channels should be stable and well defined at all stages of flow (below bankfull flow stage) in order to facilitate accurate measurement of the cross section and ensure uniformity of conditions during and between discharge measurements.
5. The curves of the distribution of velocities over depth and width should be regular (in the vertical and horizontal planes of measurement.)
6. Conditions at the section and in its vicinity should also be such as to preclude changes taking place in the velocity distribution during the period of measurement.

Average River Width (m)	**Mean River Depth (m)**	**Estimated Distance for Complete Mixing (km)**
5	1	0.08 – 0.7
	2	0.05 – 0.3
	3	0.03 – 0.2
10	1	0.3 - 2.7
	2	0.2 - 1.4
	3	0.1 - 0.9
	4	0.08 – 0.7
	5	0.07 – 0.5
20	1	1.3 – 11.0
	3	0.4 - 4.0
	5	0.3 - 2.0
	7	0.2 - 1.5
50	1	8.0 – 70.0
	3	3.0 – 20.0
	5	2.0 – 14.0
	10	0.8 - 7.0
	20	0.4 - 3.0

Table 4.1: Estimated distance for complete mixing in streams and rivers (after Bartram & Balance, Water quality monitoring, E. & F.N. Spon, London, 1996)

7. Sites displaying vortices, reverse flow or dead water should be avoided, especially when associated with structures in the streambed or with bed rock outcrops.
8. The measurement section should be clearly visible across its width and unobstructed by trees, aquatic growth or other obstacles. When gauging is only possible from a bridge with divide piers, each section of the channel should be treated accordingly.
9. The depth of water at the section should be sufficient at all stages to provide for the effective immersion of the instruments, whichever is to be used.
10. The site should have easy access at all times, for all necessary measurement equipment.
11. The section should be sited away from pumps, sluices and outfalls, if their operation during a measurement is likely to create flow conditions not enough close to uniform flow.
12. Sites should be avoided where there is converging or diverging flow.
13. In those instances where it is necessary to make measurements in the vicinity of a bridge, it is preferable that the measuring site be upstream of the bridge. Although in special cases and where accumulation of logs or debris is liable to occur it is acceptable for the flow-measuring site be downstream of the bridge, sediment should preferably be sampled at another location. Particular care should be taken in determining the velocity distribution when bridge apertures are surcharged.
14. It may, at certain states of river flow or level, prove necessary to carry out sediment measurements on sections other than that selected for the station. This is quite acceptable if there are no substantial ungauged flow and sediment losses or gains to the river in the intervening reach and so long as all measurements are related to levels recorded at the principal reference section.

5 MEASURING FREQUENCY

5.1 GENERAL

Common, though often-unanswered questions in seminars on sediment transport measurements are:

- How frequently to take suspended sediment samples?
- When to take suspended sediment samples?
- How many verticals to sample?
- How many samples to take on each vertical?
- How to adjust suspended load sampling-frequency during flood events?
- How frequently to take bed material samples

Less frequent questions, though probably even important are related to bed load:

- Are bed load samples to be taken with the same frequency as suspended load, and if not, how often?
- How to adjust bed load sampling frequency during flood events?
- Are measurement frequencies to be related to the purpose of the sampling or to the further use of the sediment samples?

In this section of the manual, “frequency” is understood as the timing of sediment measurements, not the number of samples to be taken at single verticals or at individual sampling points in the vertical. Although these aspects are related, they should only be treated by specialists.

The determination of a sediment measuring frequency is a difficult issue because of the complex relationship between sediment transport and flow. Therefore, it is advisable to make a distinction between the criteria for routine measurements of the suspended load and those for other sediment measurements. This is especially true for normal flow conditions, when some stable relationship, or a rating curve may exist. Only in exceptional cases does the flow exhibit stable relationships to all sediment parameters, that allows a sampling-frequency similar to the one for flow discharge measurements, i.e. all sediment sampling carried out together with the flow discharge measurements. Most often, sampling frequency would be determined by the criteria for sediment sampling, rather than by those for flow measurements.

Selecting appropriate sediment sampling frequency is critical, because the main part of the sediment fluxes occurs during flood events, when sediment measurements are most difficult to conduct. For the lower reaches of flash flood rivers, the fluxes during flood events may be close to 100 % of the total yearly sediment discharge.

Though suspended sediment is likely to be observed even during the lean season under the form of wash load, bed material movement will be initiated above a certain threshold level and would therefore be often nil or negligible during the lean season. Furthermore, in particular streams and during particular flow conditions - e.g., in large sand-bed streams - near-bed transport of bed material may contribute more than contact load to the “bed load transport”.

Failing to acknowledge the complexity of the sediment transport phenomena is likely to be the reason why, all over the world, so many sediment data appear to be rather defective, or resulting in faulty design of works or deficient water resources management. Sufficient resources need to be made available when sediment transport data are required. The hydrology project adopted bathymetric surveys with reservoir sedimentation survey boats, for each reservoir, to know the status of sedimentation as a supplementary exercise keeping the above in view. Sediment transport is recommended to be measured as it moves in the rivers and as it collects in the storages.

At present, the general trend in hydrological practice is to reduce the frequency of streamflow discharge measurements. In stable and controlled stations, automatic water level recorders make possible the operation of full-automatic, non-permanently staffed stations, where current meter gauging is performed only occasionally. However, reducing the frequency of direct sediment measurements may only be possible after carefully assessing the stability of the relationship between suspended sediment concentration and discharge. The benefit of roving staff must be evaluated with caution.

For unstable river reaches, the decision to start up sediment measurements should be made on the basis of a cost-benefit analysis. It is better not to commence measurements if the required minimum measurement frequency can not be met for the given goals and required levels of accuracy.

5.2 SUSPENDED SEDIMENT MEASUREMENT FREQUENCY

5.2.1 INTRODUCTION

In this section, the frequency of suspended measurement is discussed in general terms, with the objective of developing a methodology for determining the appropriate timing for each gauging station, whether suspended sediment records are available or not yet.

In general the peninsular rivers are monsoon fed and the region is covered by south-west and north-east monsoons, with floods commencing either on August or November. With sampling being very important as the passage of raising limb of a flood hydrograph at a station. There is need for emphasis on sediment data collection during the period August-November, with sample collection being done during raising floods more frequently.

5.2.2 STATIONS WITH EXISTING SUSPENDED SEDIMENT DATA RECORDS

The procedure is the following:

- Based on the observations of stage and flow discharge, select periods with typically similar hydraulic behaviour (lean season; monsoon season; separate flood events, possibly in different seasons/months);
- For each of these time periods, establish graphs showing the relationships between the observed suspended sediment concentrations versus flow, for the different fractions, whenever available: fine (F), medium (M), coarse (C), M + C, or total (F+M+C).
- Make regression- and statistical analyses for each of the samples and identify possible relationships or rating curves with discharge, or identify peculiar behaviour of the suspended load concentration with the flow velocity and/or the discharge.

On the basis of the analysis, typical periods will appear. For some periods exhibiting a stable suspended sediment concentration and/or a strong relationship of it with the flow, sampling frequency may be reduced. However, before restricting the frequency, daily observations must have proved that fluctuations are not significant in the given period.

5.2.3 STATIONS WITHOUT PRE-EXISTING SUSPENDED SEDIMENT OBSERVATIONS

At permanently staffed stations, observations of sediment should be started daily for one or two years. In special cases, such as tidal reaches, flash flood rivers, or where irregular sediment input occurs - downstream from mines, from landslide-prone areas or from artificial drainage systems - sampling may be more times a day, up to hourly. In principle, the initial frequency for suspended sediment measurements should not be less than the one for flow discharge measurements.

The method used for suspended sediment measurements to be selected in the initial phase should yield information on the sediment distribution in the river cross-section as detailed as for the flow measurements. This has obvious consequences for the staffing of the station. In some of particular cases, the sampling procedure may be simpler, but this should be rather the exception than the rule.

In unusual situations, the frequency of the suspended sediment measurement and the sampling method may be reduced as compared to the daily measurements: e.g., during an exceptional flood situation, a single point sampling in single vertical, possibly from the bank only is better than no observation at all.

5.3 BED LOAD MEASUREMENT FREQUENCY

5.3.1 INTRODUCTION

Bed load movement is by nature irregular and random. It is not often measured and a consensus does not seem to exist about how to determine the frequency of bed load gauging. As bed load has not yet been routinely observed in the Indian Peninsula, only crude rules may be suggested for determining in advance the minimum required bed load sampling frequency. In this respect, analyses of pre-existing suspended load observations and bed material sizes may be of some help.

Bed movement occurs above a flow threshold, e.g., a critical level of velocity or of shear stress. For all flow under this threshold, the bed material will not or barely move; above the threshold, bed material will be transported.

The geomorphic setting should be established before starting bed load observations. A survey with a questionnaire about the characteristics of river basin, river course and gauging station would reduce significantly the investment and cost for operation and maintenance of a bed load measurement network. Routine bed load measurement is not envisaged for HIS.

5.3.2 STATIONS WITH EXISTING SUSPENDED- AND/OR BED MATERIAL DATA RECORDS

Analysis of existing suspended sediment measurements

Set up relationships between flow discharge and suspended sediment concentration for the different size fractions, when available: fine (F), medium (M), coarse (C), M+C, or total (F+M+C). If a recurrent pattern appears for all, or if the sediment load remains wash load (almost exclusively F or F+M, with little or no C), then a stable relationship might exist between suspended load and bed load, possibly a rating curve. In this case, the frequency of bed load sampling should coincide with the one for suspended load gauging, except during the lean season when it might be reduced or even skipped.

Analysis of existing bed material data

The nature and size distribution of the bed material may give some idea about the kind of bed load transport occurring in the station.

- When the river bottom is composed of non-cohesive alluvium, its size distribution will determine which size fraction may be transported as bed load and which as suspended load, depending on the flow intensity. Comparison with the F, M and C fractions of the suspended sediment measurements, when available, may give some indication of this. With the D50 of bed material transported as bed load, utilise the Shield’s graph to calculate the indicative threshold streamflow discharge above which bed load needs to be measured (if bed load is to be determined).
- When the river bottom is composed of cohesive alluvium, no simple rules apply. Most likely, bed load transport measurements would not be needed, or not be useful. Moreover, there are no reliable methods to determine the threshold for initiation of bed motion or scour.
- When the river bottom is composed of hard bedrock, bed load will accumulate in preferential areas and their size determined. Size analysis might give some idea of the kind of bed load transport occurring, possibly the threshold of flow above which the bed load would be initiated (also with Shield’s criterion).

5.4 ADDITIONAL COMMENT

In the case of suspended sediment, it is advisable to make a survey of the stations, asking the observers about their experience. Most often, the knowledge of the river behaviour at their station, also about the concentration of sediment in suspension will help establishing suspended sediment sampling timing and frequency.

6 MEASURING TECHNIQUES

6.1 GENERAL

6.1.1 INTRODUCTION AND DEFINITIONS

As explained in Section 1.2 of this manual on Sediment Transport Measurements, the total sediment transported by the stream can be classified under various load and transport modes:

1. **according to origin:**
   - bed material load, which may be moving as:
     - bed load
     - suspended load
   - wash load moving as suspended load
2. **according to transport mechanism:**
   - bed load
   - suspended load, including bed material in suspension and wash load.

The concentrations and related transport rate of suspended load may be measured with quite a large range of devices, making use of either samplers, or other kind of instruments, based on various physical principles. The bed load discharges are usually not determined by direct measurement techniques, but rather indirectly or computed with transport formulas.

Sediment transported as suspended load may be measured by:

- the **direct method**, in which the suspended load transport rate at a point is measured directly with the aid of a single device over a given time lapse;
- the **indirect method** in which the suspended sediment concentration and the current velocity at a point are measured almost simultaneously over a given time lapse, with the aid of separate devices, and multiplied to obtain the sediment load transport rate.

Sediment transported as bed load can be measured by:

- the **direct method**, in which the bed load transport rate at a point is measured directly over a given time lapse with the aid of a single device;
- the **indirect method** in which the movement of the bed material is **assessed** by an observation, e.g. the movement of dunes resulting from the bed load, over a given time period.

The selection of method and/or device should be made cautiously, taking into account the kind of environment and objectives, e.g. the type of river, the geomorphic setting, the variation of hydraulic conditions and sediment characteristics with changing stages, the data needs and their users. Sediment gauging strategies may be set up by adapting the methods, techniques and instruments depending to the conditions, for one station or for the network in a catchment.

