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P.O. Box 245
Berkeley
California 94701

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Measuring the Fraction of Pool Volume Filled with Fine Sediment

Sue Hilton **Thomas E. Lisle**

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The fraction of pool volume filled with fine sediment (usually fine sand to medium gravel) can be a useful index of the sediment supply and substrate habitat of gravel-bed channels. It can be used to evaluate and monitor channel condition and to detect and evaluate sediment sources. This fraction (V*) is the ratio of fine-sediment volume to pool water volume plus fine-sediment volume. These volumes are computed for the residual portion of the pool that lies below the elevation of the downstream riffle crest. Fine-sediment thickness is measured by driving a graduated metal probe into a fine-grained deposit until the underlying coarser substrate is felt. Water depth and fine-sediment thickness are measured across transects, and volumes are computed by summing products of cross-sectional areas and distances between transects. Replicate measurements of V* were made in 20 pools, and the variability of V^*_w, the weighted mean value of V* for a reach, was analyzed in 12 reaches. The largest source of variability in V* was the measurement of fine sediment volume. Topographic irregularities in pools and on riffle crests and effects of variation in discharge on measurement of riffle crest elevation also affected V*. Ten to 20 pools are needed to estimate V^*_w in a reach, depending on acceptable error and variability between pools.

Retrieval Terms: fine sediment, pools, monitoring, sedimentation, fish habitat

Experienced hydrologists and geomorphologists can estimate the relative mobility of a streambed by looking at indicators of bedload transport, such as the freshness of bed-surface material. Another such indicator is the amount of fine sediment in pools. Pools in gravel-bed streams commonly contain deposits of fine sediment (mostly sand and gravel) that overlie a coarser substrate of coarse gravel, cobbles, or boulders. In such channels, the fraction of pool volume filled with fine sediment can be used as an index of the supply of mobile sediment. This fraction (V*) is the ratio of fine-sediment volume to pool water volume plus fine-sediment volume. In a previous paper, we investigated the relationship of V^*_w, the weighted mean value of V* for a reach, to qualitative evaluations of sediment yield in eight tributary basins of the Trinity River in northwestern California.[1] This study suggested that V^*_w could be used to evaluate sediment supply in gravel-bed channels without directly measuring sediment transport or sediment delivery from hillslopes. In one channel, V* increased abruptly downstream of a sediment source, suggesting that V* could be used to identify significant sediment sources.

We are conducting ongoing research on the relationship between V^*_w, sediment supply, and basin characteristics and are attempting to link V* to habitat suitability for aquatic organisms. If this is successful, V* could be used to simultaneously evaluate sediment supply and its effects on aquatic ecosystems. These relationships could then provide a needed link between watershed condition and fish habitat.

This paper describes a method to measure V* and discusses factors affecting the accuracy of estimates of V* and V^*_w.

APPLICATIONS AND LIMITATIONS

V* can be used to evaluate and monitor channel condition and to identify and quantify effects of discrete sediment sources. There are, however, limits to the types of channels where it can be used, and care must be taken in interpreting differences in V* between channels.

The usefulness of V* is limited to channels in which significant volumes of fine sediment can be deposited in pools. To date, we have found that V* can be accurately measured and results consistently interpreted in channels that have:

• a wide range in particle size between armor layers and fine sediment in pools. Sediment supply needs to include at least moderate proportions of sand and fine gravel. We have found V* to be very low and insensitive to sediment supply in basins that are formed in basalt or competent, fine-grained metamorphic or sedimentary rocks, for example.

• stable banks of densely rooted alluvium, bedrock, or armored colluvium.

• a single thread. In braided channels, the volume and proportion of fine sediment can vary widely between anabranches and thus create wide variations in V*.

• gradients less than about 5 percent. We are uncertain about how V* varies inherently between step pools, which are associated with steep slopes, and bar pools, which are commonly associated with gentle slopes.

Care should be taken in interpreting differences in V^*_w between different stream channels. Knowledge of variations of V* between streams with different geologies and stream types is needed to interpret variations in V* with respect to sediment supply. For example, a value of V^*_w of 0.15 would be expected to represent high sediment supplies in basins underlain by competent metamorphic rocks, but would be considered low for basins in weathered granite. V* values can be expected to be associated with substrate conditions important to aquatic organisms, such as embeddedness or infiltration, but specific responses will depend on the community present, which will in turn depend on the natural range and variability of substrate conditions in the channel.

