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The reliability of suspended sediment load data

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ABSTRACT The growing significance of suspended sediment load data has directed attention to the reliability of measurement procedures and published data. The efficiency of sampling equipment and laboratory techniques has been studied by many workers, but much less attention has been given to the problems of assessing long term loads. In the absence of detailed records of suspended sediment concentration, a number of indirect methods of estimating such loads based on interpolation and extrapolation procedures have been employed. These may lead to serious under- or overestimation of the actual loads. A detailed assessment of both the accuracy and precision of load estimates produced for the River Creedy in Devon, UK, using these procedures is presented.

La validité des données relatives aux charges solides en suspension

RESUME L'importance croissante des données relatives aux sédiments en suspension a attiré l'attention sur la validité des techniques pour la mesure. L'efficacité de l'équipement pour la prise d'échantillons et des techniques de laboratoires ont été étudiés par plusieurs chercheurs mais moins d'attention a été apportée aux problèmes concernant l'évaluation à long terme des débits solides. Faute des données détaillées sur les concentrations des sédiments en suspension, plusieurs méthodes indirectes, fondées sur les techniques d'interpolation et d'extrapolation, ont été employées. Ces méthodes peuvent sousestimer ou surestimer sérieusement les données véritables. Une évaluation detaillée de l'exactitude et la précision des évaluations effectuées pour la rivière Creedy en Devon, RU, en utilisant ces techniques est présentée dans cette communication.

INTRODUCTION

Scientific investigations of suspended sediment transport in rivers have now been undertaken for more than 100 years. Today, data are available from well over 1500 measuring stations scattered throughout the world (*cf.* Walling & Kleo, 1979) and the expansion of measurement activities has been paralleled by an increasing need for information on suspended sediment loads.

The growing significance of suspended sediment load data, e.g. in the evaluation of nonpoint pollution, has inevitably directed attention to the accuracy of associated measurement techniques and to the reliability of available information. Studies of the efficiency and improvement of sampler design are well known and the US Federal Inter-Agency Sedimentation Project (e.g. FIASP, 1963) must be recognized as having played a pioneering role in such work. The efficiency of laboratory techniques employed to determine the concentration of individual suspended sediment samples has similarly received attention (e.g. Douglas, 1971) and national and international standards relating to sampling apparatus and techniques and to laboratory procedures have now been established. To many it might, therefore, appear that the major problems associated with obtaining accurate measurements of suspended sediment load have been overcome, and that published data pose few potential problems in terms of reliability.

The problem

Such a view is perhaps justified in relation to the measurement of *instantaneous* suspended sediment loads in a cross section, although the estimation of suspended sediment transport in the "unmeasured zone" close to the river bed, and the need for a clear distinction between loads relating to total suspended solids and those relating solely to the inorganic fraction introduce some uncertainties. However, many problems surround the assessment of longer term loads and annual suspended sediment yields. These problems centre around the marked and rapid fluctuations in suspended sediment concentration exhibited by many rivers. The accurate assessment of suspended sediment loads for specific periods necessitates detailed records of sediment concentration which may be combined with the records of water discharge. Continuous records of stream discharge are readily available at most measuring stations, but an equivalent record of sediment concentration may be difficult to obtain by a programme of manual sampling.

On large rivers it may be possible to collect sufficient manual samples to define meaningfully the record of sediment concentration during periods of fluctuating concentration, and procedures have been developed to assist in establishing the trend between individual samples (e.g. Porterfield, 1972). On smaller streams, concentrations fluctuate more rapidly during flood events and operational constraints may limit the frequency with which manual sampling may be undertaken. Considerable uncertainty concerning the accuracy of sediment load calculations may result in the latter situation and also on larger rivers where sampling is relatively infrequent.

Attempts have been made to resolve these difficulties through the development of equipment and instruments capable of automatic collection of sediment concentration data. Automatic pump-sampling equipment (e.g. Walling & Teed, 1971) has been used in many studies and continuous recording turbidity meters (e.g. Fleming, 1969) and nuclear probes (e.g. Rakoczi, 1976) have also been successfully employed. Difficulties may arise in relating the point values of concentration obtained with such equipment to the mean value for the cross section, but this limitation is frequently of restricted significance when compared to the positive improvements in temporal resolution obtained.

Where frequent manual samples or additional information from automatic samplers or recording equipment are unavailable, the detailed record of sediment concentration cannot be defined and *indirect* load calculation procedures involving either *interpolation* or *extrapolation* of the available concentration data must be used. In this context, interpolation procedures essentially involve the assumption that the values of concentration or sediment discharge obtained from instantaneous samples are representative of a much longer period of time (e.g. days or weeks), whereas rating curve techniques may be viewed as the classic example of an extrapolation procedure. In the latter case, a limited number of sediment concentration measurements are extrapolated over the period of interest by developing a relationship between concentration or sediment discharge and stream discharge, and by applying this relationship to the streamflow record (e.g. Campbell & Bauder, 1940; Walling, 1977a). The streamflow record may be in the form of either a flow duration curve or a continuous series, and in many studies rating relationships developed from a short period of measurement have been applied to streamflow records covering a much longer length of time.

