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Stream suspended sediment transport monitoring – why, how and what is being measured?

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ABSTRACT With increasing interest in erosion and sedimentation, considerable effort has been expended in both developing and maintaining programs to monitor stream suspended sediment transport. There is much literature examining the accuracy of sample collection, analytical and load estimation techniques. Little concern has been given to the underlying rationale of monitoring programs and what the resulting data represent. This paper examines the various aspects of monitoring programs and raises some questions about their validity and viability. The questions of why monitor, particularly with respect to alternative techniques, and how to monitor in the light of increasing costs and a greater demand for cost effective studies are addressed. The relevance of results obtained is questioned especially where short term studies are used to infer longer term trends. Here the role of natural variability in the stream sediment transport system is considered. The paper does not provide any simple answers but rather raises a number of fundamental questions which need to be addressed.

INTRODUCTION

Erosion, sediment transport, sedimentation and their associated water quality implications are of increasing concern in basin management and are assuming greater economic importance. These processes have commonly been examined using some form of contemporary monitoring program and considerable research has been carried out examining the accuracy of the data collection, analysis techniques and subsequent methods used for sediment load estimations. Unlike other processes in the hydrologic cycle, such as precipitation and streamflow, there has not been large scale, long term systematic monitoring programs and most studies are based on limited data bases. In the current economic environment this is unlikely to change in the foreseeable future and there will be increasing emphasis on a cost-benefit approach to problem solving. Monitoring programs have always been high cost exercises and in recent years there has been the development of a number of alternative approaches to them. In the light of these developments, this paper addresses the questions of why monitor sediment transport, how to monitor and just what is being measured particularly with respect to how representative results are of the processes which operate in the stream system?

WHY MONITOR?

There are an increasing number of reasons for monitoring stream suspended sediment. Traditionally, research has focussed on the the total amounts of material eroded and transported by streams and this quantification has been centred on some form of monitoring system. In many cases, sediment loads and erosion rates (t km^{-2} $year^{-1}$) were calculated and from this there was an inference of average regional or longer term erosion and denudation rates. These have been summarised by several authors, for example Walling and Webb (1983). In addition, monitoring programs have been utilized to examine the processes involved in the detachment and transport of fluvial suspended sediment.

With greater appreciation of the economic impact of erosion and sediment, there is an increasing requirement for a greater understanding of quantities and sources of sediment, the processes involved in its detachment and transport and its movement through the system (Walling, 1988). Human activities have led to considerable changes in erosion with accelerated erosion resulting in major problems on site where the loss of soil depth and fertility have lead to a decline in agricultural productivity and a general environmental degradation. There is increasing awareness of the off-site or downstream impacts and costs through sedimentation of waterways, lakes and dams and a general decline in water quality. Clark *et al.* (1985) estimated that off-site impacts had an economic cost in the United States of $6100 million making no allowance for impacts on natural ecology. Suspended sediment also is the host for the transport of many contaminants including nutrients and heavy minerals and any understanding of these depends on a good understanding of the sediment transport processes.

Traditionally, the various erosion and sediment questions and problems outlined above have been examined using a monitoring approach but increasingly other approaches are being used. Lake sediment studies, where sediment yields are determined from depositional cores, were originally utilized to examine longer termed "average" rates but are now being used to examine shorter termed rates and any changes in sediment yield associated with basin disturbance (Oldfield 1977, Foster *et al.* 1988, Walling 1988). This has been made possible by utilizing lakes associated with dams and by the development of shorter termed dating techniques such as caesium and lead. Others have examined sediment storage in basins recognising the importance of residence times of sediment in the system and the remobilization of previously deposited material (Roehl 1962, Trimble 1981, Meade 1982 and Meade & Parker 1986). These studies have shown the role of both storage and remobilization in downstream sedimentation and the question of sediment delivery ratios. A major recent development has been the use of a range of sediment tracers or signatures particularly to examine sediment sources. A variety of tracers have been used including physical and chemical characteristics (Peart & Walling 1988 and Walling 1988), mineral magnetics (Oldfield *et al.* 1979, Walling *et al.* 1979, Murray *et al.* 1990) and several radionuclides including ^{210}Pb (Oldfield & Appleby 1984, Wasson *et al.* 1987), ^{137}Cs (McHenry & Ritchie 1977, Walling & Kane 1984, Loughran *et al.* 1988, Peart & Walling 1988, Murray *et al.* 1991) and various members of the uranium series (Murray *et al.* 1991). Tracing techniques have usually been utilized in conjunction with other methods, originally with lake sediments then being extended to sediment storages within the basin and most recently by direct sampling of suspended sediment in the stream by use of a continuous flow centrifuge.