6.1.2 SUSPENDED LOAD

The name “suspended load” is given to all solids that move with the water, away from the riverbed. The suspended load may contain all sorts of solid materials, of all kind of composition and sizes. Usually, the largest part of the suspended load is composed of minerals, such as clay, silt and sand (mostly quarts). The higher the discharge, the more the suspended load will contain coarser particles. These may come from soil erosion in the catchment, from mass wasting (e.g. bank slides), from riverbank erosion, or from riverbed erosion (scouring).

Solid organic material may be present at all or at certain stages only, depending on their origin. They may be freshly detached from the land (such as leaves, branches, trees etc) or enter the steam as vegetation debris. Most of them float at the surface but some may be transported under water, mixing with the sediment minerals and possibly disturbing the sampling.

Before starting sediment measurements in a new station or when introducing new methods and/or instruments, the nature and the composition of the suspended sediment should be observed so that the most suited sediment gauging methods and instruments would be applied, possibly different ones for various ranges in stage. In many rivers of the Indian Peninsula, the suspended load is mostly wash load: this is the finest fraction, composed of clay and fine silt. Possible changes in the sediment yield - such as by change of land use or extensive construction activity of roads, railways or hydraulic structures or by operation of hydraulic structures - should be detected in due time so that methods and/or instruments would be adapted accordingly.

The quality of the suspended sediment data does not depend only on a correct operation and maintenance of samplers. Most important is the choice of the appropriate sampler and sampling method and procedure for each of the conditions encountered in the field. In this sense, a flexible gauging strategy should be preferred to a strict application of well-defined measurement procedures. However, this kind of strategy is difficult to implement, as field teams would work with strict instructions, leaving little initiative to observers.

For suspended sediment investigations or measurements, the following characteristics of the sediment should be assessed in view of defining the most appropriate instrument and method:

- the variability with time of the suspended sediment content and how it varies with stage;
- the variability in space - both in the cross-section and in plan form - of the suspended sediment content and how it varies with stage;
- the suspended sediment size, its degree of heterogeneity – in size and composition - and how these vary with stage;
- the bed features (e.g. bed forms, bars, rock outcrops, channel and stream sinuosity) and how they change with stage;

besides other elements, e.g. those of importance for the geomorphic setting. The following discussion is given to illustrate the relevance of this assessment.

6.1.3 SELECTION AND USE OF SUSPENDED LOAD SAMPLER FOR GIVEN SITE AND STAGE

The selection of the most appropriate instrument or sampler must depend, among other, on the following criteria or conditions prevailing at the observed stage:

1. Flow
   - Water depth
   - Flow velocity
2. Site and measurement conditions
   - Method of handling/operating the instrument
   - Elevation of the handling/hanging point above the river bed, or above the water surface, for different stages
3. Sediment
   - Future use of the sediment data
   - Average suspended sediment concentration at different stages
   - Distribution of the suspended sediment concentration in the gauging cross-section
   - Size and/or concentration of the coarsest fraction of the suspended sediment

When required, the change from one sampler to the other would usually take place at the same stage. However, some decisions about sampler/instrument selection can be taken on the site, though some should be taken at higher hierarchy levels. Operators (karkoons) should communicate with the Junior Engineer whenever problems arise in the use of the selected sampler. The Junior Engineer will check the implementation of transparent instructions about the selection of sediment instruments.

6.1.4 RECOMMENDATIONS ABOUT THE SELECTION PROCEDURE FOR SEDIMENT SETS

In low flow conditions it might well be that the suspended load would be mainly wash-load with little variation in concentration in a single position of the cross-section. However during flood events - the normal and/or the exceptional ones - a significant amount of coarser bed material would be brought into suspension. If the flood is producing large-scale turbulent flow features, such as eddies and boils (the typical up-welling above large-scale bed forms, e.g. dunes), then the instantaneous concentration will change erratically, but in a more or less periodic manner (the sediment “patches” or “clouds” well known in sand-bed streams. These features might change with stage, depending on the adaptation of the bedforms to the changing flow conditions. Furthermore, the presence of an underwater shoal upstream of the gauging section may produce partition of the flow lines around it with confluencing flows more downstream. In some cases, this may lead to a sediment “plume”, caused by bed material stirred up by the high turbulence at the confluence of the water masses. This picture will obviously change with stage, as the degree of submersion of the shoal varies. In other cases, a rock outcrop may be the source of the increased turbulent energy. In such cases, more bed material can be brought into suspension than would be the case in a smoother reach of the stream.

When the suspended sediment concentration varies significantly, the instantaneous sample taken at 0.6 of the depth with a streamlined volume-concentration sampler may yield large errors in the computation of the suspended sediment transport rate, e.g. if the sample is taken in the vertical with strongest flow at the moment of highest suspended sediment concentration at the sampling point (overestimation), or when the concentration is lowest (underestimation). Samples taken by depth-integration may improve the quality of the data, as the sampler will pass through the patches, making a kind of an average, if the time scale of the periodic variation of the concentration is shorter or of the same magnitude as the sampling transit time. As the patches are carrying coarser material, the error may be significant for estimates of sediment balances. The variability of the suspended load concentration of the coarsest fraction of the load is higher close to the bed (Figure 6.1). Samples taken at or near the surface may be more reliable, but they may be not so well related to the average concentration over the vertical.

A transport-rate sampler would usually collect the suspended sediment during a time span larger than the time needed for the patch to pass along the sampling point. The measured transport rate might then be much closer to the actual solid discharge. Furthermore, some instruments allow sampling very close to the streambed, almost touching the level at which contact bed load is measured, which reduces or eliminates the "unsampled zone", i.e. that part of the water column out of reach of the suspended sediment sampler (Figure 6.2). The Delft Bottle is such a device useful for sandbed streams, either hung in the water column for suspended sediment sampling, or mounted on a frame - the sleigh - which allows sampling between 0.5 and 0.05 m from the bed. If complemented with a bed load pressure-difference type sampler - e.g. the Bed Load Transport Meter Arnhem (BTMA) - the entire vertical can be sampled for the sand fraction. The wash load fraction (silt and clay) being more homogeneous across the gauging section, it may be determined with lesser samples taken with the streamlined volume-concentration sampler, or even with a simple bottle.

These cases show the need to have a sediment gauging strategy, i.e. adapt the gauging instruments, techniques and methods as to obtain the most useful information.

The usefulness of the selection of instruments proposed in Tables 6.1 and 6.2 has to be checked for the Indian situation.

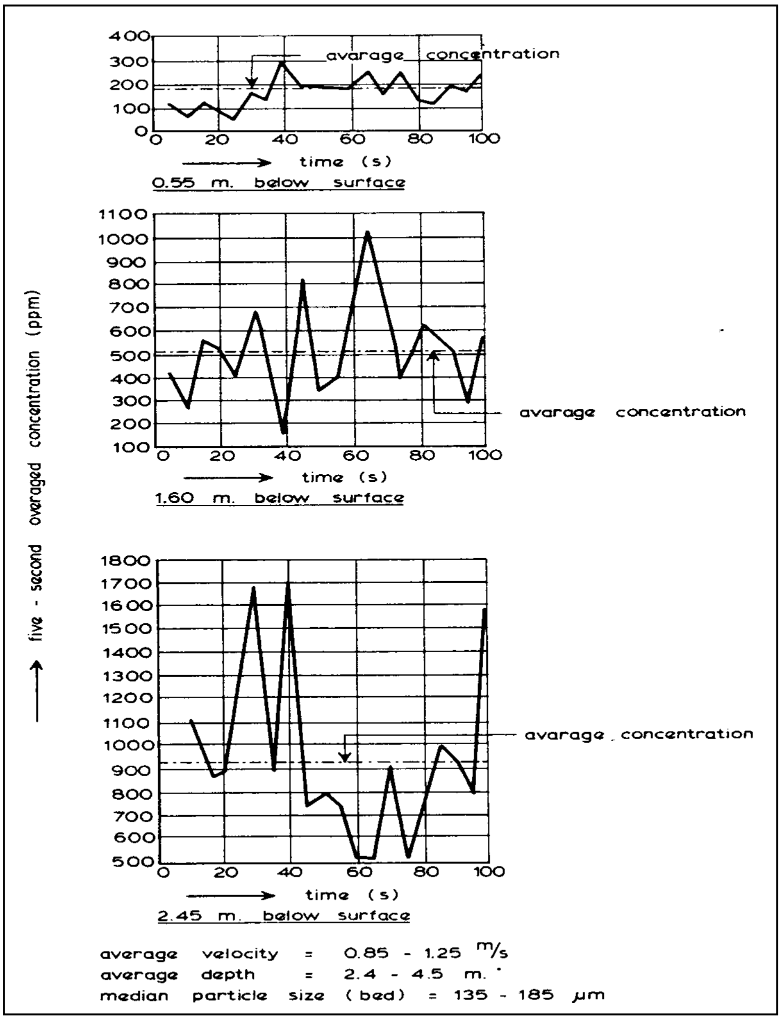

Figure 6.1: Variability of suspended sediment concentration, with time, over depth

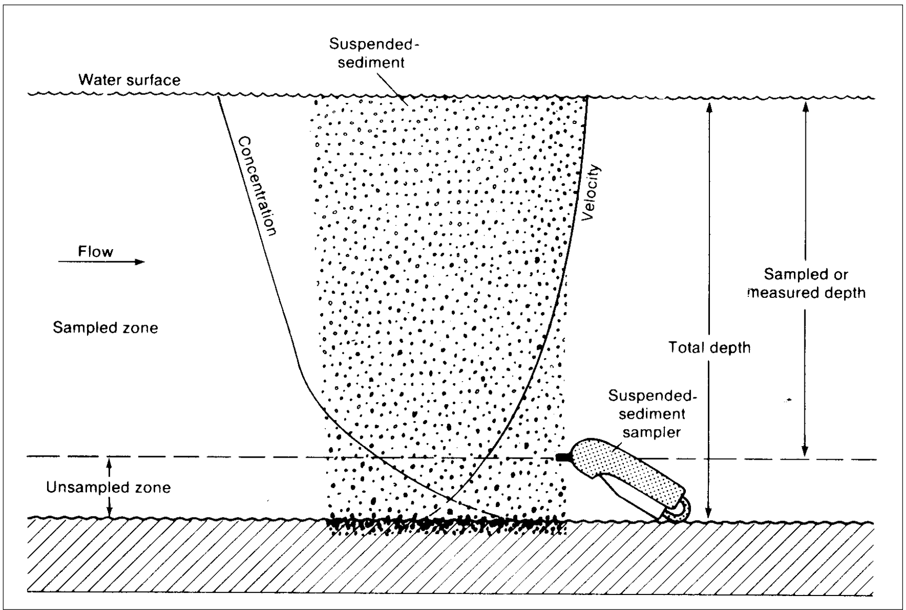

Figure 6.2:
Sampled and unsampled zone of suspended sediment

For **sediment balance studies** e.g. for reservoir sedimentation, the instruments listed in Table 6.1 are recommended for the indicated stream categories:

Type of device	**Stream size**		
	Small	**Medium**	**Large**
Suspended load			
Bottle	**A, D**	**A, D**	(A)
Volume-concentration, streamlined	**B, C, E, F, G, H, I**	**B, C, E, F, G, H, I**	**B, C, D, E, F, H, I**
Transport rate***	(F), (H), (I)	(C), (E), (F), (H), (I)	(B), C, (E), F, (H), I
Special: pump, turbidity	N.A.	(C), E	F, H, I
Near-bed load			
Pressure-difference	N.A.	(H), (I)	(E), **F, H, I**
Bed load			
Bucket, Box, Pan	**H*, I***	N.A.	N.A.
Pit	(B)*, (H)	N.A.	N.A.
Pressure-difference	(C), **F, I**	C, **F, I**	**C, F, I****
Dune tracking	(E), (H)	(E), H***	(H)

Note: Bold strongly recommended
Normal recommended
Brackets recommended, but depends on local conditions
* for steep slope rivers
** for mild slope rivers
*** complementary to other methods
Refer Table 3.1 for A B C D E F G H & I used here

Table 6.1: Selection of instruments in sediment balance studies

For problems related to **river morphology**, the instruments listed in Table 6.2 are recommended for the indicated stream categories:

Type of device	**Stream size**		
	Small	Medium	Large
Suspended load			
Bottle	A, D	A, D	(A)
Volume-concentration, streamlined	**B, C, E, F, G, H, I**	**A, B,** C, **D, E,** F, **G,** H, **I**	**A,** B, C, **D,** E, F, **G,** H, I
Transport rate	C, F, H, I	**C,** E, **F,** H, **I**	**B, C,** D, **E, F,** G, **H, I**
Special: pump, turbidity	N.A.	(C), E	C, F, H, I
Near-bed load			
Pressure-difference	N.A.	**C, F, H, I**	**C, E, F, H, I**
Bed load			
Bucket, Box, Pan*	**H*, I***	C*, H*,	N.A.
Pit	(B)*, (H)	N.A.	N.A.
Pressure-difference	**C, F, I**	**C, F, I**	**C, F, I**
Dune tracking***	(B), C, (E), F, (H), I	(B), C, (E), F, (H), I	B, C, E, F, H, I

Note: Bold strongly recommended
Normal recommended
Brackets recommended, but depends on local conditions
* for steep slope rivers
** for mild slope rivers
*** complementary to other methods
Refer Table 3.1 for A B C D E F G H & I used here

Table 6.2 Selection of instruments in morphological studies

6.2 SUSPENDED SEDIMENT MEASUREMENTS

6.2.1 INTRODUCTION

Suspended sediment measurement techniques can be classified into direct and indirect methods. The indirect measurement method is the most commonly applied. It considers the sediment concentration as a quality parameter of the water, moving at the same speed as the water. This may be considered as valid for very fine material, at all stages. However, the method is also applied when the sediment sizes vary across the stream channel, over the depth and over the width. Doing so, some errors are generated, which can be avoided by a careful selection of instruments and methods. Information about the variation of particle size and concentration over the cross-section is in principle needed before selecting the instruments and methods.

