Water Quality Monitoring - A Practical Guide to the Design and Implementation of Freshwater Quality Studies and Monitoring Programmes
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Published on behalf of United Nations Environment Programme and the World Health Organization

ISBN 0 419 22320 7 (Hbk) 0 419 21730 4 (Pbk)

Chapter 13 - SEDIMENT MEASUREMENTS

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Sediments play an important role in elemental cycling in the aquatic environment. As noted in Chapter 2 they are responsible for transporting a significant proportion of many nutrients and contaminants. They also mediate their uptake, storage, release and transfer between environmental compartments. Most sediment in surface waters derives from surface erosion and comprises a mineral component, arising from the erosion of bedrock, and an organic component arising during soil-forming processes (including biological and microbiological production and decomposition). An additional organic component may be added by biological activity within the water body.

For the purposes of aquatic monitoring, sediment can be classified as deposited or suspended. Deposited sediment is that found on the bed of a river or lake. Suspended sediment is that found in the water column where it is being transported by water movements. Suspended sediment is also referred to as suspended matter, particulate matter or suspended solids. Generally, the term suspended solids refers to mineral + organic solids, whereas suspended sediment should be restricted to the mineral fraction of the suspended solids load.

Sediment transport in rivers is associated with a wide variety of environmental and engineering issues which are outlined in Table 13.1. The study of river suspended sediments is becoming more important, nationally and internationally, as the need to assess fluxes of nutrients and contaminants to lakes and oceans, or across international boundaries, increases. One of the most serious environmental problems is erosion and the consequent loss of topsoil. Although erosion is a natural phenomenon, the rate of soil loss is greatly increased by poor agricultural practices which result, in turn, in increased suspended sediment loads in freshwaters. Loss of topsoil results in an economic loss to farmers, equivalent to hundreds of millions of US dollars annually, through a reduction in soil productivity. Good environmental practice in agriculture, which may include contour ploughing and terracing, helps to protect against soil loss and against contamination of surface waters.

Table 13.1 Issues associated with sediment transport in rivers

Sediment size	Environmental issues	Associated engineering issues
Silts and clays	Erosion, especially loss of topsoil in agricultural areas; gullying	
	High sediment loads to reservoirs	Reservoir siltation
	Chemical transport of nutrients, metals, and chlorinated organic compounds	Drinking-water supply
	Accumulation of contaminants in organisms at the bottom of the food chain (particulate feeders)	
	Silting of fish spawning beds and disturbance of habitats (by erosion or siltation) for benthic organisms	
Sand	River bed and bank erosion	River channel deposition: navigation problems Instability of river cross-sections
	River bed and bank erosion	Sedimentation in reservoirs
	Habitat disturbance	
Gravel	Channel instability when dredged for aggregate	Instability of river channel leads to problems of navigation and flood-control
	Habitat disturbance	

Water users downstream of areas of heavy soil run-off may have to remove suspended sediment from their water supplies or may suffer a reduction in the quantity of water available because of reservoir siltation. The rapid reduction in the storage capacity of reservoirs due to siltation is a major sediment- related problem world-wide. Moreover, the availability of water for irrigation from the reservoir leads to more intensive land use and increased soil erosion. These effects may also be exacerbated by desertification (impoverishment of vegetative cover and loss of soil structure and fertility), whether anthropogenic or climatic in origin. In addition, gradual enrichment of reservoir waters with nutrients (some of which also arise from agricultural practices) leads to enhanced production and increased sedimentation of organic material originating from the water column (from decaying plankton) or littoral zones (from decaying macrophytes). Consequently, the rate of reservoir siltation often greatly exceeds that predicted during design. Monitoring data for sediment transport to, and productivity within, reservoirs are therefore required for accurate calculations of sediment transport and deposition and for the management of major reservoirs. Further information on monitoring and assessment approaches for reservoirs is given in the companion guidebook *Water Quality Assessments*.

In order to protect surface water resources and optimise their use, soil loss must be controlled and minimised. This requires changes in land use and land management, which may also have an impact on water quality. Control of the siltation rate in reservoirs requires that adequate data are available at the design stage. This, in turn, demands an understanding of sediment transport and appropriate methods for measuring sediment load and movement.

Recognition of the importance of sediments and their use in monitoring and assessment programmes is increasing and methods are constantly being refined. For the purposes of water quality monitoring a distinction can be made between measuring sediment quantity and sediment quality. Some of the techniques available for studying sediment quality (as a component of water quality studies) are not yet widely accepted or used and have not been standardised. Although they may be suitable for special surveys, some methods are too complex and costly for routine monitoring programmes. A full discussion of the role of sediments and particulate material in water quality monitoring and assessment is available in the companion guidebook *Water Quality Assessments*. This present chapter concentrates on some of the fundamental procedures required for the more common sediment measurements necessary for water quality monitoring programmes.