There is an increasing requirement for information on erosion and sediment transport ranging from long term geomorphic considerations of erosion rates, sediment yields and delivery to shorter termed problems of accelerated erosion. These have traditionally been examined by some form of monitoring program but in more recent times a range of other techniques have been developed which either complement or provide alternatives to monitoring. Monitoring is often an expensive and labour intensive operation which makes some of the less expensive alternatives attractive. In any study however, the questions should be what information is required and how can the information be provided to the required level of detail and accuracy in the most cost efficient manner? It may be that a combination of approaches provides this solution. This will lead to decisions between various alternatives but also within monitoring itself where there are a range of alternatives which will be considered in the next section.

HOW TO MONITOR?

Monitoring of stream sediment transport has been carried in a range of forms throughout most of this century. Early monitoring focussed on quantifying the total amount of material transported and erosion rates. It was usually based on manual collection of stream samples and the establishment of a relationship between sediment concentration or load and stream discharge - the sediment rating curve. The techniques involved and many of the associated problems have been reviewed by Colby (1956). These rating relationships, which were used to estimate stream sediment yields, were log linear with high correlation co-efficients and have been widely used to determine total stream sediment transport. A major appeal of this technique is that it only requires a limited field monitoring program which can be achieved by manual sample collection so a quantification of sediment transport is easily achieved. Most of the accuracy concerns focussed on the accuracy of the various sediment samplers (Inter-Agency Committee on Water Resources 1963) and analytical techniques used for sediment concentration determination (Loughran 1971, Douglas 1971).

With increasing research, there was a growing awareness of the importance of storm events in sediment transport. This co-incided with major technological advances and monitoring became more storm or synoptic based with the use of automatic samplers providing detailed information on these events. Such techniques generate large numbers of samples requiring time consuming and costly analytical analysis. More recently, continuous monitoring has been carried out using in stream turbidity meters, a more time and cost efficient technique. Such studies, in many cases, revealed a more complex relationship between suspended sediment and discharge than that suggested by the simple regression model of the rating curve (Wood 1977, Walling & Webb 1982, Olive & Rieger 1985). These more detailed data bases also enabled testing of the accuracy of estimations of sediment load based on rating curves which commonly revealed a significant underestimation of loads determined by the rating curve technique (Walling 1977, Olive *et al.* 1980, Walling & Webb 1981, Farr & Clarke 1984). Research by Fergusson (1984, 1986, 1987) suggested that a large part of these errors was due to an inherent bias in the use of log-transformed regression to derive the rating relationships. This error can be removed by applying a simple correction factor based on the standard error of the estimate of the logarithmic regression (CF_1). In a comparison between actual loads and bias corrected and non corrected rating curve estimates, Fergusson illustrated dramatic improvements. Koch and Smillie (1986) outlined an alternative non-parametric function for bias correction (CF_2) and Hansen and Bray (1987) reported good results using it. Others have expressed doubt over the improvement in accuracy achieved by the correction factors (Koch & Smillie 1986, Ashmore 1986). Walling and Webb (1988) compared load estimates using standard rating curves and the two correction factors using various sampling strategies, with actual loads based on continuous monitoring of turbidity for three rivers in Devon. They found that the bias correction procedures did not provide accurate estimates and in some cases were no more accurate than normal uncorrected rating curves. They claimed that other sources of errors were more important, particularly those associated with the varying relationship between discharge and sediment concentration which negates the assumption of a constant relationship which underlies the use of regression. Rating curves continue however to be widely used for load determinations.

