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Detecting change in sediment loads: where and how is it possible?

KRISTIN BUNTE & LEE H. MACDONALD
Department of Earth Resources, Colorado State University, Fort Collins, Colorado 80523, USA

Abstract A constraint on land managers is that their activities should not significantly increase the sediment load in the basin of interest. Practical reasons preclude directly measuring sediment yield from all sources. The alternative – detecting significant change in fluvial sediment loads – is constrained by the temporal variability of sediment transport, measurement uncertainty, and distance between sediment sources and the sampling location. The issue of spatial scale is rarely recognized but can greatly affect the result. The best location to detect a change in sediment load depends on the rate at which sediment from different sources moves through the stream network, and this is primarily a function of the particle sizes, sequence of channel types, and flow regime. Existing literature and data sets were used to analyze and quantify temporal variability of sediment transport, sampling accuracy, variability between basins, and rate of sediment travel.

INTRODUCTION

Forest management and other land uses in mountainous watersheds generally increase low flows, peak flows, and sediment production. Increased sediment loads can alter stream channel morphology, damage both fish and riparian habitat, and reduce channel capacity (e.g. Salo & Cundy, 1987; Meehan, 1991). Although individual management activities can increase sediment production and, to a lesser extent, sediment loads, more severe effects can result from the simultaneous deposition of sediment from several sources. Biologic responses, such as a decline in spawning success, can be disproportionately large relative to the change in sediment load. Hence the ability to predict the location and magnitude of sedimentary cumulative effects is of great interest to land managers.

Primary sediment sources include mass wasting, surface runoff, and in-channel scour. Sediment from each of these sources will generally have very different grain size distributions and downstream transport rates. Downstream transport of coarse sediment is a highly sporadic process, with individual particles being stored for periods ranging from seconds to centuries. The transport and storage of sediment in the downstream direction also depends on the flow regime and the sequence of channel types, as these determine the energy available for sediment transport. These factors can result in a large longitudinal spread within the stream network and tremendous temporal variability in the arrival of a particular slug of sediment.

Clearly the ability to recognize and minimize adverse change is limited by the sensitivity of our monitoring procedures. Given such different transport rates for particles of different sizes from different sources, it is essential to address the following issues:

* To what extent will a slug of sediment be attenuated in the downstream direction, and what are the implications for detecting change?
* How fast will sediment from various sources and locations be transported to the monitoring location, and then out of the reach of interest?
* What is the underlying uncertainty in terms of our ability to accurately measure sediment transport rates and detect a change in sediment loads?

ANALYSES

The diversity of sediment transport processes, grain size spectra, and basin response to altered flow and sediment supply all contribute to the observed variability of sediment transport across a range of temporal and spatial scales. This variability in sediment transport limits the accuracy of sediment load estimates which, in turn, determine the detectability of a change in sediment load (Table 1). Information on each of these topics was compiled through comprehensive literature reviews. Both published and unpublished data were used to quantify the key components in Table 1. Of particular concern were: (a) the temporal variability at different scales, and (b) measurement accuracy. Together these two factors set an absolute limit on our ability to detect change.

The finest analytic scale is the variability over short periods (seconds to hours). The variability on this scale and its implications for sampling were analyzed from approximately 40 high-resolution data sets of bed load transport from flumes and natural channels. The spatial equivalent of this short-term fluctuation is the variability of sediment transport within the channel cross section.

The next analytic scale examined temporal variability in sediment discharge relations for single storms or runoff seasons. Of particular concern was: (a) the variation in the magnitude and direction of hysteresis loops, and (b) the accuracy and precision of annual load estimates according to the sampling strategy for rating curves (Walling & Webb,

Table 1 Temporal and spatial scales of variability and their implications for estimating sediment loads and detecting change.

Scales of temporal and spatial variability	Affected measurements	Means to improve the accuracy and detectability of changes in sediment load
* Short-term * Cross-sectional	Sediment transport rate, sediment concentration	Intensive measurements to identify patterns of temporal and spatial variability in order to devise appropriate sampling regimes
* Intra- and inter-event * Site-specific	Sediment rating curve; estimated event and annual sediment load	Refined, event-based sampling strategies to account for hysteresis, site-specific effects, and the duration and spacing of high flow events
* Inter-annual * Inter-basin	Limits detection of change in annual sediment loads over time and between basins	Collect long-term data sets to quantify mean and variability in annual sediment load on a regional basis and variability in the basin-specific response to disturbance

1982, 1988) and summation (time integration) procedures (Walling & Webb, 1981), respectively.