13.1 Types of sediment transport

Sediment transport is a direct function of water movement. During transport in a water body, sediment particles become separated into three categories: suspended material which includes silt + clay + sand; the coarser, relatively inactive bedload and the saltation load.

Suspended load comprises sand + silt + clay-sized particles that are held in suspension because of the turbulence of the water. The suspended load is further divided into the wash load which is generally considered to be the silt + clay-sized material (< 62 µm in particle diameter) and is often referred to as “fine-grained sediment”. The wash load is mainly controlled by the supply of this material (usually by means of erosion) to the river. The amount of sand (>62 µm in particle size) in the suspended load is directly proportional to the turbulence and mainly originates from erosion of the bed and banks of the river. In many rivers, suspended sediment (i.e. the mineral fraction) forms most of the transported load.

Bedload is stony material, such as gravel and cobbles, that moves by rolling along the bed of a river because it is too heavy to be lifted into suspension by the current of the river. Bedload is especially important during periods of extremely high discharge and in landscapes of large topographical relief, where the river gradient is steep (such as in mountains). It is rarely important in low-lying areas.

Measurement of bedload is extremely difficult. Most bedload movement occurs during periods of high discharge on steep gradients when the water level is high and the flow is extremely turbulent. Such conditions also cause problems when making field measurements. Despite many years of experimentation, sediment-monitoring agencies have so far been unable to devise a standard sampler that can be used without elaborate field calibration or that can be used under a wide range of bedload conditions. Even with calibration, the measurement error can be very large because of the inherent hydraulic characteristics of the samplers and the immense difficulty with representative sampling of the range of sizes of particles in transit as bedload in many rivers. Unless bedload is likely to be a major engineering concern (as in the filling of reservoirs), agencies should not attempt to measure it as part of a routine sediment-monitoring programme. Where engineering works demand knowledge of bedload, agencies must acquire the specialised expertise that is essential to develop realistic field programmes and to understand the errors associated with bedload measurement. Local universities or colleges may be able to assist in this regard.

Saltation load is a term used by sedimentologists to describe material that is transitional between bedload and suspended load. Saltation means “bouncing” and refers to particles that are light enough to be picked off the river bed by turbulence but too heavy to remain in suspension and, therefore, sink back to the river bed. Saltation load is never measured in operational hydrology.

13.2 Sediment measurement

While the underlying theory is well known, the measurement of sediment transport requires that many simplifying assumptions are made. This is largely because sediment transport is a dynamic phenomenon and measurement techniques cannot register the ever-changing conditions that exist in water bodies, particularly in river systems. Some of the sources of extreme variability in sediment transport are discussed below.

13.2.1 Particle size

Knowledge of the size gradient of particles that make up suspended load is a prerequisite for understanding the source, transportation and, in some cases, environmental impact of sediment. Although particles of sizes ranging from fine clay to cobbles and boulders may exist in a river, suspended load will rarely contain anything larger than coarse sand, and in many rivers 50-100 per cent of the suspended load will be composed only of silt + clay-sized particles (<62 µm). The size of particles is normally referred to as their diameter although, since few particles are spherical, the term is not strictly correct. Particle size is determined by passing a sample of sediment through a series of sieves, each successive sieve being finer than the preceding one. The fraction remaining on each sieve is weighed and its weight expressed as a percentage of the weight of the original sample. The cumulative percentage of material retained on the sieves is calculated and the results are plotted against the representative mesh sizes of the sieves. A series of eight sieves can be used for sediment analysis, with mesh sizes from 1.25 mm to 63 µm or less. Further details of these methods are available in the appropriate literature (see section 13.6).

Table 13.2 Particle size classification by the Wentworth Grade Scale

Particle description	Particle size (mm)	Cohesive properties
Cobble	256-64	Non-cohesive
Gravel	64-2	
Very coarse sand	2-1	Non-cohesive sediment
Coarse sand	1-0.5	
Medium sand	0.5-0.25	
Fine sand	0.125-0.063	
Silt	0.062-0.004	Cohesive sediment
Clay	0.004-0.00024	

Clay particles are plate-like in shape and have a maximum dimension of about 4 µm. Silt particles, like sand, have no characteristic shape; their size is between those of clay and sand with diameters ranging from 4 µm to 62 µm. Since the smallest mesh size of commercially available sieves is about 40 µm, the sizes of clay and small silt particles cannot be determined by sieving, and sedimentation techniques are used instead. The sedimentation rate of the particles is measured and their diameter calculated from the semi-empirical equation known as Stokes' Law.

