Sediment Budgets 1 (Proceedings of symposium S1 held during the Seventh IAHS Scientific Assembly at Foz do Iguaçu, Brazil, April 2005). IAHS Publ. 291, 2005.

Hydrological and instrumentation aspects of monitoring and analysing suspended sediment transport crossing international borders

G. SCHINDL, M. STUDNICKA, A. ECKELHART & W. SUMMER
FH-Campus Vienna, Civil Engineering-Management, Daumegasse 1/2, A-1100 Vienna, Austria
bau@fh-campuswien.ac.at

Abstract The transport of suspended sediment in rivers and streams is a natural process increasingly influenced by human activities. It has ecological as well as economic impacts. In order to recognise and react to these changes in river basins, it is important to record the quantities of suspended sediment in a technically correct as well as directly comparable way. The monitoring often has to be undertaken on transboundary river systems. Technical discrepancies in the monitoring strategies as well as institutional, organizational and legal difficulties are a major problem in the adoption of common standardized procedures. This paper summarises the outcome of an International Commission on Continental Erosion (ICCE) Task Force activity aimed at providing general *Guidance on standardization and comparison of methods used for the evaluation of sediment transport crossing international borders*, focusing on hydraulic aspects as well as on monitoring techniques.
Key Words hydraulics; international; monitoring; suspended sediment; transboundary

INTRODUCTION

An important component of controlling the transboundary impact of anthropogenically influenced natural processes involves comparing and assessing the effectiveness of control measures. The exchange of hydrological information on, for example, soil erosion, water discharge, sediment transport and effluent monitoring, will reduce or even prevent negative transboundary impacts. Thus, riparian parties should harmonise procedures for setting up and operating monitoring programmes, which include measurement systems and devices, analytical techniques, data processing and evaluation techniques. Such issues are of relevance to the management of river basins, rivers and reservoirs and the protection of ecosystems, as well as water sources.

Table 1 indicates that a large number of international river basins exist where there is a need for cooperation in the monitoring of natural processes, based on bilateral and/or international guidelines and regulations. In order to develop successful strategies it has to be clear what type of information has to be supplied from the monitoring system. Focusing on technical aspects, high-tech monitoring stations and equipment can be installed, but may not supply the answers needed and are not taken care of, since they might not fit into the existing monitoring organization. It is therefore essential, before any monitoring takes place, that those responsible for sediment monitoring in joint bodies, define and understand the information objectives, the complex physics of turbulent water flow and sediment transport, and that they appreciate the several types of monitoring that can therefore exist.

Table 1 Overview of international river basins with ≥2 riparian countries.

