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Measuring Suspended Sediment in Small Mountain Streams

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Measuring suspended sediment concentration in streams provides a way of monitoring the effects of forest management activities on water quality. Collecting data on suspended sediment is an act of sampling. The nature of the delivery process and the circumstances under which data are collected combine to produce highly variable results that are difficult to analyze and interpret. Data-collection stations are set up to compare one set of measurements to another. They should be located with regard to channel morphology. Deciding when to measure suspended sediment is a major problem in carrying out most studies. Concentration depends heavily on streamflow discharge, which can be used to allocate sampling resources to appropriate flow levels. Restrictions in budgets and technical concerns have fostered the increased use of automatic pumping samplers in measuring suspended sediment.

Retrieval Terms: suspended sediment, sampling, measurement, pumping samplers

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Land management agencies are under increasing pressure to monitor the effects of their activities. One consequence has been a concern about the amount of sedimentation in streams near logging operations in forest stands. Sedimentation can adversely affect water quality as well as fish habitat. The Forest Service, U.S. Department of Agriculture has responded to this concern by increasing its collection of data on suspended sediment in streams. However, a unique set of problems exists when suspended sediment concentration is measured in forested catchments-especially those in which rain is the dominant form of precipitation.

Most suspended sediment moves during infrequent high flows that collectively account for only a small portion of the measurement period. The associated high transport rates and variances dictate that most data be collected during high flows, but the infrequency and brevity of the high flow periods combined with measurement and access problems cause acute problems in collecting data.

These problems will not be solved merely by increasing the amount of suspended sediment data collected. The collection process is both complex and expensive. Therefore, it is vital that such efforts yield maximum return. Often, data are collected without giving adequate thought to identifying the objectives or the administrative and technical problems that largely define what can be measured and how to measure. In such situations, analyses are difficult and interpretation ambiguous. No matter how sophisticated, analysis and interpretation can never substitute for well collected data.

This report describes the administrative and technical problems that define what to measure and how to measure suspended sediment in small mountain streams. It examines the factors that govern the quality of data collected in a monitoring program, with particular attention to use of automatic pumping samplers.

STATISTICAL CONSIDERATIONS

Hydrologists measure suspended sediment to compare one set of values with another. For example, they collect data above and below a logging site to determine how disturbance affects sediment concentration by comparing two sets of values. When checking for standards compliance, they compare their measurements to the standard. Even when “background” levels are being established, future data will be collected to compare with these levels.

A major concern is how such comparisons can be made “fairly.” Hydrologists should be sure that any detected differences result from real differences between conditions and not from unrecognized factors in the measurement process. Keeping such factors to a minimum is not simple. Hydrologists must pay constant attention to details to ensure that they do not inadvertently introduce any unintended effects.

Data sets ate formally compared by one of several standard statistical techniques. Such techniques must be used because the data ate samples from larger populations that are impossible or impractical to measure totally. Each technique is based on a set of assumptions. Data collection must conform to these assumptions–at least approximately–for the test outcome to perform as designed. These assumptions bear not only on the nature of the measured phenomena, but also on how they are measured. The procedure used to choose values or items for inclusion in the sample is at least as important as the actual mechanics of measuring.

Measuring suspended sediment in streams is really sampling. Compared with continuous flow records that are essentially complete, only a very small proportion of the potential suspended sediment samples are actually collected and measured. Because inferences are based on samples, the procedure by which samples are selected greatly affects the properties of the inferences made.

Most data can be placed into one of two classes—time series or independent: The first type depends fundamentally on time or some other continuum along which the data occur. This class is characterized by dependence among data close together along the continuum, and by the fact that the order in which the data ate sampled is of central importance in the analysis. The parent sequence and the sample taken from it are both called *time series.* Time series are usually sampled at equal time intervals, and the major sampling consideration is the length of the interval.

The second type of data is more common and does not depend on time. Instead, sample elements ate chosen according to a formal random process that ensures statistical independence. Samples of this type are referred to as *independent.*

Elements of a population should not be selected purposefully for inclusion in a sample. Estimates of basic population characteristics based on purposeful samples are often "biased;” that is, the sample estimates of means and variances are *systematically* distorted from their population values. This means that the averages of the estimates of means or variances from all samples that could be collected do not equal their population values. This systematic distortion of estimates applies to the samples as a group rather than to any individual sample.

Most data sets of suspended sediment concentration in small mountain streams are not subject to time-series analyses because of the sporadic nature of the process and acute difficulties of measurement. This problem may be partially solved by the recent increase in the use of automatic pumping samplers that can be operated at equal intervals of time or flow. An excessive amount of data would be collected, however, if data ate taken during low flows with a time-based sampling interval short enough for describing variation during high flows. Therefore, time series analyses of sediment data are likely to be used only for special theoretical investigations, and independent samples used for application-oriented studies.