The streamflow measurement method should possibly be adapted to the need of the sediment data, as the degree of detail to be obtained about the flow (distribution in space and time) will depend on the data needs and users. The flow and sediment gauging procedures should be a compromise between simplicity in the field and the appropriateness of the data, taking into account the available resources.

6.2.2 SELECTION OF THE INSTRUMENT

The selection of the kind of instrument or measuring device should be based on the stream type, sediment load and objectives. Tables 6.1 and 6.2 are designed to help in this selection. For a description and illustration of the various instruments mentioned in this section, please refer to the Technical Specifications (Chapter 7).

General rules are difficult to apply, and the recommendations should be interpreted on the basis of the local conditions, human resources, project objectives etc. The type of stream restricts the choice. As a general rule, simple bottle samplers should be selected when suspended load is mainly wash load, streamlined bottle (volume-concentration) samplers when both suspended load and wash load need to be known.

Select always the most simple suspended sediment sampler and procedure appropriate for the site and the stage.

Do not use samplers under flow, site and sediment conditions for which they were not designed. The following working conditions are given as a rule of thumb; however, the conditions prevailing at the site should always be assessed carefully. Sampling may take place:

- by wading
- from a bridge
- from a boat or survey vessel
- from a cableway

These methods are discussed below.

1. **Sampling by wading** can be made when depth (in m) x flow velocity (in m/s) is < 1, with:

   - *Bottle type sampler (e.g. Punjab sampler)*
     To be used only if suspended sediment does not contain significant proportions of medium and coarse fractions.

   - *Light-weight streamlined, fixed-volume point sampler or depth-integrated sampler (e.g. US DH-48)*
     To be used when suspended sediment contains more than 5 % medium + coarse fractions and when the sediment concentration of the sample is higher than 100 g/m³.

2. **Sampling from a bridge** when it is less than 5 m above river bed and when the flow velocity does not exceed 1 metre per second, can be made with:

   - *Bottle type sampler fixed to a weight, preferably fish shaped (e.g. adapted Punjab sampler)*
     To be used only if suspended sediment does not contain significant proportions (<5%) of medium and coarse fractions; only a near-surface sample would be taken in higher flows or possibly at 0.6 depth whenever feasible.

   - *Light-weight streamlined, fixed-volume point sampler or depth-integrated sampler (e.g. US DH-48)*
     To be used when suspended sediment contains more than 5 % medium + coarse fractions and when the sediment concentration of the sample is higher than 100 g/m³.

3. **Sampling from a small boat or survey vessel** can be made when flow depth and flow velocity do not exceed respectively 5 metres and 2 metres per second, with:

- *Bottle type sampler fixed to a weight, preferably fish shaped (e.g. adapted Punjab sampler)*
  To be used only if suspended sediment does not contain significant proportions of medium and coarse fractions, only near-surface sample in higher flows and 0.6 depth sample when feasible.

- *Light-weight streamlined, fixed-volume point sampler or depth-integrated sampler (e.g. US DH-48) or*

- *Medium-weight streamlined, fixed-volume point or depth-integrated sampler (e.g. US DH-59)*
  To be used when suspended sediment contains more than 5 % medium + coarse fractions and when the sediment concentration of the sample is higher than 100 g/m³.

4. **Sampling from a large boat or survey vessel or from a bridge or cableway** when flow depth and flow velocity exceed respectively 5 metres and 2 metres per second, can be made with:

- *Heavy-weight streamlined, fixed-volume point sampler or depth-integrated sampler (e.g. US P-61 or US P-63)*
  To be used when suspended sediment contains more than 5 % medium + coarse fractions and when the sediment concentration of the sample is higher than 100 g/m³.

6.2.3 GENERAL RECOMMENDATIONS FOR HANDLING PROCEDURES

Depending on the stream depth, hand samplers or cable-suspended samplers can be used and depth-integrated or point samplers have to be applied. Stream velocity in combination with the water depth determines if the stream is wadable or not. A rule of thumb: for depth (m) x velocity (m/sec) >1 the stream is not wadable. This product affects also the action of each sampler: the larger it is, the heavier and more stable the sampler should be. In difficult situations, it is by trial and error that the type of sampler has to be determined.

Samplers to be used in low flow and in shallow water are mounted on a rod, while the others are hanging from a wire or cable.

Most samplers are designed so as to have the velocity within the cutting circle of the intake equal to the ambient stream velocity (called iso-kinetic sampling). The well-designed sampler always faces the approaching flow and its intake protrudes upstream from the disturbance created by the sampler (see Figure 6.3).

This feature is essential when the suspended sediment contains significant proportions of coarse + medium fractions. This explains why the bottle sampler (e.g. the Punjab sampler) is suited only for low flow conditions and for wash load, i.e. suspended load without medium and coarse particles. The point sampler requires a nozzle/ valve mechanism to control the sampling period and time. In India three nozzle sizes of 6.2, 4.8, and 3.2 mm are used. The average velocity, depth of water and time taken for operating the lowering and raising of the sampler are important. Calibration of sampler is needed to determine the nozzle dia matching the site variables above. The overall design of the suspended sediment samplers should always be checked by towing them in still water or keeping them in flowing water of known velocity. This check must be performed with the complete set up used for the measurement, for example with a fish-weight eventually attached for countering the dragging by the flow.

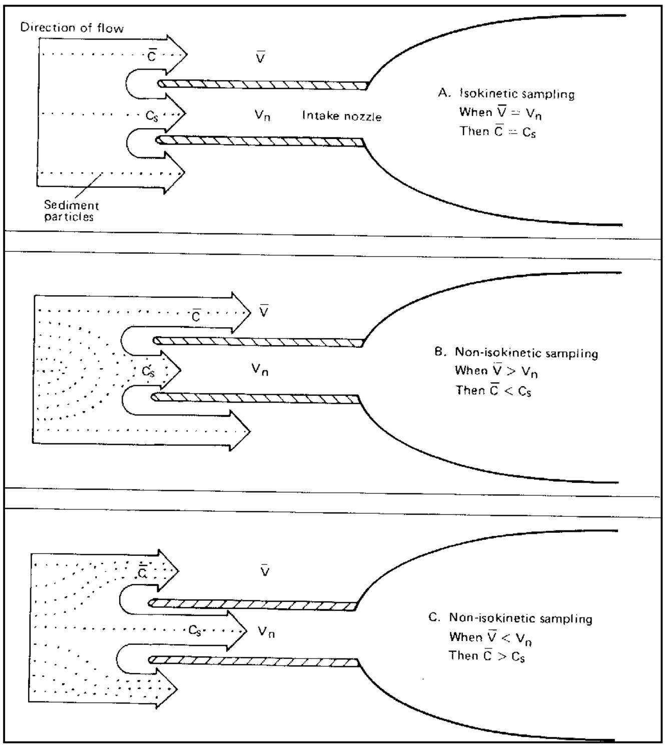

Figure 6.3:
Intake velocity for isokinetic and non-isokinetic sand sampling

This feature is essential when the suspended sediment contains significant proportions of coarse + medium fractions. This explains why the bottle sampler (e.g. the Punjab sampler) is suited only for low flow conditions and for wash load, i.e. suspended load without medium and coarse particles. The point sampler requires a nozzle/ valve mechanism to control the sampling period and time. In India three nozzle sizes of 6.2, 4.8, and 3.2 mm are used. The average velocity, depth of water and time taken for operating the lowering and raising of the sampler are important. Calibration of sampler is needed to determine the nozzle dia matching the site variables above. The overall design of the suspended sediment samplers should always be checked by towing them in still water or keeping them in flowing water of known velocity. This check must be performed with the complete set up used for the measurement, for example with a fish-weight eventually attached for countering the dragging by the flow.

Regular maintenance (check and replacement of the equipment) is necessary to ensure a proper functioning and to have effective and safe working conditions. A file of these operations should be kept at the field office.

6.2.4 SMALL HANDHELD OR CABLE-OPERATED DEVICES

The recommended precautions for operating current meters on a rod apply. A correct assessment of the water depth is essential, prior to sampling. The measurement is usually depth-integrated, but can be at fixed depth (often 0.6 of the depth) which requires accurate positioning.

For the simple **bottle**-type (e.g. the Punjab sampler, non-iso-kinetic filling), the instrument should be kept vertical and lowered to the desired depth with the mouth closed. The mouth should then be kept open for a time long enough as to have sufficient sample, but without overfilling which would otherwise result in an overestimation of the silt content. The duration of the filling has to be assessed experimentally, as it depends on depth and stream velocity. The sampler can not measure very close to the river bottom, and even when this would be desirable, the operators should be made aware not to hold the instrument in inclined position, what would bring the mouth in a lower position.

For the **streamlined**-type the **fixed volume sample container** (e.g. the US DH-48 or US DHS-48 developed by US-GS) can be used in depths up to 2.5 m and in velocities up to 1.5 or 2 m/s, in small and intermediate sized streams. It is very important to have the intake nozzle correctly oriented in the flow.

6.2.5 DEVICES OPERATED FROM A BRIDGE OR CABLEWAY

Some instruments can be used handheld from a low bridge (e.g. the US DHS-48), but usually the device is suspended by means of a winch (US DH-59). Attention should be paid to a correct assessment of the water depth, which may become difficult in strong currents when the height of the bridge above the water surface is large. In this case, dry- and wet-line corrections should be made as for the current measurements (see part of the manual on measurements of depths).

For **depth-integrated** measurements, the accuracy of the positioning is not critical, if the sampler is not lowered too quickly against the streambed, which could otherwise result in catching bed load or bed material.

For **time-integrated** measurements, the required accuracy is higher, especially when the gradient of the sediment concentration and of the sediment size over the vertical is steeper, thus closer to the streambed.

6.2.6 DEVICES OPERATED FROM A SURVEY VESSEL

For devices operated from a vessel, dry/air-line corrections are less critical if the flow current is not too strong. In strong currents, the angle at the protractor should be measured. In addition to the recommendations made for the devices operated from a bridge, the risk of wrong depth assessment when the vessel is positioned over a steep riverbed slope should be mentioned, e.g. when at the edge of a submerged shoal. This is important as the vessel may swing around its anchor point due to wind, flow turbulence, especially when in deep water. In that case, the vessel may be stabilised with a second anchor.

6.2.7 DIRECT MEASURING TECHNIQUES

As a general rule, transport-rate samplers would be used when the wash load is of minor interest, e.g. for morphological problems in gravel or sand-bed rivers. These measurements are not envisaged routinely in HIS, but may be done for special problem solving.