No. of international river basins	No. of riparian countries	Name of international river
1	17	Danube
2	11	Congo, Niger
1	10	Nile
2	9	Rhine, Zambezi
2	8	Amazon, Lake Chad
8	6	Aral Sea, Ganges-Brahmaputra-Meghna, Jordan, Kura-Araks, Mekong, Tarim, Tigris and Euphrates (Shatt al Arab), Volta
3	5	La Plata, Neman, Vistula (Wista)
17	4	Amur, Daugava, Elbe, Indus, Komoe, Lake Turkana, Limpopo, Lotagipi Swamp, Narva, Oder (Odra), Ogooue, Okavango, Orange, Po, Pu-Lun-T'o, Senegal, Struma
49	3	Asi (Orontes), Awash, Cavally, Cestos, Chiloango, Dnieper, Dniester, Drin, Ebro, Essequibo, Gambia, Garonne, Gash, Geba, Har Us Nur, Hari (Harirud), Helmand, Hondo, Ili (Kunes He), Incomati, Irrawaddy, Juba-Shibeli, Kemi, Lake Prespa, Lake Titicaca-Poopo System, Lempa, Maputo, Maritsa, Maroni, Moa, Neretva, Ntem, Ob, Oueme, Pasvik, Red (Song Hong), Rhone, Ruvuma, Salween, Schelde, Seine, St. John, Sulak, Torne (Tornealven), Tumen, Umbeluzi, Vardar, Volga, Zapaleri
176	2	Akpa, Alesek, Amacuro, An Nahr Al Kabirm, Artibonite, Astara Chay, Atrak, Atui, Aviles, Aysen, Baker, Bangau, Bann, Baraka, Barima, Barta, Beilun, Belize, Benito, Bia, Bidasoa, Buzi, Ca (Song-Koi), Cancoso (Lauca), Candelaria, Castletown, Catatumbo, Changuinola, Chico (Carmen Silva), Chilkat, Chira, Chiriqui, Choluteca, Chuy, Coatan Achute, Coco (Segovia), Colorado, Columbia, Comau, Corubal, Coruh, Courantyne (Corantijn), Cross, Cullen, Daoura, Dasht, Don, Douro (Duero), Dra, Elancik, Erne, Etosha/Cuvelai, Fane, Fenney, Firth, Flurry, Fly, Foyle, Fraser, Gallegos-Chico, Gauja, Goascoran, Golok, Great Scarcies, Grijalva, Guadiana, Guir, Han, Hsi (Bei Jiang), Isonzo, Jacobs, Jurado, Kaladan, Karnafauli, Klaralven, Kogilnik, Kowl-E-Namaksar, Krka, Kunene, Lagoon Mirim, Lake Fagnano, Lake Natron, Lake Ubsa-Nur, Lava (Pregel), Lielupe, Lima, Little Scarcies, Loffa, Ma, Mana- Morro, Massacre, Mataje, Mbe, Medjerda, Mino, Mira, Mississippi, Mius, Mono, Motaqua, Murgab, Naatamo, Nahr El Kebir, Negro, Nelson-Saskatchewan, Nestos, Nyanga, Olanga, Oral (Ural), Orinoco, Oued Bon Naima, Oulu, Oyupock (Oiapoque), Pakchan, Palena, Pandaruan, Parnu, Pascua, Patia, Paz, Pedernales, Prohladnaja, Puelo, Rezvaya, Rio Grande (North America), Rio Grande (South America), Roia, Rudkhaneh-ye (BahuKalat), Sabi, Saigon (Song Nha Be), Salaca, Samur, San Juan, San Martin, Sarata, Sarstun, Sassandra, Sembakung, Seno Union (Serrano), Sepik, Sixaola, Song Vam Co Dong, St. Croix, St. John, St. Lawrence, St. Paul, Stikine, Suchiate, Sujfun, Tafna, Tagus (Tejo), Taku, Tami, Tana, Tano, Terek, Tijuana, Tjeroeka/Wanggoe, Tuloma, Tumbes-Poyango, Umba, Utamboni, Valdivia, Velaka, Venta, Vijose, Vuoksa, Wadi Al Izziyah, Whiting, Yalu, Yaqui, Yelcho, Yenisey (Jenisej), Yser, Yukon, Zarumilla

Moreover, since the process of sediment transport (from soil erosion to the transport in and through water bodies) is often difficult to access, obtaining the essential information might be technically difficult and costly. Consequently, limitations in sediment assessment have to be accepted and also need to be recognized in the interpretation and use of monitoring results. This will also influence the possible strategies in soil conservation, river and reservoir management, and sediment monitoring in water bodies.

DISCHARGE MEASUREMENTS AND MASS FLUX COMPUTATION

Discharge measurements are a basic requirement for mass flux computation. Velocity varies approximately as a parabola from zero at the channel bottom to a maximum near the surface. It has been shown empirically that for most channels the velocity at six-tenths of the total depth below the surface is a close approximation to the mean velocity in that vertical. However, the average of the velocities at two-tenths and eight-tenths of the depth below the surface in the same vertical provides a more accurate value of mean velocity for that vertical.

Velocity also varies across a channel, and measurements must therefore be made at several points across the channel. The depth of the river varies across its width, so the usual practice is to divide the cross-section of the stream into a number of vertical sections as shown in Fig. 1, and measure velocity at each of these. No section should include more than 10–20% of the total discharge. Thus, between 5 and 10 vertical sections are typical, depending on the width of the stream. The measuring procedure should consider the following aspects:

(1) All measurements of distance should be made to the nearest centimetre.
(2) Measure the horizontal distance b_1, from reference point 0 on shore to the point where the water meets the shore, point 1 in Fig. 1.
(3) Measure the horizontal distance b_2 from reference point 0 to vertical line 2.
(4) Measure the channel depth d_2 at vertical line 2.
(5) With the current meter make the measurements necessary to determine the mean velocity v_2 at vertical line 2.

Repeat Steps 3, 4 and 5 at all the vertical lines across the width of the stream.