These problems are not encountered when monitoring changes in V^*_w over time or in using V* to evaluate sediment sources. Volumes of sediment from landslides, for example, can be easily measured from air photos or in the field, but evaluating the intensity, extent, and duration of their impacts on channels has been problematical. V^*_w measurements upstream and downstream of such sources can potentially be used to evaluate and monitor their mobile sediment inputs.

Measuring V* in large rivers has practical limitations, although pools can be sounded and fine sediments probed from tethered rafts. We have measured V* in pools as wide as 30 m and 2000 m^3 in volume. Small pools create no logistical problems, but measurement precision may need to be increased in very small pools (<1 m^3 in volume). We have measured V* in second- through fifth-order channels.

METHODS

V^*_w is estimated in a section of a stream channel by measuring the water and fine sediment volume in the residual pool in all of the pools in a study reach and then calculating the weighted average value of V* for the reach.

Time and Equipment

Two or three experienced people can measure a wadable pool in half an hour to an hour, but accurate measurement of large pools requires a raft, which takes more people and more time. The minimum equipment required is two tapes, chaining pins, and a graduated rod. The rod must be long enough to measure water depth plus fines depth in the deepest part of the pool. A rod made of one-half inch diameter stainless steel probes fine sediment deposits well without bending. Systematic sampling also requires a calculator with a random number generator or a random number table. We use a palmtop computer with a spreadsheet to choose transect locations, enter the data, and calculate V*. This reduces data processing time and provides an opportunity to catch and correct errors in the field.

Choosing a Study Reach and Identifying Pools

The general location of a study reach is set by the purpose of the study. Reaches may be located upstream and downstream of a sediment source or downstream of a watershed rehabilitation project, for example. The specific location is chosen to avoid complicating factors which might affect V* within the reach, such as intra-reach sediment inputs, braided sections, or tributaries. A reach should include enough pools to provide an accurate estimate of V^*_w for the stream segment. The number of pools needed depends on the variability of V* between pools and on the desired accuracy of the estimate of V^*_w. In channels where V* does not vary greatly between pools, 10 to 15 pools are often sufficient (see Discussion).

After a study reach has been selected, the length of the reach is surveyed to identify pools to measure and determine what constitutes fine sediment in this channel. For our purposes, a measurable pool is an area of channel which (1) has a significant residual depth[2,3] (the deepest part of the pool must be at least twice as deep as the water flowing out of the pool at the downstream end); (2) has an essentially flat water surface during low flow (water surface slope <0.05 percent); and (3) includes most of the channel (it must include the thalweg and occupy at least half of the width of the low-flow channel). The specific criteria can vary, as long as they are repeatable and consistent across all reaches compared. We allow for possible variation in depositional patterns between different types of pools by measuring all pools in a reach, regardless of origin, but pool type could be a selection factor if enough pools are available. One should avoid measuring potential pools with unclear boundaries, such as long glides containing small deep areas or small deep areas in rocky channels, because it is difficult to measure such pools consistently.

What constitutes fine sediment in a channel is determined by the distribution of particle sizes and patterns of fine-sediment deposition in the channel. Fine sediment is defined as the material forming the matrix among the gravel framework of the bed material.[4] This material is commonly winnowed from areas of high shear stress, such as riffles, and deposited in pools.[1] Fine sediment in a reach is defined as material which (1) is distinctly finer than the bed surface (median particle size (D_{50}) of fine sediment approximately one tenth or less of the D_{50} of the bed surface) and (2) can be distinguished from underlying coarser sediment by probing with the rod. Deposits of fine sediment that are armored (covered by a layer of larger sediment) or densely occupied by roots of riparian plants are not considered available for transport and are not measured. In most channels, fine sediment is defined for working purposes as deposits with a D_{50} of 11 mm or less, but deposits with a D_{50} of 16 mm (medium gravel) can be measured in channels with large surface particle sizes and high transport energy.