6.3 METHODS FOR DETERMINATION OF SUSPENDED SEDIMENT LOAD

6.3.1 GENERAL

In this sub-chapter methods are discussed to determine the instantaneous mean discharge-weighted suspended-sediment concentration at a cross-section.

The sediment concentration of the flow is determined by collecting depth-integrated suspended-sediment samples that define the mean discharge weighted concentration in the sample vertical, and collection from sufficient number of verticals to define the mean discharge-weighted concentration in the cross-section.

There are many different ways to collect suspended sediment data, depending on the available infrastructure, the conditions of the flow, the kind of sediment transported and its distribution across the channel, the purpose of the sediment data collection. In some cases, a single surface sample may be sufficient, in other cases multiple-vertical depth-integrated sampling is convenient, sometimes, exploration of the cross-section with point samplers may be needed.

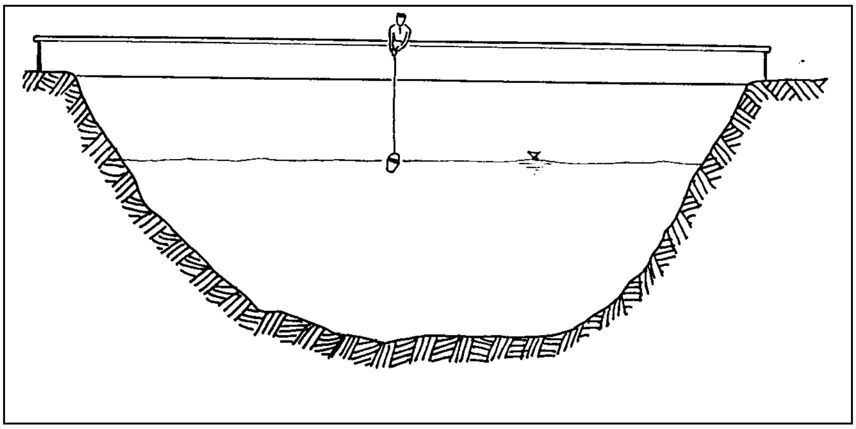

Figure 6.4:
Example of single vertical, surface sampling from a bridge

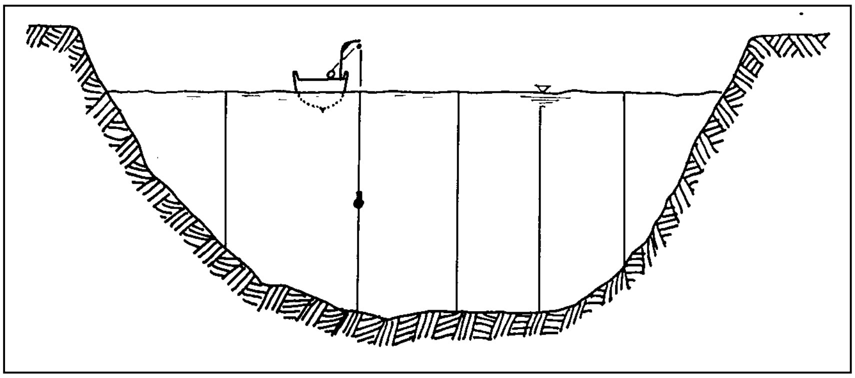

Figure 6.5:
Example of multivertical sampling from a survey vessel, one single sample taken in each station, either depth-integrated or at 0.6 of the depth

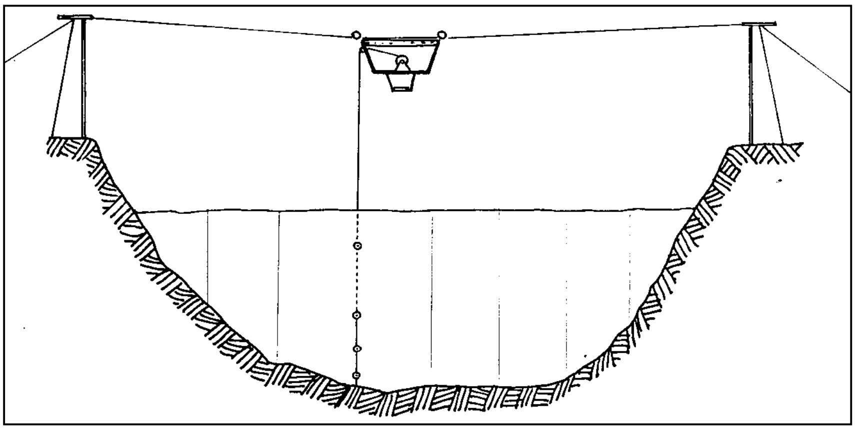

Figure 6.6:
Example of multivertical sampling from a cableway, samples taken at multiple depths (e.g., at 0.2d, 0.6d, 0.8d and 0.5 m from the bed)

6.3.2 SINGLE VERTICAL SAMPLING

Objective: *to obtain a sample that represents the mean discharge-weighted suspended - sediment concentration in the vertical being sampled at the time of sample collection.*

Method: *depending on flow conditions and particle size of suspended sediment transported, four types of situations can be distinguished:*

1. Low velocity (v< 0.5 m/s)

   At these velocities, little or no sand would be in suspension, and distribution of the sediment is relatively uniform over the cross-section. In shallow streams, the sample may be collected by submerging by hand an open-mouth bottle into the stream. The bottle should be filled by moving it from the surface to the streambed and back, or at 0.6 of the depth. If the stream is not wadable, use weighted bottle type sampler. The samples are not discharge-weighted.

2. High velocity (0.5 m/s ≤ v < 3.5 m/s), depth ≤ 4.5 m

   Use standard depth-integrating samplers. The transit rate used during raising has to be different from the one used in lowering, but both rates must be constant in order to obtain a velocity or discharge-weighted sample.

   For streams that transport heavy loads of sand, at least two complete depth integrations of the sample vertical should be made as close as possible in time.

3. High velocity (0.5 m/s ≤ v < 3.5 m/s), depth > 4.5 m

   It is possible to use depth-integrating samplers only with special precautions. In principle, point-integrating samplers should be utilised. Point samplers may be used to collect depth-integrated samples in verticals where the depth is larger than 4.5 m.

4. Very high velocities (v ≥ 3.5 m/s)

   Only surface or dip sampling is recommended with flow velocities preferably determined by the float method.

6.3.3 SURFACE OR DIP SAMPLING

Objective: *to sample at the water surface for determining the instantaneous suspended load concentration representative for the vertical or for the entire cross-section, if sampling conditions do not allow measurements over the depth, particularly when the flow is too strong and/or carrying debris (the concentration is supposed to be homogeneous over the depth).*

Method: *take single point-sample(s) wherever possible - in the middle of the stream or from the bank - but preferably at a vertical where concentration was found to be representative and/or well correlated to the cross-section-average concentration*

A surface sample is one taken on or near the surface of the water with or without a standard sampler. It can be expected that all except the largest particles of sediment will be thoroughly mixed within the flow and therefore a sample near the surface is representative of the entire vertical. Extreme care should be used, however, because often such high velocities occur during floods when large debris are moving, especially on the rising part of the hydrograph. Because of the many problems associated with surface and dip sampling, these samples should be correlated to regular depth-integrated samples, to be collected as soon as possible after the high flow recedes enough to allow collection of a full depth-integrated sample.

6.3.4 MULTIVERTICAL SAMPLING

Objective: *to determine either the cross-sectional distribution of the suspended sediment concentration by point sampling, or the distribution over the width of the depth-average concentration by depth-integrated sampling*

Method: *sample the suspended sediment all over the cross-section, either with point sampling distributed over the depth on each of the verticals, or with one depth-integrated sample for each vertical; the minimum number of verticals and their location need to be carefully assessed*

There are many methods applied all over the world, with solution of the spacing according to specific criteria. To determine the instantaneous sediment concentration at a cross-section, US-GS for example uses two methods to define the location on spacing the verticals so that the end result will be a sample that is representative of the mean discharge weighted sediment concentration. One is based on equal increments of water discharge (EDI), the other on equal increments of stream or channel width (EWI).

1. The equal-discharge-increment method (EDI)

With the EDI method, samples are obtained from the centroids of equal discharge increments (Figure 6.7). It requires some previous knowledge of the distribution of the stream flow in the cross-section. If this is already known, the method saves time and labour, as fewer verticals are required. The flow distribution across the channel should therefore be determined prior to sampling.

A minimum of four and maximum of nine verticals should be used when applying the EDI procedure. The method assumes that the sample collected at the centroid represents the mean concentration of the subsection. In some countries, the recommended number of composite samples is three. This may not be appropriate, especially in sand-bed streams that are morphologically unstable.

The cumulative discharge distribution is used to determine the location of the centroids (of equal increments of discharge). An alternative method of estimation is to plot cumulative percentage of total discharge versus distance in the cross-section, a method that has the advantage of showing the variation in stations for the same percentage of flow for different discharges.

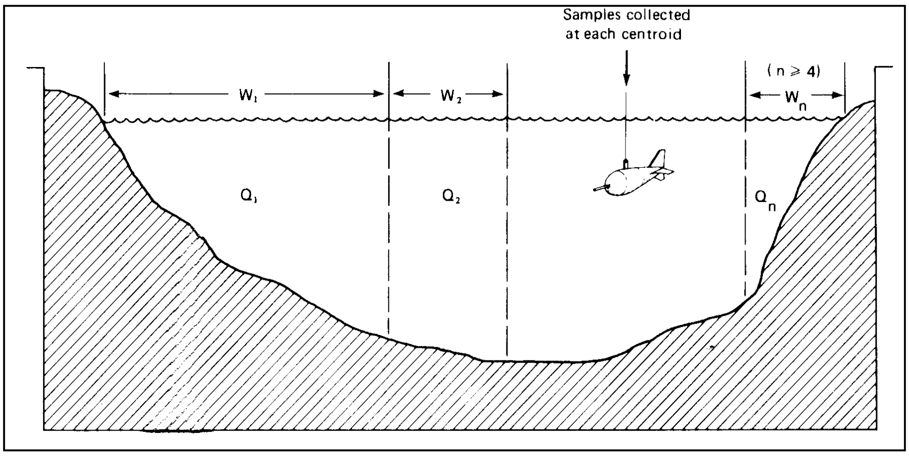

Figure 6.7: Equal discharge increment samples collected at the centroids of flow of each increment

Depth-integrated sample(s) are collected at each centroid and equal sample volumes are of primary importance when using the EDI method. The advantage of this method is that data describing the cross-sectional variation in concentration is produced.

The method is not applicable where the distribution of water discharge in the cross-section is not stable, or when the distribution of the sediment load is governed by morphological factors instead of by the flow. A main disadvantage to the EDI method is that a water-discharge measurement must precede the sediment-discharge measurement.

2. The equal-width-increment method (EWI)

For this method, a cross-sectional suspended-sediment sample requires a sample volume proportional to the amount of flow at each of several equally-spaced verticals in the cross-section. This equal-spacing between the verticals and sampling at an equal transit-rate at all verticals yields a gross sample volume proportional to the total streamflow (Figure 6.8).

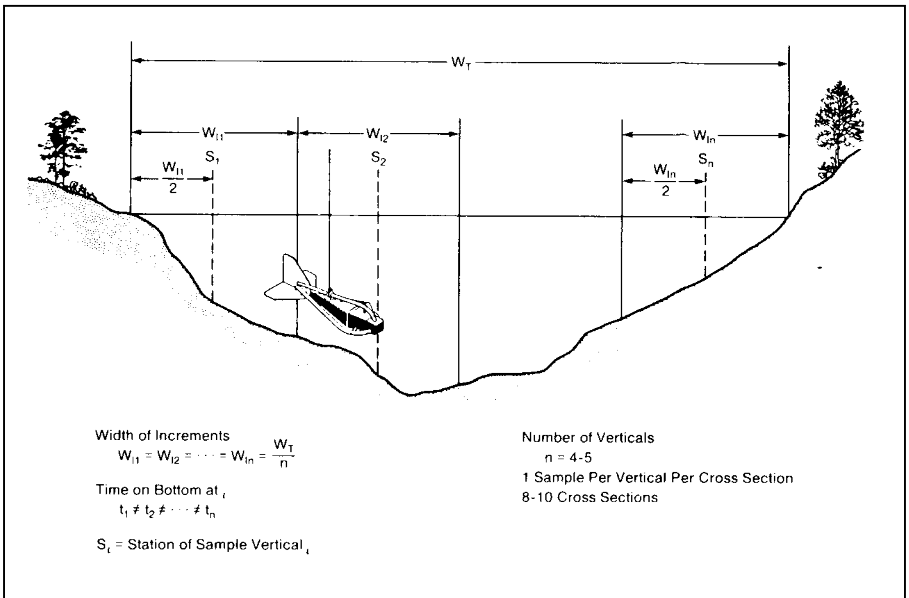

Figure 6.8: Equal width increment sampling technique

The number of verticals required for an EWI sediment-discharge measurement depends on the distribution of concentration and flow in the cross-section at the time of sampling as well as on the desired accuracy of the result. The distance between the verticals is determined by dividing the cross-sectional width by the required number of verticals.