There is no universally accepted scale for the classification of particles according to their sizes. In North America, the Wentworth Grade Scale (see Table 13.2) is commonly used; elsewhere, the International Grade Scale is preferred. There are minor differences between the two scales and it is, therefore, important to note which scale has been selected and to use it consistently.

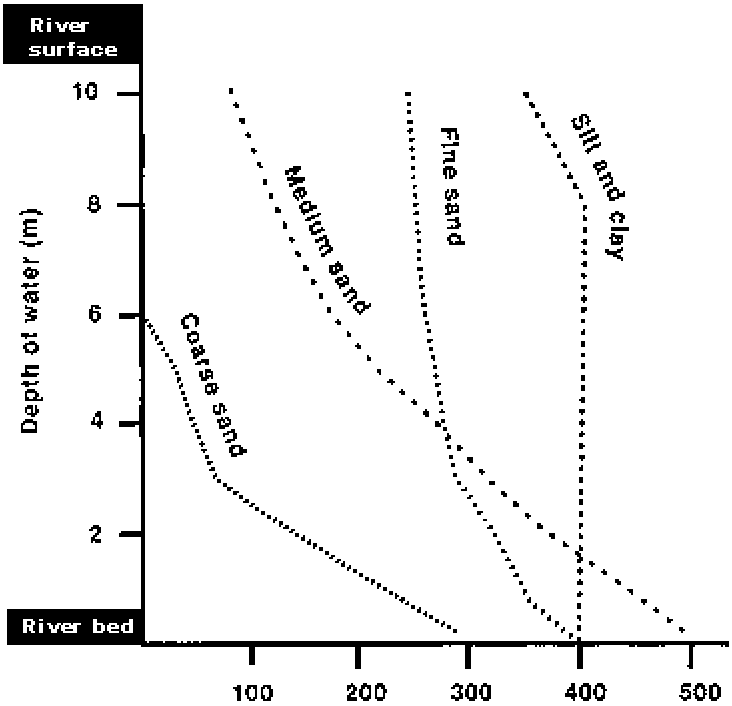
The boundary between sand and silt (62 µm) separates coarse-grained sediments (sand and larger particles) from fine-grained sediments (silt and clay particles). Coarse-grained sediments are non-cohesive, whereas fine-grained sediments are cohesive, i.e. the particles will stick to one another as well as to other materials. Particle cohesiveness has important chemical and physical implications for sediment quality.

Sedimentology and water quality programmes have adopted a convention that considers particulate matter to be larger than 0.45 µm in diameter; anything smaller is considered to be dissolved. This boundary is not entirely valid because clay particles and silt can be much smaller than 0.45 µm. For practical purposes, however, the boundary is convenient, not least because standard membrane filters with 0.45 µm diameter pores can be used to separate suspended particles from dissolved solids. A general procedure for the measurement of total dissolved solids (TDS) is described in Chapter 7, section 7.24.

13.2.2 Composition of sediment

The amount and nature of suspended load in a water body is affected by the availability of sediment as well as by the turbulent forces in the water. The sand component of the suspended load in a river originates mainly from the river bed. As discharge increases, so do the turbulent forces that cause the sand to be taken into suspension. Sand particles tend to settle quite rapidly because of their shape, density and size. Therefore, the concentration of sand is highest near the bed of a river and lowest near the surface. The curves for medium and coarse sand in Figure 13.1 show this variation of concentration with depth. In lakes, coarser material is deposited rapidly at the point where the river enters the lake and is only resuspended and redeposited under highly turbulent conditions (such as generated by high winds).

Figure 13.1 Variations in concentration of suspended sediment with water depth for sand, silt and clay as measured at one field site