At the largest temporal and spatial scale we analyzed annual and inter-basin variability. Annual variability was evaluated from 37 data sets ranging in length from 10 to 35 years. Spatial variability was evaluated by comparing annual loads and response to management from paired basins.

Three basic procedures can be used to evaluate downstream sediment delivery, and these are: (a) dilution model; (b) delivery ratios; and (c) field measurements of the rate of downstream sediment movement or, conversely, sediment storage. The precision and applicability of each of these methods were evaluated using existing studies, simple models, and our analyses of published data.

RESULTS

Variability of sediment transport and accuracy of load estimates

The temporal variability between samples can easily be an order of magnitude at the short-term, inter-event, and annual time scales. The high short-term variability of bed load transport in streams (e.g. Carey, 1985; Reid *et al.*, 1985; Whiting *et al.*, 1988; Lisle, 1989; Gomez *et al.*, 1991; Bunte, 1992; Dinehart, 1992) suggests that one must measure over a time period sufficient to capture this variability, and this can be done either by sampling at individual locations for longer time periods or by increasing the number of shorter-term samples. The appropriateness of each strategy depends on the sampler capacity and the representativeness of the sampling period on a longer (e.g. daily or weekly) time scale.

Measurement accuracy is another important factor which limits the ability to detect change. Helley-Smith samplers, for example, do not provide accurate bed load transport measurements in many mountain streams. Problems include an opening too small to capture coarse gravels (Bagnold, 1977), an unrepresentative sampling of different grain sizes due to the hydraulic efficiency (Hubbell *et al.*, 1985), clogged bags (Beschta, 1983), and poor contact between the sampler and the stream bed. The resulting measurements of bed load transport rates can easily be off by half or even a full order of magnitude. In general, the measurement error increases with particle size, since the largest particles are transported most sporadically and are usually not sampled representatively with small bed load samplers. The cross-sectional variability of suspended sediment (e.g. Edwards & Glysson, 1988; Bley & Schmidt, 1991) and the problems of taking a representative sample of suspended sediment lead to similar inaccuracies with automated pump samplers.

We defined sampling intensity as the percent of the time and channel cross section actually sampled divided by the total amount of time and cross-sectional width which could be sampled. One hundred percent sampling intensity means that the entire cross section is sampled all the time (as would be the case with a continuously operated vortex sampler). Intensive research studies using a hand-held Helley-Smith typically measure only a fraction of one percent of the potential samples, and sampling intensity is much lower for most monitoring studies. For example, taking twenty 2-min samples with a 7.6 cm Helley-Smith sampler across a stream 10 m wide on a weekly basis yields a sampling intensity of only 0.003%; extrapolating from these measurements requires multiplying by a factor of approximately 33 000. Even if the measurements are assumed to be representative of the total cross-sectional bed load flux over the entire 40-min sampling period, the observed transport rate must still be multiplied by a factor of 250 to estimate the weekly sediment load.

Another problem is that samples taken during normal working hours may not be representative of the total population of samples which could be taken. Continuous bed load measurements from a 105 km^2 basin in south-central Montana during snowmelt high flows indicated that only 25% of the hourly measurements fell within 3-h time periods (the assumed sampling period) when actual transport rates were within 75 to 150% of the mean bed load transport for that day (Bunte & MacDonald, 1993). These 3-h blocks tended to occur on the rising limb of the daily snowmelt hydrograph, although they could occur at any time depending on the hysteresis for that particular day. Sampling or estimating ***mean*** transport rates is critical when sediment load is calculated by integrating over time (e.g. Ketcheson, 1986).

In contrast, sampling should focus on high flows to estimate sediment loads when using a rating curve. For most snowmelt-dominated basins, there typically is a lag of 4-12 h between peak melt and peak runoff, which means that peak runoff and periods with bed load transport rates close to the daily mean usually occur in the late afternoon or at night when few management agencies are sampling. To use either the summation or the rating curve approach effectively, one must make intensive measurements to identify site-specific patterns of temporal and spatial variability; only then can an appropriate sampling regime be developed (Table 1).

