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Measuring sediment yields of storms using PSALT

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ABSTRACT Storm yields of water and sediment are being measured as part of a study of the effects of roading, logging, and burning in a second-growth redwood forest in northern California. Two primary basins, each about 500 ha, and 13 sub-basins in one of them are measured for sediment flux and the presence and magnitude of sediment-based "cumulative effects". Study objectives require a more sophisticated sediment sampling design than typically used in watershed experiments. Sediment is sampled and estimated by using PSALT - a probability-based method for sampling that enhances data collection during high flows. The method is applied to storms defined after field data are collected. The sampling sites are visited at arbitrary times during storm periods. Because PSALT data are independent they can be combined to give unbiased estimates of suspended sediment yield and its variance during storms. Problems of applying the method to a large number of basins are discussed along with their solutions.

Le calcul des débits de sédiment provenant des averses en utilisant la méthode PSALT

Résumé Les débits de l'eau et des sédiments, provenant des averses sont mesurés comme un élément de l'étude des effets de la construction de routes, du déboisement et du brulage qui y fait suite dans une forêt de bois rouge deuxième génération dans le nord de la Californie. Sur deux bassins versants principaux, chacun d'une étendue d'à peu près 500 ha, ainsi que sur 13 sous-bassins qui se trouvent dans l'un des deux, on mesure le flux des sédiments et la présence et la grandeur des "effets cumulatifs" de ceux-ci. Les objectifs de l'étude exigent un échantillonnage des sédiments qui serait plus sophistiqué que celui qui est typiquement employé dans les analyses des versants. Le sédiment est donc échantillonné et estimé par moyen de PSALT – une méthode d'échantillonnage fondée sur la probabilité, qui donne plus de poids à la quantité des données rassemblées pendant les écoulements abondants. Or, la méthode s'applique aux averses définies après que les données aient été collectées, les sites d'échantillonnage étant visités a des moments arbitraires pendant les périodes d'averses. Puisque les données de PSALT sont indépendantes, elles peuvent etre rassemblées pour donner une appréciation sans déviation systématique du débit des transports solides et de sa variance pendant les averses. Les problèmes pour appliquer la méthode à un grand nombre de bassins y sont discutés avec des solutions éventuelles.

INTRODUCTION

Sediment discharge from forested basins is often accelerated by land management activities, such as road building and logging. Because of possible negative environmental effects, the relationship of such activities to increased sediment delivery is of concern to land managers.

A paired-basin study can detect changes in sediment discharge by comparing a treated basin to an untreated control. But this traditional approach poses problems. Annual estimates make studies either time consuming and costly, or may yield insufficient data. Also, recent work has emphasized that commonly used sediment estimators are often seriously biased and have unknown variances (Walling & Webb, 1981). Data are usually available at few stations, providing only crude indications of sediment movement in the basin.

Another approach to evaluating treatment effects is to use sediment budgets (Dietrich et al., 1982). This method identifies and quantifies sediment sources, storage elements, and transport processes in a basin network. Sediment budgets are particularly useful when developing conceptual models of how processes operate and interact. The method depends heavily on geomorphic expertise, however, and emphasizes understanding long- term basic geomorphological processes rather than evaluating relatively short-term management effects.

A third approach is the basic paired-basin method used with greatly increased density and accuracy of sampling. It uses improved field measurement technology and statistical sampling and estimation techniques. The method still measures only in-channel sediment discharge, but does so at many locations, thereby being a partial compromise between sediment budgets and paired basin studies. This paper outlines an intensive paired-basin study in northern coastal California and describes a greatly improved sampling design called PSALT (Piecewise Selection At List Time). A set of 15 basins, some nested, will allow tracking of sediment throughout the system and assessing changes due to road building and logging.

For any of these methods of studying sediment delivery, measurement (quantifying a characteristic of interest), sampling (deciding what population units to measure), and estimation (using sample data to estimate population properties) are major concerns. Procedures with unknown bias, or no reliable estimates of variation make interpreting the data difficult. Estimates of flux could then be incorrect by unknown amounts, leading to invalid comparisons or to misspecification of models.

