Erosion and Sediment Transport Monitoring Programmes in River Basins (Proceedings of the Oslo Symposium, August 1992). IAHS Publ. no. 210, 1992.

Some sampling considerations in the design of effective strategies for monitoring sediment-associated transport

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ABSTRACT The sediment-associated component frequently accounts for a major proportion of the load of many substances transported by rivers, such as nutrients, heavy metals and radionuclides. However, many monitoring programmes which aim to assess river loads are based on traditional approaches to water quality monitoring and fail to take account of existing knowledge regarding the behaviour of suspended sediment in rivers and the problems of measuring suspended sediment loads. In consequence, the resultant load estimates may be unreliable. Data obtained from the River Exe in Devon, UK are used to demonstrate some of the considerations which need to be taken into account in obtaining reliable assessments of the loads of sediment-associated substances and to emphasise the need for greater interaction between water quality and sediment monitoring programmes.

INTRODUCTION

Recent years have seen an increasing interest in the transport of material by rivers. Information on river loads has, for example, been used to investigate rates and patterns of physical and chemical denudation or erosion, to evaluate the flux of material from the land to the oceans and elucidate global geochemical cycles and budgets, to establish catchment nutrient budgets, and to document the flux of pollutants through terrestrial and aquatic ecosystems and from the land to the seas. In many cases, however, the river load data used for such studies have been unreliable because they have been calculated using inappropriate load calculation procedures or inadequate river sampling programmes (e.g. Dickinson, 1981; Dolan *et al.*, 1981; Ongley *et al.*, 1987; Walling & Webb, 1981, 1982, 1985). One of the greatest problems associated with the provision of reliable river load data is the assumption that the infrequent samples typically associated with routine water quality monitoring programmes can be used to generate reliable estimates of river loads. In most situations, the accurate assessment of river loads will require a sampling programme specifically designed for this purpose. Thus, for example, whilst flood periods may not be explicitly sampled by a routine water quality monitoring programme which aims to document the general pattern of variation of water quality through time, they are of fundamental significance to the transport of material by a river, in view of the large volumes of water and fluxes involved, and must be adequately sampled if accurate load estimates are required.

In considering further the problems of obtaining accurate estimates of river loads, it is useful to make a distinction between the dissolved and particulate components of river loads. In many situations, the concentrations of most dissolved substances in river waters will vary over a limited range and the use of infrequent samples may introduce only relatively limited errors into load assessments, providing accurate information on water discharge is available. In the case of the particulate- or sediment-associated components, however, concentrations (mg l^{-1}) may vary over several orders of magnitude, particularly during flood events, and unless the sampling programme has been designed to document these variations, load estimates may be characterized by substantial errors. The sediment-associated component is likely to be of major importance in the transport of many substances, particularly nutrients and contaminants such as heavy metals, pesticides and radionuclides (cf. Allan, 1979, 1986). For example, in the case of heavy metals, detailed studies undertaken on the lower reaches of the Bow and Oldman Rivers in Alberta, Canada, by Blachford & Ongley (1984) indicated that for all metals, with the exception of mercury, the suspended sediment-associated load comprised most, if not virtually all of the total load of the river. Similar findings have been reported for the Rhine by de Groot & Allersma (1975) and for the Yukon and Amazon Rivers by Gibbs (1977). Many of the problems of obtaining reliable estimates of suspended sediment loads have been addressed by sediment monitoring programmes and such programmes commonly involve frequent sampling, with particular emphasis on flood events. However, because the assessment of pollutant loads and the loads of specific substances is frequently undertaken within the framework of routine water quality monitoring programmes which take only limited account of the dynamic nature of material flux in river systems, the experience gained in monitoring suspended sediment transport is often overlooked in assessing sediment-associated loads (cf. Walling & Webb, 1985). Thus, whereas it may readily be accepted that a programme of regular weekly sampling is likely to be inadequate for providing reliable estimates of suspended sediment transport, the implications for the assessment of the loads of sediment-associated substances may be less well recognised. This paper attempts to emphasise the significance of existing knowledge of the behaviour of suspended sediment in rivers and of the problems of monitoring suspended sediment loads to the wider problem of obtaining accurate estimates of the flux of sediment-associated substances in rivers. The data used for illustrative purposes were obtained from the 1500 km² basin of the River Exe in Devon, UK, which has been monitored by the senior authors for more than 20 years.