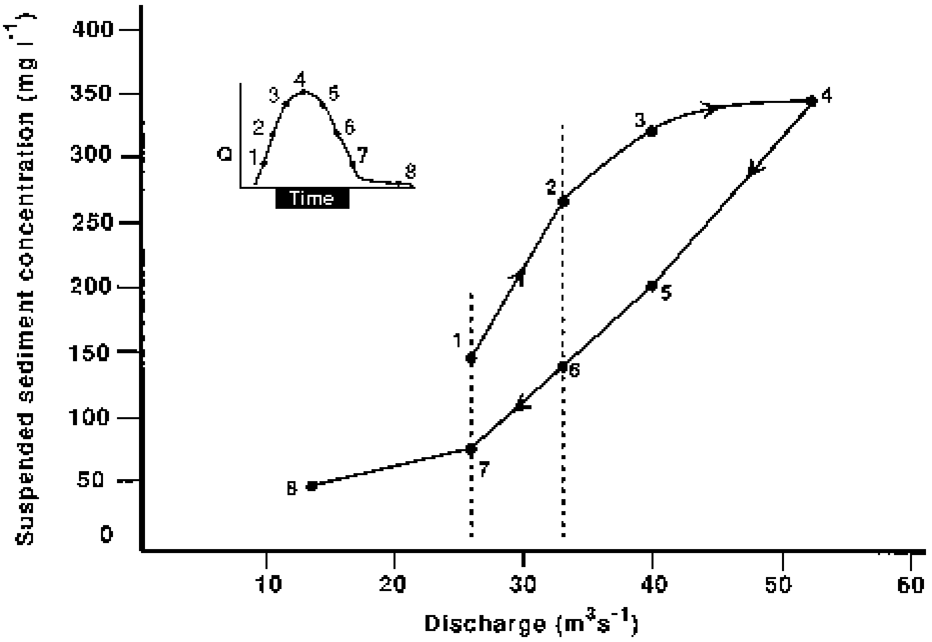


The bed sediment of a river contributes only a small portion of the clay and silt-sized particles (<62 µm) present in the suspended load. Most of this fine material, which may be 50-100 per cent of the suspended load in many rivers, is eroded and carried to the river by overland flow during rainstorms. This fraction does not easily sink in the water column, and slight turbulent forces keep it in suspension for long periods of time. As a consequence, the silt + clay fraction tends to be fairly evenly distributed throughout the depth of a river as illustrated by the vertical profile for silt + clay in Figure 13.1. In lakes and reservoirs, fine suspended material originates from river inputs, shoreline and lake bed erosion and organic and inorganic material generated within the lake by biological activity. In eutrophic waters the latter source can be quite significant. Fine material can be repeatedly resuspended by lake currents (generated by wind stress) until it is eventually deposited in an area where water movements are insufficient to resuspend or remobilise it. Such depositional basins in lakes or reservoirs are important for sediment quality studies because they can indicate the history of anthropogenic influences on the composition of the sediment.

13.2.3 Hysteresis effects

A rainstorm causes an increase in discharge and an associated increase in turbulence in a river. This turbulence takes bed sediments into suspension leading to relatively high concentrations of suspended material in the water. During prolonged rainstorms, discharge and turbulence may remain high but there is usually a progressive decline in the quantity of suspended material present in the water. This is because the quantity of sediment on a river bed, and which is introduced into the river by erosional processes, is limited and the amount of sediment available to be taken into suspension gradually diminishes during a storm event. When a series of discharge measurements and water samples are taken at intervals throughout a storm event (when flow increases, reaches a peak, and then decreases), the graphical plot of the concentration of suspended sediment against discharge will often take the form of a hysteresis loop. This is shown in Figure 13.2, where samples 1 and 7 were taken at the same discharge rate but sample 7 (taken late in the discharge event) has a lower concentration of suspended sediment than sample 1. Similar differences in concentration are evident for samples 6 and 2. In Figure 13.2, the inset graph shows the time sequence of sampling in relation to the discharge.

Figure 13.2 Typical hysteresis effect observed in suspended sediment. Sample numbers are those noted in the storm hydrograph illustrated in the insert.



Hysteresis may also be observed in plots of seasonal data. This reflects periods of the year when sediment may be more readily available than at other times. Higher concentrations may occur, for example, after a long, dry period or in dry months when vegetation is not able to hold back soil particles that are being eroded.

13.3 Sampling for sediment

The methods and equipment used for sampling suspended sediment are different from those used for deposited sediments. Also sampling methods for measurements of the quantity of sediment in transport are different than for measurement of sediment quality. The reason for these differences reflects the fact that sediment quantity must include the sand-size fractions which are unequally distributed in depth, whereas sediment quality focuses on the silt + clay fraction which is not depth-dependent. These differences are more fully described in the appropriate literature (see section 13.6).

For bottom sediments it may be necessary to collect deposited sediments with minimum disturbance in order not to lose the fine material on the sediment surface, or because the vertical distribution of the sediment components is important (such as during establishment of historical records or depositional rates). In deep waters this necessitates the use of grabs or corers (see also section 11.2.2), but in shallow water a scoop or spatula may be used. Further discussion of the relative merits of different sampling techniques is available in *Water Quality Assessments* and other relevant publications.

There are four main types of samplers for suspended sediments:

- integrated samplers,
- instantaneous grab samplers,
- pump samplers, and
- sedimentation traps.

It was shown in Figure 13.1 that the concentration of the coarser fractions of suspended sediment increases towards the bottom of the river channel. This segregation of material by particle size requires that, for the purposes of measuring quantity of suspended sediment, a depth-integrating sampling technique is used to obtain a sample that accounts for different sediment concentrations throughout the vertical profile of a water body. Many types of sampler have been designed for depth-integrated sampling of suspended sediment. Some are available commercially but are rather expensive. All of them have a number of features in common:

- Each has a water inlet nozzle and an air outlet. As the water and suspended sediment enter, air is displaced through the air outlet.