Increasingly, studies of suspended sediment have expanded to consider not just the traditional quantitative information such as sediment concentration and load or yield but to also include examination of the physical and chemical characteristics of the sediment

(Walling 1988). This has arisen with a recognition of the role of suspended sediment in the transport of nutrients and contaminants. This often results a major changes to the monitoring program to satisfy the requirements for such data.

A wide range of options are now available when deciding how to monitor suspended sediment. The technology is available to carry out continuous monitoring through in stream turbidity meters or to take automatic pump samples over very short time increments. A major consideration in any program is the cost of the monitoring program. While it is possible to carry out intensive sampling, the resulting costs of sample collection and analytical analysis are high and may be prohibitive. One of the major appeals of determining loads using a rating curve approach is that it can be carried out using a limited field monitoring program and so is relatively inexpensive, however, there appears to be considerable problems with such a technique leading to errors which are unacceptable to many. If a rating curve approach produces unacceptable errors, then at present the only viable alternative is some form of field monitoring enabling the direct calculation of loads as there is no viable prediction model for stream or basin scale sediment transport. With such a program there are a number of analytical errors involved but probably the major source of error involved in any load calculation relates to the variability of sediment concentration response through time and the ability of the sampling program to accurately characterise the pattern. This will be be determined to a large extent by the frequency of sampling especially when sediment concentrations are likely to be changing rapidly, predominantly during storm events (Olive & Rieger 1988). The required sampling frequency will depend on the level of detail and accuracy of the data required and the size of the basin. Commonly, as basin size increases the response times of sediment concentration increase and it is possible to increase the time interval between samples without decreasing the accuracy of the results. Commonly however the sampling program is determined by cost constraints rather than accuracy requirements. For most studies, a pilot study to determine the optimum sampling program which provides the best information within budget constraints is strongly advisable before embarking on a full scale monitoring program. If continuous monitoring is utilised then this sampling interval is not a problem.

When establishing a monitoring program the major considerations should be: what are the data requirements; how can that data be best collected; what errors are involved in the results and are they within acceptable limits given the requirements of the problem? Commonly the question of errors and accuracy is inadequately addressed. The ultimate question should be why are we monitoring and what is the most cost effective method of obtaining the results to the required level of accuracy?

WHAT IS BEING MEASURED?

The answer to the question of what is being measured appears obvious - suspended sediment. The real question however is how well do the results obtained represent the processes operating in the stream and are the sediment quantities in terms of loads or yields an accurate representation of stream transport. Parker (1988) suggests that uncertainties arise due to sampling and analytical error, inaccurate extrapolation of data through time and natural variability in the stream sediment regime. There has been considerable research examining the accuracy of the various techniques involved, with analyses of sampling strategies and techniques, analytical procedures, and load calculation methods which have been outlined above, so that the errors involved in these steps can be reasonably quantified. Little consideration has been given however to the influence of natural variability in the stream and to how representative the data obtained is with respect to what is happening in the stream in the longer term. Most studies based on monitoring programs have a limited data base with information collected with either poor temporal coverage, or where there is more detailed synoptic or continuous monitoring, the duration of the study is commonly short, usually a maximum of a few years. There are very few longer term detailed monitoring programs. Frequently, short term data are used to infer longer termed average rates of sediment transport and yield and in any sediment budgeting, measured transport rates are related to longer termed sediment stores. In impact studies, which examine accelerated erosion, the inference is that the results represent the general response and they are frequently applied outside the study both spatially and temporally. Such extensions of the results outside the study period will only be valid if the study sample accurately reflects the behaviour of the stream sediment regime in the longer term. One of the appeals of the use of the rating curve methodology has been that the relationship can be developed based on a limited sampling program and can then be applied over longer time scales as detailed stream discharge information is often available.