THE BEHAVIOUR OF SUSPENDED SEDIMENT IN RIVERS

In the context of load estimation, the most important feature of suspended sediment transport by rivers is its episodic nature. Significant suspended sediment transport is commonly restricted to flood events when sediment concentrations increase, and sampling should focus on

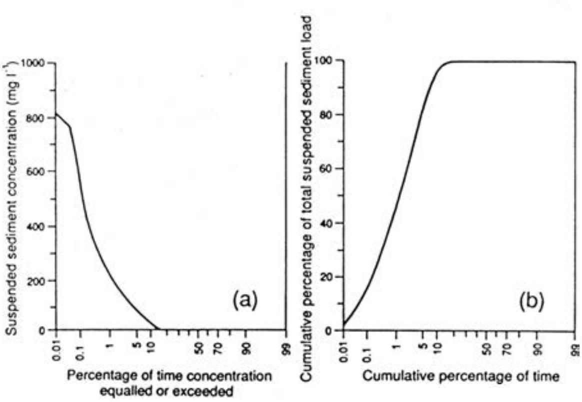

FIG. 1 Duration characteristics of suspended sediment transport by the River Exe at Thorverton during the period 1978-1980.

these periods. In rivers with a well-defined flood season, such as the spring melt, it may be relatively easy to concentrate sampling effort on flood periods. However, in rivers characterized by a more random timing of flood events, coverage of important floods may be less easy to achieve. Figure 1, based on detailed records of suspended sediment transport by the River Exe at the Thorverton gauging station (601 km²) for the 2 year period 1978-1980, serves to emphasise the limited period of time during which significant suspended sediment transport occurs. Concentrations in excess of 100 mg l^{-1} occur during only 5% of the time (i.e. the equivalent of 18 days per year). Furthermore, approximately 50% of the total suspended sediment load for the period was transported during 1% of the time (i.e. the equivalent of about 90 hours per year) and 90% of the load was transported within approximately 5% of the time. Sampling programmes aimed at documenting the loads of sediment-associated substances must be designed to cover these short-lived periods of significant suspended sediment transport.

THE RELIABILITY OF SUSPENDED SEDIMENT LOAD ESTIMATES BASED ON INFREQUENT SAMPLING

In the absence of a detailed record of the variation of suspended sediment concentration through time, such as might be provided by a continuous turbidity monitor or an intensive sampling programme, and where the suspended sediment load must be estimated on the basis of infrequent samples, load calculation procedures involving either *interpolation* or *extrapolation* techniques are commonly used (cf. Walling & Webb, 1981). Interpolation techniques essentially assume that the values of flow and concentration associated with individual samples are representative of the periods between samples. Two load calculation procedures based on interpolation techniques which are frequently used may be defined as follows:

$$\text{Total load} = K\sum_{i=1}^{n}\left(\frac{C_iQ_i}{n}\right) \qquad \text{Method 1} \qquad (1)$$

$$\text{Total load} = \frac{K\sum_{i=1}^{n}(C_iQ_i)}{\sum_{i=1}^{n}Q_i}\,Q_r \qquad \text{Method 2} \qquad (2)$$

Where: K is a conversion factor to take account of the period of record, C_i is the concentration associated with individual samples, Q_i is the instantaneous discharge at the time of sampling, Q_r is the mean discharge for the period of record and n is the number of samples.