Traditionally, suspended sediment data have been collected opportunistically and treated as though they were independent data. Considering the large variation in such measurements and that samples were infrequent, perhaps the dependence structure of the sediment delivery process is not too critical for crude estimates. However, more samples need to be collected during high flows than is usually done.

One strategy widely used with independent data is stratification. The population is partitioned into several strata, each of which contains relatively homogeneous measurements of interest as compared with the total population. An efficient plan can then be developed to distribute sampling effort where most needed on the basis of stratum size and significance as well as variance. Prior knowledge about the structure of a population is better used in defining strata than in selecting a purposeful sample.

MEASURING SUSPENDED SEDIMENT

Suspended sediment is commonly measured with devices ranging from a vessel dunked in a stream to automatic pumping samplers. Regardless of the device used, the size of each water sample taken is extremely small. Consider taking one 500-ml water sample every hour from a stream flowing at 0.01 m^3/sec. For a sampling frequency and water sample size that are high by current standards, and for low discharge and suspended sediment concentration, this water sample represents only about 0.0014 percent of the flow! Another way to look at this is that of the 71,429 samples of 500 ml, that could have been collected during one hour's discharge, only one is selected. In sample survey work a 1 percent sample is considered small, but in this example under favorable conditions, the sample is only about 1/700th of that. For higher discharges-when suspended sediment concentration is higher and, therefore, more critical-or lower sampling frequencies, the proportion sampled is even smaller.

A small sample size is not necessarily inadequate; a small sample may be adequate if the variance of the process measured is small. But suspended sediment data sets from small mountain streams tend to have large variances, at least when considered across a wide range of flow conditions. It is this high variance, which increases with increased discharge, that causes most data collection problems. Suspended sediment concentration data from undisturbed watersheds in rain-dominated areas are characterized by periods between storms when concentration is relatively low and steady, interspersed with storm periods that produce wide fluctuations in discharge and concentration. In snow-dominated regions, these fluctuations are not as great, but the relationship between level and variation remains. Management activities can make this pattern more pronounced.

As an aid in planning suspended sediment measurement programs, consider the process of sediment transport and the associated physical quantities. At a stream cross section, a flux of both water and suspended sediment can be expressed as volume or mass rates for any instant in time. Water discharge is usually expressed as a volume rate and is represented as a time function on a hydrograph. An analogous time function gives the mass rate of sediment transport. The ratio of the suspended sediment mass rate to the water volume rate for a specific time is the mean suspended sediment concentration in the cross section. Three quantities of interest change over time-water discharge, suspended sediment transport, and suspended sediment concentration-each with its own actual or conceptual graphical representation.

For sediment studies, defining the suspended sediment transport process would be sufficient, but this process cannot be measured directly. A second approach is to approximate the transport process by multiplying water discharge and suspended sediment concentration measured continuously. It is not possible to measure instantaneous mean cross sectional suspended sediment concentration, and is difficult and expensive to measure continuous suspended sediment concentration at a point The usual compromise is to measure suspended sediment concentration periodically at a point or along verticals in the cross section and use those values to estimate the mean concentration in the section as a whole.

In turbulent mountain streams, mixing can be fairly complete so that suspended sediment concentration will be similar throughout a cross section except near the bed. In slower streams, however, the concentration at a given point in a section may not be the same as the concentration at another point or as the mean concentration for the whole section. Channel morphology, velocity gradients, and sediment size distribution combine to produce this variation. Each point in the cross section is associated with a time function, giving the concentration at that point which may be similar to but is not identical with the one for the stream as a whole. Each measurement, therefore, should either cover the section adequately to allow a good estimate of average concentration, or should come from a point with a known relationship to this average.

Also, cross sections at different locations on the same stream cannot be expected to have the same concentration time series even when close together. Downstream, more water and new sediment sources, combined with changes in channel morphology, can produce changes in patterns of sediment mobilization, suspension, and deposition.

These conceptual time function and associated graphical representations are useful tools for focusing the hydrologist's attention on data collection problems and on the disparity between what one intends to measure and what actually is measured.

When collecting suspended sediment data, the use of different sampling schemes or different measuring devices for the several conditions to be compared can bias measurements. By sampling various flow classes at different relative frequencies before and after a logging operation, for example, a false "difference" could be introduced solely or in part by the sampling system itself. The different and complex hydraulic properties of measuring devices virtually ensure that comparing them will be subject to inherent differences and, therefore, will be suspect. Two primary ways to overcome this problem are either to use the same measuring devices and techniques at all stations, or to calibrate to a standard.

Where to Measure

The question "where to measure" usually has a simple answer because most often a particular activity dictates, in large degree, where data must be collected. Occasionally, however, the suspended sediment concentrations or loads of an entire area need to be characterized, so the more complex question arises of what watersheds to measure and where to measure them. The answer depends largely on the information wanted and the particular situation being studied. Often these kinds of investigations have poorly defined goals, so general prescriptions for sampling networks cannot be given. For such projects the hydrologist should carefully consider how the data will be used, and what questions they are intended to answer, and then get statistical help in designing an appropriate sampling plan.