The computation for discharge is based on the assumption that the average velocity measured in a vertical is valid for a rectangle that extends half the distance to the verticals on each side of it, as well as throughout the depth at the vertical. Thus, in Fig. 1, the mean velocity v_2 would apply to a rectangle bounded by the dashed line *p*, *r*, *t* and *s*.

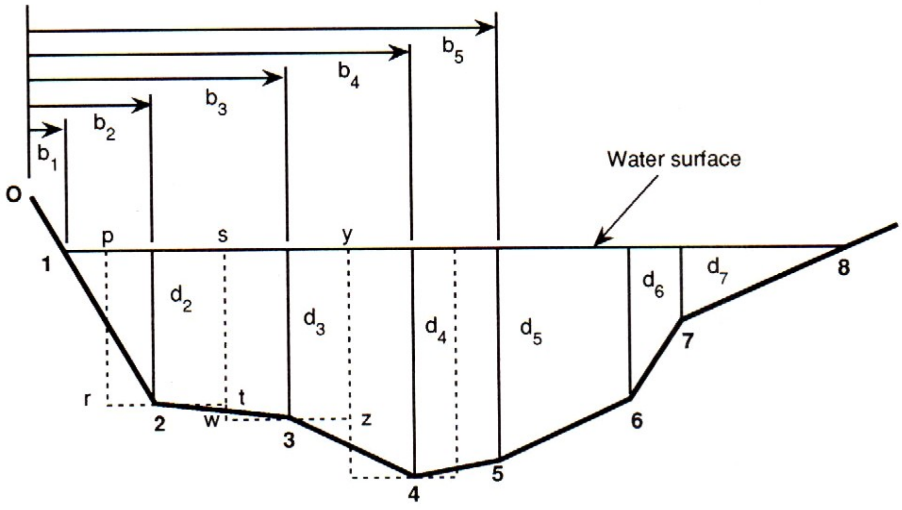

Fig. 1 Cross-section of a stream divided into vertical sections for measurement of discharge.

In the example in Fig. 1, $n = 8$. The discharges in the small triangles at each end of the cross-section, Q_1 and Q_n will be zero, since the depths at points 1 and 8 are zero. If the water is shallow, the operator may wade into the stream holding the current meter in place while measurements are being made. Wherever the water is too deep for wading (more than 1 m) the current meter must be lowered from a bridge, an overhead cableway or a boat. The section where flow measurement is made does not have to be at exactly the same place as either the monitoring station or the water level indicator, provided that there is no significant inflow or outflow between these points along the stream.

When samples have been taken and discharge has been measured in each of the vertical sections across a stream, the instantaneous mass flux is given by:

$$\sum_{i=1}^{n} C_i \times v_i \times A_i \qquad (1)$$

where n is the number of vertical sections; C_i is the concentration of the variable in section i (mg l^{-1}); v_i is the mean velocity in section i (m s^{-1}); and A_i is the cross-sectional area of section i (m^2). The average concentration at the cross-section can be obtained from: Q_m/Q where Q is the instantaneous discharge (m^3 s^{-1}) and Q_m is the instantaneous mass flux of the variable (g s^{-1}).

The mass flux over a period (t_0, ..., t_m) may be determined quite accurately, but this requires many measurements of water quality (e.g. suspended sediment concentration) and the use of a complex formula. Normally, water quality determinations are carried out at relatively long time intervals (weekly or monthly). By contrast, discharges are often determined daily, based on daily observation of the water level and the stage-discharge relationship. The simplest way to estimate daily concentrations of a variable is to assume that each measured value of concentration is valid for half of the preceding and following intervals between the collection of samples. However, this assumption is valid only when variations in the concentration of a variable are small; suspended sediment changes rapidly during a flood event. It is usually necessary to use more complicated interpolation procedures.

Regression techniques are appropriate if a reliable relationship can be established between the concentrations of the variable of interest and some other physical variable that is measured at frequent intervals. The most suitable variable will often be discharge (determined easily from water level). Thus the consistency of the relationship between the concentration of a variable and the discharge should always be checked. If the relationship is reasonably consistent, discharge can serve as the basis for estimating the mass flux of a variable. If it is inconsistent, however, some other relationship should be sought.

In small streams and during flood peaks, the discharge may vary considerably over a 24-h period. A variation in the concentration of a variable in excess of at least an order of magnitude is typical (hysteresis effects), and both sampling and discharge measurements need to be frequent. If the daily maximum flow is two to three times the average flow, a 4-h interval between samples is recommended. If the maximum is greater than three times the average, discharge should be measured and samples taken every hour. This information can be obtained during a short-term pilot study.