Measuring Riffle-Crest Depth and Defining Pool Boundaries

Calculation of V* requires measuring the volume of water and fine sediment in the "residual" pool. The residual pool is defined as the portion of the pool that is deeper than the riffle crest forming the downstream lip of the pool, that is, the pool that would remain if there were negligible surface flow *(figure 1A)*.[3] The riffle crest is a high point on a longitudinal profile and usually the shallowest place at the downstream end of a pool. During low flows, when the water surface in pools is nearly flat, the riffle crest can be identified by the beginning of the riffled, more sloping water surface.

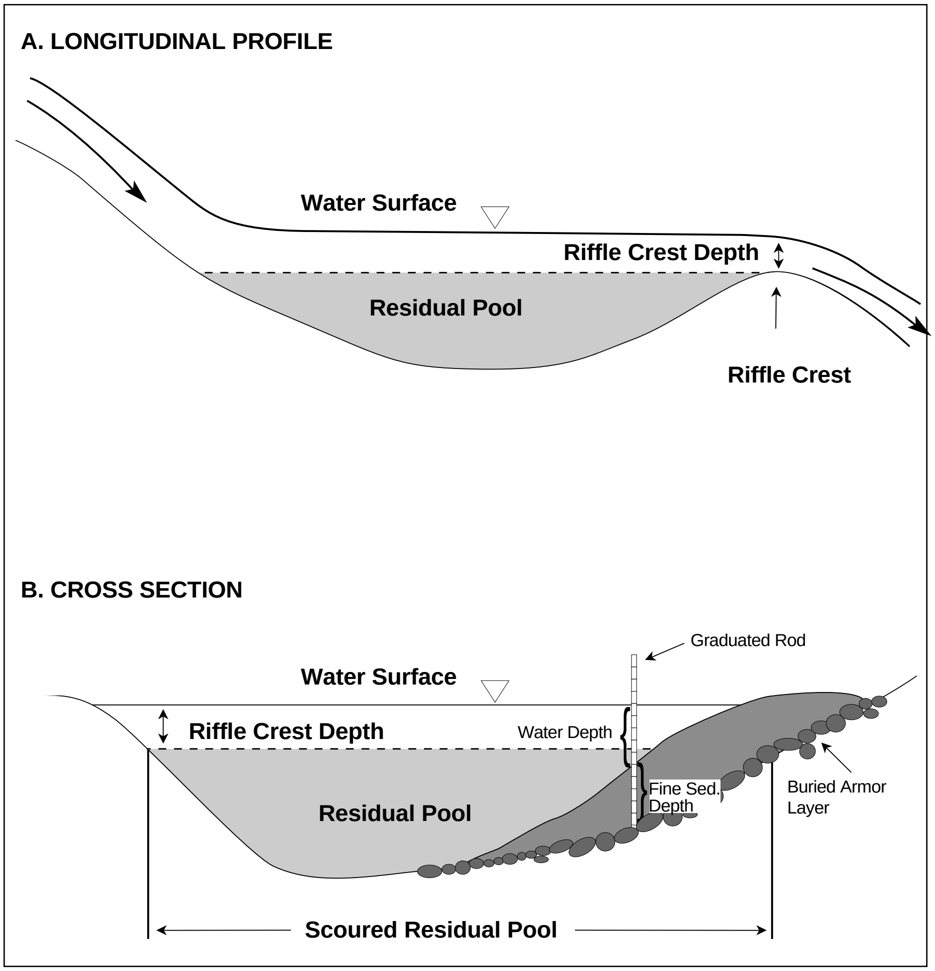

Figure 1—(A) Longitudinal profile of a pool, showing the riffle crest and the area included in the residual pool volume. (B) Cross section of a pool, showing measurement of water and fine sediment depth and volume of water and fine sediment in the scoured residual pool.

The first step in calculating V* is to measure the riffle-crest depth and define the pool boundaries. Water depth at the riffle crest is measured by taking the median of several depth measurements taken across the thalweg at the riffle crest *(figure 2)*. Because the riffle-crest depth defines the residual pool, it is important to measure it consistently. Near the riffle crest, the water surface may break in several places, discontinuously, or gradually over a distance. The riffle crest is identified as the shallowest continuous line (usually not straight) across the channel close to where the water surface becomes continuously riffled. Depths are measured across the deepest part of the flow at 5-20 evenly spaced locations along this line, depending on the width and irregularity of the measured section. To consistently measure the same section of the riffle crest, measurements are taken where we expect water to flow at minimum discharge. Thus the measured section occupies a smaller proportion of the total wetted width at high flows than at low flows. Defining and measuring the riffle crest can be confusing. Survey teams should discuss measurement locations and periodically take duplicate measurements to maintain consistency.