The EWI method makes it possible to estimate the water-discharge rate for the stream if the vertical spacing, the stream depth at each vertical, the sampler submergence time and the volume of sample is recorded. The mean velocity v_m of the flow sampled in the verticals can be determined by the equation:

$$V_m = \frac{V}{T_t\, A_n} \tag{6.1}$$

Where
- V = volume of the sample (m^3)
- T_t = total transit time to obtain sample (s)
- A_n = cross-section area of nozzle (m^2)

The major disadvantage of this method is the inability to distinguish obviously bad samples in the sample set.

6.4 SPECIFIC PROCEDURES

6.4.1 POINT SAMPLES

A point sample is a sample of the water-sediment mixture collected from a single point in the cross section. It may be collected using a point-integrating sampler.

The purpose for which point samples are to be collected determines the collection method to be used. If samples are collected for the purpose of defining the horizontal and vertical distribution of concentration and/or particle size, samples collected at numerous points in the cross section with any of the streamlined volume-concentration type samplers will be sufficient. If point samples are collected, on the other hand, to define the mean concentration in a vertical, 5 to 10 samples should be collected from the vertical.

6.4.2 TYPICAL SITE RELATED PROBLEMS

The choice of the site should in principle be governed by hydraulic criteria, mostly similar to those used for flow gauging selection. However, in many rivers the site is taken at existing facilities such as bridges. When the river stretch is stable, straight and the riverbed is regular and prismatic, few problems occur. Even in such cases, the flow lines may not be parallel to the overall direction of the river bed during the lean season because of the presence of bars that make the main flow meander or braid, or in presence of bed rock. In such cases, the flow and sediment gauging may be transferred to a more straight and uniform-shaped section, upstream of the site.

Figure 6.9:
Photo of straight river-stretch where a sandbar produces oblique flow

Most important for the operators is to observe before each measurement how the flow is approaching the gauging section and to detect possible changes in this approach due to modifications of the river bed, such as by the movement of large bars (see sketch Figure 6.10). Changes in flow approach should be noted in the records; eventually, the procedure can be adjusted.

If the measurement site is not fixed (not a bridge, structure or cableway), then the site may be moved if it becomes unsuited for sediment gauging. This may be the case in streams with an unstable morphology.

A sediment measurement site should be far downstream of any external sediment input, such as drainage pipes, sliding riverbanks or landslides in valley slopes (mass wasting).

6.4.3 NUMBER OF VERTICALS – GENERAL RULES

The number of suspended-sediment sampling verticals at a measuring site depends on the kind of information needed in relation to the physical aspects of the river. It must be adequate to represent the cross-section. It shall be a compromise between the maximum quality required and the maximum cost allowed, given the maximum time available for performing the gauging. In rapidly varying flow, this may lead to a difficult decision-making process.

Both EDI and EWI methods of sediment-discharge measurement produce a volume of sample at each vertical, weighted with the water discharge for the vertical. The volumetric sum from all verticals yields a sample volume proportional to the water discharge for the stream.

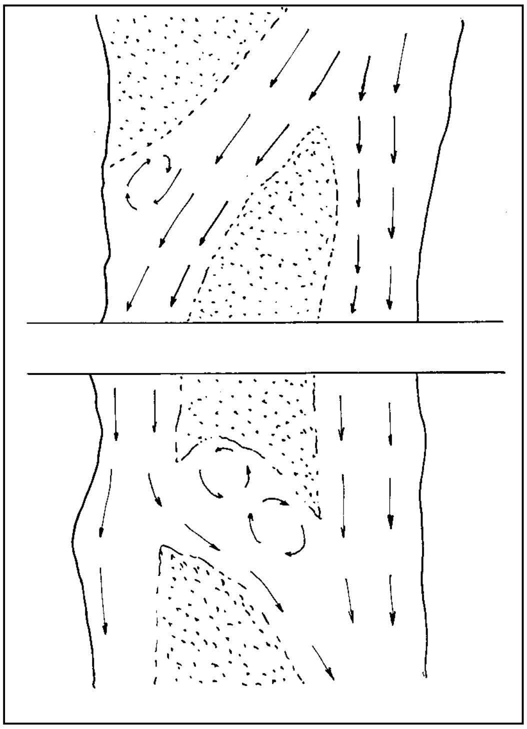

Figure 6.10: Sketch of straight river-stretch where a sandbar produces oblique flow

The variability of sediment concentration at different sampling verticals is closely related to the variability of V^2/D where D is the total sampled depth. Based on the V^2/D index concepts of variability, P.R. Jordan (1968) used data from Hubbell et. al. (1956) to prepare a nomogram (Figure 6.11) that indicates the number of sampling verticals required for a desired maximum acceptable relative standard error based on the percentage of sand and the V^2 /D index. This procedure is quite popular, but may lead in some cases to erroneous assessments, especially when the river morphology is dynamic.

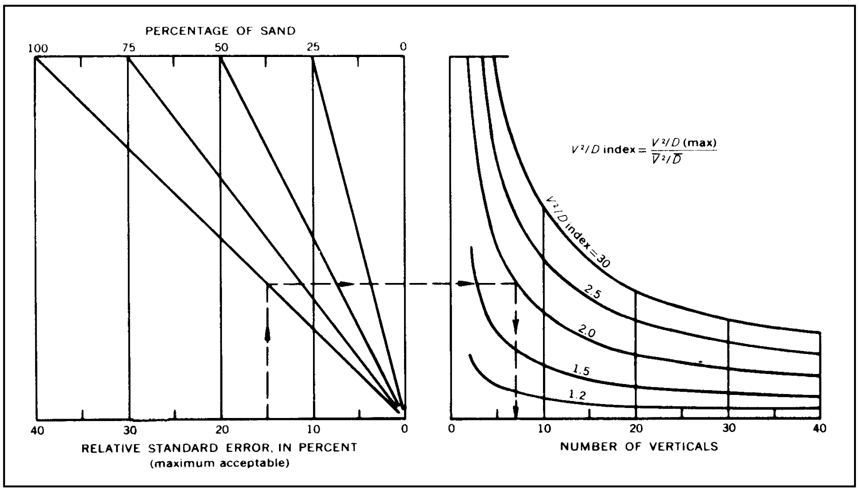

Figure 6.11:
Nomograph to determine the number of sampling verticals required to obtain results within an acceptable relative standard error

6.4.4 TRANSIT RATES FOR SUSPENDED-SEDIMENT SAMPLING – GENERAL RULES

The sample obtained by passing the sampler throughout the full depth of a stream should be quantitatively weighted according to the velocity with which it moves. The maximum transit rate used with any depth-integrating sampler must be regulated to ensure the collection of representative samples. Figure 6.12, in which the ratio of transit rate to mean velocity for different nozzle sizes is represented, can be used to determine the appropriate transit rate for a given nozzle-size/sample-container-size combination.

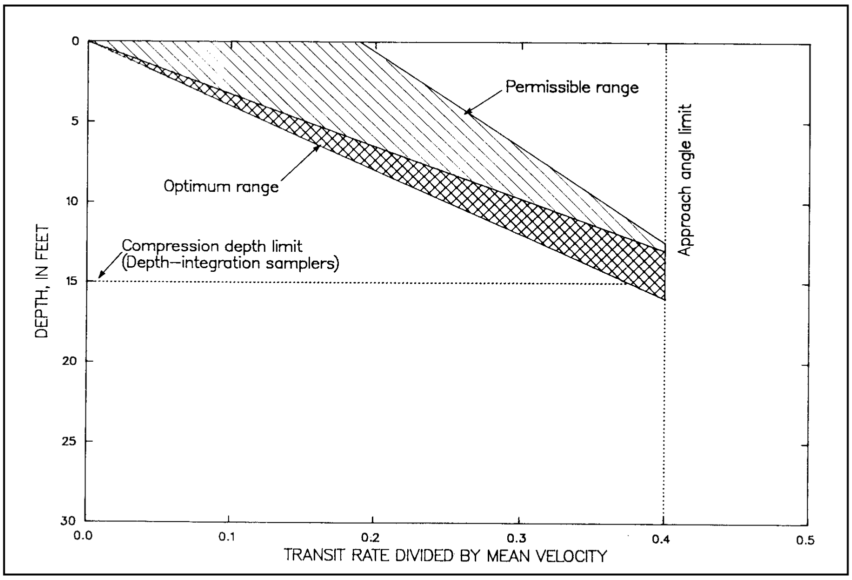

Figure 6.12:
Ratio of transit rate (R_t) to mean velocity (V_m): transit rate determination for 3/16 inch nozzle and pint bottle of the US P type sampler

The rate to be used in a given situation depends upon the depth of the sample vertical, the mean velocity in the vertical, the nozzle size being used and the sample-bottle size used in the sampler. If sampler operation within the optimum rate is not possible, a rate determined from the permissible range is acceptable.

6.4.5 OBSERVER SAMPLES

In order to save money, travel time, and most importantly, to ensure timely collection of data on an irregular basis and during extreme events, local residents are often contracted to work as observers. They usually lack technical background but can be trained to collect cross-section samples using either the EDI or EWI method.

To overcome the above-mentioned problem, observers most often collect samples from an established single vertical in the cross-section, as previously mentioned. Adjustment coefficients to relate observer samples with cross-section samples should be established and regularly verified.

6.4.6 PRACTICAL CONSIDERATIONS ABOUT SAMPLING VERTICALS (PENINSULAR INDIA)

General comments (Circle and sub-division level)

The choice of the number and spacing of sampling verticals depends on various factors, among which:

- Goal of the measurement (what do we want to know ? – e.g. data for reservoir studies, for soil conservation studies, for river regime studies, for river morphological studies)
- Type and concentration of the suspended sediment – e.g. suspended load with only wash load or also with sand
- Composition of the river bed (bed-rock or erosion-prone bed material)
- Variability of the suspended load during flood events
- Time constraints (total allowed duration for the measurement)

The time constraints are probably the most stringent, as many stations are located on more or less wide rivers. A compromise will have to be sought between the shortest duration of the measurement and its minimum required accuracy. The larger the number of verticals, the larger the points of sampling on the vertical and the larger the sample volume, the better the accuracy and information provided by the measurement. If the set goals necessitate a detailed measurement procedure, with many verticals and sampling points on each vertical, and if the total duration becomes too large, supplementary resources should be made available in the sediment station.

A key element for appreciating the optimum number of verticals and sampling points on each vertical is the heterogeneity of the suspended sediment distribution in the cross-section, both concentration and size.

If, at the particular stage, the suspended load contains only wash load - very fine silt, no medium and no coarse particles - then the suspended sediment would be uniformly distributed in the cross-section. Sampling on a limited number of verticals may be acceptable, with depth-integrated sample or a sampling at 0.6 depth. Surface sampling may be performed at higher stages.

If, at a particular stage, the suspended load contains significant proportions of medium and/or coarse particles, the distribution of the concentration in the cross-section would not be uniform. However, the distribution of the concentration in wash load would usually be rather uniform.

When the vertical distribution of the sediment concentration is not uniform along the vertical, the depth-integration method should be avoided and point samples should be taken, certainly in wide alluvial rivers with changing morphology.