Particle size composition and concentration vary not only in the vertical section, but may also vary considerably across a river section. Therefore, measurements of suspended sediment concentration must take these variations into account. 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 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) each having equal discharge. The number of increments n 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 mean discharge-weighted suspended sediment concentration (*SSc*) is obtained by taking the average of the concentration values C obtained for each interval i.

$$SSc = \frac{\sum_{i=1}^{n} C_i}{n} \tag{2}$$

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 (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 monitoring agencies:

$$SSl = \sum_{i=1}^{n} (C_i Q_i) \times 0.0864 \tag{3}$$

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 and 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.

SEDIMENT COMPOSITION AND SAMPLING FOR SUSPENDED SEDIMENT

While the underlying theory is well known—sediment transport is a direct function of water movement—the measurement of sediment transport commonly involves many simplifying assumptions. 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.

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% of the suspended load will be composed only of silt and clay-sized particles (<62 μm).

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 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 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 sediment (sand and larger particles) from fine-grained sediment (silt and clay particles). Coarse-grained sediment is non-cohesive, whereas fine-grained sediment is 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 being 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.

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

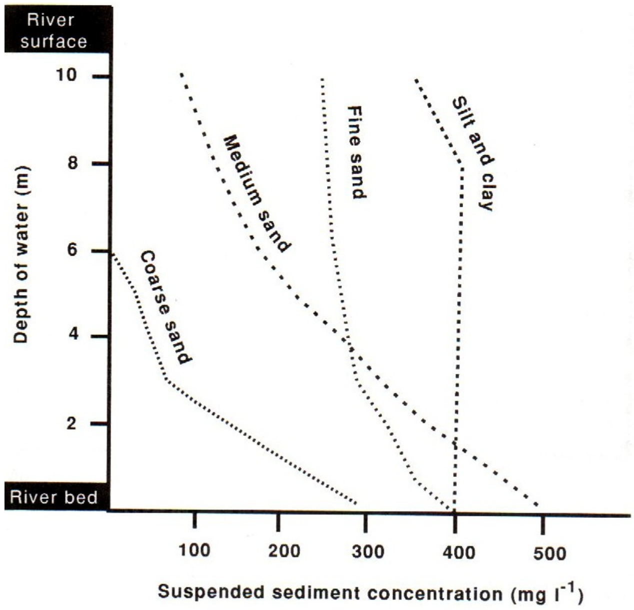

Fig. 2 Variations in the concentration of suspended sediment with water depth, for sand, silt and clay sized particles, as measured at one field site.

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 presented in Fig. 2 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 re-suspended and re-deposited under highly turbulent conditions.

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% of the suspended load in many rivers, is eroded and carried to the river by surface runoff during storm events. This fraction does not easily settle in the water column, and slight turbulent forces can keep it in suspension for long periods of time. As a consequence, the silt and clay fraction tends to be fairly evenly distributed throughout the depth of a river as illustrated by the vertical profile for silt and clay in Fig. 2. 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 re-suspended by lake currents (generated by wind stress) until it is eventually deposited in an area where water movements are insufficient to re-suspend or remobilize 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.

The methods and equipment used for sampling suspended sediment are different from those used for deposited sediment. Also, sampling methods used for measuring the quantity of sediment in transport are different from those used for collecting sediment samples for measurements 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 commonly focuses on the silt + clay fraction, which is not depth-dependent.

For bottom sediment it may be necessary to collect deposited sediments with minimum disturbance, in order to avoid losing the fine material on the sediment surface, or because the vertical distribution of the sediment constituents is important (such as during reconstruction of the historical record of sediment deposition, or the estimation of deposition rates). In deep water, this necessitates the use of grabs or corers, but in shallow water a scoop or spatula may be used.

There are four main types of sampler for suspended sediment:

(a) integrated samplers,
(b) instantaneous grab samplers,
(c) pump samplers, and
(d) sedimentation traps.

As described in Fig. 2 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 the 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 (bottle and pump sampling techniques) 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:

(a) Each has a water inlet nozzle and an air outlet. As the water and suspended sediment enter the sampler, air is displaced through the air outlet.
(b) Each permits isokinetic sampling. That is, the 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.
(c) Each has a metal body (for weight) that encloses a glass or plastic bottle for collecting the sample. The bottle is changed after each sample is taken.
(d) 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% 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.