Estimates of suspended sediment load produced using these indirect load calculation procedures may involve considerable errors and the resultant data must be treated with caution. A striking example of the potential problems is provided by recent work on the suspended sediment loads of New Zealand rivers by Griffiths (1979) and Adams (1980). Both workers have used the same basic discharge and concentration data collected by the New Zealand Ministry of Works to estimate the mean annual suspended sediment load of the Cleddau River, which drains a basin of 155 km^2 in the southwest of South Island. Both used rating curve procedures, but their published loads of 13 300 t km^{-2} $year^{-1}$ and 275 t km^{-2} $year^{-1}$ are different by nearly two orders of magnitude. Loads presented by the two authors for other rivers in South Island New Zealand exhibit less marked differences, but those cited by Adams average 70% higher than those evaluated by Griffiths. Similarly, Ongley *et al.* (1977) have studied the suspended sediment loads of five basins in southwestern Ontario, Canada, and have indicated that loads reported by the Sediment Survey of Canada were up to five times greater than those obtained using an alternative data base and load calculation procedure. The literature contains many other examples of major discrepancies in loads presented by different workers for the same river and which may be accounted for in terms of sampling strategy, data availability and load calculation procedures. Equally, a considerable degree of uncertainty must surround the likely accuracy and reliability of all sediment yield data produced using these interpolation and extrapolation procedures.

Although concern for the accuracy of suspended sediment load data has now been expressed by a number of workers (e.g. Dickinson *et al.*, 1975; Loughran, 1976; Walling, 1977b; Olive *et al.*, 1980), it is suggested that this question requires greater attention, both in terms of the potential limitations of existing data and the design of effective strategies for documenting suspended sediment loads in future studies. Particular concern must surround the potential limitations of sediment loads calculated using data assembled for general water quality monitoring purposes with little or no regard for the specific requirements of sediment load measurement.

THE RIVER CREEDY CASE STUDY

The existence of a continuous record of suspended sediment concentration from the River Creedy in Devon, UK, for a 7 year period, further highlights the nature and magnitude of the reliability problem. Figure 1 presents a comparison of the actual load for the 7 year period with nearly 100 load estimates for the same period obtained using typical manual sampling strategies and a selection of indirect load calculation procedures involving both interpolation and extrapolation. The estimates span a wide range, and underestimation by as much as 60% is common. The availability of this record has further prompted the ensuing review of the errors associated with particular procedures and sampling strategies.

The data base

Continuous records of turbidity have been obtained from the River Creedy at Cowley near Exeter since October 1972, using a light transmission sensor mounted directly in the river. Although some workers have experienced considerable difficulty in establishing relationships between turbidity and suspended

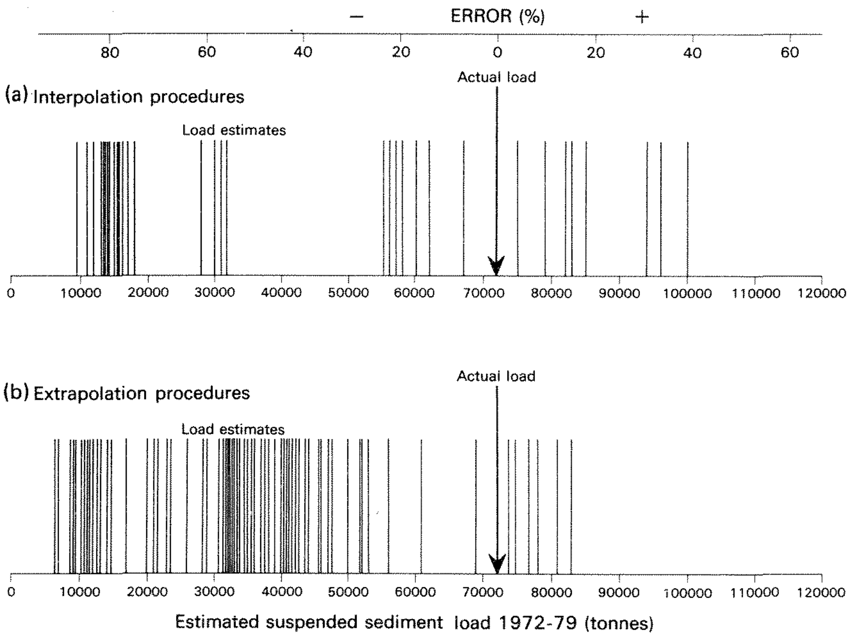

Fig. 1 A comparison of suspended sediment load estimates for the River Creedy obtained using interpolation and extrapolation procedures with the actual load for the period 1972–1979.

sediment concentration, a well defined relationship has been developed for this site. The continuous chart record of turbidity has been digitized at hourly intervals, and the resultant values have been converted to concentrations. Values of annual sediment yield have been obtained by integrating the concentration record with the equivalent hourly flow series. These annual loads are viewed as an accurate baseline against which to assess the estimates produced by various manual sampling strategies and indirect load calculation procedures.

The availability of the continuous series of hourly concentration data readily permits the synthesis of records representing different sampling strategies and allows the replication of a particular strategy by using different sampling times. For example, a weekly interval sampling programme can be replicated by sampling at different times of the day and on different days of the week.