When a specific disturbance is being monitored, the question of where to measure in the local sense is more pertinent. Generally, measurements should be made downstream as close to the disturbance as possible. The effect of a sediment-producing condition is attenuated and its effect confounded with the effects of dilution and other sediment sources farther downstream. If the downstream effects of a disturbance are being studied, it is best to measure at the site being affected.

Suspended sediment concentration data are often collected above and below a disturbance and the difference between stations taken as a measure of change caused by the activity. This can be a useful approach, but it is often done in a way that gives equivocal results. It may be assumed that suspended sediment concentration patterns at the two stations are identical, that "background" levels are uniform along the stream, and that any measured differences can be attributed to effects of the disturbance This is not always a valid assumption, however, and should be tested in all cases by monitoring the two stations before the activity is begun. Usually, a regression relationship can be developed to estimate the "undisturbed conditions" response at the lower station given a measurement at the upper station. This relationship can be compared to actual levels measured at the lower station after the management activity has occurred. If the background levels at both stations are shown to be the same, comparisons can be made directly.

Such comparisons of "before" and "after" require mom time and effort—something not often available before logging or some other change. The fact remains that if the disturbance is measured only after it occurred, any indicated differences between effects of the "treatment" and natural differences at the two stations cannot be apportioned. The activity may have caused the change, but there may have been a difference between stations before treatment-which posttreatment data cannot indicate. In some such cases, the best monitoring decision may be to forego measuring because collecting data that can give no valid results is a waste of money and effort.

Where to locate measurement stations also depends on the hydraulic conditions in streams. Often found in mountain streams are pool/riffle sequences (Leopold and others 1964). These generally stable features result from interactions between storage and transport of coarse sediment, and hydraulic control from channel bends, bedrock outcrops, and large organic debris. The conditions that exist at different positions within a pool/riffle element can be expected to affect not only the suspended sediment concentration, but flow measurements as well.

Paired stations should be set up in the same relative position within their respective pool/riflle elements. It is best to measure just above the downstream end of a pool where the stream spills over the crest into the riffle below. This crest acts as a control section having relatively uniform sediment and flow profiles thereby making it easier to collect accurate data. During high flows, however, control may be affected by bank conditions and channel morphology. Therefore several pool/riffle elements should be investigated to select one that will maintain control through an adequate range in flow. In some streams, control can be effected by geology or large organic debris. Bedrock cropping out at the crest of major riffles or falls can provide excellent control in natural channels. In some situations, well emplaced logs stabilize channels and provide good locations to measure both suspended sediment concentration and discharge.

If suspended sediment concentration characteristics vary up and down stream according to position within the pool/riffle sequence, care must be taken to occupy the exact same cross section for all measurements at a station. Small changes in position of the intake of the measuring device—either up and down stream, or within a cross section-can adversely affect measurements. Reliable markers should be installed at the stations so that data will be collected at the same places each time to remove this avoidable source of difference.

When to Measure

Once stations have been established, the data collection system must be decided on. Questions about sampling protocol are the most often asked and the most difficult to answer. A complete answer depends on the purpose for which data are taken, the analysis techniques to be used, and the characteristics of the particular set of data being collected. Short of defining the ideal sampling system, several general principles can help the hydrologist improve data collection. One general principle involves the relationship between flow and suspended sediment concentration

Discharge and Suspended Sediment Concentration

In most streams suspended sediment concentration is strongly correlated with discharge. Large river systems usually contain abundant channel materials available for movement, so the energy of water discharge is often a good predictor of concentration. Streams draining small mountain catchments, however, often depend for their suspended load on episodic contributions of fine materials from banks and upland areas. In these "event response" streams (Yaksich and Verhoff 1983) suspended sediment concentration depends on supply as well as discharge, and so they tend to have poorer relationships between suspended sediment concentration and flow. Nevertheless, discharge remains the best commonly measured correlate of concentration, and is useful as a guide to sampling.

The flow/suspended sediment concentration relationship is often exploited to estimate total suspended sediment yield for a period of record. Numerous discharge/concentration pairs am measured across a range of flows to form a "rating curve" that is usually a power function of the form:

$$C = aQ^b, \qquad (1)$$

in which C is suspended sediment concentration, Q is discharge and a and b are parameters. This function can be used with the streamflow record or means of flow duration classes to estimate the total suspended sediment yield for a period.

