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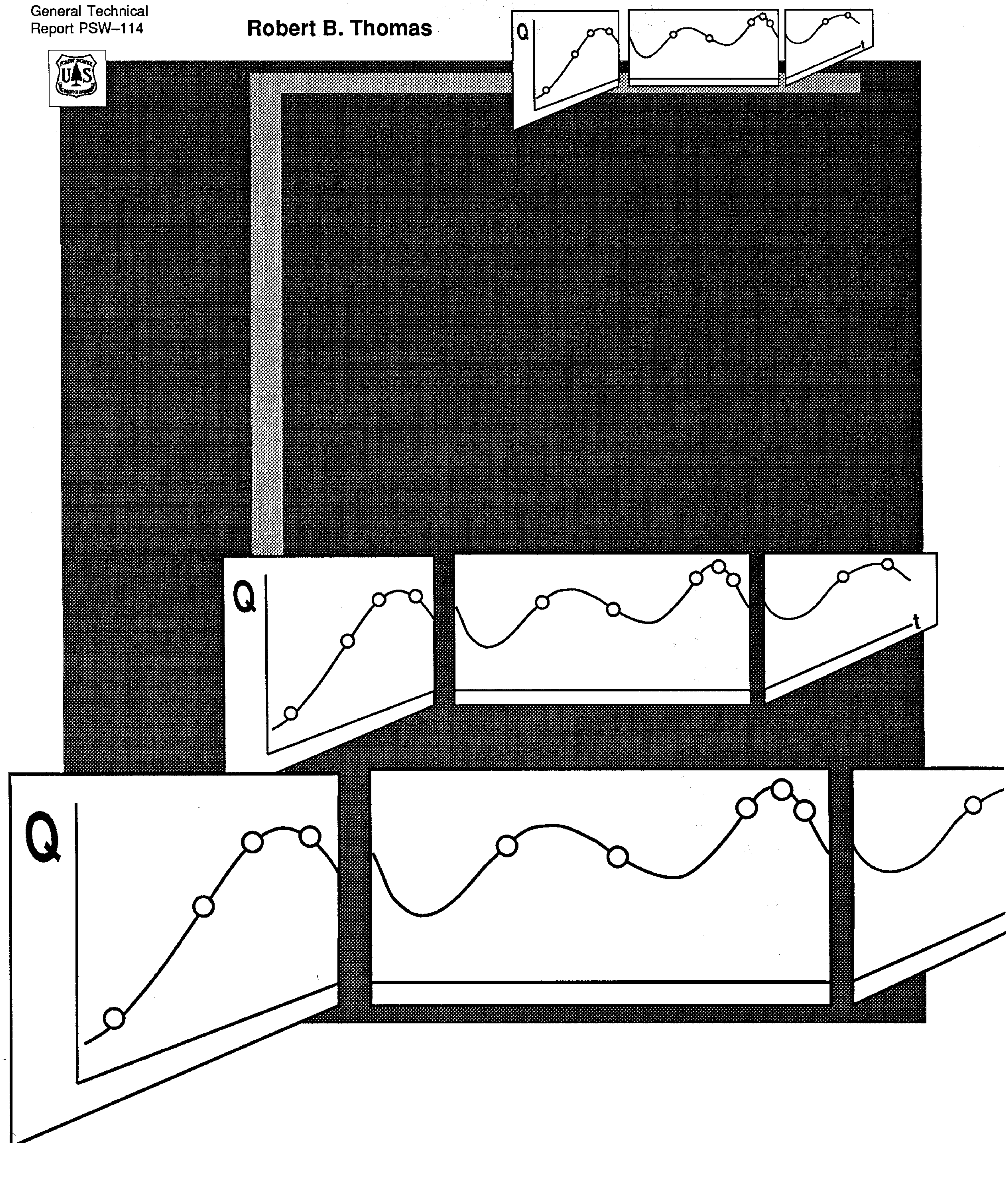
Piecewise SALT Sampling for Estimating Suspended Sediment Yields

Robert B. Thomas



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A probability sampling method called SALT (Selection At List 'Time) has been developed for collecting and summarizing data on delivery of suspended sediment in rivers. It is based on sampling and estimating yield using a suspended-sediment rating curve for high discharges and simple random sampling for low flows. The method gives unbiased estimates of total yield and variance. The technique has been modified by replacing the rating curve with a user-specified average sampling rate function. This function allows easier specification of field sampling parameters for specified conditions and helps avoid the extremes of data collection. It also improves the distribution of samples if the intent is to estimate suspended sediment yield during storms specified after data collection. This form of SALT sampling is called Piecewise SALT sampling.

Retrieval Terms: suspended sediment, sampling, probability sampling, measurement, SALT sampling

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IN BRIEF . . .

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Forest activities such as logging, road building, and mining can reduce water quality in streams and rivers. Increased sediment delivery is a possible result of such activities. Increased sediment production can have direct effects on sedimentation and fisheries, or indirect effects by acting as a vehicle for chemical pollutants.

Sediment measured at a cross section in a channel system comes from dispersed sources in the watershed and follows diverse paths according to irregular and sporadic pulses in response to geologic and hydraulic factors. The sediment carried by a stream within the flow (as opposed to rolling, bouncing, or sliding along the stream bed) is termed "suspended load," and in most streams, is the majority of the load and is often monitored as an indicator of general water quality.

Suspended sediment discharge cannot be measured directly, but must be calculated from measures of water discharge and suspended sediment concentration. Discharge can easily be measured by continuous mechanical or electronic recording of stage. Concentration, however, is usually measured gravimetrically on small water samples collected by hand-operated or automatic equipment. Difficult access to river stations and restrictions on laboratory processing of samples limit the number and distribution of water samples that can be collected. The basic questions when sampling suspended sediment yield are how many concentration samples to collect and when to collect them. Recent techniques allow continuous monitoring of concentration, but require expensive equipment and line electrical power. For installations having this equipment there is no problem of temporal sampling.

Traditional monitoring of suspended sediment concentration is characterized by a schism between the process of temporal sampling and the methods used to calculate load. Load-calculating procedures are often based on sediment-rating curves, which have been shown to produce misleading results. While convention dictates that high flows need to be heavily sampled to obtain good estimates, the lack of well-defined temporal sampling protocols and procedures for calculating load have limited the quality of suspended load data.

Probability sampling that is based on finite populations and that uses an auxiliary estimate of suspended sediment discharge to control selection of measurement times can solve all these problems. The SALT sampling scheme does this, but requires inexpensive battery-powered equipment at each stream station. Field servicing of this equipment is arduous, but reflects the validity of the conventional exhortation to sample heavily during high flows.

Piecewise SALT is a modification of the original SALT procedure. It allows the user to adjust sampling to special needs such as measuring smaller storms and to limit sample collection to logistically possible regimes. Piecewise SALT also provides estimators for periods essentially disconnected from the times of station visits. Piecewise SALT retains the same desirable features of basic SALT: unbiasedness of the estimates of the total yield, estimates of variance, and calculation of sample size required for specified performance.

GLOSSARY

Auxiliary variable: Variable related to primary variable, which fact is exploited to control SALT sampling, x_i.

Average sampling rate: The average number of sampling units collected per hour under the piecewise SALT process at a fixed stage.