Inspection of Fig. 2 provides an indication of the general problems surrounding the accurate assessment of suspended sediment yields from this basin using a programme of manual sampling. Figure 2(a) indicates that concentrations in excess of 100 mg l^{-1} only occur for 5% of the time and higher concentrations above 1000 mg l^{-1} are found less than 0.05% of the time. Likewise, the plot of cumulative percentage load *vs.* cumulative percentage of time, derived from a ranked series of hourly loads (Fig. 2(b)), demonstrates that 50 and 80% of the load are respectively carried in 0.75 and 3% of the time. This situation introduces serious problems into any attempt to cover the major periods of sediment transport by a programme of sampling at regular intervals. Similarly, the relatively even distribution of major sediment transporting events through the year, evident in Fig. 2(c), poses considerable problems for establishing event-based sampling, when compared to a situation where these events are limited to one major period of the year (e.g. snowmelt). The limitations of extrapolation procedures such as rating curves are also clearly shown in Fig. 2(d) which illustrates the variation in sediment concentration during a sequence of storm events and shows that there is no well-defined relationship between sediment concentration and discharge. The characteristics of the sediment record shown in Fig. 2 provide a ready explanation of the lack of reliability in the load estimates evident in Fig. 1.

In reviewing the reliability of various load estimation procedures, attention must be given to both the *accuracy* and the *precision* of estimates produced by particular combinations of calculation procedure and sampling strategy. Consideration of precision is important since it reflects the consistency with which errors may be apportioned to individual procedures and therefore the potential for applying correction factors. For example, Ongley *et al.* (1977) have suggested that certain load calculation procedures may underestimate the loads of rivers in their study area in Ontario, Canada, but that the rank order of the loads will be estimated correctly. The validity of the latter suggestion will clearly depend heavily upon the precision of the calculation procedures. In the present study, precision

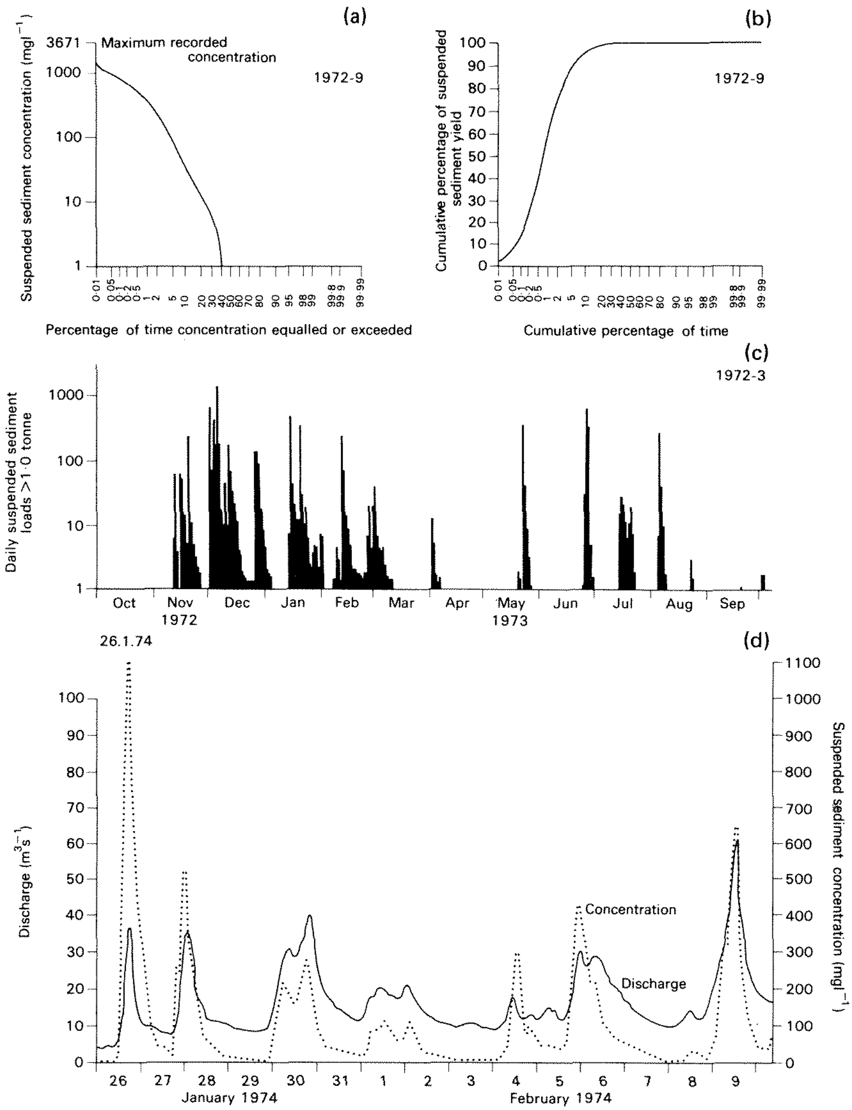

Fig. 2 Characteristics of the suspended sediment regime of the River Creedy.

has been assessed by considering the variability of load estimates obtained using replicate data sets relating to particular sampling strategies.

INTERPOLATION PROCEDURES

Interpolation procedures are frequently used to calculate loadings from the regular sampling associated with water quality surveillance programmes, and the accuracy and precision of a number of these procedures have been assessed by applying them to replicate sets of data representing sampling at 1, 2, 4, 7, 10 and 14 day intervals. Replication has been undertaken by using a random number generator to select sampling times within the interval and retaining these times throughout the period of record. A standard 50 replicates has been generated for each sampling interval, except 1 and 2 days where only 24 and 48 replicates are possible. Sampling on a monthly basis, and involving the collection of 1, 2, and 4 samples per month, has also been represented using a similar approach, in order to test a load calculation procedure requiring estimates of mean monthly concentration.