One consequence of this relationship can be seen by selecting, for a period of record, a "large" number of discharge classes containing equal volumes of flow. The product of this volume and the mean sediment concentrations estimated from the rating curve using the midclass discharges estimates the total sediment yielded in each class. Because the water volume is constant across classes, the sediment volume increases for higher flow classes depending on the rating curve. When b > 1, which is the usual situation, this increase can be quite dramatic. It is not unusual to find situations where more than one-half of the sediment is carried by high flows that account for less than 15 percent of the water volume and that occur, perhaps, 2 percent of the time. Another factor characterizing suspended sediment concentration data in the high flow classes is their increased variability. Both of these factors indicate that most sampling should take place during high discharge.

Perhaps the most common shortcoming of existing suspended sediment data sets from small catchments, however, is the lack of measurements taken during high flows. Large storms increase the discomfort of taking measurements, make access difficult, and produce hazards because of high discharge. Also, the timing of high flows is often difficult to predict when people are not at the station. Nonetheless, data collected during high flows are essential to the development of good sediment rating curves. Because of the infrequency of high flows and difficult logistical problems, it is almost impossible to get adequate high flow measurements from hand sampling alone.

The advent of automatic pumping samplers and their increasing use encourage the hope that some problems of suspended sediment concentration data collection at high flows may be overcome. Unfortunately, pumping samplers have their own set of problems, some of which will be discussed in a following section. Still these samples afford the opportunity to collect data where little have been collected before, and to improve estimates of total suspended sediment loads. This additional information can also be expected to affect the design of sampling programs.

Sample Allocation

Data collection efforts must be distributed throughout flow classes in such a way that classes with (a) a large volume of sediment, and (b) high variance are most frequently sampled. Sampling these classes is similar to the allocation problem in stratified random sampling with finite populations if the flow classes are thought of as strata.

The basic (Neyman) allocation formula (Cochran 1963) is:

$$\mathbf{P}_i = \frac{N_i \sigma_i}{\sum_{j=1}^{k} N_j \sigma_j} \qquad (2)$$

in which $\mathbf{P}_i$ is the proportion of the sample taken in the i^{th} stratum, $N_i(N_j)$ is the size (that is, number of objects) and $\sigma_i(\sigma_j)$ is the standard deviation in stratum i(j), and k is the number of strata. For each stratum the product of its size and its standard deviation is formed the proportion of the sample to take in that class is this product divided by the sum of the corresponding products across all strata.

The Neyman allocation was applied to sampling large "event response" rivers where daily suspended sediment yields can be characterized by a single sample (Yaksich and Verhoff 1983). For their sampling, N_i is the number of days in the i^{th} flow class. For small mountain catchments; however, variation in suspended sediment concentration is too large to use daily values and shorter time periods are not practical without automatic sampler control equipment. Another technique therefore must be used Because the purpose is to estimate the quantity of suspended sediment in each flow class, it is masonable to use suspended sediment yield in class i as a measure of size in place of N_i. The analogy is not strictly correct, but the approach will give a useful allocation.

If pertinent suspended sediment concentration data are available, sample estimates of σ_i will allow equation 2 to be used directly. More often such values are not available. One surrogate for the standard deviation is the range of values in a class-either suspended sediment concentration or discharge at flow class boundaries (Murthy 1967). Flow and sediment volume curves, however, often result from several sediment rating curves developed for different time periods or hydraulic conditions. Therefore, there may be no unique suspended sediment concentration associated with a flow volume class boundary. Because discharge is readily available, it can be used instead. Using the range of discharge to estimate the standard deviation deemphasizes the proportion of samples to be allocated to the higher flow classes.

Suppose S_i is a measure (mass or percent) of the sediment in class i, and R_i is the range of discharge in the i^{th} class, the allocation formula becomes approximately:

$$P_i \cong \frac{S_i R_i}{\sum_{j=1}^{k} S_j R_j} \qquad (3)$$

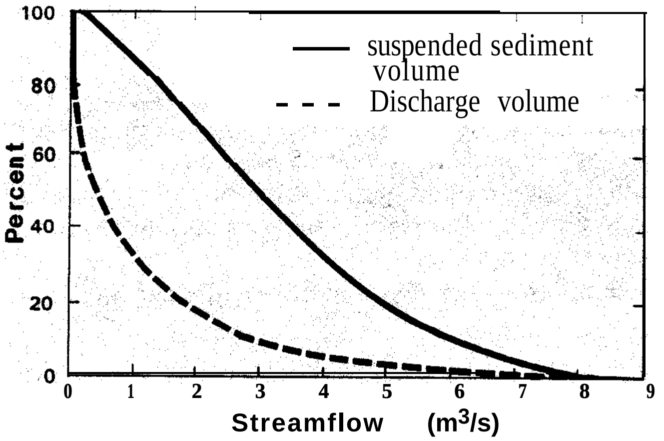

Figure 1–Percentage of suspended sediment and discharge volumes occurring at greater than indicated streamflows, Caspar Creek, northern California (Rice and others 1979).