THE CASPAR CREEK STUDIES

The USDA Forest Service began a paired-basin study in 1962 in two forks of Caspar Creek near Fort Bragg in coastal northern California. It was designed to assess the effects of road building and logging on hydrology and water quality. Both basins were initially forested with 80 year old stands of redwood, Douglas fir, Grand fir, and hemlock. The 424 ha South Fork was logged and the 508 ha North Fork used as a control. The study was continued until 1976 (Rice et al., 1979).

Logging and road building effects on the water regime were slight. Large percentage increases in some small early-season peaks occurred, but their hydrological significance was slight (Ziemer, 1981). Peak response to precipitation input, however, was shifted later in time (Sendek, 1985). Road building and logging had much greater effects on sediment. Sediment production for four years after road building rose about 75% over predicted levels. In the five years after logging, the sediment increased about 4.5 times. These values include suspended sediment and material caught in settling basins at the gauging stations. The increases came from a rise in the available sediment supply rather than from a change in the ability of the stream to carry an increased load. The 1962 study yielded useful information on gross changes in water and sediment regimes for one method of road building and logging. However, more detailed information is needed on sediment movement within the watershed system immediately after disturbance.

In 1978, a second study was started at Caspar Creek to measure sediment and to investigate cumulative effects (the combined effects of treatments applied over space or time). In the second study logging and road building will be done in the North Fork with the South Fork used as a control. The North Fork was partitioned into 13 sub-basins ranging from 11 to 362 ha. The sub-basins are partly nested and their configuration allows study of sediment movement throughout the basin network among several treatment combinations. The South Fork and three North Fork control sub-basins will be used to calibrate the North Fork and its treated sub-basins. Increases in per-unit-area sediment production for increased basin size will be taken as an indication of cumulative effects.

A road will be built on the contour about two-thirds of the way up the slopes. Logs on the steeper slopes below the road will be transported by a skyline logging system. Logs on the gentler ground above the road will be moved by tractor skidding. Several areas of clearcut logging, some burned and some not, will be compared in the second study. The dense network of stations will allow separation of the effects of various treatment combinations.

In the 1962 study, the settling basins were surveyed annually to measure bed load, and flow duration/sediment rating curves were used to estimate suspended sediment yields. These estimates provided seasonably independent data, but the data sets were small. For the second study, more detailed data are required; so sediment yields from individual storms will be analysed. This should yield about four times as much data as a study based on annual values.

Concern about bias and variation in rating curve estimates encouraged developing sampling methods based on random sampling. A probability-based method termed SALT (Selection At List Time) has been developed to sample and estimate suspended sediment yields (Thomas, 1985). Another version of the method called PSALT (Piecewise SALT) estimates sediment yield for storms defined after data are collected. It also facilitates management of data collection.

PSALT

A comparison of SALT and PSALT

SALT was originally developed to estimate timber volume (Norick, 1969). SALT is a variable probability sampling scheme that uses an auxiliary variable to select an efficient sample. SALT sampling for suspended sediment takes advantage of available information to sample higher flows, reducing the variance for a given sample size or reducing the sample size needed to attain given levels of precision (Thomas, 1985). The known variable probabilities weight the SALT estimates of suspended sediment yield and variance to make them unbiased. Neither variance estimation or unbiasedness are possible for the usual sediment yield estimators.

SALT uses a rating curve as an auxiliary variable to control sampling. When rating curves are based on adequate data this works well, especially for long-term monitoring. Rating curve quality is not critical (Thomas, 1986), but the power function form of the rating curve can result in excessive sampling at high discharges. Even though SALT is intended to heavily sample high flows, logistics limit the amount of data that can be collected. Limits are also imposed by maximum sampling rates for the automatic pumping samplers usually used with SALT, and by sample processing costs. PSALT shares most of the benefits of SALT, but modifies it in two ways (Thomas, in preparation). The auxiliary variable in PSALT is a user defined ***average sampling rate*** (ASR) function allowing better control of data collection. Another difference between SALT and PSALT concerns estimating sediment yields for storms. Storms must be defined after the hydrograph is known, so sampling cannot be preplanned for storm periods. Also, pumping sampler bottles must be changed and data collected from field computers (used to operate SALT) when capacities are reached - not when the storm is over. PSALT allows field data collection and storm-estimating procedures to be essentially independent. Field data sets can then be combined “piecewise” to estimate sediment yields for any arbitrarily defined storm.