NEW SUSPENDED SEDIMENT MEASUREMENT TECHNIQUES

The measurement of suspended-sediment concentrations is an important topic that merits continuing research. Accurate measurements of suspended sediment concentration are difficult to obtain, since suspended sediment loads are highly variable in both time and space. The use of ultrasonic devices for measuring suspended sediment provides improved temporal and spatial resolution, the ability to measure an entire profile of sediment concentration values, and remote, autonomous operation.

Single frequency acoustic backscatter measurements of suspended sediment in the ocean were carried out at least as early as in the early 1980s. Single frequency measurements require the assumption that the sediment particle size distribution remains homogeneous throughout the water column and it is usually assumed that this distribution is equal to that of the bottom sediments at the site. Multi-frequency measurements make the measurement of both particle concentration and size distribution possible. Although much work has been done on the topic, there is still no commercially available hardware and software package for the measurement of suspended sediments in flowing water.

Table 2 describes methods for measuring suspended sediment concentration and, in some cases, particle-size distribution. The operating principles, advantages, and disadvantages of the techniques are also listed. Recording techniques refer to methodologies that log data in real time. Of the well known techniques, only pump sampling and bottle sampling are not instrumented techniques.

Acoustic methods

Short bursts (~10 ms) of high frequency sound (1–5 MHz) emitted from a transducer are directed toward the measurement volume. Sediment in suspension will direct a portion of this sound back to the transducer (Thorne *et al*., 1991). When the sediment is of uniform size, the strength of the back-scattered signal allows the calculation of sediment concentration. The water column is sampled in discrete increments based on the return time of the echo. The backscattered strength is dependent on particle size as well as concentration. This can be exploited by using multiple frequencies for the investigation of both particle size (Crawford & Hay 1993) and concentration. Various authors have presented techniques for converting backscatter data into sediment concentration and size distribution. At the high frequencies generally employed, backscatter devices have a range of 1–2 m due to the attenuation of the signal by water and sediment and the desire for high resolution measurements (Downing *et al*., 1995). Measurements in water depths >2 m may be made by submerging the transducer(s) to the desired depth. The validity of the acoustic approach has been established by several researchers (Thorne *et al*., 1991, 1993, 1994, 1995; Thorne & Campbell, 1992; Crawford & Hay, 1993; Schat, 1997; and others). Improvement of the acoustic method has also been encouraged (Van Rijn & Schaafsma, 1986; Van Rijn, 1993).

Focused beam reflectance

In focused beam reflectance measurement, a laser beam focused to a very small spot (<2 μm^2) in the sample volume is rotated very quickly (many times per second). As it rotates, the beam encounters particles that reflect a portion of the beam. The time of this reflection event is used to determine the chord length of the particle(s) in the path of the laser. This information is used to calculate the volume of a sphere representing the particle (Phillips & Walling 1995b; Law *et al*., 1997).

Table 2 Suspended sediment measurement techniques.

Technology	Operating principle	Advantages	Disadvantages
Acoustic	Sound back-scattered from sediment is used to determine size distribution and concentration	Good spatial and temporal resolution, measures over wide vertical range, non-intrusive	Back-scattered acoustic signal is difficult to translate, signal attenuation at high particle concentration
Bottle sampling	Water-sediment sample is taken isokinetically by submerging container in streamflow, and is laser analysed	Accepted, time tested technique, allows determination of concentration and size distribution, most other techniques calibrate against bottle samplers	Poor temporal resolution, flow intrusive, requires laboratory analysis to extract data, requires on site personnel
Pump sampling	Water-sediment sample is pumped from stream and later analysed	Accepted, time tested technique, allows determination of concentration and size distribution	Poor temporal resolution, intrusive, requires laboratory analysis, does not usually sample isokinetically
Focused beam reflectance	Time of reflection of laser incident on sediment particles is measured	No particle size dependency, wide particle size and concentration measuring range	Expensive, flow intrusive, point measurement
Laser diffraction	Refraction angle of laser incident on sediment particles is measured	No particle size dependency	Unreliable, expensive, flow intrusive, point measurement only, limited particle-size range
Nuclear	Back-scatter of transmission of gamma or X-ray through water-sediment samples is measured	Low power consumption, wide particle size and concentration measuring range	Low sensitivity, radioactive source decay, regulations, flow intrusive, point measurement only, instrument fouling
Optical	Back-scatter or transmission of visible or infrared light through water-sediment sample is measured	Simple, good temporal resolution, allows remote deployment and data logging, relatively inexpensive	Exhibits strong particle-size dependency, flow intrusive, point measurement only, instrument fouling
Remote spectral reflectance	Light reflected and scattered from body of water remotely measured	Able to measure over broad areas	Poor resolution, poor applicability in fluvial environment, particle size dependency