Method 1 calculates the mean of the sampled instantaneous loads which is then applied to the whole period of record and this procedure has been used in the UK Harmonized Monitoring Programme (Dept. of the Environment, 1979). Method (2) advocated by Verhoff *et al.* (1980) calculates a flow-weighted mean concentration from the available samples and combines this with the mean discharge for the period of record. Method 1 can be used in situations where discharge information is only available for the times of sample collection, whereas Method 2 requires a continuous discharge record for the sampling site, and is generally to be preferred.

Extrapolation procedures utilise a different approach and make use of a sediment concentration / discharge (Q) relationship or rating curve established using the available samples, to synthesise the record of concentration from the continuous record of discharge. The discharge and synthesised concentration records are then combined in order to estimate the sediment load for the period of record. The sediment concentration / discharge relationship is commonly described by the equation

$$\text{Concentration} = aQ^b \qquad (3)$$

Equation (3) is generally fitted to the entire data set, but this is sometimes stratified according to season or stage tendency in order to generate several equations. It has also been suggested by several authors (e.g. Ferguson, 1986; Koch & Smillie, 1986) that use of a least squares regression procedure with log-transformed data to derive the concentration / discharge relationship will introduce an under-estimation bias, and both parametric and non-parametric bias correction factors have been proposed (cf. Koch & Smillie, 1986) to take account of this problem.

The interpolation and extrapolation procedures outlined above have frequently been used in association with a programme of infrequent sampling to derive estimates of suspended sediment loads. However, the reliability and more particularly the *accuracy* and *precision* of the resultant load estimates must be carefully assessed. The potential problems can be usefully demonstrated by considering a 2 year period of record of suspended sediment loads for the River Exe at Thorverton. A continuous turbidity recorder was operated at this site during the period 1978-1980 and this has been used to generate a continuous record of suspended sediment concentration. Combination of this continuous concentration record with the discharge record for the site has provided an accurate estimate of the *actual* suspended sediment load. This value can be compared with the estimates that might have been obtained

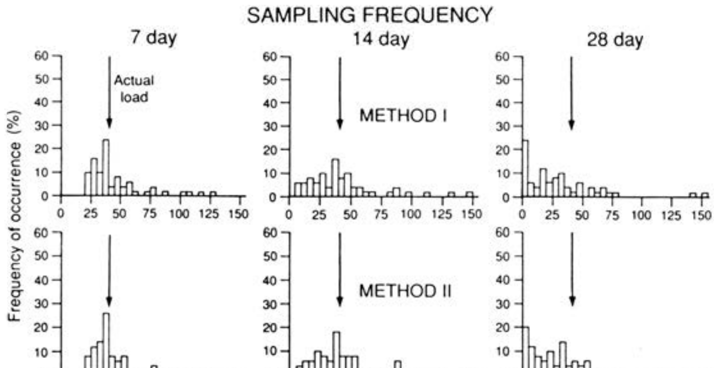

FIG. 2 A comparison of the estimates of the suspended sediment load of the River Exe at Thorverton for the 2 year period 1978-80 obtained using the specified interpolation procedures and sampling frequencies with the actual load for the period.

from a programme of infrequent sampling coupled with the load calculation procedures outlined above. Replicate sets of sample data representing specific sampling frequencies and strategies have been generated from the continuous record of suspended sediment concentration. For example, 50 potential sets of sediment concentration data representing regular 7-day, 14-day and 28-day interval sampling programmes have been abstracted from the continuous concentration record by assuming different starting dates and times for the sampling regime. It is important to include replicate data sets since the load estimate produced by one set of samples might differ substantially from that obtained from another set if one included samples from one or more major flood events and the other did not, and this potential variability in the resultant load estimates is an important aspect of their reliability.