- Each permits isokinetic sampling. That is, water velocity through the inlet nozzle is equal to the water velocity at the depth of the sampler. This is important for larger particles, such as sand, because the sampler would otherwise tend to over- or under-estimate the amount of suspended sediment. Errors caused by lack of isokinetic sampling are minimal for small particles (< 62 µm) and for practical purposes can be ignored.

- Each has a metal body (for weight) that encloses a glass or plastic bottle for retaining the sample. The bottle is changed after each sample is taken.

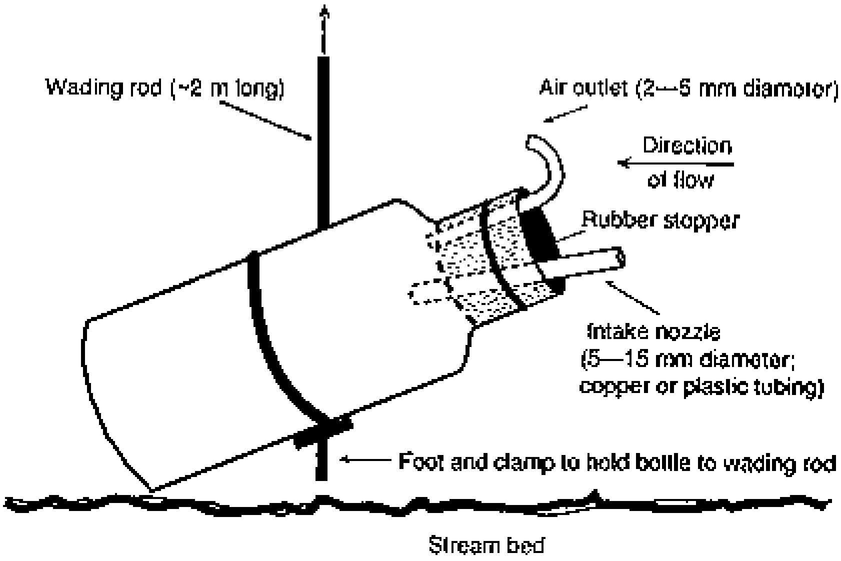
- The diameter of the water inlet can be selected (or changed) so that the sampler will fill more or less quickly, depending on the depth of the river.

In practice, depth-integrating samplers are lowered to the river bottom, then immediately raised to the surface; lowering and raising should be done at the same rate. The objective is to fill the sampler to about 90 per cent capacity; if the sampler is completely full when it emerges from the water the sample will be biased because the apparatus will have stopped sampling at the point at which it filled up.

Large, heavy samplers are usually only necessary when samples must be obtained from a bridge, boat or similar situation. In shallow streams, where all points can be reached by wading, a bucket (if nothing else is available) or a small sampler attached to a metal rod can be used. It is possible to make a simple depth-integrating sampler for use in shallow streams, using a wide-mouth, 1-litre bottle, a rubber stopper and short pieces of rigid tubing. The tubing forms the water inlet and air outlet. The lengths and diameters of the tubes may require experimentation but, in general, the air outlet tube should be of a smaller diameter than the water inlet. The bottle is secured to a metal rod or wooden pole, then lowered and raised as outlined above. An example of a home-made sampler is shown in Figure 13.3. The sample must be taken facing upstream so as to avoid sampling bottom sediment that was resuspended by the operator's feet.

For measurements of sediment quality, such as for phosphorus, metals, pesticides, etc., it is generally only the silt and clay-size material that is relevant. Also, the amount of sample required is often much larger (e.g. several grams in some instances) than is necessary for the physical measurement of suspended sediment concentration.

Figure 13.3 Home-made suspended sediment sampler



Therefore, it is often necessary to use methods which concentrate the suspended material from a large volume of water. For some types of chemical analyses it is possible to obtain values from digestion and analysis of the sediment which is retained on a filter with pore diameters of 0.45 µm. However, the errors in the results obtained can be quite large. Alternatively, where the sampling site is close to a laboratory, large volumes of water can be left to settle for several days and the resultant supernatant water siphoned off, leaving the solids on the bottom of the container. This method can also lead to errors in results due to contamination and/or the chemical and microbiological modification of compounds during the settling period. More commonly, raw water samples are taken to the laboratory where they are centrifuged by standard or continuous-flow centrifuges. In more remote locations portable continuous-flow centrifuges can be used. However, these are expensive and require mains or portable electrical power. It is most important to note that there is no single recommended method for collection and analysis of the chemistry of suspended sediment (see also section 13.5).