Laser diffraction

In laser diffraction, a laser beam is directed into the sample volume where particles in suspension will scatter, absorb, and reflect the beam. Scattered laser light is received by a multi-element photo-detector consisting of a series of ring-shaped detectors of progressively larger diameter, that allow measurement of the scattering angle of the beam. Particle size can be calculated from knowledge of this angle, using the Fraunhofer approximation or the exact Lorenz-Mie solution. By basing concentration measurements on these measured particle sizes, particle-size dependency is eliminated (Swithenbank *et al.*, 1976; Knight *et al.*, 1991; Riley & Agrawal, 1991; Agrawal & Pottsmith, 1994). However, in the absence of additional information, particle density must be assumed.

Nuclear measurement

In general, nuclear sediment measurement utilizes the attenuation or backscatter of radiation. There are three basic types of nuclear sediment gauge:

(a) those that measure backscattered radiation from an artificial source;
(b) those that measure transmission of radiation from an artificial source; and
(c) those that measure radiation emitted naturally by sediments (McHenry *et al.* 1967; Welch & Allen, 1973; Tazioli, 1981).

The first two have the broadest applicability and will be described below. In backscatter gauges, radiation is directed into the measurement volume with the radioactive source isolated from the detector by lead. A sensor in the same plane as the emitter measures radiation backscattered from the sediment. In transmission gauges, the detector is placed opposite the emitter, and the attenuation of the radiation caused by the sediment is measured and compared to the attenuation of the rays caused by passage through distilled water. The ratio between these measurements allows the sediment concentration to be calculated. Ratio-type transmission instruments eliminate errors associated with radioactive decay of the source, drift in electronic components, and changes in water density due to temperature (McHenry *et al*., 1967, 1970; Rakoczi 1973; Berke & Rakoczi, 1981).

Optical backscatter (OBS)

In OBS sensing, infrared or visible light is directed into the sample volume. A portion of the light will be backscattered if particles are in suspension. A series of photodiodes positioned around the emitter detect the backscattered signal. The strength of this backscattered signal is used to determine the sediment concentration. Readings from known sediment concentrations are used to calibrate the instrument.

Optical transmission

In optical transmission sensing, light is directed into the sample volume. Sediment present in the sample volume will absorb and/or scatter a portion of the light. A sensor located opposite the light source allows the degree of attenuation of the light beam to be determined. Using information from known sediment concentrations, the sediment concentration can be calculated from instrument readings.

Spectral reflectance

Spectral reflectance measurement of suspended sediment concentration is based on the relationship between the amount of radiation, generally in the visible or infrared range, reflected from a body of water and the properties of that water. The radiation is measured by a handheld, airborne, or satellite-based spectrometer. The correlation between concentration of suspended sediment and the reflected radiation has been observed and validated by several researchers (Blanchard & Leamer, 1973; Ritchie & Schiebe, 1986;

Novo *et al*., 1989a,b; Bhargava & Mariam, 1991; Choubey, 1994). This relationship is dependent on many parameters such as the optical properties of the sediment type, sensor observation angle, solar zenith angle, and the spatial resolution of the measurements (Novo *et al*., 1989a,b; Choubey, 1994; Gao & O'Leary, 1997).

Vibrating tube

In this measurement scheme, water is routed through a vibrating tube in a stationary housing located either on the stream bank or in the stream. The tube vibrates continuously and is electronically monitored. Use of the vibrating tube is based on two relationships: (a) between the sediment concentration and the density of the sediment-water mixture; and (b) between the density of the sediment water mixture and the vibrational period of the tube. There are several sources of error. Shifts in dissolved solids concentration, water temperature, water pressure, flow rate, and debris on the tube's walls all contribute to error. The first four errors can be eliminated by the use of sensors to quantify the changes in the parameters. However, changes in vibration caused by debris or algae have not been successfully represented in a fluvial environment (Skinner, 1989).