Data segment: A duration of time containing an integral number of sampling periods and corresponding to the time between consecutive station visits. (A data segment usually starts with a few periods during which the SALT apparatus is shut down [the unsampled portion], followed by a large number of periods during which SALT was operating [the sampled portion]. The data for a data segment are collected as a unit.)

Partial segment: An integral but arbitrary number of sampling periods in a data segment (which may or may not include the unsampled portion). Partial segments are usually needed when estimating total suspended sediment yields for storms.

Piecewise SALT: A form of SALT sampling intended for estimating total suspended sediment yields for periods defined after sampling (storms), which generally uses preselected average sampling rates instead of sediment rating curves as auxiliary variables.

Primary variable: Variable of interest for which the total is being estimated, y,

SALT (*S*election *At* *L*ist *T*une): A form of unbiased variable-probability sampling that preferentially selects "important" elements in a population to reduce variance.

Sample: The set of sampling units selected for measurement by either the SALT or the simple random sampling process.

Sampled portion: That part of a data segment for which the SALT algorithm was operating (i.e., the set of sampling periods *not* occurring during down-time).

Sampling interval: An interval on the sampling-interval axis with length equal to the value of the auxiliary variable for the corresponding SALT sampling period. The auxiliary variable estimates suspended sediment discharge for basic SALT and "samples" for piecewise SALT.

Sampling parameters: Values to be set before doing SALT sampling that govern sampling intensity at different stages. (For piecewise SALT sampling they consist of a, b, n_b, n*, and Y*.)

Sampling period: An arbitrary period of time established to form a finite population for sampling (10 minutes is commgly used in small flashy streams). (One midperiod discharge and concentration measurement are assumed to measure the total water and suspended sediment yields for the period.)

Sampling unit: Element of population being sampled. In both types of SALT sampling, a sampling unit is any of the y_i values in the sampled population.

SRS (*S*imple *R*andom *S*ampling): A form of probability sampling wherein each possible unordered sample has an equal probability of being selected.

Storm: An arbitrary period of time used in SALT sampling and consisting of an integral number of sampling periods; it can consist of a portion of or span several full or partial data segments.

Unsampled portion: That portion of a data segment during which the station is being serviced and the SALT algorithm is *not* operating; this usually lasts from 10 to 30 minutes.

MATHEMATICAL NOTATIONS

a: Coefficient of the exponential average-sampling-rate function.

b: Power of the exponential average-sampling-rate function.

c: Measured suspended sediment concentrations in a set of rating curve data, mg/L.

$\hat{c}$: Estimated suspended sediment concentrations from a sediment rating curve, mg/L.

c_i: Measured suspended sediment concentration for *i*th sampling period, mg/L.

$\hat{c}_i$: Estimated suspended sediment concentration for *i*th sampling period, mg/L.

C_v: Coefficient of variation for the simple random sampling stratum.

d: Proportion of true total within which the simple random sample estimator is required to lie.

e: Probability with which the simple random sample estimate of the total is to lie within proportion d of the true value.

f: Probability of selecting a sampling period in simple random sampling.

h: Number of SALT sampling periods in a data segment containing at least one random number, i.e., the number of sample bottles taken.

k: Constant for adjusting units when calculating "true" or estimated suspended sediment yield for a sampling period.

m: Number of sampling periods actually sampled in the simple random sampling stratum (the value of m is random).

m': Number of sampling periods supposed to be sampled in the simple random sampling stratum. Used for selecting sample size for simple random sampling stratum.

M: Number of sampling periods in the simple random sampling population.

M': Number of sampling periods supposed to be in the simple random sampling population. Used for defining selection probability for simple random sampling.

n: Actual SALT sample size (the value of n is random).

n_b: Number of bottles in the pumping sampler.

n_c: Number of "collisions" (i.e., more than one random number in a sampling interval) in the SALT sampling periods.

n_I: Number of equal length intervals in a monitoring period at a constant stage. Used to set SALT sampling parameters.

n*: Number of random numbers stored to perform SALT sampling.

N: Number of sampling periods in the SALT stratum, i.e., the SALT population size.

p_i: Probability with which the *i*th interval is sampled ($p_i = x_i/X$).

q_i: Measured water discharge for the *i*th sampling period, m^3/s.

r_i: Number of random points in the *i*th sampling interval.

$S^2(.)$: Estimator of the sampling variance of the parenthesized quantity.

s: Water stage, m.

s_1: Lower design stage for defining average sampling rate function, m.

s_2: Upper design stage for defining average sampling rate function, m.

t: Time duration of sampling periods, seconds or hours.

v: Average sampling rate, samples/hour.

v_1: Average sampling rate corresponding to lower design stage.

v_2: Average sampling rate corresponding to upper design stage.

x_i: Auxiliary variable for *i*th sampling period. It is the estimated sediment yield in kg for the period in basic SALT, and the number of "samples" in piecewise SALT.

x_u: Average value of auxiliary variable in the unsampled portion. Estimated sediment yield in kg for basic SALT, or "samples" for piecewise SALT.

X: Total of auxiliary variable values for all sample periods in a monitored period ($X = \sum^{N} x_i$). Estimated sediment yield in kg for basic SALT, or "samples" for piecewise SALT.

y_i: Measured suspended sediment yield (primary variable) for *i*th sampling period, kg.

$_{SALT}$: Estimate of the suspended sediment yield in the SALT stratum for a monitored period, kg.

$_{SRS}$: Estimate of the suspended sediment yield in the SRS stratum for a monitored period, kg.

Y*: Length of sampling interval axis.

INTRODUCTION

SALT (*S*election *A*t *L*ist *T*ime) is a new method for collecting data on suspended sediment concentration and estimating total suspended sediment yield (Thomas 1985). It is based on the original SALT developed by Norick (1969) to sample timber volume. The technique produces variable probability random samples based on estimating the concentration for short time periods by using a suspended sediment rating curve. SALT gives unbiased estimates of the total and its variance and provides presampling estimates of required sample size-even though the method preferentially samples high-flow periods. Most suspended sediment is transported during high flows when the yield and its variance are greater. And so SALT is more efficient in the sense of reducing the sample size required for a given precision. In other papers, the effects of changing the duration of the SALT sampling periods were described (Thomas 1983), and the required quality of the sediment rating curve was reported (Thomas 1986).

Estimators for total suspended sediment and its variance and a method for estimating required sample size were described earlier (Thomas 1985). SALT estimates can also be made for arbitrary periods of time (for example, storms) defined after sampling. The SALT estimates can consist of composites or portions of several SALT-monitored periods. Using SALT in this way is termed "piecewise SALT sampling."

This paper describes how to collect data and estimate sediment yield and its variance by piecewise SALT sampling, and discusses another method for setting sample size which is particularly appropriate for piecewise SALT sampling.

SALT SAMPLING

SALT Algorithm

The SALT population is composed of the suspended sediment yields of short (usually 10- to 30-minute) "sampling periods" covering the time to be monitored. The yields are determined from measures taken at the midpoints of each period. Sampling period duration should therefore be chosen appropriate to the expected variation in the sediment hydrograph. This ensures that the total of the finite "sampled" (i.e., SALT) population is acceptably close to that of the continuous "target" population from which it was formed.