Water depths and fine-sediment depths are measured within the "scoured residual pool," which is the residual pool that would result if all of the fine sediment in the pool were removed. If the water surface over the pool is essentially horizontal, the boundary of the scoured residual pool is where water depth plus fine-sediment depth equals riffle-crest depth *(figure 1B)*. Where the water surface is not completely horizontal, as at the upstream ends of many pools, the boundary is where a plane at the elevation of the riffle crest would intersect the streambed with fine sediment removed (see *figure 1A)*. In a few situations, we exclude sections of stream channel which would be included in this definition. For example, a long glide extending into a pool may be excluded, even if the glide is deeper than the riffle-crest depth. Similarly, if the upstream end of the pool is a riffle that is deeper than the riffle crest, the upstream boundary of the pool is defined as where the nearly horizontal water surface would begin at a minimum flow.

Measuring Water and Fine Sediment Volume

Volumes of water and fine sediment in the residual pool are calculated from measurements of water and fine-sediment depth along a series of cross sections in the pool. The basic technique is essentially a systematic sample, with cross sections spaced evenly along the length of the pool. Zero-area cross sections are assumed at the ends of the pool. Depth-measurement points are spaced evenly across each cross section and at either end. The locations of both the cross sections and the depth-measurement points are determined from a random start. The basic system is modified in some cases to improve the accuracy of the estimate. The basic systematic sample will be described first, followed by examples of modifications for specific situations.

Basic systematic sample (figure 2).

1. Stretch a tape along the length of the pool, from the upstream end to the furthest point on the riffle crest or along the longest dimension of the pool. This tape must be straight, since bends will distort the volume calculations. If the pool is so irregular that a bend cannot be avoided, divide the pool into sections and measure each separately *(figure 3)*.

2. Draw a sketch map of the pool, showing locations of the upstream end of the pool, riffle crest, areas of fine-sediment deposition, and major features of the pool, such as logs and outcrops.

3. Decide on the number of cross sections and the distance between depth-measurement points. The appropriate sampling intensity depends on the complexity of the pool and on the accuracy required. We take from 4 to 10 cross sections in each pool and