Differential pressure

Lewis & Rasmussen (1996) described a method for using two pressure transducers to determine differences in the specific weight of sediment bearing water. They proposed a method for field application, but field experiments had not been performed.

Impact sampler

Van Rijn & Schaafsma (1986) described an impact sampler developed at the Institute of Oceanographic Sciences in Taunton, UK. The sampler works on the principle of momentum transfer. The impact rate of sediment particles hitting a sensor is measured. The detected impact rate is dependent on the mass, velocity, and angle of particle impact.

Video microscopy

In video microscopy, a video camera films the water-sediment mixture *in situ*. This film can be used to visually confirm the nature of the sediment. The film can also be examined by a computer-controlled automated analysis system for determining the size, shape, and number of sediment particles. Key variables in this measuring scheme are the type of lighting used, the sensitivity of the video system, and the method of image processing used to analyse the samples (Baier & Bechteler, 1996). This process does not appear feasible for the study of sediment flux, although it has the potential to provide excellent information on the specific nature of sediment particles.

REFERENCES

Agrawal, Y. C. & Pottsmith, H. C. (1994) Laser diffraction particle sizing in STRESS. *Continental Shelf Res*. **14**(10/11), 1101–1121.

Agrawal, Y. C. & Pottsmith, H. C. (1996) Laser instruments for particle sizing and settling velocity measurements in the coastal zone. In: *Proc. Oceans Conf. 1996*, vol. I, 1135–1142. IEEE, Piscataway, New Jersey, USA.

Baier, V. & Bechteler, W. (1996) An underwater videomicroscope to determine the size and shape of suspended particles by means of digital image processing. In: *Proc. Sixth Int. Offshore and Polar Engng Conf*., 138–144. Los Angeles, California, USA.

Berke, B. & Rakoczi, L. (1981) Latest achievements in the development of nuclear suspended sediment gauges. In: *Erosion and Sediment Transport Measurement*, 83–90. IAHS Publ. 133. IAHS Press, Wallingford, UK.

Bhargava, D. S. & Mariam, D. W. (1991) Light penetration depth, turbidity and reflectance related relationships and models. *Int. J. Photogram. Remote Sens*. **46**, 217–230.

Blanchard, B. J. & Leamer, R. W. (1973) Spectral reflectance of water containing suspended sediment. *Remote Sensing and Water Resour. Manage.* **17**, 339–347.

Choubey, V. K. (1994) The effect of properties of sediment type on the relationship between suspended sediment concentration and radiance. *Hydrol. Sci. J.* **39**(5), 459–471.

Crawford, A. M. & Hay, A. E. (1993) Determining suspended sand size and concentration from multifrequency acoustic backscatter. *J. Acoustic Soc. Am*. **94**(6), 3312–3324.

Downing, A., Thorne, P. D. & Vincent, C. E. (1995) Backscattering from a suspension in the near field of a piston transducer. *J. Acoustic Soc. Am.* **97**(3), 1614–1619.

Gao, J. & O'Leary, S. (1997) The role of spatial resolution in quantifying suspended sediment concentration from airborne remotely sensed data. *Photogramm. Engng Remote Sens.* **63**(3), 267–271.

Law, D. J., Bale, A. J. & Jones, S. E. (1997) Adaptation of focused beam reflectance measurement to *in-situ* particle sizing in estuaries and coastal waters. *Marine Geol*. **140**(1/2), 47–59.

Lewis, A. J. & Rasmussen, T. C. (1996) A new, passive technique for the in situ measurement of total suspended solids concentrations in surface water. Tech. Completion Rep. for Proj. no. 14-08-00l-G-2013 (07), US Dept of the Interior, US Geol. Survey, Reston, Virginia, USA.

McHenry, J. R. *et al.* (1967) Performance of nuclear-sediment concentration gauges. In: *Proc. Isotopes in Hydrology Symp*., 207–225. International Atomic Energy Agency, Vienna, Austria.

McHenry, J. R., Coleman, N. L, Willis, A. C, Sansom, O. W. & Carrol, B. R. (1970) Effect of concentration gradients on the performance of a nuclear sediment concentration gage. *Water Resour. Res*. **6**(2), 538–548.