As a "measure" of suspended sediment yield, let the *primary variable*, y_i, be expressed as

$$y_i = q_i c_i \Delta t k \qquad (1)$$

in which q_i is the water discharge and c_i is the suspended sediment concentration both measured at the middle of the period. The constants At giving the period duration and k for adjusting units are selected before sampling begins. The variable q_i is calculated from stage in real time, and the value of c_i comes from a gravimetric lab determination of a concentration sample.

If the yields in all of the periods could be measured, the total of the entire (sampled) population would be known. Because there are many periods, it would be difficult to measure and process all concentrations even using automatic pumping samplers. And there is no need to do so because most sediment flux occurs during relatively rare high flows. A method is needed to intensify sampling during periods of high sediment flux and to still give statistically valid estimates.

These goals can be achieved by using *variable probabilities* proportional to "estimates" of suspended sediment yield in each period. The estimates are values of the *auxiliary variable* x_i given by

$$x_i = q_i \hat{c}_i \Delta t k \qquad (2)$$

which are calculated the same as the measures described above except that a suspended sediment rating curve estimate of concentration, c_i, is substituted for the physical concentration measurement, c_i,. (Equation 2 defines x_i for standard SALT sampling; the definition for x_i used in piecewise SALT sampling will be given in equations 14 and 18.) The values of x_i are calculated for *every* sampling period during the time monitored while the values of y_i are known only for those periods actually sampled (i.e., for which a physical concentration sample was taken). The individual values of x_i are stored only for the periods actually sampled, but their cumulative sum for all periods is retained.

The estimate of suspended sediment yield for a period, x_i, is used in real time to determine whether or not a physical sample of concentration will be collected for a given period. The determination is done using a "sampling interval axis" extending from 0 to a sampling parameter,Y*,chosen before sampling begins. A set of preselected uniform pseudorandom numbers is also chosen before sampling starts and placed on the axis. For each sampling period during the actual sampling process, a interval having length equal to the estimated suspended sediment yield for that period, x_i, is placed on the axis adjacent to and following the previous interval. Periods having associated intervals covering one or more random numbers are sampled by making a physical concentration measurement (usually with a pumping sampler). Selecting Y* and the number of random numbers will be discussed in the section on setting sample size.

In small watersheds and those having a highly variable sediment response, the stage is sensed electronically, the physical sample is obtained by using an automatic sampler, and the process is controlled by a battery-powered microprocessor (programmable calculator) (Fads and Boolootian 1985). The calculator is programmed to retain stages at "break points" in the slope of the trace to form an electronic record of stage. These data are used not only to calculate discharge, but also to perform certain recalculations in piecewise SALT sampling. This method gives a high-quality record of stage while retaining only a fraction of the data, and simplifies the transfer of data to the office computer. In larger rivers where the stage changes more slowly and the periods comprising the SALT population can be much longer, it may be possible to carry out the SALT process manually.

Effects of SALT

Those periods having high estimated sediment yields (i.e., with high discharges and rating-curve-estimated concentrations) have longer intervals and, therefore, higher probabilities of covering one or more uniformly selected random numbers. This fact ensures thathigh-flow periods are more heavily sampled on average. Even though groups of closely spaced high discharge periods are more likely to be sampled, the estimates of total yield and variance are still unbiased. The lack of bias is due to the independence of the uniform random numbers and to the known probabilities of selection which are proportional to the estimated yields in each period.

Although the operation of the SALT process requires diligence, collecting data according to the technique has several advantages. One is that the estimates of total and variance are unbiased; that is, the expected value of the distribution of estimates is equal to the true total yield. The unbiasedness of SALT estimates contrasts with traditional "nonstatistical" methods (Thomas 1985) which are usually biased to an unknown and often considerable extent. Valid estimates of variance are not even possible with traditional methods. Estimation of required sample size enables better planning of a sampling program and determination of the effort required to attain a desired level of accuracy and precision.

PIECEWISE SALT SAMPLING

The basic SALT paper (Thomas 1985) describes a method for selecting sample size to attain desired precision. That approach is predicated on the assumptions that the period for which an estimate of total and variance is wanted is known beforehand, and that samples can be taken at any time required. This approach is intended primarily for long-term monitoring, such as annual or seasonal estimates.

Under some conditions, however, this mode of operation does not work well. Because the suspended sediment rating curve is generally expressed as a power of discharge with the exponent greater than one, sampling rates at high flows can become prodigious. At times, a sample unit is collected at each wake-up, soon exhausting the set of sample bottles. Conversely, at low flows, few sample units are taken. Studies sometimes require suspended sediment estimates for storm periods which cannot be defined until after the discharge and sediment data have been collected. Using the standard SALT approach can result in little or no data being available for estimating the suspended sediment yield for small storms.

Use of the basic SALT method is not without some logistical problems. Automatic pumping samplers require periodic servicing to collect filled bottles and install empty ones. The stage record and SALT sampling data must also be obtained from the calculator. Sampling periods occurring during shutdown pose minor problems, but more serious difficulties arise when carrying over sampling parameters after the shutdown period, and in providing an adequate set of random numbers. Calculator malfunction under this mode of sampling can be serious.

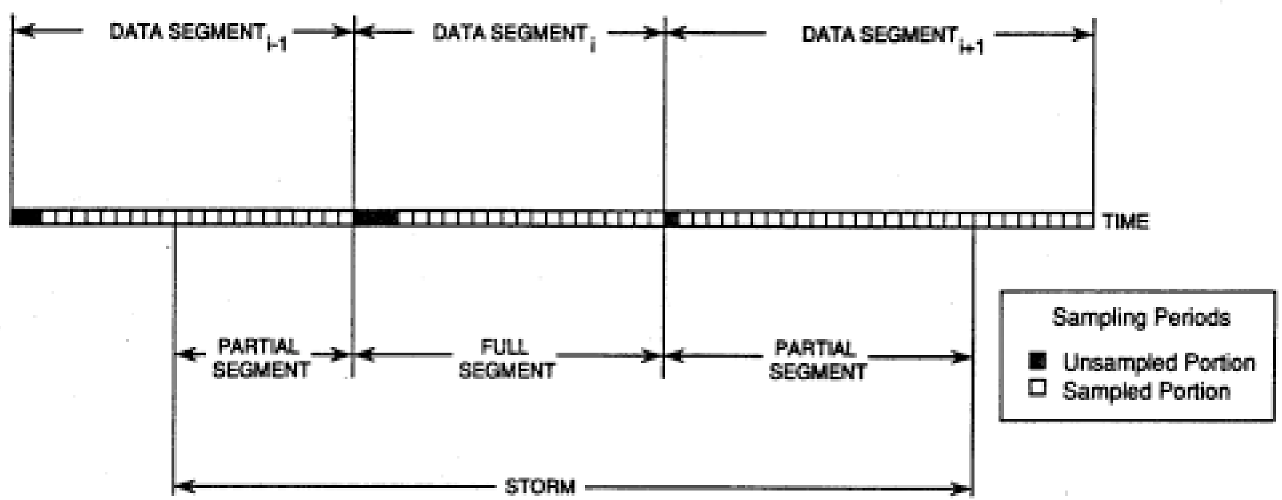

Figure 1-Typical Piecewise SALT (Selection At List Time) time diagram. Data segments (time between station visits) contain integral numbers of sampling periods. Several sampling periods heading each segment are called the unsampled portion because the SALT program is idle for station servicing. The remainder of the segment is the sampled portion. Storms defined after data collection can consist of several whole or partial data segments.