Only a few studies have have examined the implications of natural variability in introducing uncertainties and these have concentrated on inter-annual variability in sediment loads. Day and Spitzer (1985) have quantified these uncertainties in terms of the standard error of the mean and using annual sediment data determined using rating curves for several Canadian rivers, Day (1988) reported that the mean characteristics were sufficiently stable for most engineering and environmental applications after 10 years of record. However in the example given by Day the standard error of the mean was in the order of 40% after 10 years. Using the long term daily record of the Missouri River, Parker (1988) found that inter-annual variability led to considerable uncertainty in terms of a sediment budget even with a relatively long period of record. Nordin and Meade (1981) suggest that variability is greater in small basins than large ones and so a longer record is required to obtain the same relative accuracy.

As natural variability of the stream sediment regime changes then so will the uncertainty associated with mean loads and the length of record required to obtain the same level of confidence will differ. As suggested by Nordin and Meade (1981) this can occur with varying basin size within a particular environment but it will also arise where variability changes between environments. In all cases this uncertainty can be quantified in terms of the standard error of the mean which has been outlined by Day and Spitzer (1985) as

$$Se = 100\ C_V / \sqrt{n}$$

Where Se = standard error of the mean suspended sediment discharge (%), C_V = coefficient of variation and n= number of years of record.

Figure 1 shows the behaviour of the standard error over time with a range of coefficients of variation of the mean annual load. Where coefficients are high a long period of record is required to reduce the standard error associated with annual variability. Inter-annual variability is obviously only one measure of stream variability and others could be used, for example inter-storm and intra-annual variability are also important. Inter-annual variability is used here as sediment yields are frequently expressed in terms of annual loads and data on them is more readily available, but it is recognised that this does involve some generalisation of the data.

Very few studies have published "actual" load data for a reasonable time scale based on detailed or continuous monitoring. Walling and Webb (1988) have determined loads for two small basins near Exeter for periods of eight and 10 years. Parker (1988) has reported C_Vs and standard errors for rivers in the Missouri River for loads calculated from daily samples for periods ranging up to 36 years. A detailed eight year record has been determined for three small streams in the Ord River basin in north west Western Australia (Wasson *et al.* 1991). The results from these studies are shown in Table 1. More data is available for loads determined using the rating curve approach because of its ease of calculation, but this data is subject to question as outlined in the previous section. However, while there is doubt about the accuracy of loads determined in this way, examination of the results of Walling and Webb (1988) reveals that, while they

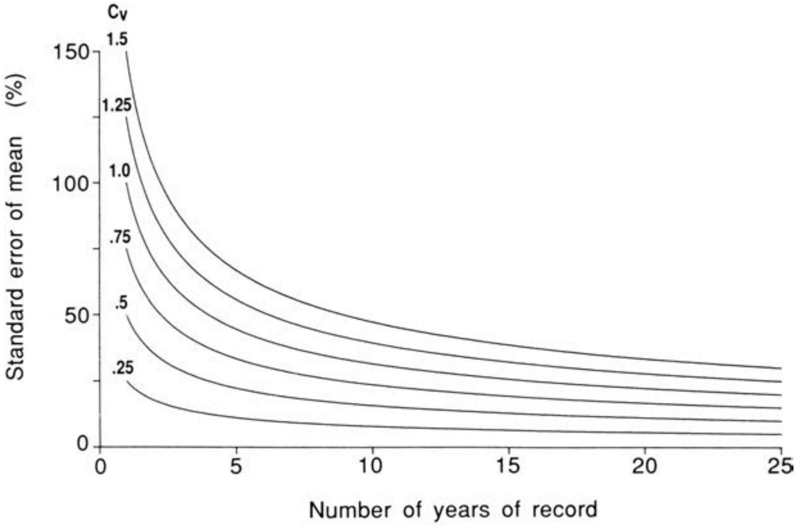

FIG. 1 Relation between standard error of the mean annual load and length of record for a range of coefficients of variation.