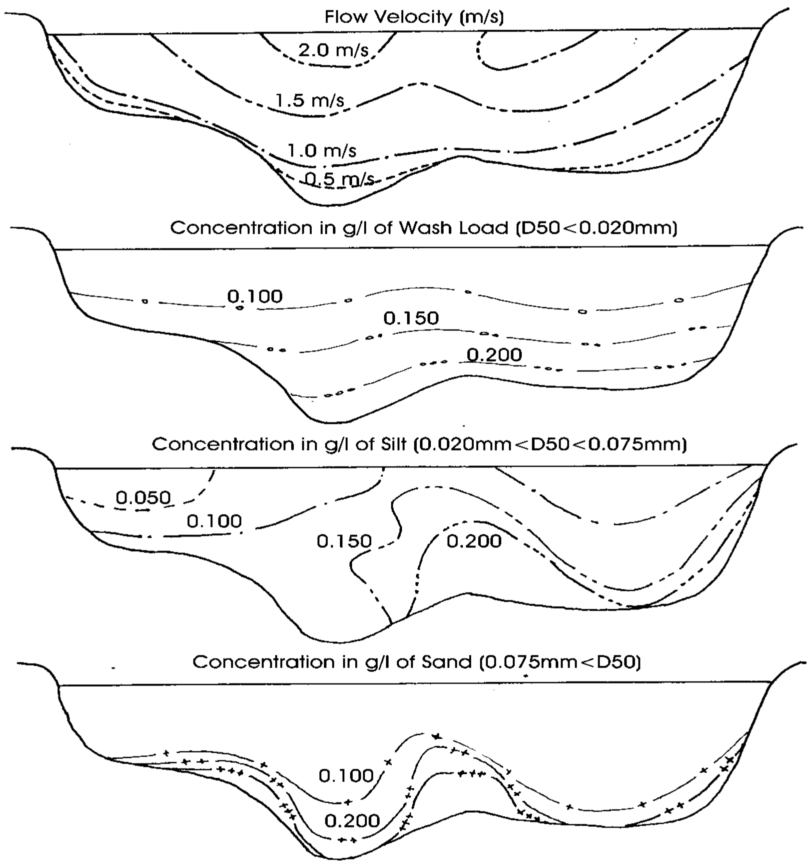

Figure 6.13: Distribution of flow and concentration in wash load, silt and sand

Because of the large width to depth ratio in most of the stations, the vertical distribution of suspended sediment would usually be quite uniform when suspended load contains little or no medium + coarse material (pure was load), while the horizontal (transverse) distribution may be non-uniform.

Each of the sediment measuring stations will have its own particular cross-sectional sediment distribution, varying with stage. It is therefore recommended to have site investigations in the lean season and in the monsoon season, to measure the distribution of sediment concentration and size, on a large number of verticals and with at least 3 depths on each vertical. Considering the time needed for performing such a detailed measurement, additional manpower and equipment should be mobilised temporarily. The optimum vertical spacing and sampling points on the vertical would so be determined in order to have more representative suspended sediment data.

Selection of number and locations of sampling verticals

The determination of the optimum number of the sampling verticals, of their location, as well as the choice of measurement procedure (e.g. depth-integrating or point sampling) needs to be decided at the level of the sub-division. It should be based on special detailed measurements.

Methods for selecting the locations of sampling verticals for suspended load are many, the most common being:

- Single vertical at mid-stream
- Single vertical at thalweg or point of greatest depth
- Verticals at ¼, ½ and ¾ width
- Verticals at 1/6, ½, and 5/6 width

- 4 or more verticals at mid-points of equal-width sections across the stream
- Verticals at centroids of sections of equal water discharge

The Bureau of Indian Standards (BIS) suggests a procedure to select the minimum number of verticals:

- divide the section into as large a number of equally spaced segments as practicable to be completed in one day, or
- divide the section into a large number of segments of approximately equal discharge

The samples are taken at the central vertical of each segment and the mean concentration in the vertical is weighed with the discharge in the respective vertical.

BIS also recommends the following specific criteria for rivers and canals:

River Width (m)	Number of verticals	**Location of verticals**	
		Normal section and sloping sides (in % of total width)	Uniform depth and velocity distribution (in % of total width)
< 30 m	3	25, 50 & 75 %	15, 50, 85 %
30 m – 300 m	5	20, 35, 50, 65 & 80 %	10, 30, 50, 70, 90 %
> 300 m	7	15, 30, 40, 50, 60, 70, 85 %	7, 21, 36, 50, 64, 79, 93 %

Point sampling: selection of the number and location of sampling points on the verticals

The number of sampling points on the vertical will depend on several factors, among which the acceptable duration of the sediment measurement and the distribution of the suspended load across the measurement section.

The common practice in India is to measure at 0.6 of the depth during low and normal flow, at the surface during high flow conditions. This corresponds also with the station at which the velocity is observed. Little has yet been done to analyse the correction factors needed to convert the values of sediment concentration at 0.6 d or at the surface into depth averaged concentrations. It is therefore recommended to have special observations made when the water level exceeds a certain stage, and certainly at the highest stages.

A procedure was presented in India for finding a suitable correlation at flood stages between the surface sediment load and the load sampled at 0.6 depth in the left and right near-bank segments (corresponding each to 20 % of the total width).

In the stations where sediment concentration and size vary in an unpredictable way on the verticals, such as in very wide, deep and dynamic sand bed rivers, more sampling points are required on the vertical. Possibly, the 6 point (0.2 x d) method would be the more detailed procedure to be used (0.2d, 0.4d, 0.6d, 0.8d, near-bottom).

Depth-integrated sampling

Depth-integrated samples may be taken at all stations where the vertical distribution of the suspended sediment is varying from bottom to surface in a regular and progressive way. This would be the case when the measurement section is located in a river with a stable bed, in a straight reach with little or no secondary flow.

The appropriateness of depth-integrated sampling should be investigated for all stages, prior to setting up the suspended sediment gauging procedure. It should also be checked from time to time, as the suspended load may change in the course of time. It might be necessary in some stations to change from depth-integrated to point sampling according to the stage, certainly in sand-bed rivers with complex morphology.

Depth-integration sampling may not suit for sand bed rivers with a very mobile course, as quite some bed material is moving close to the bed. In strong currents, it might be difficult to detect when the sampler touches the bottom, what might lead to disturbing the bed sediment and result in a much too high catch, being a mixture of suspended load and bed material.

6.4.7 SAMPLING FREQUENCY, SEDIMENT QUANTITY, SAMPLE IDENTIFICATION AND INTEGRITY

Sampling frequency

The timing of sample observations is as important as the technique for taking them. Observers should be shown typical hydrographs or recorder charts of their stations or nearby stations to help them understand the importance of timing their samples so that each sample yields maximum information. The desirable time distribution for samples depends on many factors, such as the season of the year, the runoff characteristics of the basin, the adequacy of coverage of previous events, and the accuracy of information desired or dictated by the purpose for which the data are collected.

The accuracy needed in the sediment information also dictates how often a stream should be sampled. The greater the required accuracy and the more complicated the flow system, the more frequently it will be necessary to obtain samples. For a given kind of record, the optimum number of samples should be a balance between the cost of collecting additional samples and the cost of a less precise record. The frequency of collection of bed-material samples depends upon the stability of the streambed at the sample site.

Determining the optimum frequency of sampling is a challenging issue, as sediment load variations do not obey simple laws. Each river and each measurement site may display particular sediment behaviour, depending on factors such as the origin of the sediment, the fluctuations in flow and the possible local disturbances. This can be exemplified as follows:

Case A: Small or medium-size river, reach downstream of a reservoir that is large enough to retain all coarse and medium suspended load even during flood events.

Case B: Large alluvial, sand bed river in which suspended load is composed of a mixture of bed material (sand) and wash load drained from land.

Case C: Medium-size, irregular shaped bed-rock river with sand (medium and coarse sizes) or even pebbles deposited on the river bed in the lean season, carrying during the floods significant amount of sand or pebbles in suspension, but less wash load.

In **case A**, most the suspended load would be trapped in the reservoir during the lean season, making the reservoir outflow carrying little or no suspended load. In this case, it makes no sense to sample continuously during the lean season, except possibly just after the monsoon season when quite some wash load may remain suspended in the reservoir water. During flood events, sampling frequency would be low, because of the buffer effect of the reservoir, the transit time of the suspended sediment in the reservoir being large.

In **case B**, flood events may immediately put into suspension quite some bed material, mainly in the rising phase, while the wash load would arrive at the station later on, depending on the orographic characteristics of the catchment. At the start of the lean season, wash load may be deposited on the riverbed, in some preferential zones (e.g. dead water or on shoals/bars). It may then be resuspended during small floods in the lean season, when the flow reworks the riverbed and transports some fine sand and silt. Sampling may be required the whole year round, with low frequency during the stable flows in the lean season (once a week or fortnightly) but higher frequencies in the monsoon season (daily or even more during floods or quickly varying flow, like the small floods in the lean season).

In **case C**, the rocky bed makes a series of pools and rapids in which suspended load would settle at low discharges, making the lean season flow almost sediment free. At the start of the monsoon season, the sediment deposited on the bed in the pools will be resuspended, making suspended load containing large proportions of bed material. Even medium flow may resuspend large quantities of bed material due to the high turbulence produced by the irregular bedrock. The bed material will be mixed with the wash load coming from the land drainage. Sediment measurement frequency would be very low during the lean season (fortnightly, monthly or even nil); it would be high during the monsoon season, daily or even more.

Obviously, the frequency would also depend on specific requirements, such as the goal or further use of the sediment measurements. Because of this, frequency may be adapted to the changing measurement objectives. Also changes in the river environment or engineering works may affect the relationship between flow and suspended load concentration and size.

Sediment quantity

The size range and quantity of sediment needed for the several kinds of sediment analyses in the laboratory are given in Table 6.3.

Although it is possible to conduct the laboratory operation for particle size analysis in a manner that will also give the sediment concentration, it is best to obtain separate samples for size analysis and concentration analysis.

	Analysis	Size range (mm)	Desirable minimum quantity of sediment (g)
Size	Sieves		
	Fine	0.062 - 0.500	0.070
	Medium	0.250 - 2.000	0.500
	Coarse	1.000 - 16.000	20.000
	VA tube		
	Smallest	0.062 - 0.500	0.050
	Largest	0.062 - 2.000	5.000
	Pipette	0.002 - 0.062	* 0.800
	BW tube	0.002 - 0.062	* 0.500
Exchange capacity	Fine	0.002	1.000
	Medium	0.002 - 0.062	2.000
	Coarse	0.062 - 2.000	10.000
Mineralogical	Fine	0.002	1.000
	Medium	0.002 - 0.062	2.000
	Coarse	0.062 - 2.000	5.000

* Double the quantities shown if both native and dispersed media are required

Table 6.3: The desired quantity of suspended sediment required for various sediment analyses

Sample integrity

Every sample taken by a field person should be the best sample possible considering the stream conditions, the available equipment and the time available for sampling. Each bottle sample must be inspected in the field immediately after removing it from the sampler in order to detect significant differences in the amount of sediment and the sediment sizes.A more subtle error in sample concentration may occur when a bottle is overfilled. This error also results in too high a concentration.

Sample identification

Explanatory notes such as time, method or location, stationing, unusual sampling conditions etc. can be recorded on the sample or inspection sheets.

6.5 BED LOAD MEASUREMENTS

Bed load gauging (also called bed load transport measurement) is often mixed up with bed material sampling. Bed load gauging is the measurement of the amount of sediment that is moving as “bed load”, i.e. rolling, sliding and bouncing (in “saltation”) on or over the stream bottom, while bed material sampling is the collection of the material composing the stream bottom.

Bed load transport measurements are rightly considered as very difficult and complicated. The reasons for this are:

- the poor understanding of the transport processes: (what are we measuring?)
- the very irregular character of the particle movement in the bed load
- the disturbance of the flow and of the bed load transport processes when a sampling device is lowered on the stream bottom.

As bed load accounts only for a small fraction of the total load and because they are difficult to perform, bed load transport measurements are most often discarded and replaced by computations. However, the uncertainties on computations with bed load transport formulas are as bad as those on measurements. Moreover, the economic importance of bed load observations is usually underestimated, especially in sand bed streams.

Because of the complexity of bed load transport measurements, extensive training is required. Besides the obvious need for training in a proper operation and maintenance of bed load instruments, bed load gauging strategies are required to get the most representative samples and measurements. **Bed load measurements should be avoided if a good training and a thorough follow up of the measurement procedures can not be ensured.**

Details about bed load measurements are presented in the Volume 5: Sediment Transport Measurement, Reference Manual.

6.6 BED-MATERIAL SAMPLING

6.6.1 INTRODUCTION

Data on the size of material making up the streambed (across the entire channel, including floodplains) are essential for the study of the long-range changes in channel conditions and for computations of unmeasured or total load.