These considerations led to focusing SALT sampling pro-grams on the time periods between station visits (called "data segments") (*fig. 1*). This approach helps ensure that each segment has enough data to allow calculation of storm period yields and assists in limiting problems caused by instrument malfunctions. Each segment has its own set of random numbers, sampling parameters, and values describing its sampling performance. A data segment can, therefore, be treated as a unit for analysis purposes because the SALT information applies only to the samples taken during that segment. Consequently, data analysis can proceed more or less continuously as data from each segment are brought into the office.

During visits, data (both electronic and physical) are removed, fresh bottles are installed in the pumping sampler, and a new set of random numbers is created and stored in the microprocessor. An ideal station visit would be made just before the pumping sampler runs out of bottles, which depends on the discharge history since the last visit. During usual flow conditions, for example, station visits may average once a week or even longer, whereas during storms visits may be required more than once a day.

Because the pattern of visits is not in general related to the time periods for which estimates of totals and variance are wanted (e.g., storms), it is necessary to have estimating techniques for portions and combinations of data segments. Also, a technique is needed for estimating sample size (i.e., controlling sampling frequency) that will fit better with this approach to doing SALT sampling. Such features have been developed.

None of these changes in planning for SALT sampling seriously affects the unbiasedness of either the totals or the variance. A minor exception is when estimates are made for periods during shutdown. Because such periods comprise a small portion of a data segment, however, the bias introduced because they have a zero probability of being sampled is negligible. As in basic SALT, small biases are also introduced because sample sizes are random variables.

Depending on the hydrograph, piecewise SALT estimates can have higher variance than those with standard SALT. The greater information content contained in a sediment rating curve is foregone to attain better "coverage" of the population and to ease station servicing. The "efficiency" of the sampling program may also be reduced because the "optimal" number of samples may not be taken at any stage. Basic SALT should be used when possible because it takes advantage of all available information to control the sampling process. Piecewise SALT sampling is better for many applications, however, while still giving the benefits of probability sampling. It can be considered a compromise wherein precision and efficiency are sacrificed for logistical feasibility and a more balanced set of concentration data for particular requirements.

The importance of basing the sampling on uniformly selected random numbers cannot be overemphasized. Random sampling ensures that the samples are composed of *independent* values, a condition producing several salutary effects. Independent samples, in turn, produce valid estimates, estimates having the properties defined by theory. Such samples are required for calculating variances, computing confidence intervals or making hypothesis tests, and estimating sample size. Independent samples also mean that estimates of total yields andvariances for different time periods are independent as well and, like quantities for the separate periods, can be added to obtain estimates for composite periods. Finally, independence means that sampling periods can be divided into parts and valid estimates of suspended sediment yield made for each one. All of these factors are needed for doing piecewise SALT estimation.

ESTIMATORS FOR PIECEWISE SALT SAMPLING

SALT/SRS Strata and Boundary

Because the values for x_i are calculated for every SALT interval, their total (X) for the monitored period is known. Also, because the random numbers are selected uniformly on the sampling interval axis, the probability, p_i, of the *i*th period being chosen for the sample is x_i /.X; that is,

$$X = \sum^{N} x_i \tag{3}$$

in which N is the number of SALT periods in the monitored period, and

$$p_i = \frac{x_i}{X}. \tag{4}$$

The ratio y_i/p_i is important in SALT estimation. Dividing the measure of suspended sediment for the *i*th period by the probability of its being selected for the sample is an unbiased estimator of the total for the monitored period. (The unbiased estimator for the total suspended sediment yield in the monitored period is just the mean of these ratios.) As will be evident from equation 7, the SALT variance is small when this ratio is nearly constant. For low discharges, however, x_i often does not predict yi well (the measured values tend to be higher than the predicted ones), so these ratios can be quite variable which reduces the precision of the SALT estimators.

The problem of variability can be solved by dividing the sampling periods within a segment into two classes or *strata*. Those sampling periods having stages greater than some se-lected threshold are sampled by SALT, while those having stages equal to or smaller than the threshold are sampled by another method. The lower stratum carries a relatively small amount of suspended sediment and its variance is limited by the boundary. It can therefore be adequately sampled using simple *random sampling* (SRS). Using two strata avoids contaminating the SALT estimate in the more important upper stratum.

When the SALT algorithm is operating, the stage is first used to determine which stratum the period falls into. If it is the SRS stratum, x_i is not calculated. If the stage for the period is above the boundary, x_i is calculated and added to an accumulator to determine X. SALT and SRS periods can be intermixed within a data segment, and the estimators in each stratum are still unbiased.

Selecting an appropriate boundary between the strata is done by plotting the y_i/x_i ratios against stage. These ratios cancel to $c_i/\hat{c}_i$ apart from the constant, X, which can be derived from a set of rating data and used to investigate this pattern before sampling begins. If such data are available, plot $c/\hat{c}$ against a range of corresponding stages. (The quantity c is the observed and $\hat{c}$ the corresponding predicted concentration from the rating regression.) A typical plot *fig*. 2) shows a nearly horizontal pattern of moderate variation towards the right with a pronounced increase in variation of the ratio to the left of a low value of stage. A stage just to the right of this increase in variation should be chosen as the boundary.

SRS sampling is done by comparing the output of a uniform random number generator in real time to the desired probability of sampling, f = m'/M'. The values m' and Mare pre-sampling *estimates* of the sample and population sizes for the SRS stratum. After the SRS/SALT boundary is selected, M' is determined by dividing the time the hydrograph is expected to be below the boundary by the sampling period duration. The estimated SRS sample size, m', is calculated by standard methods described later in the section on setting sample size.

For each SRS sampling period the calculator program selects (in real time) a uniform random number on the interval [0,1]. If the random number is less than f, a sample is taken; otherwise it is not. Hence, the actual sample size (m) is a random variable which inflates the variance over that given by the variance

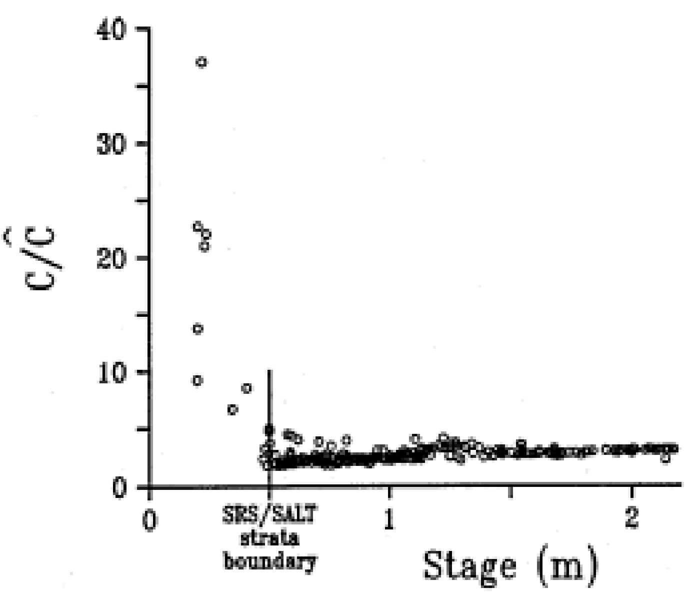

Figure 2-Ratio of measured to estimated suspended sediment concentration ($c/\hat{c}$) against stage for the North Fork of the Mad River near Korbel, California (water year 1984). The boundary between the simple random sampling and the SALT (*S*election *A*t *L*ist *T*ime) strata is indicated by the vertical line at about 0.5 m stage. Values of the ratio for stages above the boundary have nearly constant slope and are suitable for SALT sampling. Values less than the boundary stage are not constant and are sampled with simple random sampling.

formula used when m is known. The increase depends upon the reciprocal of the random sample size. If the random sample size is small, the percentage increase in variance is larger than it would be if the sample size were fixed.But this is the case when the SRS stratum accounts for little of the suspended sediment, and so is unimportant. For larger random sample size the percentage increase in variance is smaller. For example, if m = 2, the percentage increase is about 50 percent, but when m = 8 the percent increase in variance is only about 13 percent.