The numerical bases of the six load calculation procedures employed are listed in Table 1. Method 1 uses the assumption that the values of concentration and discharge associated with individual samples may be averaged to provide representative mean values for the period of record (e.g. Verhoff *et al.*, 1980). In method 2 the individual values of concentration and discharge are essentially combined to produce a value of sediment discharge representative of each interval, and summed over the period of record. Alternatively, this method can be viewed as calculating the mean of the sampled instantaneous loads, which is in turn applied to the whole period of record. This approach has been employed in the UK Harmonized Monitoring Programme (Department of the Environment, 1979). Whereas methods 1 and 2 make use only of the instantaneous flow values associated with individual samples, the remaining procedures utilize the full flow record from the measuring stations, by incorporating either the mean discharge for individual intervals, mean monthly discharge values or the mean discharge for the period of record. Method 3 evaluates loads as the product of average concentration and the mean discharge for the period of record (e.g. Ongley, 1973), whilst method 4 combines the flow-weighted mean concentration with the mean discharge for the period (e.g. Verhoff *et al.*, 1980). Method 5 assumes the sampled concentration is representative of the sampling interval and calculates the load as the sum of the products of sampled concentration and mean discharge for individual intervals. Finally, method 6 calculates load as the sum of mean monthly load values which are in turn calculated as the product of mean monthly sampled concentrations and the mean monthly discharge. The mean monthly concentration may thus be based on samples from several years. This method was used by Ongley *et al.* (1977).

Estimates of the suspended sediment load of the River Creedy for the 7 year period, produced using these six interpolation procedures in combination with the data provided by different sampling frequencies, are listed in Table 2. Both the mean and standard deviation of the replicate estimates are listed. The standard deviation may be used as a measure of the precision of the estimate, since it directly reflects the variability of the individual values produced by the replicate sample sets. When compared to the actual load for the period of 71 754 t, the mean values associated with individual calculation procedures indicate that methods 1, 3 and 6 underestimate the loads by 70% or more. This suggests that the procedures weighting the concentration values by the discharge at the time of sampling (methods 2, 4 and 5) are likely to produce more accurate load estimates.

Table 1 Load interpolation procedures

Method	Numerical procedure
1	Total load $= K\,(\Sigma_{i=1}^{n} \frac{C_i}{n})\,(\Sigma_{i=1}^{n} \frac{Q_i}{n})$
2	Total load $= K\Sigma_{i=1}^{n}\,(\frac{C_i Q_i}{n})$
3	Total load $= K\,\bar{Q}_r\,(\Sigma_{i=1}^{n} \frac{C_i}{n})$
4	Total load $= \frac{K\Sigma_{i=1}^{n}\,(C_i Q_i)}{\Sigma_{i=1}^{n} Q_i}\,\bar{Q}_r$
5	Total load $= K\Sigma_{i=1}^{n}\,(C_i \bar{Q}_{pi})$
6	Total load $= K\Sigma_{m=1}^{12}\,(\bar{C}_m \bar{Q}_m)$

K = conversion factor to take account of period of record
C_i = instantaneous concentration associated with individual samples (mg l^{-1})
Q_i = instantaneous discharge at time of sampling (m^3 s^{-1})
$\bar{Q}_r$ = mean discharge for period of record (m^3 s^{-1})
$\bar{Q}_{pi}$ = mean discharge for interval between samples (m^3 s^{-1})
$\bar{C}_m$ = mean monthly concentration (mg l^{-1})
$\bar{Q}_m$ = mean monthly discharge (m^3 s^{-1})
n = number of samples

Table 2 Mean and standard deviation of replicate suspended sediment load estimates for the period 1972-1979 obtained using various interpolation procedures

Load calculation procedure (Table 1)		Sampling interval (days) 1	2	4	7	10	14
1	$\bar{x}$	14 990	15 092	15 145	15 280	15 523	14 199
	s	1 284	1 387	1 988	4 065	3 818	4 787
2	$\bar{x}$	72 643	73 589	72 548	72 927	79 391	69 020
	s	7 054	9 542	16 598	24 024	26 317	30 600
3	$\bar{x}$	15 260	15 045	14 660	14 975	14 958	15 401
	s	1 109	1 230	1 718	3 547	3 328	3 768
4	$\bar{x}$	73 421	73 996	69 698	71 614	77 874	68 849
	s	6 664	7 381	15 427	19 935	23 075	27 629
5	$\bar{x}$	57 100	50 931	43 963	37 748	39 570	31 850
	s	3 287	6 555	8 709	7 356	11 245	9 253
6	$\bar{x}$	—	—	—	22 225	—	23 184
	s				4 295		7 247

$\bar{x}$ = mean of replicate results (t)
s = standard deviation of replicate results (t)

The standard deviation values must, however, also be considered and their significance in terms of precision is clearly demonstrated in Fig. 3. Here, the variability of the estimates, produced by individual interpolation procedures applied to the replicate data sets for sampling frequencies of 7 and 14 days, has been portrayed in an idealized form by plotting

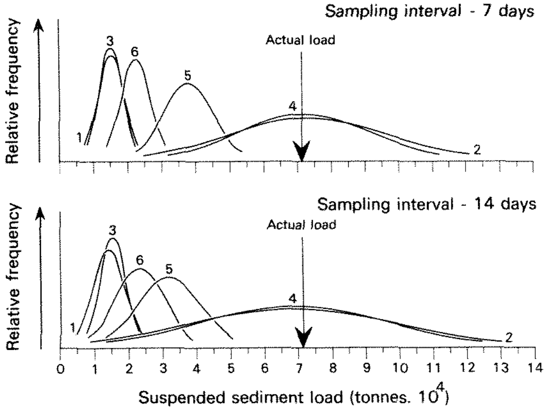

Fig. 3 Idealized distributions of replicate load estimates for the period 1972-1979 obtained using the various interpolation procedures in combination with data provided by sampling frequencies of 7 and 14 days. Curve numbers refer to individual interpolation procedures listed in Table 1.

the normal distributions represented by the appropriate values of mean and standard deviation. These distributions have been truncated at two standard deviations and afford an indication of the 95% confidence limits of the replicate load values.