Figure 2 compares the actual suspended sediment load of the River Exe at Thorverton for the period 1978-80 with the load estimates generated using the 50 replicate sets of sample data collected at 7-day, 14-day and 28-day intervals in conjunction with the two interpolation procedures outlined above (i.e. Methods 1 and 2). Two features of the results merit particular comment. First, the load estimates for the 50 replicate sample sets obtained using both interpolation procedures span a considerable range, indicating that the methods lack *precision* and that although the load estimate could be close to the actual load, significant under- or over-estimation is more likely. The load estimate obtained using this approach could be less than 10% or as much as 300% of the actual load. Secondly, as might be expected, the likelihood of underestimating the sediment load increases as the sampling frequency decreases. Thus with a 28-day sampling interval and only 26 samples for the 2 year period, it is possible that the samples may not include any flood events and their associated suspended sediment concentrations will be low.

Figure 3 presents the results of a similar exercise aimed at comparing the actual suspended sediment load of the River Exe for the period 1978-80 with load estimates derived using suspended sediment rating curves. In this example only a single rating curve for the period has been used and this has been fitted to concentration and discharge data obtained from both regular weekly sampling (i.e. 104 samples) and a programme of regular weekly sampling supplemented by the collection of 70 additional samples during flood events (i.e. 40 samples for discharges of 30-60 m^3s^{-1} and 30 samples for discharges >60 $m^3 s^{-1}$). Again 50 replicate data sets have been assembled for each sampling strategy. The timing of the flood-period samples was random and differed between the individual replicates. In addition to load estimates derived using the rating curve in the standard manner, loads corrected using the parametric (I) and non-parametric (II) bias correction factors of Ferguson (1986) and Koch & Smillie (1986) have also been presented. Figure 3 demonstrates that suspended sediment load estimates based on rating curves may be associated with substantial underestimation, particularly when the rating curves are derived using regular weekly sampling. Use of bias correction procedures appears to offer some improvement in the reliability of the load estimates, but they do not offer the panacea implied by Ferguson (1986). Again, therefore, it is clear that load estimates based on infrequent sampling and the application of extrapolation procedures may involve very substantial errors.

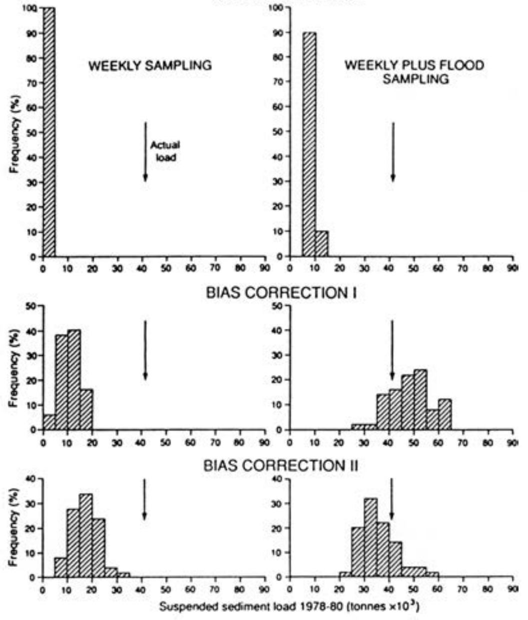

FIG. 3 A comparison of the estimates of the suspended sediment load of the River Exe at Thorverton for the 2 year period 1978-80 obtained using the specified sampling strategies and rating curve procedures with the actual load for the period.

The above examples clearly demonstrate the potential errors and uncertainties involved in estimating the suspended sediment loads of rivers and these findings are directly applicable to the estimation of the fluxes of sediment-associated substances since such fluxes essentially represent the product of suspended sediment load and the concentration (mg g^{-1}) of the substance in the sediment. The two interpolation procedures used in the above analysis are, in fact, those recommended by the Paris Commission for assessing river inputs of Red List and other substances to the North Sea.