Estimating Totals and Variances

SALT Estimators

The number of SALT sampling periods in a data segment containing *at least* one random number is designated as h, which equals the number of physical concentration samples (i.e., "sampling units") collected for the SALT stratum. Also, let r_i be the number of random numbers in the *i*th interval. And r_i is nonzero for exactly those intervals containing at least one random number. Then define

$$n = \sum^{h} r_i \qquad (5)$$

The value n, a random variable, is the SALT sample size. Now define $\hat{Y}_{SALT}$ by

$$\hat{Y}_{SALT} = \frac{1}{n} \sum^{h} r_i \frac{y_i}{p_i}. \qquad (6)$$

$\hat{Y}_{SALT}$ is an unbiased estimator for the total suspended sediment yield in the SALT stratum. $\hat{Y}_{SALT}$ is the average of n ratios y_i/p_i with each one repeated a number of times equal to the number of random numbers that occurred in its associated sampling interval. The estimate of the variance of $\hat{Y}_{SALT}$ (Thomas 1985) is given by

$$S^2(\hat{Y}_{SALT}) = \frac{1}{n(n-1)} \sum^{h} r_i \left(\frac{y_i}{p_i} - \hat{Y}_{SALT}\right)^2. \qquad (7)$$

SRS Estimators

Now let M be the true number of sampling periods in the SRS stratum, and m the number of periods actually sampled (these must both be determined after sampling). Then an essentially unbiased estimator of the total suspended sediment yield in the SRS stratum, $\hat{Y}_{SRS}$, is given by

$$\hat{Y}_{SRS} = \frac{M}{m} \sum^{m} y_i, \qquad (8)$$

and an estimate of its variance, $S^2(\hat{Y}_{SRS})$, by

$$S^2(\hat{Y}_{SRS}) = \frac{M(M-m)}{m(m-1)} \sum^{m} \left(y_i - \frac{1}{M}\hat{Y}_{SRS}\right)^2. \qquad (9)$$

The definition of y, used in SRS sampling is identical to that used in SALT sampling (Cochran 1963).

Equations 6 through 9 will be altered appropriately to enable estimation in partial data segments.

Defining Storms

A data segment consists of the set of adjacent sampling periods occurring between station visits (*fig*. 1). By convention for estimation purposes, the sampling periods during the time the station instruments are shut down are included with the periods *after* start-up and until the next station visit. Because these periods have zero probability of being sampled, they are known as the *unsampled portion* of the data segment. A data segment, therefore, starts with a small number of sampling periods known as the unsampled portion, and is followed by a relatively much larger number of periods actually available for sampling. (An exception to this pattern is when a segment has a "cold start." This type of segment follows an extended downtime and has no leading unsampled portion.) Data for use in estimation are collected as a unit for each data segment; that is, the values of X, M, the sets of r_i., q_i, and x_i, etc. are all collected in association with a particular data segment. During the next station visit these values are written from the calculator onto a second calculator or to magnetic tape for transfer to the office. For the next data segment the accumulators are erased, and data recording is begun anew.

For convenience the portions of time for which totals and variances are to be calculated will be referred to as "storms." Any arbitrary period of time can be used, with the restriction that it consist of an integral number of sampling periods; that is, a storm must start at the beginning of one sampling period and stop at the end of another. Because sampling periods are of short duration relative to storm length, this restriction should not be a serious limitation. Storms may divide data segments. A storm, therefore, will consist of a set of one or more adjacent complete or partial data segments (*fig*. l).

Calculating Totals and Variances for Partial Segments

Calculation of totals and variances for partial segments for both the SRS and SALT strata is done by using the same equations 6 through 9 that are used for complete segments. The only changes are to ensure that the sums are over the correct set of values and that sample and population sizes are adjusted accordingly. Also, for SALT sampling, the value of X must be recalculated.

Unsampled Portions

The approach for dealing with the unsampled portion is based on the assumption that the unsampled portion is much shorter than the whole length of the data segment. Under normal circumstances there is noreason for the unsampled portion to be more than two or at most three sampling periods. These periods are, therefore, included in the population for purposes of estimation even though there is no chance of them being sampled.

The ending stage for shutdown of the previous segment is saved and averaged with the start-up stage for the present segment. The average stage is first used to assign the unsampled portion to the correct stratum. If the stage is above the boundary, *all* periods in the unsampled portion are put into the SALT stratum. In this case, the average stage is again used to estimate the average suspended sediment yield, x_u, from the unsampled period. The product of x_u and the number of unsampled periods is then added to the sum of the x_i for the sampled portion, X (x_u is calculated by using the average stage from equation 2 or 18 depending on the type of SALT auxiliary variable being used). The new value of X is then used as described in equations 6 and 7 in which the values for p_i now reflect the corrected value for X.

If the average stage for the unsampled portion is less than or equal to the stratum boundary, the unsampledportion is included entirely in the SRS stratum. In that case M is increased by the number of unsampled periods. Finally, equations 8 and 9 are calculated by using the corrected value for M.

Partial Segments

Calculating totals and variances for partial data segments in both the SALT and SRS strata requires further changes. Rather than presenting formulas for each of the numerous cases, we describe a general approach that can be applied to each situation.

Partial data segments must be changed in two ways so yields can be estimated. The first change has to do with the populations to which the estimators are applied, treating the SALT and SRS strata separately, as usual. For the SALT stratum, a new value for X will have to be recalculated for all SALT sampling periods contained in the partial segment. The recalculation is done using the recorded stage data because the real-time values of x_i are known only for the sampled periods in the segment and for those periods the stage algorithm saved. Most stages, therefore, will have to be interpolated. Again, the appropriate formula (2 or 18) for x_i must be used. Then the recalculated value for X is used to compute the p_i's in equation 4.

For the SRS stratum in a partial segment, the value of M must be recalculated. M is recalculated by using the recorded and interpolated stages to count the number of sampling periods in the partial data segment having stages below the stratum boundary. It can also be done by subtracting the number of SALT periods from the total number of periods in the partial segment. If the partial segment contains an unsampled portion, it will have to be included in either the SALT or SRS stratum in the obvious way after the populations are adjusted as described.

The second type of change to be made to partial data segment estimators concerns the samples to be used in the estimator sums. In the SALT stratum, h becomes the number of sampling periods actually sampled (i.e., the number of concentration samples taken) during SALT sampling periods in the *partial* data segment, and the sums in equations 6 and 7 are understood to be over only those samples. The values of r_i are carried along with their respective samples. The value of n is changed to be the sum of the r_i for the sampled periods in the partial segment.