PSALT populations and variables

The sampling population for SALT and PSALT is defined by setting the duration of equal-length “sampling periods” covering the period to be monitored. Mid-period measurements are assumed to describe the entire period, so its length must be chosen carefully. Ten-minute periods have worked well for flashy coastal California streams, but periods could be longer for larger and less variable rivers. Sediment yield estimates are made for the finite population; the difference between this population and the underlying continuous one should therefore be acceptably small.

The primary variable for a period is a measure of sediment flux given by the product of the discharge and pumped sediment concentration, both taken at mid-period, and the period length. All mid-period discharges are known because stage is monitored continuously. If all concentrations were also measured, the population could be completely known. Because this is impractical, period concentrations are sampled. The sampled periods are exactly those with a pumped concentration sample.

Variable probability sampling associates an auxiliary variable with the primary variable. The intent is to control sampling of the primary using information from the auxiliary. Because selection probabilities depend on the auxiliary variable, its value must be known for every sampling period. The auxiliary variable, therefore, must not only predict the primary variable well, but must also be easy to measure. Using an auxiliary variable will improve precision over simple random sampling when there is positive "covariance" of the auxiliary with the square of the primary variable divided by the auxiliary (Raj, 1968).

Because concentration varies with stage, some function of stage is a suitable candidate for an auxiliary variable. Sediment rating curves relate stage and concentration (through discharge), and stage is easy to measure. Therefore, SALT uses an auxiliary variable consisting of the product of the discharge, a rating curve estimate of concentration, and the period duration.

PSALT uses an ASR function of stage as auxiliary variable (Fig. 1). The ASR function is established by specifying "lower" and "upper" design

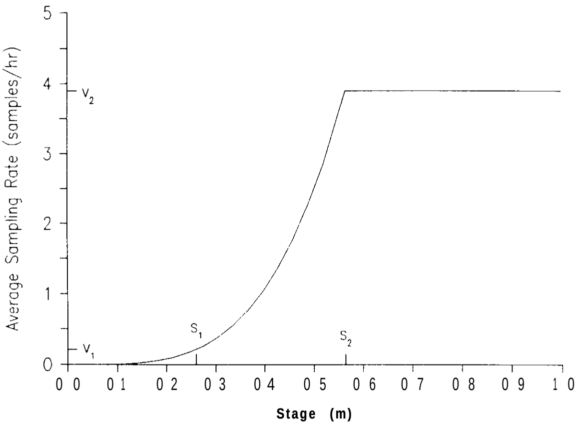

Fig. 1 *A typical ASR (Average Sampling Rate) curve for the PSALT (Piecewise Selection At List Time) technique. The lower and upper design stages are* s_1 *and* s_2 *with associated design average sampling rates of* v_1 *and* v_2*. The ASR is constant at* v_2 *for stages above* s_2

stages and corresponding average sampling rates in samples per hour. With these values selected, the parameters for the ASR power function can be computed (Thomas, in preparation). This function gives the ***average*** sampling rate for the range of stages; that is, the ASR function gives the average number of samples taken per hour at a given stage. This number of samples is not expected ***each*** hour, but on a per hour basis over a "long" period of time. The ASR function does not increase for stages above the upper design stage which limits upper-flow sampling. To maintain PSALT efficiency, this upper design stage and its associated ASR should be chosen as high as can be logistically supported.

With many stations such as in Caspar Creek, similar numbers of samples are wanted at all stations for each storm. Obtaining this ideal requires some effort. The lower design stages (s_1) are peaks of storms occurring four times a year. The corresponding ASR (v_1) is l/2 samples/h. The upper design stage (s_2) is set at the five-year storm peak and its ASR (v_2) at four samples/h. At first this did not work well for all storms, but experience allowed parameter adjustment to balance sampling across storms.

PSALT operation

Because sampling periods are frequent and most measurement stations remote, the auxiliary variable must be computed automatically. Present applications sense stage electronically. A transducer gives a voltage proportional to stage which is sensed by a battery-powered electronic circuit connected to a programmable calculator (Eads & Boolootian, 1985). The calculator computes the auxiliary variable, performs the PSALT algorithm, stores needed data, and signals the pumping sampler to operate when required. Stage data are collected efficiently by an algorithm that retains only those stage/time pairs at significant changes in hydrograph slope.