TEMPORAL VARIATION IN SUSPENDED SEDIMENT QUALITY

In discussing procedures for estimating sediment-associated pollutant fluxes in rivers Chapman (1992) identifies two major approaches where only infrequent samples are available. These are the *constant flux* approach, where the flux is treated as constant during the period between samples, and the *constant concentration* approach, where attention focuses on obtaining an accurate estimate of the total particulate load and the concentration of pollutant in the sediment is assumed to be constant during a given period. The errors and uncertainties involved in the former approach are essentially those already highlighted for the use of interpolation procedures in estimating suspended sediment loads, although it is important to recognise that variations in the concentration of the sediment-associated substance in the sediment will introduce additional uncertainties. Such variations are clearly also a major constraint on the applicability of the latter approach since this assumes constant concentration. The degree of variability of the concentration of sediment-associated substances in suspended sediment will vary according to the origin of the substance, the nature of the sediment, and the processes governing the mobilisation and transport of the sediment.

Figures 4 & 5, which are again based on data collected from the River Exe at Thorverton during the period 1978-1980, illustrate two contrasting examples of the variability of the concentration of sediment-associated substances in suspended sediment. In the case of the radionuclide caesium-137, there is some evidence of a decline in radiocaesium concentrations with increasing discharge (Fig. 4a), but concentrations can essentially be viewed as varying in a random manner around a mean value over the entire range of flows. In the case of total phosphorus, however, there is a clear trend of decreasing concentrations with increasing flow (Fig. 4b). Figure 5 attempts to demonstrate seasonal variability in sediment quality by plotting the range of concentrations of caesium-137 and total phosphorus encountered in the suspended sediment for individual months. Again, caesium-137 concentrations appear to vary in an essentially random fashion around a mean concentration of ca. 20 mBq g^{-1}, but total phosphorus concentrations demonstrate a clear pattern of seasonal variation, with low concentrations in the winter and early spring and higher concentrations in the summer and autumn. The contrasting behaviour of radiocaesium and total phosphorus concentrations can be related to the different origins of these substances. In the case of caesium-137, the radionuclide is associated with surface materials within the basin which accumulated radiocaesium during the main period of atmospheric fallout from weapons testing in the late 1950s and the 1960s. Erosion of

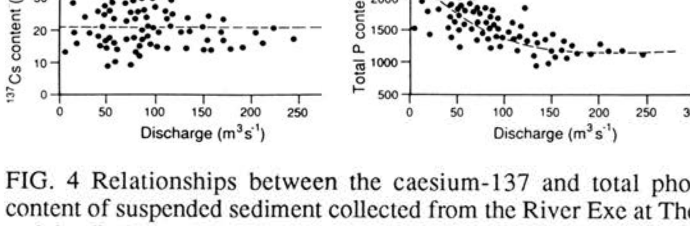

FIG. 4 Relationships between the caesium-137 and total phosphorus content of suspended sediment collected from the River Exe at Thorverton and the discharge at the time of sampling.

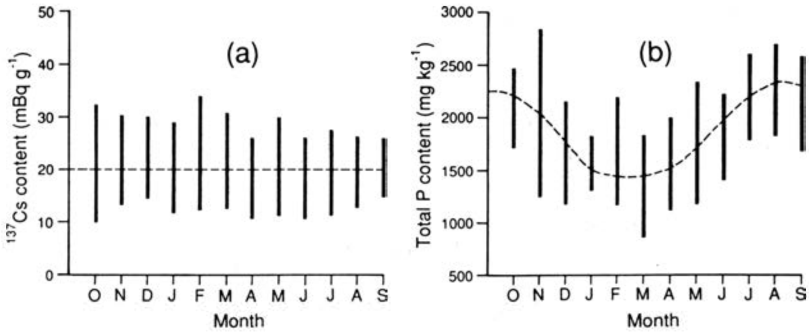

FIG. 5 Seasonal variation in the caesium-137 and total phosphorus content of suspended sediment collected from the River Exe at Thorverton. The bars represent the range of concentrations encountered in individual months.