Using equation 3 is still difficult because quantities, to be estimated from the sample are required to estimate sample size. Prior data on the same or similar streams may exist that can be used to form a suspended sediment volume curve from which estimates of the volume of suspended sediment coming from each flow class can be obtained. It is sometimes necessary, however, to set up an arbitrary sampling plan for a year or so to get preliminary information that can be used to modify the plan later.

The application of equation 3, can be illustrated by using data collected from Caspar Creek in northern California (Rice and others 1979) *(fig. 1).* The percent axis was partitioned into 20 classes each containing 5 percent of the flow volume. Discharge rates corresponding to class boundaries were then read from the graph and percentages of sediment deliveredat flows greater than these values were determined. (percentages or proportions of sediment can be used in place of actual volumes or weights as long as they are used consistently.) For this stream the allocation indicates that samples should. be heavily concentrated in the higher flow classes; in fact, it shows that nearly three quarters of the measurements should be taken in the highest flow class alone. This is not-surprising when it is considered that more than half of the range of flows occurred here as well as 30 percent of the suspended sediment volume, so this class contained a large portion of the suspended sediment as well as being highly variable.

Each class should be allocated a minimum of about five samples so that mean discharge for the class and its variance can be estimated. For example, if 100 samples are to be collected, most classes in *table 1* are too small. By experimenting with the number of discharge classes and their boundaries an allocation can be produced that has at least five samples in each class. To accomplish this allocation, the two highest flow classes were left intact and the next two, the following three, and the last 13 classes were grouped to form a five-class allocation *(table 2).* With 100 samples under this allocation, six would go into each of the two lowest flow classes.

A minimum number of samples in the low flow classes was obtained at the expense of samples previously allocated to the high flow classes. This is because the ranges and sediment contributions of the composite classes increase, making the denominator of equation 3 larger. A practical compromise must be

Table 1--Data and calculations to establish suspended sediment sample allocation using data from Caspar Creek (Rice and others 1979)

Water volume yielded at greater than indicated flows (pct)	Flows at class boundaries m³/s	Sediment volume yielded at greater than indicated flows (pct)	R_i Flow range (m³/s)	S_i sediment volume in class (pct)	R_iS_i	P_i (pct)
0	8.5	0				
5	4.1	30	4.4	30	132.0	73
10	2.7	55	1.4	25	35.0	20
15	2.1	64	0.6	9	3.6	2
20	1.7	72	0.4	8	3.2	2
25	1.4	79	0.3	7	2.1	1
30	1.1	84	0.3	5	1.5	1
35	0.9	87	0.2	3	0.6	1
40	0.7	91	0.2	4	0.8	
45	0.6	93	0.1	2	0.2	
50	0.4	95	0.2	2	0.4	
55	0.3	96	0.1	1	0.1	
60	0.2	97	0.1	1	0.1	
65	0.2	97	<0.1		<0.1	
70	0.1	98	<0.1		<0.1	
75	0.1	98	<0.1		<0.1	
80	<0.1	99	<0.1		<0.1	
85	<0.1	≅100	<0.1		<0.1	
90	<0.1	≅100	<0.1		<0.1	
95	<0.1	≅100	<0.1		<0.1	
100	0.0	100	<0.1		<0.1	
					$\sum R_iS_i = 179.8$	

Table 2-Calculations for five. class suspended sediment sample reallocation formed by grouping classes in table 1

Water volume yielded at greater than indicated flows (pct)	Flows at class boundaries (m^3/s)	Sediment volume yielded at greater than indicated flows (pct)	R_i Flow range (m^3/s)	S_i Sediment volume in class (pct)	R_iS_i	P_i (pct)
0	8.5	0				
5	4.1	30	4.4	30	132.0	63
10	2.7	55	1.4	25	35.0	17
20	1.7	72	1.0	17	17.0	8
35	0.9	87	0.8	15	12.0	6
100	0.0	100	0.9	13	12.0	6
					$\sum R_iS_i = 208.0$	

struck between having many classes to reduce the overall variance and having fewer classes so that each class will contain at least a minimum number of samples. For most suspended sediment sampling programs five or six strata should be adequate.

The primary benefit of using equation 3 is to emphasize the need to collect suspended sediment concentration data at higher flows and to estimate approximate proportions of sampling effort to expend at different flows. This technique should be kept in perspective and not used slavishly. Scenarios based on synthesized flow and sediment volume curves can be developed that bracket a particular set of field conditions. Applying the equation to these scenarios can help develop reasonable sampling programs that should serve to emphasize the need to sample more heavily in the higher flow classes than is typically done.

Several factors are not addressed by equation 3. One of these is the total sample size. Formulas to estimate total sample size in stratified random sampling are available (Cochran 1963), but either cost information or specification of the variance of the total suspended sediment volume are required, in addition to variance and size estimates in all strata. This complex of assumptions strains credibility in applying the total sample size formulas to this situation. In any event, sample size usually depends on constraints on time, funds, and personnel.