Figure 3 exhibits an inverse relationship between accuracy and precision. Methods 2 and 4 produce mean values of load which are close to the actual load, but the scatter of the replicate estimates is great and it would be extremely difficult to apply a consistent correction factor to loads estimated using these two methods, or to place reliance on the rank order of loads calculated for different basins. Methods 1 and 3 produce the greatest underestimation of the sediment load for the 7 year period (*c.* 80%) but provide more consistent results and may therefore be preferable.

The influence of sampling frequency upon the reliability of the resultant load estimates can be assessed by comparing the results listed in Table 2 for different sampling frequencies. Surprisingly, perhaps, sampling frequency appears to have little influence upon the accuracy of methods 1-4, as indexed by the mean load values. With method 5, however, the degree of underestimation increases with increasing sampling interval. The influence of sampling interval on precision, as reflected by the values of standard deviation, is more marked. In all cases precision sharply decreases with an increased sampling interval and would appear to be an important criterion in the selection of an appropriate frequency.

Table 3 introduces a further aspect of reliability by considering a 7 day sampling interval and the ratio of mean loads estimated for individual years using methods 1-5 to the actual loads for those years. The ratios associated with methods 1 and 3 are relatively consistent, again indicating potential for application of a correction factor, whilst those produced by methods 2 and 4, and to a lesser extent 5, exhibit considerable variability. However, any attempt to make use of a correction factor in estimating annual loads must also consider the

Table 3 A comparison of the ratios between actual loads and the mean loads obtained for individual years using the replicate data sets, for a 7 day sampling interval and various interpolation procedures

Interpolation procedure	Ratio of estimated/measured load							
	1972-73	1973-74	1974-75	1975-76	1976-77	1977-78	1978-79	1972-79
1	0.22	0.23	0.22	0.32	0.35	0.18	0.27	0.21
2	0.48	1.12	0.90	3.13	1.18	0.83	1.10	1.02
3	0.28	0.20	0.20	0.17	0.26	0.22	0.25	0.21
4	0.49	1.02	0.84	2.10	1.10	0.82	1.05	1.00
5	0.48	0.55	0.48	1.53	0.59	0.47	0.63	0.53
Actual load (t)	7482	20619	10547	1941	16234	10214	4717	71754

precision of the replicate load estimates, since the ratios listed in Table 3 relate to the mean values for the replicates. As in the case of the load estimates for the 7 year period, methods 1 and 3 are associated with the lowest values of standard deviation for the replicate load estimates for individual years.

Any attempt to evaluate the relative merits of the load estimation procedures listed in Table 1 must clearly consider both accuracy and precision criteria and may involve some compromise. The low degree of precision must effectively rule out methods 2 and 4 and the most worthwhile results are probably to be obtained from methods 1 and 3. Both exhibit a marked tendency to underestimate but the relatively high precision suggests that the methods will reproduce relative rankings and it has been shown that some scope exists for the application of correction factors

EXTRAPOLATION PROCEDURES

The reliability of load estimates obtained using rating curve techniques has been evaluated in a similar manner to that employed for interpolation procedures. Four data sets, containing 50 replicates and representing different sampling strategies, have been assembled from the 7 year record and the resultant rating relationships have been applied to several frequently used load calculation procedures.

The sampling strategies employed to generate the replicate data sets include regular sampling at weekly intervals, and attempts to improve the coverage of storm events by introducing additional random aperiodic sampling when flows exceed certain thresholds (Table 4). Fifty replicate rating relationships of the form

$$\text{concentration} = aQ^b$$

where Q = instantaneous discharge at time of sampling, have been established for each of the four sampling strategies, using least squares regression. In addition, the data sets for the type 3 and 4 ratings were subdivided according to season and to rising and falling stage conditions (3a, 4a) and four separate rating relationships were developed for each (*cf.* Walling, 1977a). The

Table 4 The sampling strategies used for rating curve derivation

Strategy	Sampling programme
1	Regular weekly sampling
2	Strategy 1 plus 200 random samples collected when discharge > 15 $m^3 s^{-1}$
3	Strategy 1 plus 150 random samples collected when discharge > 15 $m^3 s^{-1}$ and 50 random samples collected when discharge > 30 $m^3 s^{-1}$
4	Strategy 1 plus 750 random samples collected when discharge > 15 $m^3 s^{-1}$ and 250 random samples collected when discharge > 30 $m^3 s^{-1}$