surface materials from the drainage basin introduces sediment-associated radiocaesium into the river. Since the major sediment sources remain essentially constant through time, little systematic variation in the radiocaesium content of suspended sediment would be expected. However, random variations in the areas of the 601 km^2 drainage basin contributing sediment during individual flood events could be expected to cause random variations in the radiocaesium content of the sediment, by virtue of differential fallout receipt over the basin. Equally, minor variations in the relative importance of individual sediment sources, between and within events, will also cause variations in the caesium-137 content of suspended sediment. The total phosphorus content of suspended sediment will, in contrast, reflect a variety of sources, including eroded soil, land use activities, point source effluent discharges and authigenic processes. These could be expected to respond to variations in flow magnitude and to seasonal influences and the well-defined patterns of flow-related and seasonal variation of the total phosphorus content of suspended sediment shown in Figs. 4b & 5b are therefore not unexpected. For example, contributions from point source effluent discharges could be expected to be diluted during times of high discharge, leading to a reduction in the total phosphorus content of suspended sediment during high flows and during the winter months. Authigenic production of particulate phosphorus will, however, be greatest during the summer months leading to higher concentrations during the summer.

Variations in the grain-size composition and organic matter content of suspended sediment may also cause variations in the concentration of sediment-associated substances. Most such substances will be preferentially associated with the finer (clay) fraction of the sediment and with the organic fraction. Figure 6 depicts the variation of the grain-size composition and

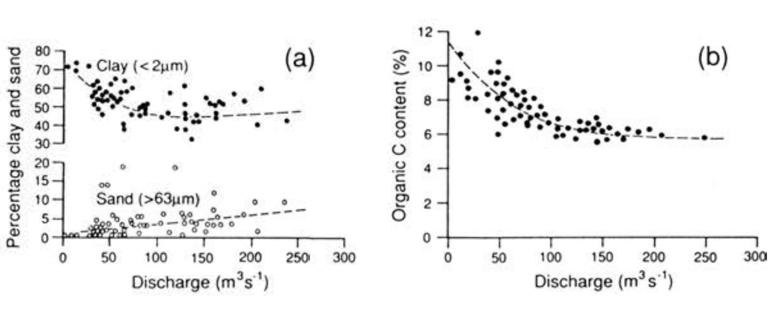

FIG. 6 Relationships between the grain size composition and organic content of suspended sediment collected from the River Exe at Thorverton and discharge at the time of sampling.

organic matter content of suspended sediment collected from the River Exe at Thorverton in terms of their relationship with discharge. In this river, the clay fraction decreases and the sand fraction increases with increasing flow and the organic matter content demonstrates a well defined inverse relationship with discharge.

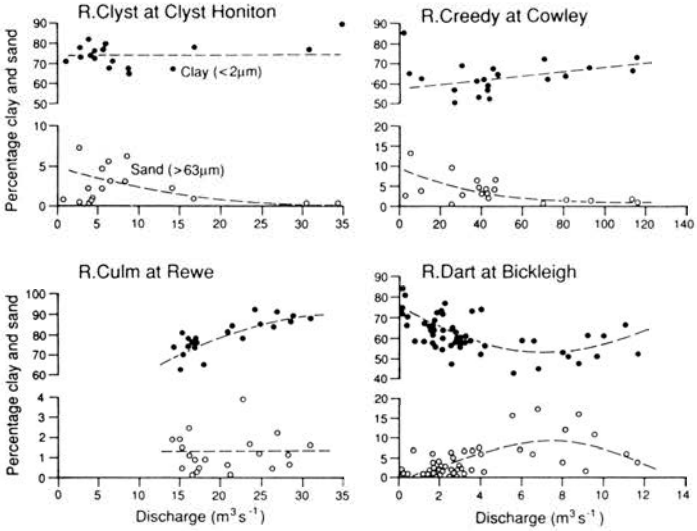

FIG. 7 Relationships between the grain-size composition of suspended sediment and discharge at the time of sampling for several sampling stations within the Exe Basin, Devon, UK.