Equation 3 does not indicate when to take the prescribed number of samples in each class. For the mean and variance estimating formulas to be strictly correct, the data in each class should be randomly selected. As a practical matter, however, such selection is seldom possible, and requires automatic sampling control equipment that is not generally available. As an accommodation until such- control techniques are accessible, samples should be distributed more or less evenly throughout the time period in each class rather than being clustered during a few intensive episodes. This requirement is particularly important for high flows that should be sampled more frequently, but that occur infrequently.

Sampling at regular intervals in high flow classes may help reduce the effect of dependence as long as the sampling interval is not too small. It is in these classes where automatic equipment is most useful because the logistics of measuring high flows by hand in most studies of small mountain streams is virtually insurmountable. Some provision is required for sampling less frequently during lower flows to avoid collecting excessive data where they are not needed. Making the automatic sampling interval dependent on stage is one solution to this problem (Hicks and Bright 1981). Collecting samples at equal intervals of water discharge (or estimated sediment discharge) ensures that data will be better distributed throughout flow classes, but is more difficult to accomplish.

Sources of Variation

Suspended sediment concentration values vary because of several factors. Some of these are at least partially predictable, but others are not. The unpredictable factors are collectively called *random variations*, and these are large in most suspended sediment sampling programs. The effects of random variation on the estimates of means and variances are usually reduced by collecting a larger sample. This is one factor that should increase allocation of sampling effort to high variance strata.

Partially predictable factors are sometimes ignored and remain to add to the random errors, but they can be used to partition a data set into subsets, each of which represents the process under particular conditions. For example, separate rating curves can be developed for rising and falling flows. This approach is based on recognition that rising and falling flows of the same magnitude often show quite different suspended sediment concentration (Walling 1977). Plotting suspended sediment concentration/discharge pans for a storm period often shows a classical “hysteresis” effect in which the trace advances along one path, but returns to prestorm conditions along another (Gregory and Walling 1973). This condition implies a fundamental if temporary change in the deterministic component of the rating curve.

Rating curves also undergo long-term changes. A commonly observed change over a season is that suspended sediment concentration at a given stage will usually be higher early in the runoff season than later on (Gregory and Walling 1973). Also, major events can permanently change the response of concentration at a given station. The hydrologist will have to decide for each situation how to partition a data set to best represent the particular conditions but must keep in mind that an improvement in sensitivity will be at the expense of greater analytical and sampling efforts.

The previous discussion tacitly assumed that suspended sediment concentration data collected in the usual way are independent rather than time series data, which is actually the case. If the measured values are not too close together in time, their dependence may not severely distort the estimates. It will eventually be practically feasible to measure concentration at regular intervals of flow, to measure concentration continuously, or to employ techniques to obtain independent samples from time seties processes. Until then the best strategy is to distribute the data collected within each flow class as evenly as possible.

Another point concerning time of measurement refers to the "above and below" monitoring situation introduced earlier. In addition to ensuring that the stations are located at similar points in their respective pool/riffle sequences, and that the stations are calibrated before disturbance, accounting for the problem of variation over time is needed. Why suspended sediment concentration varies quickly over time in small streams is not well understood. Assigning a cause for a particular spike in concentration is often difficult.

The intent to equalize measurement conditions suggests that both stations should be measured simultaneously. An objection could be made that whatever sediment is measured at the upper station would take time to arrive at the lower station requiring a lag time between stations proportional to average velocity. Basing sampling at the lower station on the time it takes a water mass to travel from the upper station, however, raises practical and theoretical problems. Velocity and, therefore, lag time, varies with discharge and them is no simple way to measure average velocity between stations to decide when to operate the lower sampler. Because both sediment and water can be added and sediment can be removed from the flow in a reach, it is not even clear what is meant by measuring the same water mass at the two stations. It is probably best to calibrate by measuring at both stations simultaneously or at a constant time difference–to allow the data collector to travel from the upper to the lower station–and relying on enough measurements throughout each flow class to give valid comparisons. By matching measurements in this way, the variance is reduced and more sensitive comparisons can be made with fewer observations.

A final aspect concerns how long monitoring should be carried out both before and after a treatment. This depends on several factors, chief among which are the purposes of the study, the characteristic changes in the suspended sediment regime produced by a treatment, and the pattern of storm impacts. Each application presents unique problems so it is difficult to generalize, but several important conditions can be mentioned.

Perhaps the most stringent requirement is that the pretreatment and posttreatment monitoring include a wide and similar range of flow conditions. Otherwise only part of the suspended sediment concentration/discharge relationship will be measured for prediction or comparison. This means that these periods need to be long enough to allow a reasonable chance that the vagaries of climatic variation will produce storms of the required size. This will vary by locality and should be estimated for each individual case.