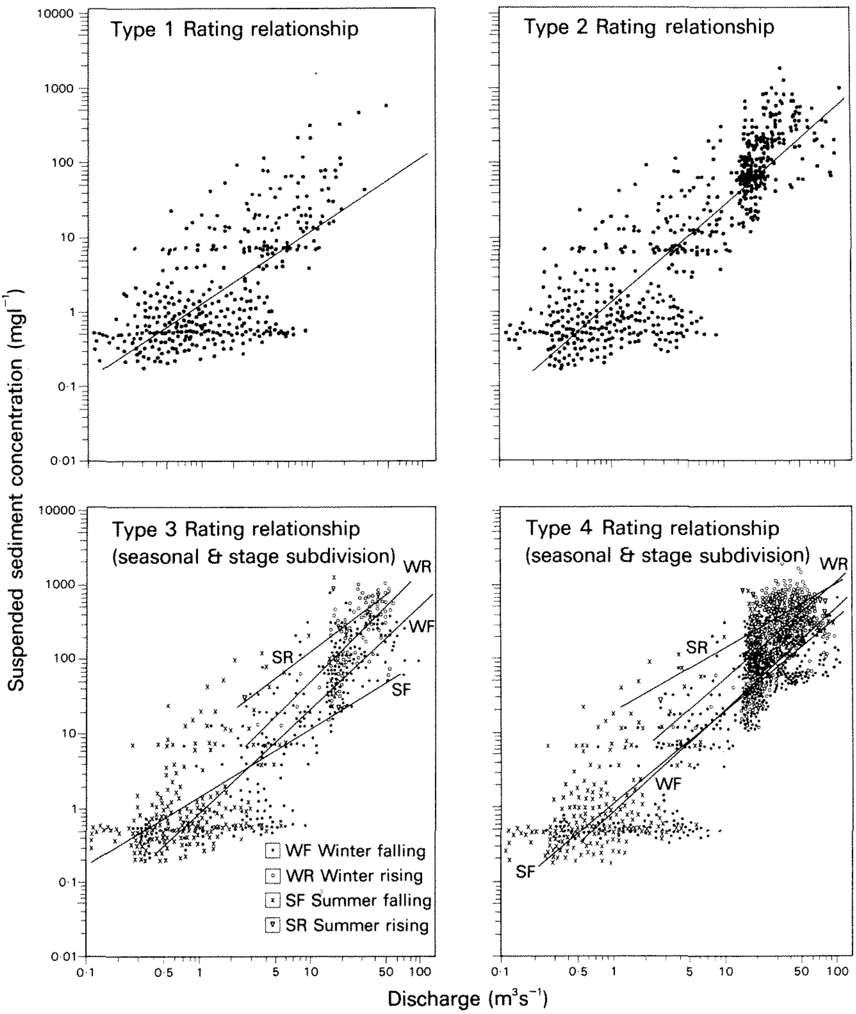

Fig. 4 Examples of rating plots and relationships established using the four alternative sampling strategies.

statistical properties of the various rating relationships are summarized in Table 5, and Fig. 4 presents examples of individual sample sets and their associated rating relationships. In all cases the scatter associated with the relationship is considerable, and the addition of aperiodic storm event sampling can be seen to change the slope of the relationship significantly (compare type 1 with type 2).

Table 5 Statistical properties of the rating relationships

	1	2	3	3a*				4	4a*			
				WF	WR	SF	SR		WF	WR	SF	SR
n	365	565	565	294	79	183	9	1365	771	368	208	18
r	0.697	0.868	0.876	0.858	0.573	0.629	0.781	0.883	0.844	0.536	0.801	0.511
a	1.172	1.242	1.236	0.769	5.460	1.304	53.069	1.309	0.898	4.731	1.469	63.480
b	1.024	1.351	1.349	1.436	1.225	0.952	1.307	1.401	1.448	1.172	1.180	0.855

r, a, b = mean values of r, a and b for the 50 replicate equations.
*Ratings subdivided according to season and stage condition as follows: WF = winter and falling stage, WR = winter and rising stage, SF = summer and falling stage, SR = summer and rising stage, n values for subdivided ratings are calculated as average values from the 50 replicate data sets.

A visual indication of the degree of variability within the rating relationships produced from replicate sample sets is afforded by Fig. 5(b). This depicts a representative selection of 10 ratings for type 1 and type 2 sampling strategies. Although the intercepts of the type 1 rating curves are similar, there is appreciable variation in the exponents or slopes. This variation is much less for type 2 rating curves and for types 3 and 4.

The rating relationships listed in Table 5 have been applied to the continuous flow series for the 7 year period of record, in order to calculate the suspended sediment load. Following common practice, both hourly and daily mean flow data have been employed, and the resultant load estimates are summarized in Table 6. In all cases, use of daily mean flow data results in estimates which are lower than those produced using the hourly flow series. Taking the mean of the replicate load estimates as an index of accuracy, it can be seen that the use of these rating relationships underestimates the sediment load for the 7 year period by between 83 and 23%. However, the increase in the number of samples, associated with the progression from sampling strategy 1 through to strategy 3, is paralleled by an increase in accuracy. Similarly the use of rating relationships subdivided according to season and stage tendency produces an increase in the accuracy of the estimate provided by a particular sampling strategy. It is pertinent to note that a previous evaluation of the accuracy of rating curve estimation of sediment load for this river, undertaken by Walling (1977a), using a very intensive sampling strategy, indicated that loads could be overestimated. Clearly, the size and representativeness of the data base used to derive the rating relationship exerts an important influence on the

Table 6 Mean and standard deviation of replicate suspended sediment load estimates for the period 1972-1979 obtained using various rating relationships applied to the hourly and daily mean flow series

Rating relationship		1	2	3	3a*	4	4a*
Hourly flow	$\bar{x}$	13 799	41 786	41 325	53 123	52 243	55 585
series	s	3 092	2 753	2 727	6 774	1 534	1 903
Daily flow	$\bar{x}$	12 376	35 274	34 897	–	43 647	–
series	s	2 656	2 254	2 205	–	1 254	–

*Not applicable to daily mean flow series.
$\bar{x}$ = mean of replicate results (t)
s = standard deviation of replicate results (t)