The composition of a streambed is the result of erosion and/or deposition processes, i.e. the balance of the actual sediment load of the river and the transport capacity of the flow. Some river reaches – the "degrading" ones - are progressively incising in the underlying geological formations. These may be rock or soil, and the rate of scouring will depend on the physical and mechanical characteristics of the bed material. Other river reaches – the "aggrading" ones - are progressively building up the streambed with the sediments carried by the flow. In one location of a "poised" river reach, scour and deposition alternate, depending on the at-the-time prevailing conditions of flow and sediment load.

A common feature of streambed in the Indian Peninsula is the frequent presence of bed rock. In this situation, the streambed may display a variety of bed materials, going from hard, erosion resistant bedrock to large boulders, pebbles, gravel, sand, silt and clay, sometimes all of these in the same river reach.

The nature and physical properties of the streambed has to be well identified when dealing with projects, studies and works, as related to dams and gates, off-take or water-withdrawal structures, bridges, bank protection works, etc. For each of those, different kind of information may be needed. Collection of relevant or useful data on the bed material is quite complex matter, and routine procedures are not easy to define, certainly not when dealing with a heterogeneous streambed.

There is quite often some confusion in the terminology, between "bed load" and "bed material". The bed material is what is found in appreciable quantity in that part of the streambed affected by the flow and eventually transported by it. The bed load is composed of those sediment particles moved by the flow in contact with or very close to the streambed. In some river reaches, the bed load composition is quite the same as the bed material; this is the case in dynamic sandbed rivers that are continuously reworking their bed. In other river reaches, the load transported on the bed (the bed load) may have a composition quite different from the underlying bed material. This is among other the case for rivers: (a) flowing in a hard bedrock streambed, or over a bottom composed of loose soils deposited in earlier geological times, or (b) when the river flow processes have produced a special bed material by sorting the sediment particles (the best known example is the "armoured" layer formed eventually in gravel bed rivers).

When the bed material and the bed load are strongly graded, the composition of this bed material may vary widely in the same river reach. Larger particles may be found on the bottom of the stream during flood events, while the bed material visible in the lean season may be fine graded. Particularly in steep or medium slope rivers carrying very different particle grades, the scour, transport and deposition pattern may produce a strong heterogeneity of the bed sediment.

In India, bed material is sampled three times a year at the gauging cross-section: once during the monsoon season, once in the post-monsoon and once in the pre-monsoon. Bed material is sampled from the flowing part of the river, as well as from the dry part when required at low stages. A minimum of three samples are taken at a date of flow gauging, most often only three.

Bed material is usually sampled with simple means. In the flow, sediment is collected by means of a scoop-type sampler. In the dry bed, the top layer of 10 to 15cm is removed after clearing it from vegetation. A 30 to 40cm pit is then dug out and samples taken from the pit walls, trying to have them as representative as possible. The samples are reduced to the required quantity by the cone and quartering technique. These reduced samples are collected in polyethylene bags, placed themselves in thick and resistant cloth bags, labelled and sent to the laboratory for analysis.

The sampling procedure is standard for all kind of streams and does not make special recommendations for particular situations, such as hard bed-rock rivers where loose sediment alternates with rock.

The selection of sampler and sampling procedure should depend on the heterogeneity and variability of the bed material in space and time, as well as on the required information, thus depend on the objectives.

6.6.2 BED SAMPLING TECHNIQUE

The selection of the sampler will primarily depend on the requested bed material data:

- Surface sediment
- Surface and sub-surface sediment

For sediment transport studies in streams with homogeneous bed load and bed material (e.g. in dynamic sand bed rivers), sediment samples taken with a surface sampler will yield the relevant information.

For bed scour studies in flowing streams, such as for the design of bridge piles, sub-surface samplers may be needed in case the bed material composition is heterogeneous and varying in space and time.

For sediment silt and mud deposition studies, as in reservoirs, behind dams, or in estuaries, the sampling must be conducted sub-surface, eventually in thick layers of deposits, in combination with soil density measurements made with in-situ probes (no samples taken).

Most important is to assess the need for undisturbed sampling, allowing possibly sampling of disturbed samples.

Sampling of hard bedrock requires drilling technology and is not considered here.

The ***choice of the sampler type*** should be governed by the nature of the bed material and the flow conditions when sampling:

Cohesive soils, consolidated

- Sub-surface samples can only be taken with corers, preferably piston corers
- Surface samples may be best taken with scoop-type devices.

Cohesive soils, loosely consolidated

- All samples would be disturbed
- Surface samples may be taken with a pumping system, for all mud densities up to 1.15 or possibly 1.2
- Sub-surface samples are very difficult to take, only with corers, but which design usually does not allow to take undisturbed samples.

Non-cohesive soils, fine graded (silt and/or sand)

- Sub-surface samples can only be taken with corers, preferably piston corers
- Surface samples may be taken with scoop-type, grab-type, and dredge-type devices.

Non-cohesive soils, medium or coarse graded (sand, gravel)

- Sub-surface samples are difficult to take and will always be disturbed ones; if armour layer covers the streambed, it must be first removed (only possible on dry bed); sub-surface sampling may also be taken from man-made pit
- Surface samples may preferably be taken with scoop-type bucket sampler, because in the other samplers the fines would easily be washed out when raising the sampler to the water surface.

Non-cohesive soils, coarse to very coarse graded (gravel to boulders)

- Sub-surface sampling should be made from dry bed in a pit, whenever possible
- Surface samples are difficult to take as only a very large sample size would yield statistically representative results; as this kind of bed material is usually found in streams with high slopes, having dry bed most of the time, visual methods such as with camera pictures or counting are best suited.

Other selection criteria's, advantages/disadvantages

Core samplers:

Usually heavy equipment, difficult to operate under water at a flow and sediment gauging site when flow velocity is high; best suited for fine graded material (clay, silt and sand); piston-type corer gives the least disturbed sample

Dredge or drag-bucket-type samplers:

Easy to use from a boat; liable to be affected by washing out of material during the actual sampling; sampler may be dragged when (1) sailing slowly up the river or (2) letting drift the boat from up- to downstream the sampling station (second procedure appropriate when flow becomes too strong)

Scoop-type grab samplers, 90° closure, not streamlined:

The sampler is difficult to operate in strong currents and is liable to be affected by washing out of material, mainly fine particles.

Scoop-type grab samplers, 180 degrees, streamlined:

The streamlined sampler (e.g. US BM-54) can easily be lowered to the streambed even in velocities as high as 2 to 3 metres per second.

Scoop-type grab samplers, 180 degrees, not streamlined:

The sampler (e.g. SHIPEK) can not be properly lowered to the streambed in high velocities.

Comment on importance of bedforms

Bedforms, mainly the large ones, affect the near-bed flow pattern and may produce sediment sorting when the stream's sediment load is graded. Bars and dunes may display different bed material sizes over their area. A typical example is the bar in the foothill reaches where the river slope changes from steep to mild and where the sediment load is heterogeneous in size. As these bars may be quite large, with characteristic sizes – bar width and wave – similar to the width of the river, one or even three samples may not be statistically representative for the streambed. The heterogeneity should be assessed at the Circle or Sub-division and the optimum number of bed samples determined on the basis of a special survey; also the location of the samples needed for getting a representative average should be clearly stipulated relatively to the bedform, e.g. on the top, in the trough between two consecutive bars, on the lee side, on the upstream side.

Materials Finer than Medium Gravel

The selection of a suitable bed-material sampler depends primarily on stream depth and velocity. When a stream can be waded, standard samplers may be used, such as the US BMH-80. If the stream is too deep or swift, the US BMH-60 or US BM-54 can be used.

Materials Coarser than Medium Gravel

Gravel in the 2 to 16 mm range can be analysed by mechanical dry sieving. In order to obtain a representative particle size distribution, the size of the sample to be collected must be increased with particle size. The size determination of very large particles can be done by the pebble-count method, which entails measurement of the dimensions of randomly selected particles in the field, or by using special particle-size analysers. A reference photograph should then be made of the streambed during low flow. The sizes registered on the counter of the particle-size analyser must be multiplied by the reduction factor of the photograph.

6.6.3 BED SAMPLING METHODS

Bed-material samples are often collected in conjunction with a discharge measurement and/or a set of suspended- sediment samples. By taking these samples at the same stationing points, any change in bed material on radical change in discharge across the stream that would affect the sediment-discharge computations can be accounted for by subdividing the stream cross-section at one or between two of the common verticals.

6.6.4 SPECIFIC PROCEDURES

As samples are obtained across the stream, the field person should visually check and compare each sample with the previous samples to see if the material varies considerably in size from one location to the next.

Proper labelling of bed-material samples is not only necessary for future identification, but also provides important information useful in the laboratory analysis and the preparation of records.

7 EQUIPMENT SPECIFICATIONS

7.1 GENERAL

Specification of sediment samplers and sediment analysis equipment relevant for the HIS are presented in a separate volume: ‘Equipment Specification, Surface Water’. This document is regularly updated to keep track with the latest development. Specifications are available for:

1. Bed material sampler, US BM-54 (see Figure 7.1)
2. Point integrating bottle, Punjab bottle sampler (see Figure 7.2)
3. Depth integrating, hand held, US DH-48 (see Figure 7.3)
4. Depth integrating, winch operated, US D-74 (see Figure 7.4)

5. Point integrating, US P-61 (see Figure 7.5)
6. Visual accumulation tube (VAT), VATSA-58 (see Figure 7.6)
7. Electronic precision balance (Top loaded)
8. Optical particle sizer (PC controlled)
9. Electric stove (Oven) (IS 2994-1992)
10. Dessicator with lid (IS 6128-1971)
11. Graduated measuring cylinders (IS 878-1975)
12. Graduated beakers
13. Wash bottle
14. Funnels (IS 1541-1978)
15. Dishes
16. Crucibles (IS 2873-1975)
17. Pipettes (IS 4162-1967)
18. Test tubes
19. Test sieves with shaker (IS 6339-1971)
20. Polythene sample bottles
21. Volumetric flask (IS 915-1975)
22. Conical flasks (IS 1381 (Part I)-1976)
23. Burettes (IS 1997-1967)
24. Filter paper
25. Portable air compressor
26. Balance, analytical (Mechanical)

Descriptions of the samplers are provided in the following sections. Photographs/sketches of some of above mentioned equipment is presented below.

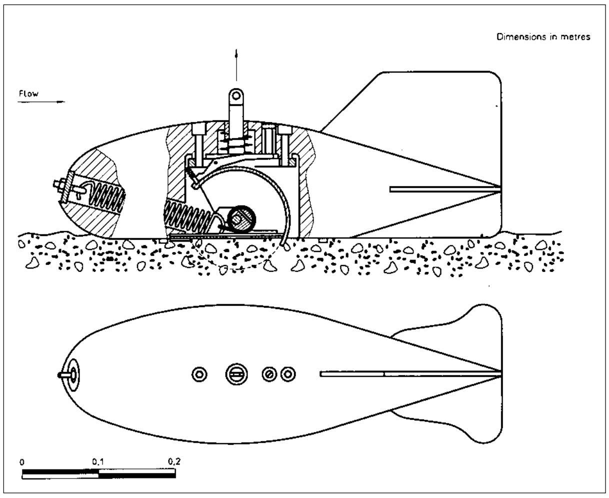

Figure 7.1: US BM-54 (above)

Figure 7.2: Punjab sampler (right)