Also, the characteristics of a particular land treatment applied at a particular site can affect the posttreatment monitoring program. The sources of suspended sediment production may develop immediately and heal over time such as loose sediment being directly pushed into the channel system by roadbuilding. Or, the sources may be delayed as would be the case where debris is produced from logging-caused landslides which occur only after decay of the root matrix. Even if these changes are anticipated there is no assurance that storm inputs of sufficient range in magnitude will occur during the period of vulnrerability or measurement.

All of these factors make the outlook for planning a successful suspended sediment measurement program problematical. The primary lessons are that the establishment of such a program is not a simple undertaking. If conditions and available monitoring time are such as to preclude a reasonable chance for collecting adequate data, the measurements would best not be made.

Measuring at a Cross Section

Data Collection

To estimate total suspended load from occasional measurements of suspended sediment concentration, water discharge information is necessary. Discharge must be known when suspended sediment concentration is measured to develop suspended sediment rating curves, and continuous discharge is required when suspended sediment yield is estimated.

A related variable sometimes measured is turbidity. In some situations it is recorded for its own sake; usually because standards restrict increases in turbidity. Another use for turbidity data is to estimate suspended sediment concentration by relating the two quantities and using the more easily measured turbidity to estimate suspended sediment concentration at times when it has not been measured directly (Beschta 1980, Walling 1977). The relationship between these two quantities is not perfect, nor should turbidimeters be calibrated in units of suspended sediment concentration. For many streams and for a wide range of particle sizes, however, a close statistical relationship can be developed, often one that is far better than the relationship between suspended sediment concentration and discharge. The relationship tends to be poorer for large particle sizes. The suspended sediment concentration/turbidity relationship must be developed separately for each measurement station by collecting a set of pairs of measurements of both quantities over a wide range of flows. It should also be checked periodically to detect changes in the relationship over time. The suspended sediment concentration values can then be regressed on the turbidity data to obtain a prediction equation. Even though this technique has problems, the opportunity for improving estimates of suspended sediment totals and for better defining suspended sediment concentration variation (especially with the use of continuously recording turbidimeters) justifies more frequent field application.

The great difference in suspended sediment concentration that can exist at different points throughout the cross section should also be considered. To collect a sample that has concentration similar to that existing throughout the stream cross section, a sampler is needed that integrates partial samples from many points in the section; that is, adequate areal coverage of the cross section is needed to ensure that a-sample with concentration and particle size properties similar to those in the stream is collected.

A set of standard suspended sediment measuring devices has been developed by the Federal Inter-Agency Sedimentation Project (FIASP 1963) along with procedures for their correct use (Guy and Norman 1970). Among these devices, the DH-48 depth-integmting sampler is probably the most widely used by forest hydrologists for sampling small streams. It can be used from a low bridge or when wading. With its nozzle pointing upstream, the sampler is lowered at a uniform rate into the flow from the surface to near the bottom and returned to the surface for each of a set of verticals across the width of a stream. Air is exhausted from the sample collection bottle to admit the water/sediment mixture at stream velocity. This condition of identical stream and nozzle velocities—isokinesis—ensures that the sample is the same concentration as that in the stream near the nozzle and that all conditions are proportionally represented. Careful use of the DH-48 sampler with enough verticals will ensure a sample with a concentration approximating that in the stream cross section. The DH-48 (or similar device designed by FIASP) will be considered in this report as the standard instrument with which to compare other suspended sediment concentration measuring &vices.

Used properly, the DH-48 sampler provides a satisfactory measure of the suspended sediment concentration in a cross section, but wide flow coverage is difficult because people must be present to make measurements. Conversely, automatic pumping samplers, which are becoming increasingly available, can be operated in either a time- or flow-dependent mode, thereby giving reasonable coverage of flow levels, but they sample only one point in a stream cross section. Although automatic samplers offer the prospect of more timely data, problems are associated with their use.

Pumping Samplers

A major problem with the pumping sampler concerns intakes: their type, orientation, and placement within a cross section. Some samplers have cylindrical intakes with a series of holes around their periphery and internal weights to help hold them in place on the streambed. These intakes are designed for wastewater sampling and are not well suited for suspended sediment measurement. Because sediment suspension depends heavily on velocity and because the hydraulics of a sediment suspension moving through one of these intakes is complex, it is difficult to quantify their effect on the sample. A better device is a nozzle similar to that on the DH-48. A nozzle can be made from a piece of thin-walled noncorrosive tubing with an inside diameter equal to that in the sampling hose, having an orifice beveled on the outside.

Hand samplers are oriented with their nozzles pointing directly into the flow so that the pressure of the incoming water will pro duce isokinetic sampling. Because pumping sampler nozzles remain in place for long periods of time between samples, pointing the nozzles upstream increases the chances of clogging. For accurate measurement of ambient suspended sediment concentration the nozzle should be pointed away from the flow rather than at any other angle except directly facing it (Winterstein and Stefan 1983). This direction gives about 90 percent or more of the "true" concentration across several particle sizes while greatly reducing the opportunities for clogging.