In the SRS stratum, m is now the number of SRS samples taken during the partial segment, and the sums in equations 8 and 9 are over exactly those samples.

The recalculations of the x_i's and determining which stratum the sampling periods fall into depend on the stage record. The actual stages available to the program in real time are in general different from those in the saved record because the algorithm keeps only those stages at "break points" in the trace. The recalculated stages will be somewhat different, but the differences are likely to be small and the bias thus introduced should not be large.

Combining Total Yield and Variance Estimates

Because SALT data are collected independently, the estimates for strata and whole and partial segments can be combined to give estimates for storms defined after sampling. Statistics for the data sets can be combined because the data sets as well as the individual samples are independent.

The total suspended sediment yield estimate for a whole or partial segment is calculated by adding the separate estimates for the SALT and SRS strata. Likewise, the variance is estimated by adding the variance estimates for the two strata in the segment.

The suspended sediment yield for an arbitrary period, or "storm," is estimated by adding all of the combined strata estimates for the whole and partial segments comprising the storm. The associated variance is similarly computed by adding the component variance estimates.

Accounting for Missing Data

Occasionally, some data from a data segment will be missing. This can happen in many ways, such as spilled concentration samples, essential information not being recorded, or electronic equipment malfunction. Because the number of possible problems is large, specifying what to do in each of them is a difficult task. Because the problems are relatively rare and result from many causes, it is probably best to assume that missing data are the result of a random process. Then the remaining observations can be treated as a random sample and the estimating done by making the obvious changes in sums and samples over which the estimates are calculated in equations 6 through 9; that is, h in the SALT stratum and m in the SRS stratum represent the good samples remaining, with the sums being over only those samples. The value of n in the SALT stratum should now be the sum of the remaining h nonzero r_i's. The values of X in the SALT stratum and M in the SRS stratum will not change unless calculations are for a partial segment as previously described.

If only one point remains, an estimate of the total can be calculated, but the variance cannot because of division by zero in equations 7 and 9. Such segments should probably be treated separately from those having variance estimates. Then the variance can be estimated for the bulk of the data.

In a few cases, all of the SALT or SRS data may be lost. It is then necessary to fall back on a sediment-rating-curve approach to estimating the yield. The great advantage of this approach is that such estimates can depend on concentration/discharge pairs not collected during the segment being estimated. The major problems are that these estimates are often highly biased (Walling 1977a, b, Walling and Webb 1981) and an estimate of variance is not possible.

SAMPLE SIZE

Setting sample size is required for all sampling schemes. Never a simple problem, it is complicated for SALT because sampling occurs in two strata and because the flow patterns and, hence, the populations for the period to be monitored are not known when sampling parameters must be set.

Selecting a particular statistical sampling scheme is often done to reduce the variance. This strategy gives better precision for a given level of effort or allows reducing the effort for the same variance. For variable probability sampling-which includes SALT-our knowledge of the process is used to help select "important" periods. When sampling suspended sediment using SALT, a sediment-rating curve is used to select those periods likely to have a high flux of sediment and to sample them preferentially.

It may seem counterproductive, therefore, to recommend piecewise SALT sampling which does not use the rating curve to select the periods to be sampled. Piecewise SALT is generally less than optimal because average sampling rates are used instead of the best estimate of sediment yield from the sampling period. This scheme should be considered a compromise which balances the distinct benefits of probability sampling with a logistically achievable field technique. The estimates are still unbiased and the variance estimate still valid; the only effect is that the variance may be somewhat larger than that obtained using a good rating curve with the standard SALT scheme.

Simple Random Sampling Stratum

When sampling a population with SRS, the required sample size, m', for the estimate of the total to lie within proportion d of the true total with probability 1-e, is given approximately by

$$m' \doteq \frac{z^2 (C_v)^2}{d^2} \qquad (10)$$

in which z is the upper e/2 percentage point on the standard normal distribution and C_v is the coefficient of variation (Cochran 1963). The values of z and d can be readily selected based on the performance wanted, but C_v depends on the population and may not be known. If data are available, C_v can be estimated;

if not, several reasonable values can be tried to get an idea of how m' behaves. The symbol m' is used to remind the reader that in the SALT scheme, the true SRS sample size, m, is not known until after sampling is completed. The sample size cannot be known because the SRS population size is not known until after sampling and because of the real-time sampling scheme described earlier. This value of m' is used with M' to calculate f for sample selection in the SRS stratum as described in the section on *SALT/SRS Strata and Boundary*.

With fixed m' and M' this method will produce an SRS sample size approximately proportional to the value of M. When the flows are low and the SRS stratum is occupied more than expected, the SRS sample size will be large; that is, the value of m will tend to be higher than m'. To avoid excessive laboratory analysis in this case the sample size can be reduced to m' at the end of the monitored period by eliminating samples at random. When the flows are larger, more time will be spent in the SALT stratum, and the SRS sample size will drop because the SRS stratum for a high-flow period will tend to have too few samples. In this case, however, the SALT stratum yield will be large so that the yield in the SRS stratum will be a small fraction of the total and its error of relatively little importance.

SALT Stratum

An entirely different approach is used to establish sample size in the SALT stratum when doing piecewise SALT sampling. Ignorance of the flow pattern to come during a period to be monitored makes it hard to specify the quantities required to establish sample size, especially when yield estimation for storm periods is wanted. Trying to do so can result in sampling levels at high flows that make adequate station servicing very difficult and sometimes impossible. The approach that will be used instead is to set desired *average sampling rates* at selected stages. At each of two design stages an average sampling rate will be specified. The number of samples collected in a monitored period of given length will still vary according to the stages experienced and the set of random numbers selected. With this approach, however, the hydrographer soon becomes adept at guessing when a station visit is required (i.e., just before all of the pumping sampler bottles are filled) on the basis of general rainfall conditions, knowledge of station behavior, and the sampling rates at different stages.

Average Sampling Rates

The discharge and sediment rating curves are power functions, so the suspended sediment discharge is also a power function of stage. The average sampling rate function is a surrogate for the sediment rating curve, so the same power function form is used. Let v be the average sampling rate (samples/hour), s the stage (m), and a and b parameters to be selected. Then define

$$v = a\,s^{b}. \qquad (11)$$

The sampling parameters a and b will be established mathematically by selecting two *design stages* for which the associated average sampling rates will be specified. Suppose we select an average sampling rate v_1 at stage s_1 and rate v_2 at stage s_2 where $s_1<s_2$. Placing the design stages and sampling rates in turn in equation 11 gives two equations in the two unknowns, a and b. Taking logarithms of both equations, subtracting equations, and solving for b yields

$$b = \frac{\ln v_2 - \ln v_1}{\ln s_2 - \ln s_1} \qquad (12)$$

for calculating b, and

$$a = v_i\, s_1^{-b} \qquad (13)$$

for calculating a.

The design stages and their associated sampling rates should be determined from discharge frequency information. An approach that has worked well is to let s_1 be the stage of a storm that occurs, on average, about four times a year. Similarly, s_2 is the stage of a 5-year storm. Then sampling levels are selected based on desired rates at the design stages. These rates should be a compromise between the technical requirements of data collection and the logistical needs of station servicing. Average sampling rates that have worked well in practice are v_1 = 0.33 samples/hour and about 2 samples/hour for v_2.