have reported large errors in the load calculations, the C_V and Se for the rating curve loads are not significantly different from those of the actual loads (Table 1) so rating curve results may give a reasonable indication of the variability of the stream system. Table 1 also lists results from several studies based on rating curve loads.

TABLE 1 Coefficients of variation of mean annual sediment load for selected streams.

River	Area (km^2)	Length Record (years)	Load estimation	Sediment Load ($t\ km^2\ yr^{-1}$)	Cv	Source
Creedy	262	8	actual	39.5	0.58	Walling
			rating CF1	29.5	0.63	& Webb
			rating CF2	32.5	0.63	(1988)
Dart	46	10	actual	245	0.46	
			rating CF1	52.8	0.42	
			rating CF2	83.7	0.42	
Missouri	724 000-	21-36	daily		0.22-	Parker
	1 368 038		readings		0.48	(1988)
Oldham	4 400	21	rating		0.85	Day (1988)
Limestone	7.8	8	actual	136	0.63	Wasson
Smoke	26.1	7	actual	34	1.00	*et al.*
Gap	9.8	8	actual	107	0.53	(1991)
Ord	7 770-	6-12	rating	112-	0.81-	Kata
	46 100			708	1.02	(1978)

While the data outlined in Table 1 is limited, it does cover a range of basin sizes and different environments and there are a range of C_Vs. In particular environments, variability does not always increase with decreasing basin size as suggested by Nordin and Meade (1981). Where data were available, it was found that the variability in sediment loads was greater than that of stream flow, which is to be expected as sediment is related to a range of variables and not just discharge. It is likely that as the variability of stream flow increases then so will that of sediment transport. Much more data is available for streamflow and Finlayson and McMahon (1988) in an analysis of world streams found that commonly, variability increased with decreasing runoff and with decreasing basin size. The streams of Australia and southern Africa were found to have high variabilities relative to other areas in the world and a comparison of areas with similar climatic regimes showed that this was not just a function of their aridity. They also found in these areas that low frequency high magnitude events were relatively larger and it is likely that such events are of major significance in terms of total sediment transport. Unfortunately, it is not possible to undertake a similar analysis for sediment loads due to lack of data but it is possible that sediment loads show similar trends.

From the data in Table 1 it is clear that inter-annual variability and its associated standard error are important when inferring longer term erosion rates or sediment budgets from relatively short term data. The basins studied by Walling and Webb (1988) experience relatively low variability of both rainfall (Cv 0.12) and runoff, but even in such an environment annual sediment loads vary considerably, with inter-annual C_Vs of 0.45 and 0.58. In the River Creedy, the most variable case, after six years of record the standard error of the mean annual load is +/- 23.7% and to get this error down to 20% would require nine years of record, in the River Dart, where the record is longer and variability less, the standard error is +/- 13%. These basins provide probably the best longer term record of "actual" loads and occur in an environment with low variability relative to most of the rest of the world so provide the most realistic estimates of longer term rates. However, even in this low variability environment, if loads are based on short term monitoring they would have relatively high standard errors, for example two years of record in the River Dart would give a standard error of +/- 31.8%. In environments where variability is greater and sediment loads are based on short term records, the standard error of annual means will be much higher and a much longer sediment record will be required to reduce the error associated with the variability. For example, in the Smoke basin data from the Ord area in Australia (Table 1) where the C_V is 1.003 a record of two years would result in a standard error of +/- 71% and this would not be reduced to 20% until 20 years of record was obtained. Unfortunately, at present little data is available over any reasonable time frame to enable any detailed analysis of general patterns of sediment transport variability, but in many areas of the world it does appear to be significant and any calculation of sediment loads or yields needs to consider the role of variability on the representativeness and viability of the results.