Both trends could be expected to give rise to a reduction in the concentration (mg g^{-1}) of many sediment-associated substances as flows increase and it may be difficult to separate this influence from other discharge-related and seasonal controls when examining variations in sediment composition. In the case of the River Exe, the data presented in Figs 4 and 6 suggest that the radiocaesium is primarily associated with the inorganic fraction, since caesium-137 concentrations show little evidence of the clear inverse relationship with discharge evidenced by the organic matter content. Conversely, the total phosphorus content would appear to be closely related to the organic fraction of the sediment, since both demonstrate a similar inverse relationship with discharge.

It is commonly assumed that the grain size composition of suspended sediment will evidence a decrease in the clay fraction and an increase in the sand fraction as discharge increases (e.g. Fig. 6), because of the increased turbulence and transport capacity for coarser particles associated with higher flows (cf. Horowitz, 1991). Such behaviour could in turn generally be expected to result in a decrease in the concentration of sediment-associated substances, in view of the preferential association of such substances with the more chemically-active fine fraction. However, in attempting to assess the pattern of variation of the concentration of sediment-associated substances, it should not be assumed that all rivers will demonstrate this 'typical' grain-size behaviour (cf. Walling & Moorehead, 1989). Figure 7 provides examples from several of the tributaries of the River Exe in Devon, UK which demonstrate a variety of patterns of grain-size response which depart substantially from the 'typical' behaviour. Figure 7 depicts cases where the clay (<2μm) content of suspended sediment increases, remains essentially constant, and evidences an initial decrease followed by an increase, as discharge increases. Equally, the sand fraction evidences situations where it decreases, remains essentially constant and demonstrates an initial increase followed by a decrease, as discharge increases. Such contrasting behaviour could be expected to introduce further complexity into the pattern of variation of the concentration of sediment associated substances.

IMPLICATIONS FOR LOAD ASSESSMENT

In considering the problem of obtaining reliable estimates of the flux of particulate-associated pollutants in rivers and the likely reliability of the constant flux and constant concentration approaches proposed by Chapman (1992), it is important to take account of the problems associated with designing a monitoring programme capable of providing an accurate assessment of both the total particulate flux and the variability in the concentrations of particulate-associated substances. The limited data from the River Exe presented in this paper suggest that the former problem demands the greater attention. An assessment of the likely reliability of suspended sediment loads estimated on the basis of infrequent samples indicated that errors of the order of ± 75% or even greater could arise. Errors associated with variability of the concentration of sediment-associated substances (mg g^{-1}) are likely to be less, since the concentrations of some substances demonstrate only limited variability and where significant variability exists this will commonly be much less than the variability in suspended sediment concentrations (mg l^{-1}). These conclusions must clearly be qualified in terms of catchment scale, since the uncertainties associated with load estimates based on infrequent samples will increase for small basins, but can be expected to reduce somewhat for larger basins where the streamflow and sediment response will be more damped.

Use of continuous turbidity monitoring equipment could greatly assist in providing an accurate estimate of the suspended sediment load transported by a river. If the suspended sediment load can be accurately assessed, the reliability of any assessment of the loads of specific particulate-associated substances will reflect the degree to which variations in the concentrations of those substances in the suspended sediment exist and the adequacy of the representation of such variability. In the absence of frequent sampling for determination of sediment quality, use of relationships between sediment quality and discharge (cf. Fig. 4) or time of year (cf. Fig. 5) or analysis of the influence of grain size composition on sediment quality and of the factors influencing the variation of grain size composition may prove useful. If the loads of particulate-associated substances transported by rivers are to be adequately documented there is a need to refine the monitoring strategies traditionally used for water quality assessment, to direct greater attention to the characteristic features of suspended sediment transport by rivers and to incorporate experience gained in suspended sediment monitoring programmes.

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