The average sampling rates for only two stages are used to calculate a and b. A plot of the values in equation 11 should therefore be examined to ensure that the rates across all stages in the range of interest are satisfactory (*fig. 3).* The design stages and average sampling rates can then be changed, new values of a and b calculated, and another plot made if the original is not acceptable. Several iterations may be necessary. Although the process is subjective, it enables the hydrologist to select average sampling rates across a range of stages appropriate to a particular application.

Depending on the choice of parameters, the average sampling rate curve can increase rapidly for high stages (i.e., if b is much greater than 1). Too many samples may then be collected at very high flows, possibly faster than the stations can be serviced, the wake-up frequency of the SALT program, or even faster than the capability of the pumping sampler. Our solution is to limit the sampling rate to v_2. The average sampling rate follows the power function from zero stage to s z, and then stays at v_2 for all higher stages (*fig*. 3). These upper limits must not be too low. If they are, the effectiveness of x in governing the SALT process will suffer. The limits should allow for a sampling rate as high as can be technically and logistically supported because higher stages will be undersampled. If a reasonable upper limit is not set, however, some higher stages are likely not to be sampled at all.

Random Number Axis

It remains to select values for the length of the sampling interval axis, Y*, and the number of random numbers, n*, to place on the axis. The length required for the Y*-axis depends on the

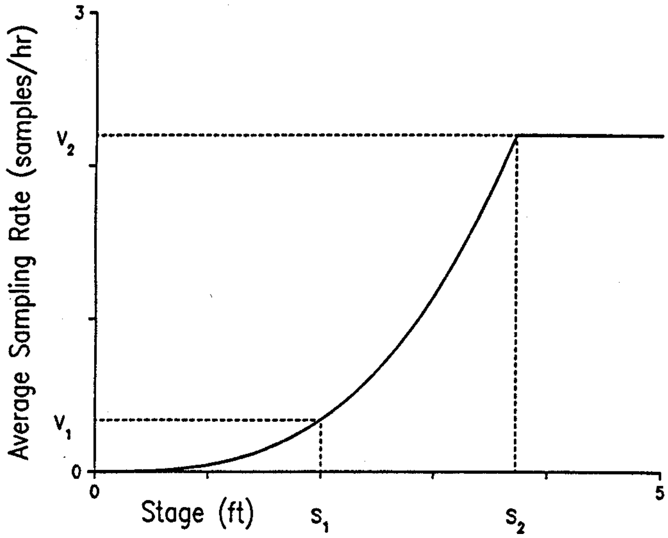

Figure 3-Average sampling rate curve. Two design stages s_1 and s_2 and their corresponding average sampling rates v_1 and v_2 define the curve. The average sampling rate is limited to v_2 for stages greater than s_2.

magnitudes of the x-value intervals to be placed on it. We, therefore, begin the process of setting these quantities by investigating x.

For basic SALT sampling, x_i is calculated according to equation 2. The value of x_i need not be "close" to the value of y_i, however, for SALT to work well. It may seem reasonable that x and y be highly correlated (i.e., that y be close to a linear function of x) for SALT to operate efficiently, and, in general, this is true. It is possible, however, to develop pathological cases having the correlation between x and y equal to one, but with SRS performing better than variable probability sampling. The actual requirement for SALT to be superior to SRS is that x and y^2/x be positively correlated (Raj 1968). Piecewise SALT sampling generally reduces this correlation in exchange for convenience of operation. For a given precision, therefore, it is usually necessary to compensate for lower efficiency (that is, higher variance for a given number of samples) by collecting more concentration samples.

For piecewise SALT sampling we define x differently from equation 2. Let

$$x_i = v_i \Delta t \qquad (14)$$

in which v_i is the average sampling rate calculated according to equation 11 for the *i*th mid-period stage, s*i*, and Δt is the duration of the period as before. (The subscripts of v and s now denote sampling periods instead of upper and lower design values.) If Δt is in hours and v is in samples/hour, then the hours cancel, leaving the units of x as "samples." Therefore, every increase of one in the sum of the x-values accounts for an additional sample being taken, on average.

For example, suppose the flow has a v of one sample every. 3 hours (i.e., v = 0.3333 samples/hour), and that the sampling period duration is 10 minutes (Δt = 0.1667 hours). Then each x-interval length is (0.3333)(0.1667) = 0.0555. If the flow stayed steady for the 18 sampling periods in 3 hours, X would increase by (18)(0.0555) or about 1, as required. During each such 3-hour period, therefore, 1 additional sample would be taken, on average. Real records would tend to vary, so that the advance of the cumulated values of x on the Y*-axis would reflect the sum of contributions from different stages during the period.

Because the x-values for each interval are measured on the Y* axis, both quantities must have the same units. The units of both quantities are "samples," therefore, as the units of x were defined to be; that is, each unit on the Y*-axis should represent one sample bottle being filled, on average. For this to happen, it is necessary that there be an average of one random number for each unit as well because, we must have $n^* = Y^*$. Therefore, it is necessary to set only one of these quantities.

Suppose there are n_b bottles in the pumping sampler. We want n^* to be as large as n_b so that all of the bottles can be filled. In fact, n^* must be larger than n_b when more than one random number occurs in a sampling interval on the Y*-axis. Whenever a random number "lands" in an interval already containing at least one random number, we say that a "collision" has occurred. Counting across all intervals in a monitored period, let the total number of collisions be n_c. Consider Y* to be equal to n_I equal-length intervals (i.e., where the stage remains constant for the entire sampling period). Then we want

$$n^* = n_b + n_c \qquad (15)$$

We do not know n_c before sampling, but there is an approximate expression for the number of collisions expected when a known number of "balls" are placed with equal probability into a known number of "cells" (Knuth 1981). In this case, the cells are the n_I equal-length intervals at a given stage, and the number of balls is n^*. For our purposes, then, we will define n_c to be this expected value,

$$n_c = \frac{N^{*2}}{2n_I} \qquad (16)$$

Also, because there are n_I intervals of length x on the axis of length Y*, we have

$$N_I = \frac{Y^*}{x} \quad , \qquad (17)$$

and substituting equation 11 in 14,

$$x = \Delta t\, as^b. \qquad (18)$$

Substituting equation 18 in 17, equation 17 in 16, and equation 16 in 15 we can write,

$$n^* = n_b + \frac{n^{*2}}{\frac{2Y^*}{\Delta t\, as^b}} \,. \qquad (19)$$

Because $n^* = Y^*$, we can solve equation 19 for n^* to obtain

$$n^* = \frac{2n_b}{2 - \Delta_t \, as^b} . \tag{20}$$

Equation 20 can be solved for n* in terms of quantities known before sampling begins. It will be largest for the highest stage to be sampled, so the upper sampling frequency limit should be used to calculate n*. For equation 20 to be meaningful the denominator must be positive, which will be true as long as the upper design sampling rate is less than the number of sampling periods in 2 hours.

This calculation should be considered as a lower bound on the values of n* and Y*. Remember that Y* must always be greater than X for the SALT process to operate. Y* and n* can be increased, provided they remain equal to each other, assuring that the density of points on the axis is the same so that sampling performance will be unchanged. A disadvantage of using a larger value of n* (and Y*) is that more random number storage space is needed in the calculator. More importantly the SALT variance is increased. The variance increase resulting from raising n* above (even many times above) reasonable starting values is modest, however, generally well under 5 percent. We now show why increasing n* above the value calculated in equation 20 does not seriously raise the variance.