The coefficient of variation (CV) can be used to calculate the number of samples needed to estimate the mean transport rate to a specified accuracy (Kuhnle & Southard, 1988). Our analysis of sequential bed load data from flume experiments with constant flow and from streams at relatively steady high flows yielded CVs of 50 to 75%. In these cases mean transport rates can be estimated with 50% accuracy from four to nine samples (Fig. 1). Bed load data taken over storms and snowmelt high flows typically had CVs of 100 to 125%, suggesting that 15 to 24 samples must be taken during an event to estimate the mean transport rate within 50%.

The variability in sediment loads within and between events also must be considered when developing a sampling procedure and evaluating the detectability of change. The physical processes of sediment supply and sediment exhaustion mean that the discharge to sediment relation is not constant (e.g. Ketcheson, 1986), nor is there necessarily any consistency in the hysteresis loops between high flow events (Olive & Rieger, 1985; Williams 1989). Fixed interval sampling on a weekly or monthly schedule yields a large number of samples with little or no sediment and only a few high flow samples to estimate the bulk of the sediment load. Such sampling strategies can result in order of magnitude errors in the estimated annual sediment load (Walling & Webb, 1988). Event-based sampling emphasizing high flows has been recognized as a much more efficient and accurate approach to estimate sediment loads (e.g. Walling & Webb, 1981; 1982; Thomas, 1985; Thomas & Lewis, 1993).

Most studies use the annual scale when assessing a change in sediment yield, but a high annual variability limits the ability to detect change. We found that the coefficient of variation for annual sediment loads typically ranged between 75 and 125%. This high level of variability in both snowmelt and rain-dominated areas means that decade-long

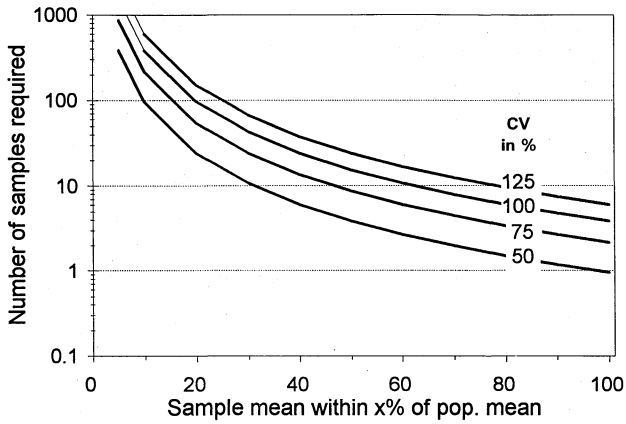

Fig. 1 Effect of the coefficient of variation (CV) on the number of samples needed to obtain a sample mean that has a 95% probability of being within the specified percentage of the population mean. The CV for each line can be associated with typical flow and sampling conditions. From top to bottom, the lines represent intermittent sampling (e.g. once per day) during seasonal high flows, yielding CVs of about 125%; sequential sampling (e.g. once per hour) during a storm event, producing CVs of about 100%; sequential sampling with nearly constant flow, obtaining CVs around 75%; and continuous sampling in a flume with constant flow, yielding CVs as low as 50%.

sampling periods are required to detect a 50% change in annual sediment loads. Land managers, however, generally cannot afford to wait this long to determine whether management is affecting sediment loads. Furthermore, stationarity cannot necessarily be assumed over such long time periods.

In the most extreme case 84% of the total sediment load over a 31-year period occurred during one storm (Grant & Wolff, 1991). Thus, mean annual sediment load may become meaningless as a standard for evaluating change. Field evaluation of mobile and stored sediment is often a better approach, especially in areas with highly variable sediment loads.

Interaction between spatial and temporal scales

The temporal variability and sampling issues described above are both parallel to and closely interlinked with the issue of spatial scale. The variability of sediment transport across the stream channel and within the water column is well documented (e.g. Pitlick, 1987; Gomez, 1983; Beschta, 1987; Bley & Schmidt, 1991), and most sampling strategies are designed to minimize this variability. If sampling effort is fixed, there is a trade-off between more sampling at key locations within the cross section and sampling for shorter time periods at more locations. Gomez *et al.* (1991) recommend repeated bed load sampling at a few cross-sectional locations because temporal variability at a site is usually larger than the spatial variability within a cross section.

Similarly, the detectability of a change in annual sediment load depends upon the location of the additional sediment sources relative to the sampling location, the particle size of the introduced sediment, flow regime, and intervening channel types. A slug of introduced coarse sediment may take years or decades to reach a cross section being monitored, while fine material may be rapidly transported through the fluvial system. The persistence of introduced sediment also varies among reaches and basins.