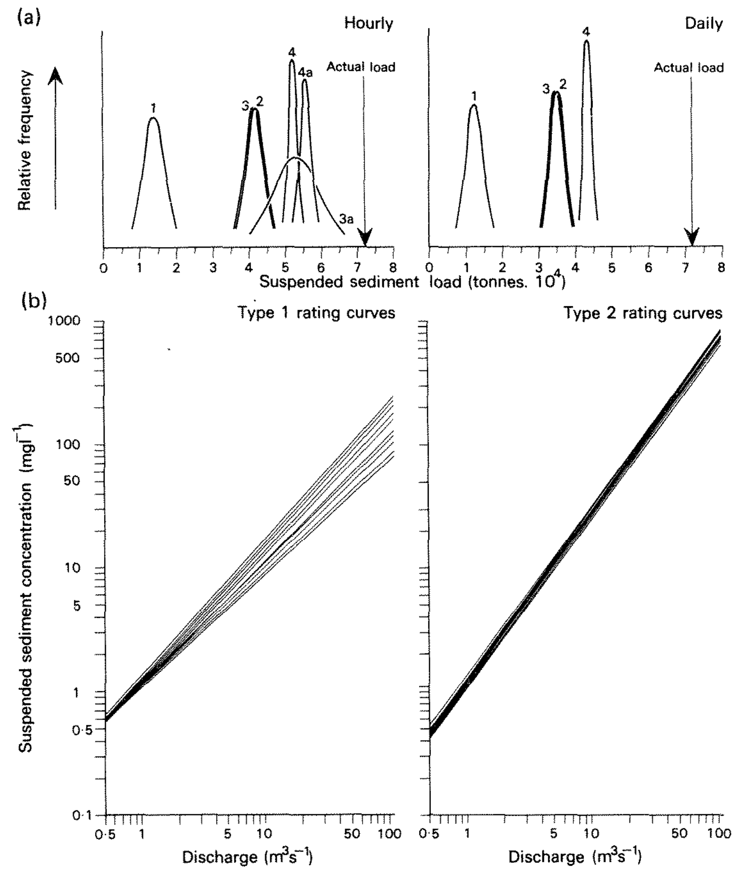

Fig. 5 (a) Idealized distributions of replicate load estimates for the period 1972-1979 obtained using the various rating relationships in combination with the hourly and daily mean flow series. Curve numbers refer to individual rating types. (b) The variability of a representative selection of replicate rating relationships of type 1 and type 2.

likely accuracy of the resultant load estimates.

Figure 5(a) indicates the precision of the load estimates produced using the various rating curves, by depicting the normal distributions associated with the relevant values of mean and standard deviation of the replicate load estimates. Precision tends to increase with the use of increasing numbers of samples to derive the rating relationship. Nevertheless, it would appear that sampling strategy 3 produces insufficient data for reliable subdivision of the rating relationships, because the spread of load estimates produced by the type 3a ratings is considerable. Overall, the precision of the rating curve estimates is generally better than that associated with the interpolation procedures (Table 2). More specifically, the results obtained from the various interpolation procedures applied to data collected at 7 day intervals (Fig. 3) may be directly compared with the load estimates producing used the type 1 ratings, also based on a regular 7 day sampling strategy (Fig. 5(a)).

The relatively high precision associated with the rating curve estimates of sediment load for the 7 year period could suggest potential for applying a general correction factor to make allowance for their more limited accuracy. However, Table 7 indicates that such potential is very restricted. This considers the ratio of the mean load, estimated for individual years using a particular rating, to the actual load for that year. Even with type 4 ratings, shown in Fig. 5(a) to produce the highest accuracy and precision, the ratio varies from 0.19 to 1.36 when using the hourly flow series. These results may be compared with those presented in Table 3 for the interpolation procedures. In that case, procedure 3 showed much more consistent ratios, with values lying between 0.17 and 0.28. To some extent this contrast reflects the basic distinction between interpolation and extrapolation procedures, in that the latter applies data collected from the whole period of record to individual years whereas the former uses only data relating to a particular year.

Table 7 A comparison of the ratios between actual loads and the mean loads for individual years calculated from the replicate estimates produced by individual rating relationships combined with the hourly flow series

	Ratio estimated/measured load							
Rating relationship	1972-73	1973-74	1974-75	1975-76	1976-77	1977-78	1978-79	1972-79
1	0.14	0.16	0.15	0.08	0.20	0.68	0.23	0.19
2	0.41	0.53	0.41	0.17	0.58	1.06	0.56	0.58
3	0.41	0.53	0.41	0.17	0.57	1.06	0.56	0.58
3a	0.50	0.78	0.52	0.18	0.69	1.32	0.59	0.74
4	0.52	0.68	0.50	0.19	0.72	1.36	0.67	0.73
4a	0.55	0.75	0.56	0.26	0.75	1.41	0.67	0.77
Actual load (t)	7482	20619	10547	1941	16234	10214	4717	71754

Use of flow duration curves

Suspended sediment rating curves are also frequently used with flow duration curve data to calculate sediment loads (e.g. Miller, 1951). Walling (1977b) has previously shown how the choice of duration increments can significantly influence the magnitude of the resultant load estimate. To explore this problem further, load estimates for the 7 year period were produced from duration curves of hourly and daily mean flows using the duration increments suggested by Miller (1951), Piest (1964), Murthy (1977) and Collins (1970). The results for type 1 and type 4 replicate rating relationships are presented in Table 8. The precision of the duration curve estimates, as indexed by the standard deviation of the replicate results, is closely similar to that achieved using the hourly and daily mean flow series. However, significant differences exist between the load estimates produced using the flow series and some of those obtained using duration curve procedures, despite the use of the same rating curves. This introduces a further element of uncertainty into any assessment of the reliability of sediment load data and its significance can be expected to increase with decreasing basin size.