Novo, E. M. M, Hansom, J. D. & Curran, P. J. (1989a) The effect of viewing geometry ans wavelength on the relationship between reflectance data and suspended sediment concentration. *Int. J. Remote Sensing* **10**(8), 1357–1372.

Novo, E. M. M, Hansom, J. D. & Curran, P. J. (1989b) The effect of sediment type on the relationship between reflectance and suspended sediment concentration. *Int. J. Remote Sensing* **10**(7), 1283–1289.

Phillips, J. M. & Walling, D. E. (1995a) An assessment of the effect of sample collection, storage and resuspension on the representativeness of measurements of the effective particle size distribution of fluvial suspended sediment. *Water Research* **29**(11), 298–2508.

Phillips, J. M. & Walling, D. E. (1995b) Measurement *in situ* of the effective particle-size characteristics of fluvial suspended sediment by means of a field-portable laser backscatter probe: Some preliminary results. *Marine Freshwater Res*. **46**, 349–357.

Rakoczi, L. (1973) Critical review of current nuclear suspended sediment gauges. In: *Tracer Techniques in Sediment Transport*. Tech. Rep. Series no. 145. International Atomic Energy Agency, Vienna, Austria.

Riley, J. B. & Agrawal, Y. C. (1991) Sampling and inversion of data in diffraction particle sizing. *Appl. Optics* **30**(33), 4800–4817.

Ritchie, J. C. & Schiebe, F. R. (1986) Monitoring suspended sediments with remote sensing techniques. In: *Hydrologic Applications of Space Technology* (ed. by A. I. Johnson), 233–243. IAHS Publ. 160. IAHS Press, Wallingford, UK.

Schat, J. (1997) Multifrequency acoustic measurement of concentration and grain size of suspended sand in water. *J. Acoustic Soc. Am.* **101**(1), 209–217.

Skinner, J. V. (1989) Model-B sediment-concentration gage: factors influencing its readings and a formula for correcting its errors. In: *A Study of Methods Used in Measurement and Analysis of Sediment Loads in Streams*. US Army Engineer District, St Paul, Minnesota, USA.

Swithenbank, J., Beer, J. M., Taylor, D. S., Abbot, D. & McCreath, G. C. (1976) A laser diagnostic technique for the measurement of droplet and particle size distribution. In: *Proc. AIAA 14th Aerospace Sci. Meeting*, 421–447. American Institute of Aeronautics and Astronautics, Reston, Virginia, USA.

Tazioli, G. S.(1981) Nuclear techniques for measuring sediment transport in natural streams: examples from instrumented basins. In: *Erosion and Sediment Transport Measurement*, 63–81. IAHS Publ. 133. IAHS Press, Wallingford, UK.

Thorne, P. D. & Campbell, S. C. (1992) Backscattering by a suspension of spheres. *J. Acoustic Soc. Am*. **92**(2), 978–986.

Thorne, P. D., Hardcastle, P. J., Flatt, D. & Humphery, J. D. (1994) On the use of acoustics for measuring shallow water suspended sediment processes. *J. Oceanic Engng* **19**(1), 48–57.

Thorne, P. D., Hardcastle, P. J. & Soulsby, R. L. (1993) Analysis of acoustic measurements of suspended sediments. *J. Geophys. Res*. **98**(C1), 899–910.

Thorne, P. D., Vincent, C. E., Hardcastle, P. J., Rehman, S. & Pearson, N. (1991) Measuring suspended sediment concentrations using acoustic backscatter devices. *Marine Geol*. **98**, 7–16.

Thorne, P. D., Waters, K. R. & Brudner, T. J. (1995) Acoustic measurements of scattering by objects of irregular shape. *J. Acoustic Soc. Am*. **97**(1), 242–251.

Van Rijn, L. C. (1993) *Principles of Sediment Transport in Rivers, Estuaries and Coastal Seas*. Aqua Publications, Amsterdam, The Netherlands.

Van Rijn, L. C. & Schaafsma, A. S. (1986) Evaluation of measuring instruments for suspended sediment. In: *Proc. Int. Conf. on Measuring Techniques of Hydraulic Phenomena in Offshore, Coastal and Inland Waters*, 401–423. British Hydraulic Research Assoc., Cranfield, UK.

Welch, N. L. & Allen, P. B. (1973) Field calibration and evaluation of a nuclear sediment gage. *Water Resour. Res*. **9**(1), 154–158.