Variability in sediment transport has important implications in any consideration of whether to monitor or not and how to carry out any monitoring program. The answers to these questions will depend to a large extend on why the information is required. In some cases it may be of very little relevance as suggested by Day (1988) where he claimed that 10 years of record was adequate for most engineering and environmental applications in a range of Canadian rivers. However, if the data is to be used to infer long term or general conditions then variability must be considered, for example in Day's study the standard error of the estimate of the annual load was still approximately 40% in the Oldman River after ten years of record. Where longer term loads or yields are determined based on a short term record, some statement needs to be made of the uncertainty of how representative the data is, maybe this could be based on streamflow variability in the absence of more sediment data. In highly variable environments it is unlikely that sediment yields based on short term monitoring accurately represent long term averages. Considerable care needs to be taken when such results are used to determine sediment budgets as the stream load is related to sediment sinks and sources which are commonly related to much longer termed geomorphic change. Also, in any analysis of the impact of landuse change in a variable environment, a long precalibration record is required to adequately characterise the sediment regime and the there is a low probability of being able to generalise the impacts outside the flow regime which occurred during the disturbance phase.

In establishing a monitoring program aimed at representing longer term trends then consideration needs to be given to the length of time required to reduce the inter-annual standard error down to an acceptable level. To optimise the accuracy of results it may require some compromise in the sampling and analytical techniques which enables an extension of the length of the monitoring to produce a more representative data set. Alternatively, some technique other than monitoring such as the analysis of dam cores or using sediment tracers may provide a better and more cost effective solution. The question of variability in suspended sediment transport needs to be given much more emphasis as it may seriously compromise the accuracy of any inference of longer term transport rates. At present, there are very few long term detailed monitoring records and so we have little information on the scale of variability and its spatial variation. This situation can only be rectified by an increase in the amount of long term detailed data. Most long term estimations are based on sediment rating curves where the is the additional problem of errors in the estimation techniques outlined above. Consideration should also be given to "calibration" of monitoring records against other techniques particularly lake sediment accumulations where there can be a testing of short term correlations and the representativeness of short term monitoring with respect to longer term sedimentation rates. Such an exercise has been carried in Britain by Foster *et al.* (1985) and Foster & Dearing (1987). The major limitation to such a comparison may be the difficulty of resolving short term sediment yield data from lakes for time periods of less than ten years (Foster *et al.* 1988).

CONCLUSION

Despite the increasing economic importance of erosion, sediment transport and sedimentation, there is still very little data longer term detailed monitoring programs and this situation is unlikely to change in the near future given the current economic climate. In the establishment of any monitoring program a number of fundamental questions need to be addressed. First, should we monitor at all or will some other technique provide the answers in a more cost effective way? Second, if the decision is to monitor, what are the data requirements and how can that data be best acquired so that it meets the required level of accuracy in the most cost efficient manner? Finally, if we are inferring trends outside the study period, are the results obtained representative of the processes operating in the stream system and do transport rates or sediment loads relate to longer term averages of the system? The question of accuracy of sampling, analytical and estimation methods has been addressed in considerable detail but that of the representativeness of the data has been given scant attention, particularly with respect to the role of natural variability in the system. In variable environments, short term monitoring will lead to high levels of uncertainty with respect to long term average loads which can only be resolved by increasing the length of record. At present we have little knowledge of the patterns of variability and this situation can only be improved by increasing the number of long term data bases over a range of environments and possibly by calibration against other techniques such as lake sedimentation studies. In inferring longer term trends we need to be aware of the limitations of our data and attempt to at least place some error terms on it. The ultimate question should be are we collecting the data to the required level of accuracy in the most cost effective manner and does it represent what we purport it to represent?

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