In lakes, the use of sediment traps provides a simple and cheap alternative for the collection of suspended material, although the samples may not be totally representative (due to the continual microbial processes within the trap and the efficiency of the particle capture). A simple sediment trap can be made from a plastic, glass or metal cylinder open at the top and closed at the bottom and with a height to width ratio greater than five. There should be nothing obscuring the opening and the trap should be suspended vertically with the aid of a weight and mooring system. A trap should not be left in place for longer than one month without removing the sample.

13.4 Measuring suspended sediment

Particle size distribution and concentration not only vary in the vertical section, but may also vary considerably across a river section. Therefore, measuring suspended sediment concentration must take into account these variations. This becomes especially important when suspended sediment concentration is being measured for the purpose of calculating sediment load in a river.

For determining suspended sediment load, it is necessary to consider all particle sizes (sand + silt + clay). Therefore, a depth-integrating sampler must be used as described in section 13.3 to ensure that the depth-dependent sand-sized fraction is correctly sampled. There are two generally accepted methods for measuring suspended sediment concentration for load determination as described below.

Equal-discharge-increment method

This method requires first that a complete flow measurement be carried out across the cross-section of the river. Using the results, the cross-section is divided into five (more on large or complex rivers) increments (i.e. vertical sections) having equal discharge. The number *n* of increments is based on experience. Depth integrated suspended sediment sampling is carried out at one vertical within each of the equal-discharge-increments, usually at a location most closely representing the centroid of flow for that increment. The sediment concentration for each equal-discharge-increment is measured according to section 13.4.1. The mean discharge-weighted suspended sediment concentration (SS*C*) is obtained by taking the average of the concentration values *C* obtained for each interval *i*.

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

The discharge-weighted suspended sediment load (SSL), in tonnes per day, for the river cross-section is obtained by multiplying the concentration, *C*, in ppm (mg l^{-1}) by the discharge, *Q*, in $m^3\ s^{-1}$ of each equal-discharge- increment, *i*, and summing for all increments. This method is very time-consuming, but is that most used by sediment agencies.

$$SS_L = \sum_{i=1}^{n} \left(C_i Q_i\right) \times 0.0864$$

Equal-width-increment-method

This method is used without making flow measurements and is usually used in small to medium rivers and especially rivers that are shallow enough for wading. The operator marks off 10-20 equal intervals across the river cross-section. At the deepest point, the operator takes a depth-integrated sample, noting the transit rate of the sampler (i.e. the uniform speed at which the sampler is lowered, then raised to the surface). Using that same transit rate, a suspended sediment sample is taken at each of the intervals. Because each vertical will have a different depth and velocity, the sample volume will vary with each vertical sampled. Note that the bottle must never be over-filled. All samples are composited into a single container which is then agitated and sub-sampled, usually two or three times, and analysed for suspended sediment concentration. The average of these analyses is the mean cross-sectional suspended sediment concentration. In this method, the results are corrected for differences in discharge at each section by virtue of using the same transit rate (and the same nozzle diameter) at all sections - i.e. a shallow section with less discharge will produce a proportionally smaller suspended sediment sample than a deep section having greater discharge.

For suspended sediment quality (section 13.5), where the primary interest is the chemistry associated with the silt + clay (<0.63 µm) fraction, sampling can be greatly simplified because this fraction is not normally depth- dependent (Figure 13.1). While there are no universally accepted rules for sampling, many scientists will collect a grab sample from a depth of 0.5 m at the point of maximum flow in the cross-section. For larger rivers, or rivers where there is concern over cross-sectional variation, grab samples can be taken from several locations across the section and integrated. For more exacting work where accurate loads are required, especially for micro-pollutants, sampling should be carried out using either of the methods noted above. It is particularly important to avoid sampling near river banks (or lake shores) where elevated concentrations of suspended matter occur and which are often contaminated by garbage and other anthropogenic materials.

13.4.1 Laboratory procedures for measuring sediment concentration

The concentration of suspended sediment is usually determined in the laboratory using the method described in section 7.25 for the determination of total suspended solids (TSS). When this method is followed, the filters used should have a pore size of 0.45 µm. Note, however, that if a sample which has been filtered for TSS determination will also be required for sediment quality analysis, a filter appropriate to the further analyses should be used (see section 13.5.1 below). Where the concentration of sediment is high, it may be difficult and time-consuming to filter a large enough volume of sample. In this case it is possible to evaporate a measured portion of sample to dryness in a pre-weighed dish and to determine the weight of the residue, although it must be recognised that any dissolved salts in the sample will increase the value obtained (this bias may be quite great if the water is saline).

Another possibility is to make measurements with a field turbidity meter that has been calibrated against natural samples, preferably from the sampling site where it is being used (this relationship would not be valid for other sites). Provided that most of the suspended sediment is fine grained, there is usually a good relationship between turbidity and suspended sediment concentration.