The paired watershed approach is an alternative means to detect a change in sediment yield, as it compares annual sediment loads between a treated and a matched control basin. Hence the ability to detect change depends largely on the quality of the relationship between the treated and control basins. Regressions of annual sediment yields from studies with two or more control basins found coefficients of determination (r^2) to vary from 0.0 to 0.9. Some basin pairs showed a marked change in their relationship with no apparent explanation. The design and limited calibration period of most paired watershed studies means that a change in the relationship between basins would usually not be detected, and any such shift would be incorporated into the estimated management impact.

Procedures for predicting sediment transport and sampling locations

Three main procedures can be used to predict the downstream delivery of sediment and hence the most appropriate location for sediment monitoring: (a) dilution model; (b) sediment delivery ratios; and (c) field analyses of the rate of downstream movement or sediment storage.

The dilution model applies mass balance equations to predict the concentration of sediment at a downstream location. Discharge must be known or estimated at each location of interest. We developed a simple model that assumed no sediment deposition but incorporated increased flow and sediment concentrations from forest management activities. Different scenarios evaluated the detectability of various increases in suspended sediment relative to background concentrations and presumed detection limits. Results suggest that it may be easier to detect an increase in suspended sediment when the background concentration is higher, as the increase is not as diluted in absolute terms. The main problem with dilution models is that they apply only to clay-sized particles which do not settle out, while from a fisheries perspective sands and fine gravel are usually of greatest concern (e.g. Chapman, 1988).

As noted by Walling (1983), it is very difficult to justify the use of sediment delivery ratios to predict the downstream delivery of sediment. Grain size distribution varies with sediment source, and different grain sizes have very different transport and storage rates. The delivery, transport, and storage of sediment is also controlled by the specific fluvial environment. Thus, delivery ratios vary greatly with grain size, flow regime, and sequence of channel types. The resulting temporal and spatial variability in delivery ratios make them too inaccurate for most predictive or modeling purposes.

Given these problems with dilution models, comparisons over time and space, and sediment delivery ratios, an alternative approach is needed to detect changes in sediment yield. One possibility is to track sediment on its way downstream and thereby predict the arrival, longitudinal spread, and residence time of a particular slug of sediment in the reach of concern.

A variety of techniques can be used to mark and trace individual particles, but a large number of marked particles and a high recovery rate are required to account for the extreme variability in the downstream rate of travel. The transport of coarse particles is also highly intermittent. Between transport periods, particles can be stored in the channel bed, in bedforms and gravel bars, around flow obstructions, or on flood plains and terraces for periods ranging from seconds to centuries. Statistical distributions describing the event-based or annual travel distance become invalid as this distance approaches the spatial scale of recurring fluvial storage elements such as gravel bars (Hassan *et al.*, 1991). The variability in channel characteristics (gradient, roughness, and morphology), type of sediment (size, density, and shape), and flow regime (Hassan *et al.*, 1992; Hassan & Church, 1992; Schmidt & Ergenzinger, 1992; Gintz, 1994) make it difficult to predict the rate of travel, and there are almost no data on travel distances over periods longer than one year. Our review indicates that the approximate mean annual transport distances in mountain streams for suspended sediment, sands, and gravel are on the order of 10^4, 10^3, and 10^2 m year^{-1}, respectively.

A feasible alternative to detect a change in sediment load is to identify storage locations and estimate their volume and residence times (Swanson *et al.*, 1982). Dietrich & Dunne (1978) present the basic procedure for constructing a sediment budget, a procedure that slowly has been gaining acceptance. Geomorphological analysis also helps to evaluate relative susceptibility to adverse effects and suitability for monitoring. Reaches with low gradients and transport capacity are the most likely locations for in-channel storage and are therefore most susceptible to damage from cumulative sedimentary effects. On the other hand, narrow and steep reaches may be suited for directly measuring sediment loads.

CONCLUSION

Sediment transport is highly variable across a wide range of temporal and spatial scales. Accurate measurements, intensive sampling schemes, and careful selection of the monitoring site relative to sediment inputs are critical to detecting a change in sediment load. Typical sampling schemes are not able to detect small changes in sediment load. The best alternative may be to evaluate changes in stored sediment over the time and space scales of interest.

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