Figure 7.3:
US DH-48

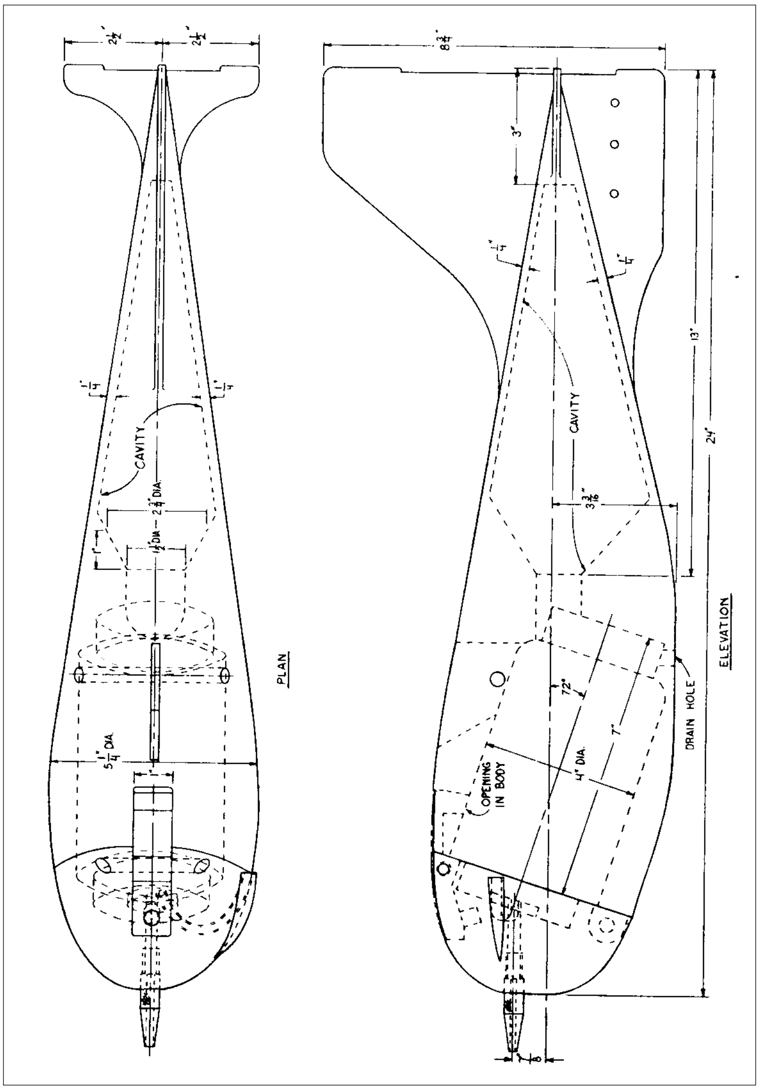

Figure 7.4:
US D-74

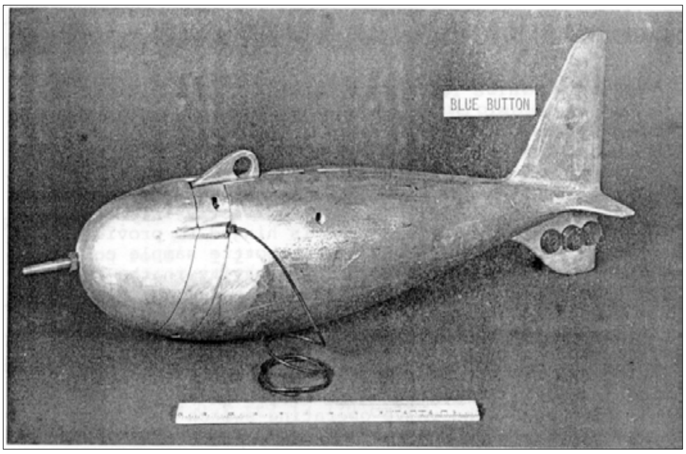

Figure 7.5:
US P-61

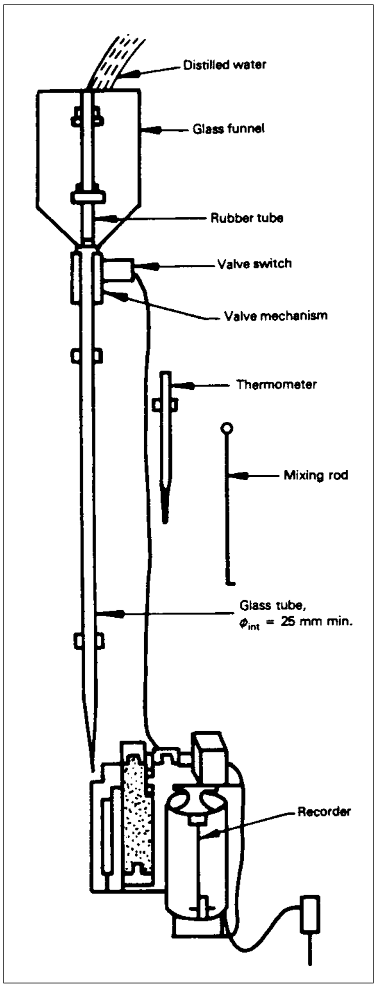

Figure 7.6:
Visual Accumulation Tube (left)

Figure 7.7:
Laboratory equipment

7.2 SUSPENDED SEDIMENT, CONCENTRATION-VOLUME SAMPLERS

7.2.1 DEPTH-INTEGRATING BOTTLE - WADING-TYPE HAND SAMPLER - FOR SHALLOW WATER

Description

Hand-held, lightweight, streamlined sampler for collection of suspended sediment. The water sample is collected in a fixed-volume rigid sample container (bottle) that can be removed easily and replaced by a spare container. It must be equipped with an exhaust in order to allow the air to escape without disturbing the inflowing sample. The assembling mechanism must be easy to handle and avoiding any leakage when the sampler is hoisted out of the water. The mechanism to fit the sampler on the rod must be designed tight, ensuring a perfect horizontal orientation of the nozzle in the direction of the flow and a constant intake elevation from the bed when the sampler touches the bottom. The instrument is delivered without rod, to be proposed as an option, but which design must be given.

Several hand-held, streamlined, depth-integrating samplers are available on the market, the best known being the US DH-48. This light-weight sampler has a aluminium casting body, originally designed for use with a round pint milk bottle sample container. An intake nozzle extends horizontally from the nose of the sampler body. While sampling, the air present in the bottle escapes through a streamlined exhaust mounted on the side of the sampler head. The sampler is easy to operate and to maintain. In India, the glass bottle was replaced by a tin one.

The original US DH-48 exists in several versions available in the US. It is also manufactured in India, though the original design was most often slightly adapted. Some local makes were however badly copied and/or some basic features were not respected, such as the 70° angle between the axis of the streamlined body and the wading rod or the fitting (alignment) of the bottle in the body. Also, the sampler has been used in India suspended at a hand-line, set up for which it is not suited at all; the US DHS-48 or the US DH-59 are especially designed for attachment at a hand-line.

Operating characteristics of hand-held samplers are:

- Simple and easy to operate
- Use restricted to wadable rivers with low velocities
- May never be used as a hand-line suspended sampler and may not be adapted for use as such
- Rate of filling must be found by experience
- Small bottle volume, requiring to take several samples if concentration of suspended load is too small.

7.2.2 DEPTH-INTEGRATING BOTTLE - TYPE HAND-LINE SAMPLER - FOR SHALLOW WATER

Description

Hand-line operated, lightweight, streamlined sampler for collection of suspended sediment. The water sample is collected in a fixed-volume rigid sample container (bottle) that can be removed easily and replaced by a spare container. It must be equipped with an exhaust in order to allow the air to escape without disturbing the inflowing sample. The assembling mechanism must be easy to handle and avoiding any leakage when the sampler is hoisted out of the water. The mechanism to hang the sampler to the line must be well designed, ensuring a perfect horizontal orientation of the nozzle in the direction of the flow at all stages of the filling; the elevation from the bed of the intake nozzle to be constant when the sampler touches the bottom.

Several hand-line, streamlined, depth-integrating samplers are available on the international market, for use suspended from a bridge or boat, possibly from a manned cableway. This type of sampler is not yet manufactured in India. The US DHS-48, D-59 and D-76 are suitable for most low and medium flow situations. These samplers have an aluminium or bronze casting body, originally designed for use with a round pint milk bottle sample container. An intake nozzle extends horizontally from the nose of the sampler body. While sampling, the air present in the bottle escapes through a streamlined exhaust mounted on the side of the sampler head. The sampler is very easy to operate and to maintain.

Typical characteristics of hand-line samplers are:

- Simple and easy to use sampler
- Use restricted to shallow water in low to medium velocities
- May never be used for deeper water and/or higher velocities by adding fish-weight
- Never use an additional line to refrain the sampler from drifting as this could bring the sampler out of balance
- Rate of filling must be found by experience
- The rather small bottle volume requires to take several samples if the concentration of the suspended load is too small.

7.2.3 DEPTH-INTEGRATING BOTTLE - WINCH-OPERATED SAMPLER – FOR SHALLOW/MEDIUM DEEP WATER

Description

Winch operated, medium-weight, streamlined sampler for collection of suspended sediment. The water sample is collected in a fixed-volume rigid sample container (bottle) that can be removed easily and replaced by a spare container. It must be equipped with an exhaust in order to allow the air to escape without disturbing the inflowing sample. Different nozzles may be needed for keeping sufficient efficiency. The assembling mechanism must be easy to handle and avoiding any leakage when the sampler is hoisted out of the water. The mechanism to hang the sampler to the suspension cable (hanger bar) must be well designed, ensuring a perfect balance of the sampler at all stages of the filling, with the nozzle kept horizontal in the direction of the flow. The elevation from the bed of the nozzle must be constant, when the sampler touches the bottom. The sampler is to be operated from a bridge or cableway.

Several streamlined, cable-suspended, depth-integrating samplers are available on the market for use from a boat, from a bridge or from a cableway. The US D-74 is suitable for many low and medium flow situations. This medium-weight sampler has a cast bronze body, originally designed for use with a round pint milk bottle sample container. The head of the sampler is hinged to permit access to the sample container. Tail vanes orient the instrument into the stream flow. A reel with a 3 mm cable is needed for safe operation. An intake nozzle extends horizontally from the nose of the sampler body. While sampling, the air present in the bottle escapes through a streamlined exhaust mounted on the side of the sampler head. The sampler is quite easy to operate and to maintain.

Characteristical features of streamlined depth-integrating samplers are:

- Quite simple and easy to use sampler
- Never use for depths and flow velocities higher than given in the specifications
- May never be used for deeper water and/or higher velocities by adding fish-weight
- Never use an additional line to refrain the sampler from drifting as this could bring the sampler out of balance
- Rate of filling must be found by experience

- The rather small bottle volume requires to take several samples if the concentration of the suspended load is too small

7.3 BED MATERIAL SAMPLERS

An overview of bed material samplers is presented in Section 6.6. Specifications are available for the US BM-54 sampler. A description is given below. Reference is made to Chapter 3 of the Volume 5 Field Manual Sediment Transport Measurements for details about the other types of bed material samplers.

7.3.1 BED MATERIAL - WINCH-OPERATED SAMPLER – SHALLOW/MEDIUM DEEP WATER (US BM-54 TYPE)

Description

Winch operated, medium-weight, streamlined sampler for collection of bed material composed of sediment ranging from gravel to compact clay. The bed material samples are collected in a revolving bucket, which can be replaced by a spare one if damaged.

The semi-cylindrical bucket is housed within a 45-50 kg streamlined, cast-iron fish-weight with tail fins. The bucket rotates from a position totally inside the fish till it surrounds and encloses the sample in such a way that it is not washed out when the device is raised and to and out of the water surface. The sample is collected from the top 5 cm of the streambed. When suspended at the steel cable, the bucket must be cocked by means of a wrench - i.e. set in open position – for taking the bed sediment. The bucket is freed and snaps shuts when the tension on the cable is released. The shutting mechanisms is operated by a spring which tension can be adjusted so that the bucket can scoop the bed material, going from stiff clay to coarse sand and fine gravel.

The device can be operated from a boat, from a bridge and from a cableway. The sampler is lowered to the stream bottom in open position and the catch is taken when the suspension steel cable is slackened momentarily. The sampler is then hoisted out of the water and the sample retrieved.

When operated from a boat, this must be maintained stationary, either with the engines or anchored. Drifting of the vessel is not allowed, as it would not be possible to control if the sampler would land correctly on the bed.

The main advantages of the device are:

- secure operation, even in relatively strong currents
- sample quite undisturbed and not washed out when sampler is properly closed
- bucket penetrates in all kind of bed material, except in rocks and when sediment contains large pebbles or cobbles
- the strength of the spring can be adjusted to penetrate to all kind of bed material

The disadvantages are:

- bucket may close by accident during handling and hurt the operator
- heavy equipment, necessitating heavy handling equipment
- rather small catch

The sampler is not easy to manufacture, especially the mechanism operating the closure of the bucket, as only drawings are available but no details such as spring characteristics.

8 STATION DESIGN, CONSTRUCTION AND INSTALLATION

The Hydrological Information system envisages the hydrometric stations to be gainfully used for sediment observations in the field and thus the station design, construction and installation procedures incorporated in the Chapter 8 of Volume 4, Design Manual, Hydrometry need to be referred to here.

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