An approximate "true" variance for the SALT estimate of the total is given by

$$\mathrm{Var}\,(\hat{Y}_{SALT}) \cong \frac{1}{X}\left[1 + \frac{1 + \frac{X}{Y^*}}{X}\right]\left(\sum_{i=1}^{N} \frac{y_i}{p_i} - Y^2\right) \tag{21}$$

from formula 8 (Norick 1969, p. 11). Norick's R is n* here, while her $\pi = X/Y^*$ here. Then $R\pi = n^*X/Y^* = X$ because $n^* = Y^*$ for piecewise SALT. The parenthesized factor is a function of population values only, so does not change with n*. For the same reason X will not change. Therefore, the only factor to change across samples is the one in square brackets. Denote that factor by F, which can be expressed as:

$$F = 1 + \frac{1}{X} - \frac{1}{n^*} . \tag{22}$$

For any population, F will attain its largest value when n* approaches infinity, because n* is always positive. Then define:

$$F_{MAX} = 1 + \frac{1}{X} \tag{23}$$

The *largest percent increase*, P_{MAX}, in the SALT variance can then be written:

$$P_{MAX} = \frac{F_{MAX} - F}{F}(100) \tag{24}$$

or, substituting equations 22 and 23 into equation 24,

$$P_{MAX} = \frac{100}{n^* \frac{X+1}{X} - 1} \tag{25}$$

Now X is a relatively "large" number so that (X+1)/X is nearly 1. Then we can write the approximation that:

$$P_{MAX} \cong \frac{100}{n^* - 1} . \tag{26}$$

P_{MAX} gives an approximate *upper bound* of the percentage increase in SALT variance to be expected for a "starting value" of n*. For likely increases in n* the percent increase in the variance will be smaller.

Most automatic pumping samplers contain at least 24 bottles. If n* were set at 24, the *maximum* increase in the variance would be only 4.3 percent. For an n* of 36 the maximum increase drops to 2.8 percent. Therefore, increasing n* to reduce the chance of running out of random numbers is not likely to cause an unacceptable increase in the SALT variance.

Equation 20 is based on an oversimplification to make the development of the expression possible. An actual stage hydrograph is rarely constant, especially during storm periods which are of primary interest. This expression should be used as a starting point and n' modified as experience dictates.

At higher flows, where more collisions will occur, the effective sample size will actually increase. The SALT sample size (n) will be larger than the number of bottles collected because the concentration determined from a bottle will be used in the estimators the number of times there were random numbers in its associated interval (equations 5, 6, 7). The available sample bottles are thereby spread out over a longer period of flow.

The primary reason for increasing Y* and n* over that calculated in equation 20 is that the SALT sampling process can continue even though no more pumped samples can be taken. The calculator is programmed to continue the SALT algorithm even though the pumping sampler bottles are all full, which means that all of the information except the concentration data will be saved. The stage and time of the intended sample as well as the number of random numbers in a SALT interval will then be known. These data can be used to make a lower quality estimate of suspended sediment load or to evaluate the performance of the SALT process for the purpose of correcting the SALT parameters as long as X<Y*.

DISCUSSION AND CONCLUSIONS

Suspended sediment yields are traditionally estimated with data on continuous water discharge and discrete concentration. Temporal sampling protocol for the concentration data is generally poorly defined. The methods of estimating, therefore, cannot be based on known properties of the sample. Consequently, these methods have been termed "nonstatistical" (Thomas 1985). As a result most estimators are biased (often to a large extent), and no estimates of temporal sampling error are possible (Walling and Webb 1981).

One remedy for this problem is to develop devices that measure concentration continuously. Sampling error would then essentially be eliminated (although error resulting from measurement at only one point in the cross section would remain). Such devices exist (Skinner and others 1986), but cost and power requirements are likely to limit their use to stations at which 120 volt a.c. current is available or to particularly sensitive measurement problems. For most suspended sediment monitoring in the foreseeable future, especially in remote forested watersheds, the traditional data-collecting pattern is likely to continue. Hence, there is a strong need for strategies that temporally sample discrete concentration and give estimates with desired properties.

The SALT method is one such technique. It collects true probability samples that are related to the estimators in known ways. Although care is required to ensure that the samples are truly random according to the scheme, the effort is repaid by estimators that are unbiased, an estimate of error for every sample, and a method for setting sample size.

Hydrologists have long known that most sediment is carried during high flows that occur infrequently. The SALT algorithm capitalizes on this knowledge in emphasizing sampling during such flows by using estimates of sediment discharge derived from a sediment rating curve. Since the probabilities for selecting the sampling units are known, they can be used to remove bias in the estimates. Therefore, SALT is more efficient than traditional methods because it automatically directs sampling effort toward the more important events.

SALT is operated in the field by a portable computer, a stage sensor, a pumping sampler, and a circuit board designed to connect the devices. The computer queries the stage sensor periodically and computes an estimate of sediment discharge based on the stored suspended sediment rating curve. The estimate and a previously stored list of uniformly selected random numbers are then used to decide whether to operate the pumping sampler. In either case, data are stored, which allows estimation of the sediment yield after the samples in the pumping sampler are analyzed. Sediment yield and water discharge data are read electronically and transferred directly to an office computer.

Piecewise SALT is a modification of the basic SALT procedure that is superior for many applications. It is used when estimates are wanted for storm periods that cannot be identified until after the records are collected. Also, it is often easier to set sampling parameters for piecewise SALT and to overcome the logistical problems inherent in collecting concentration data. Desired average sampling rates are chosen for two stages (one "high" and the other "low") that are used to create an "average sampling rate" curve that replaces the rating curve.

Piecewise SALT generally moderates the extremes of sampling rate compared to basic SALT, increasing the rate at low flows and decreasing it at high flows. The piecewise approach can be thought of as a compromise by having far superior statistical properties than traditional methods while being simpler to use and giving better storm data than basic SALT.

Most of the desirable qualities of basic SALT also exist for piecewise SALT. All estimates are essentially unbiased and variances can be estimated. Depending on the selection of design stages and rates, there can be a cost in somewhat lower efficiency as reflected in higher variance. This drop in efficiency is often worth the price to obtain better coverage of small storms.

An objection to using SALT has been that "intelligent" sampling equipment is required. While it is needed for small streams having a "flashy" suspended sediment response, its cost is quite modest. Present installations using programmable calculators cost about $1000 per station to install. Also, if electronic stage collection is used, the chart recorder can be dispensed with, thus saving its cost. Most automatic pumping samplers have microprocessors to control sampling schemes, and new hydrological data monitoring-systems are being developed around microprocessors, as well. Most of these systems could likely be readily adapted to operate we probability sampling systems such as SALT.

Data are almost always collected to enable comparisons to be made or to make quantitative estimates. Suspended sediment data are no exception. Such measurements may be a part of detecting the effects of logging or some other land management treatment on sediment production. They may be used to determine if water quality standards have been violated. Or, they could be used to help estimate the lifetime of a reservoir. In all these cases, it is important to have a way to judge the quality of the estimates or to determine if differences are significant. These judgments can be made only when one has estimates of the variance, and such estimates can be obtained only from probability samples.

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