Total sediment yield estimates are still unbiased when using an ASR curve, but the variance may be affected, usually increased. The effect depends on how well sediment rating curves and ASR functions act as surrogate variables. Because the ASR approach restricts upper sampling frequency, larger storms are likely to have larger variance increases than smaller ones. This restriction conflicts with the basic premise of variable-probability sampling which attaches a larger probability to sampling the most important units. The PSALT compromise is to limit high-flow sampling to the highest sustainable rate.

Most variable probability schemes require that all values of the auxiliary variable be known before selecting the sample. The PSALT auxiliary variable, however, depends on the stage record which cannot be known until monitoring is completed. Therefore, when the values of the auxiliary variable are known, the sampling opportunity has passed. Accordingly, the sample must be "preselected" before monitoring starts. A "sampling interval axis" is constructed containing a uniformly distributed set of pseudorandom numbers along its length. These values are computed before sampling begins and stored in the field computer. The ASR function is used with the sampling interval axis in real time to determine whether or not to sample each period. Sampling consists of measuring concentration at mid-period, usually with a pumping sampler. The value of the primary variable is, therefore, known for exactly those periods in the sample, while the auxiliary variable is calculated for each period.

The PSALT program "wakes up" from a low-power state each mid-period and computes the auxiliary variable value. This length interval is measured along the sampling interval axis following and adjacent to the last interval. A sample is taken whenever there is at least one pseudo-random number in the interval. This procedure is equivalent to selecting the sample after all values of the auxiliary variable are known. The random numbers can be selected before or after the auxiliary variable intervals are formed. The calculator then stores the data and returns to "sleep" mode. A portable calculator is used to transfer data from the station to the office computer.

Storm estimates

A data set collected between successive station visits is self-contained; it has all values needed to compute total sediment yield and variance for that period. Each field data set is stored as a unit in the office computer. Because storms are defined from the hydrograph; they do not generally coincide with field data sets. Therefore, yield estimates must be made for portions and combinations of these sets. Because the data are collected randomly, any part of a data set is also random. Not only can estimates be made for parts of any set, but the separate estimates can be combined to estimate total yields and variances for periods composed of arbitrary parts of field data sets.

The hydrograph is examined and storms defined to include a finite number of sampling periods. They can include an arbitrary number of complete or partial field data sets. Totals and variances for each of the sets are then computed separately. Estimates of total yields for storm periods are obtained by adding totals for the composite periods. Variance estimates are made in a similar manner. This procedure gives valid estimates of both totals and variances only because the data were collected randomly (Thomas, in preparation).

CONCLUSIONS

PSALT provides unbiased estimates of storm yields of suspended sediment and its variance. This approach is a radical departure from standard practice. Because it is more costly and requires more field effort, its use should be justified. An obvious benefit is having an unbiased estimator for total sediment yield. This means the distribution of PSALT estimates is centered over the true yield rather than being systematically displaced by some unknown amount. Such bias is common for widely used estimators, is usually negative, and its magnitude can be large. A second major benefit is having an estimate of variance from every sample. Data are always collected to make comparisons, and valid comparisons are not possible unless variances can be estimated.

It is known that most sediment flux occurs during brief episodes, and most data should be collected then. But many sediment sampling programmes do not take advantage of this knowledge. Fixed-interval sampling is common, but sampling at frequencies high enough to define intense storm periods can produce immense data sets. The usual compromise is to reduce sampling frequency drastically, and sometimes raise the sampling frequency arbitrarily during storm periods. This sampling is not random, and there is no rigorous connection between the way the data were collected and the estimating procedure.

An important benefit of both SALT and PSALT, therefore, is to focus attention on efforts needed to obtain reliable sediment data. Often the most important sediment information must be collected during the most inconvenient and uncomfortable times. When operating PSALT, special efforts are needed to train and outfit crews and provide for safety and support during high discharge periods. The SALT schemes require data to be collected in accordance with conventional wisdom; during the critical high-flow periods.

This fact has implications for sediment data analysis based on sampling/estimation schemes having unknown properties. Such data sets will almost always have excess low-flow data and insufficient data from high flows. This condition is especially true for smaller highly-variable streams. Sampling schemes relying excessively on data collected during low discharges are suspect. To obtain useful estimates, high flows must be sampled adequately. If precision and accuracy are to be controlled, a sound statistically-based procedure is required.

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