The size boundary between sand and silt + clay, i.e. 62 µm, is important if the nature of infilling of a reservoir is to be determined or if sediment quality is of interest. Sand will settle to the bottom almost immediately when a river enters a reservoir and velocity is reduced. By contrast, silt and clay will stay in suspension much longer and move further within the reservoir. Furthermore, it is the ≤62 µm fraction of suspended sediment that is mainly responsible for the transport of chemicals adsorbed on particles.

Measurement of the quantity of silt + clay (i.e. ≤ 62 µm) in a sample requires that a known volume [V_{sample} (ml)] of well mixed sample is first passed through a 62 µm mesh sieve. The sample is wet-sieved, i.e. distilled water is used to rinse the sample through the sieve. All of the water that passes through the sieve (original sample plus rinse water) is collected and filtered through a membrane filter of 0.45 µm pore size and of known weight. The sand collected on the sieve is dried and weighed [W_{sand} (g)] and the silt and clay collected on the filter paper is dried and weighed [$W_{clay+silt}$ (g)]. The results can be expressed as follows:

Concentration of sand (mg l^{-1})=(W_{sand}/V_{sample}) × 10^6
Concentration of clay+silt (mg l^{-1})=($W_{clay+silt}/V_{sample}$) × 10^6
Total suspended load (mg l^{-1})=[($W_{sand} + W_{clay+silt})/V_{sample}$] × 10^6
If sand concentration is not required separately, then filter a known volume of raw water through a pre-weighed 0.45 µm pore diameter filter paper. The suspended sediment concentration is then the dry weight (in grams) of the filter paper + retained sediment, minus the original weight of the filter paper, all divided by the volume (ml) of the sample, as:

$$\text{Total suspended sediment concentration (mg l}^{-1}\text{)} = [\mathrm{W}_{\text{sand + silt + clay}}/\mathrm{V}_{\text{sample}}] \times 10^6$$

13.4.2 Estimating suspended sediment concentration

Water agencies often need to calculate suspended sediment load on an annual basis, but wish to reduce the amount of field sampling required to determine suspended sediment concentration. In some rivers there is a moderately good relationship between suspended sediment concentration and discharge, i.e. the higher the discharge the higher the suspended sediment concentration. It is possible, therefore, to develop a rating curve which is a regression of suspended sediment concentration Y as a function of discharge X. This relationship is, however, subject to a high degree of variability and error, especially when the suspended sediment is comprised mainly of silt + clay. Nevertheless, when used carefully, and the rating curve is checked frequently for stability, agencies can use measurements of discharge to estimate suspended sediment concentration ($C_{estimated}$) for the purpose of calculating suspended sediment load (SSL) in tonnes per day as:

$$\mathrm{SS_L} = Q_{observed} \times C_{estimated} \times 0.0864$$

This procedure is carried out daily, and the daily loads are summed for the year.

The alternative to extrapolating from a rating curve is some form of statistical estimation in which concentration data are clustered so that they represent a specified flow interval (e.g. by dividing the annual flow record into 10 per cent intervals of discharge). Total load is then calculated by assessing the statistical probability of each interval of flow occurring, multiplying it by the average suspended sediment concentration and discharge for that range, and then summing for all flow intervals. A common application of this approach is the so-called Beales Ratio Estimator. However, there is no general consensus on the best estimator to use, since each may produce different results in different situations.

13.5 Sediment quality

Fine grained sediment (silt + clay) is responsible for a significant proportion of the annual transport of metals, phosphorus, chlorinated pesticides and many industrial compounds such as polynuclear aromatic hydrocarbons, polychlorinated biphenyls, dioxins and furans. Of the 128 priority pollutants listed by the United States Environmental Protection Agency, 65 per cent are found mainly, or exclusively, in association with sediment and biota. Consequently, water quality programmes that focus only on the water phase miss most of the more toxic contaminants (see also Figure 2.5). In North America it has been found that up to 95 per cent of the annual phosphorus load in rivers is transported in association with suspended sediment. Organic micropollutants are mainly bound to the organic component of the suspended matter, which is commonly measured as total organic carbon (see section 8.4).

Sediment measurements are not necessary for the assessment of certain water quality issues of major concern in some countries, such as faecal contamination. Nevertheless, other issues such as eutrophication of lakes and reservoirs and fluxes of nutrients and contaminants to coastal waters and oceans, which are becoming more important in all world regions, are increasing the need for sediment-quality measurements. Unfortunately, water quality agencies throughout the world still tend to pay little or no attention to suspended sediment quality. The following are the most frequently identified reasons for this:

- Lack of awareness of current techniques in sedimentology.

- Poorly defined objectives for monitoring programmes (see section 3.3).

- Programmes reflect more established concerns (e.g. major ions, faecal contamination).