Load interval method

The "load interval method" is a variant of the rating curve approach which has been used by a number of workers in recent years and which must also classify as an extrapolation procedure (e.g. Verhoff *et al.*, 1980). In this method, the discharge ordinate of the rating plot is partitioned into a number of equal classes and the average load for each class is calculated as the mean of the loads associated with individual samples falling within that class. The total load for the period of record is calculated by summing the products of mean load and discharge frequency for each class. This method has been applied to the four sets of rating curve data, using discharge frequency data based on both the hourly and the daily mean flow series. The results are presented in Table 9 and Fig. 6. Interpreting the values of mean and standard deviation as before, this method can be seen to produce a significant improvement in accuracy over the standard rating curve procedures. This improvement may be related to the fact that the mean load associated with a particular discharge class reflects only samples falling in that class, whereas equivalent estimates based on rating equations developed using regression techniques will reflect the trend evidenced by the overall data set. However, this improvement in accuracy is achieved at the expense of a loss in precision. The standard deviation values associated with the load interval method are several times greater than those produced using the standard rating curve technique. The precision of estimates provided by the data of rating type 1 is unacceptably low, whereas there is little to choose between the precision of estimates produced using data from type 2, 3 and 4 ratings.

IMPLICATIONS

Figure 2 has shown the considerable variation in the magnitude of sediment load estimates that may be associated with indirect methods of calculation of long term loads using both interpolation and extrapolation procedures. All the methods represented have been employed frequently by other workers. It is therefore suggested that detailed attention must be given to

Table 8 Mean and standard deviation of the replicate suspended sediment load estimates for the period 1972-1979 obtained using type 1 and type 4 rating relationships and flow duration curves represented by different duration increments

Rating type	Flow duration data		Duration increments: Miller	Piest	Murphy	Collins
1	Hourly	x̄	12659	13630	8115	14144
		s	2798	3046	1549	3186
	Daily	x̄	10772	11719	8033	11857
		s	2221	2474	1507	2507
4	Hourly	x̄	47026	51383	23964	53920
		s	1372	1506	682	1586
	Daily	x̄	35719	40278	23106	32275
		s	1015	1150	661	918

x̄ = mean of replicate results (t)
s = standard deviation of replicate results (t)

Table 9 Mean and standard deviation of replicate suspended sediment load estimates for the period 1972-1979 obtained using the load interval method

Rating data-set		1	2	3	4
Hourly flow series	x̄	68573	76321	77061	79020
	s	22942	7184	5859	6549
Daily flow series	x̄	67903	71015	70638	70686
	s	22926	7200	7427	7903

x̄ = mean of replicate results (t)
s = standard deviation of replicate results (t)

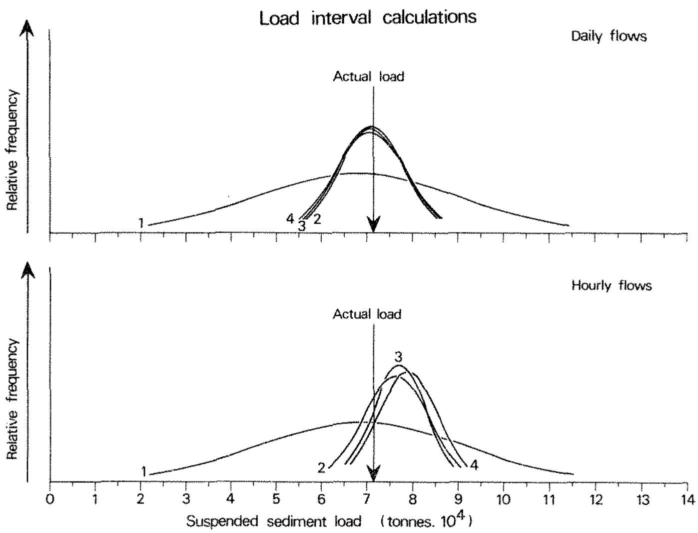

Fig. 6 Idealized distributions of replicate load estimates for the period 1972-1979 obtained using the "load interval method" in association with frequency data based on the hourly and daily mean flow series. Curve numbers refer to individual rating data sets.

the likely reliability of all such sediment load data if design calculations, comparisons between basins, and other applications are to prove meaningful. Evaluation of the reliability of individual procedures must involve consideration of both accuracy and precision and the application of simple correction factors to account for lack of accuracy must be undertaken with caution.

It is advocated that these problems should be considered by the International Standards Organization, WMO and other bodies involved in developing standards for sediment measurements. Where reliable methods of assessing long term sediment loads cannot be applied, the estimates provided by indirect methods should be qualified by a statement of potential error. For example, the load interval method described above has been developed to produce a standard error value to qualify the resultant load estimate (Verhoff *et al.*, 1980). This statistic is, however, based on the statistical properties of the individual samples rather than an analysis of the reliability of the method itself. More work is required on rivers with different sediment regimes, so that we may move towards quantitative assessments of the potential reliability of sediment load data and the selection of sampling strategies and calculation procedures necessary to achieve required levels of accuracy and precision.

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