Placement of the pumping sampler nozzle in the stream cross section is also important because concentration gradients occur across and especially up and down the section. The ideal spot to locate the intake nozzle depends on stage, concentration, particle size distribution, and cross sectional configuration. The nozzle usually cannot be positioned in one place so that it will sample correctly for all conditions. The intake should be near the center of the stream, perhaps above the thalweg, and at least 10 cm or so above the bed to avoid sampling the saltating portion of the bed load. If the nozzle is a fixed distance above the bed, it will sample a different relative position in the vertical concentration gradient for different stages, thus changing the relationship between the sampled and actual concentration under varying conditions. A better approach is a device to sample at the same proportion of depth regardless of stage (Eads and Thomas 1983).

Each automatic sampler should be calibrated against measurements made with a DH-48. This requires visiting the installation over a wide range of discharge conditions to collect simultaneous measurements with a DH-48 and the automatic sampler. These pairs 'of values can be plotted to indicate how well the pumping sampler measures what a hand sampler would have measured. For a given installation, the DH-48 values can be regressed on those for the pumping sampler. The resultant equation, if it gives a satisfactory prediction, can be used to estimate suspended sediment concentration in the cross section from the automatic sampler data. Each automatic sampler installation measures something different--from other installations and from measurements made with depth integrated samplers. For correct comparisons of mean suspended sediment concentration between Stations or for estimates of total suspended sediment transported through a cross section, pumping sampler values should be related to a standard.

Choosing and setting pumping sampler hose velocities are also problems. Some machines have no simple means for adjusting hose velocity. Even when the velocity can be regulated, stream velocities are constantly changing and no mechanism exists to alter the sampler accordingly. This means that if a pumping sampler nozzle is pointed upstream, isokinesis is possible only for the one preset velocity. For other nozzle orientations isokinesis is not possible so pumping velocities will have to be selected empirically and estimates based on calibration. The need to sample at high flows suggests setting hose v&cities to sample correctly at stream velocities- occurring at the intake during these flows. Although this practice will starve samples taken at lower velocities (Federal Inter-Agency Sedimentation Project 1941) they are not as critical and calibration will help improve these estimates. Also, from the standpoint of preventing sediment accumulation in the internal plumbing of the automatic samplers, it is better to err on the side of higher velocities.

Automatic samplers themselves cause problems that affect the data being collected. One such problem is cross-contamination; for example, a sample bottle may receive some of the sediment that belongs to the previous sample and not get all of the sediment properly belonging to it. For a series of observations when concentrations are not changing rapidly, compensation occurs reducing the effect of cross-contamination. With wide swings in concentration, however, the true change can be greatly deemphasized and sample variances falsely reduced. This problem results primarily from the design of the particular sampler and is not directly under the hydrologist's control, except when a sampler is purchased (Thomas and Eads 1983).

PLANNING STUDIES OF SUSPENDED SEDIMENT

Planning is the key to successfully studying any natural phenomenon. Objectives must be set, intended analyses identified, and sampling schemes established and balanced against available resources. The data are then collected and analyzed, and interpretations made.

Studies of suspended sediment should also be subject to these same procedures, but they often are not. This is perhaps the most common mason why such studies fail. The long-term nature of many suspended sediment measurement programs, a general feeling that "monitoring" is not a formal study, and the lack of widely accepted analysis procedures may all contribute to the situation.

There are several characteristics of suspended sediment studies that should be particularly emphasized. Setting general and then more specific objectives is absolutely essential. There is no other way to select the analyses required and the consequent sampling program needed to collect adequate information This must be done, in effect, when statistical analyses are performed (analyses answer only specific questions) and it is much better to decide before the data are collected when sampling procedures can be influenced. If definite goals are not clear at the outset, it may be because the study will not provide useful information. Suspended sediment "monitoring" should only be done when there are clear reasons for doing it.

Obtaining timely measurements of high quality represents a major portion of the effort going into a suspended sediment measurementprogram. The procedures and requirements must be defined in detail so that persons not present at the outset of a study will be able to collect comparable data later on. The planning should identify required instrumentation, techniques of use, and sampling protocol.

Many suspended sediment studies extend over long time periods. This fact increases the opportunity for personnel changes and for losing the intent of the experiment. It is essential, therefore, to document the study planning so that it can be reviewed periodically by those who set up the study and by those who may follow. The plan should be a working document wherein all of the history, reasons, and objectives for undertaking the study can be set down, the sampling plan described, and instructions given on measurement procedures, station location, and analyses to be performed. The hydrologist who prepares a complete and well thought out plan at the start of a program to measure suspended sediment goes a long way towards ensuring its success.

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