- Lack of funding, expertise, equipment, etc.

Only the last of these is a valid reason because the initial investment in sampling and analysis of suspended sediment can be high. Nevertheless, when a programme is developed with well defined objectives, a suspended sediment programme, together with water chemistry, can greatly increase the amount of useful information available to water managers, and may ultimately result in agencies saving money. When combined with an inexpensive bioassay programme (see section 11.4), limited sediment and water sampling can significantly reduce the number of expensive chemical analyses now being undertaken by agencies in industrialised, and rapidly industrialising, countries.

13.5.1 Sample collection and preparation

Collection and storage of sediment samples for sediment quality analysis require special handling in order to avoid contamination, especially if the variables to be measured occur in very low concentrations (e.g. mg g^{-1}). The necessary precautions depend on the analyses to be performed. All materials which come into contact with samples intended for metal analyses should be plastic, plastic coated or glass (i.e. samplers, sample storage containers, filtration equipment). All equipment should be acid-cleaned and thoroughly rinsed with pure (double distilled) water. If it is necessary to use a metal sampler for sediments intended for metal analysis (e.g. a grab), the portion of sample in contact with the sides of the sampler should be discarded. Plastic equipment should be avoided for any sampling and handling procedures for sediments intended for analysis of organic micropollutants; appropriately cleaned metal equipment is most suitable (preferably stainless steel). Samplers, filtration equipment and storage containers for samples intended for phosphorus analysis can be made of metal, plastic or glass but should be cleaned with a phosphate-free detergent.

Samples are collected as described in section 13.3 paying particular attention to the requirements for reducing the risk of contamination according to the the analyses to be performed. Suspended sediment is normally concentrated by ultra centrifugation or by filtration in order to collect the fine particulate matter, with which most nutrients and contaminants are associated. Standard 0.45 mm pore size filters are commonly used. Inorganic filters (polycarbonate, cellulose acetate) with low trace element contents are recommended where inorganic substances will be determined, and glass- fibre filters are recommended for organics, particulate organic carbon and chlorophyll determinations.

It is preferable that samples requiring storage prior to analysis should be dried and weighed before placing in a refrigerator (if intended for metal or nutrient analysis) or a freezer at -20°C (if intended for hydrocarbons or other organic analyses).

Chemical analyses should be performed on dry material of known weight. The precise preparation and analytical details depend on the elements or compounds to be analysed and, therefore, only the basic principles are described here. Samples for metal determinations (including the filters used to separate the suspended sediments) are digested in acid on a hot plate and diluted to a known volume with distilled water. The diluted digest is analysed using standard techniques such as atomic absorption spectrophotometry (AAS) (see section 8.1). The acid used for digestion depends on the proportion of organic matter in the sediment sample and whether it is necessary to determine total metal content or only the proportion which is thought to be most environmentally available (e.g. for bioaccumulation). It is important, when digesting filtered samples that blank filters are also included in each batch of digestions as a means of checking for contamination and allowing for any metals present in the filters themselves (see also Chapter 9 on Analytical Quality Assurance).

Samples for determination of organic micropollutants are extracted with organic solvents and analysed using standard techniques such as gas chromatography or high pressure liquid chromatography. Filters may need to be ground or pulverised in a blender prior to extraction. Many analyses can be performed on unfiltered samples.

Results of sediment quality analyses are usually expressed as mg g^{-1} or mg g^{-1} dry weight or mg l^{-1} or mg l^{-1} of sample volume. Since coarser particles tend to have low concentrations of metals, nutrients and organic micropollutants, a high proportion of coarse particles (e.g. sand) in a sample tends to dilute the contaminant concentration for the whole sample. This is known as the matrix effect. Provided that the fraction less than 63 mm (with which most metals tend to be associated) accounts for at least 30-40 per cent of the total sample, the following correction can be applied:

$$\text{Corrected value } (\mu\text{g g}^{-1}) = \frac{\text{Trace metal concentration } (\mu\text{g g}^{-1})}{\text{Per cent of sample } < 63\ \mu\text{m}}$$

The percentage less than 63 mm can be determined by wet sieving a sample of known dry weight through a pre-weighed 63 mm screen and re-weighing the screen and content after drying. This correction is only useful when there is a need to know the likely concentration of the pollutant on that fraction of the sample (the <0.63 µm component) which actually carries the pollutant, or when the chemistry of different sediment samples is being compared, in which case the correction normalises the sample chemistry for grain size effects (i.e. eliminates the matrix effect). For calculation of the load of a pollutant the correction is not necessary because the pollutant concentration in suspended sediment will be multiplied by the mean suspended sediment concentration (sand + silt + clay) that has been measured as noted in section 13.4.

13.6 Source literature and further reading

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