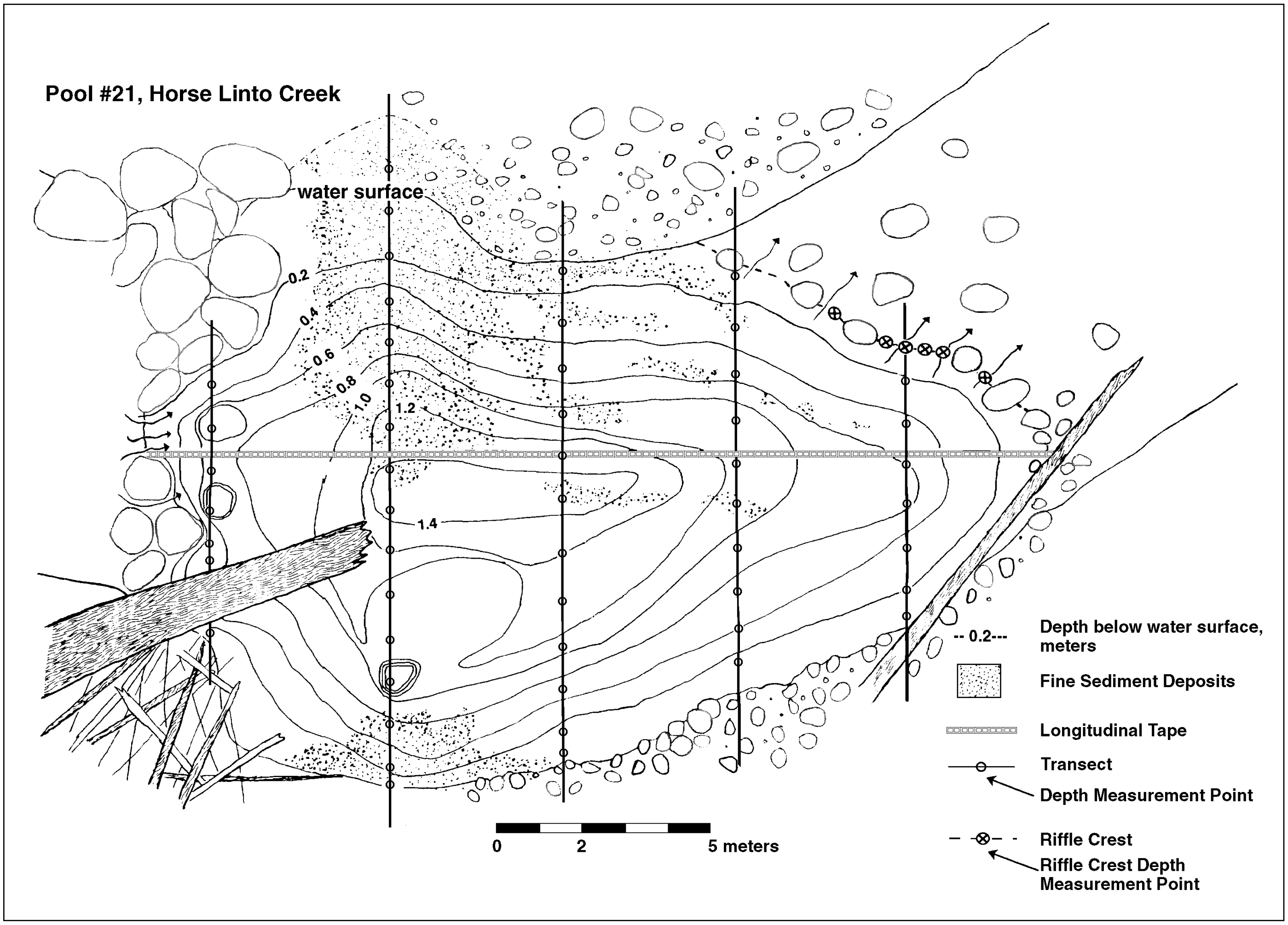

Figure 2—Pool #21, Horse Linto Creek, showing location of the longitudinal tape, transects, measurement points for water and fine sediment depth, the riffle crest, and measurement points for riffle crest depth.

set the distance between depth locations to provide 7 to 16 points across the widest cross section.

4. Determine the locations of cross sections and depth-measurement points. Divide the total length of the pool by the number of cross sections to find the distance between sections. Choose a random number between zero and this distance to locate the first cross section, and add the chosen spacing to locate the remaining sections. Choose random numbers between zero and the distance between depth-measurement points to locate the first point in from the edge of each cross section.

5. Run a tape perpendicular to the lengthwise tape at each cross-section location. Measure water depth and the thickness of any fine sediment present at each measurement point with a graduated rod. Fine-sediment depth is determined by probing with the rod until a change in resistance is felt as it strikes coarser material *(figure 1B)*. A small sledge may be useful for probing deep deposits. The cross section begins at the edge of the scoured residual pool, where water depth plus fines depth becomes greater than riffle-crest depth *(figure 1B)*. Record total water depth and fines depth at both edges of the pool, and at regular intervals across the pool as determined in step 4. If a fines deposit deep enough to be included in the scoured pool extends above the water surface, record height above the water surface as a negative water depth.

Modifications. The advantage of the basic systematic sample is that it is simple, repeatable, and statistically unbiased. The main disadvantage is that it does not use information about the pool (such as the location of fines deposits) that is available to the people taking the measurements. The basic sample can be modified in a variety of ways, from decreasing the distance between cross sections or depth-measurement points at some locations to dropping the systematic sample entirely and deliberately choosing cross-section or depth-measurement locations or both. Because deliberately chosen locations introduce potential bias, locations are chosen only when it will clearly improve the accuracy of the estimate. These are some common situations in which modifications can improve accuracy:

• In most pools, fines occupy less than one-half of the substrate area. To measure fines volume more accurately, the distance between depth measurement points is usually reduced over fines deposits, and points are added at their edges. Also, cross sections are often added to measure an area of fines more intensely or to define its upstream or downstream limits.

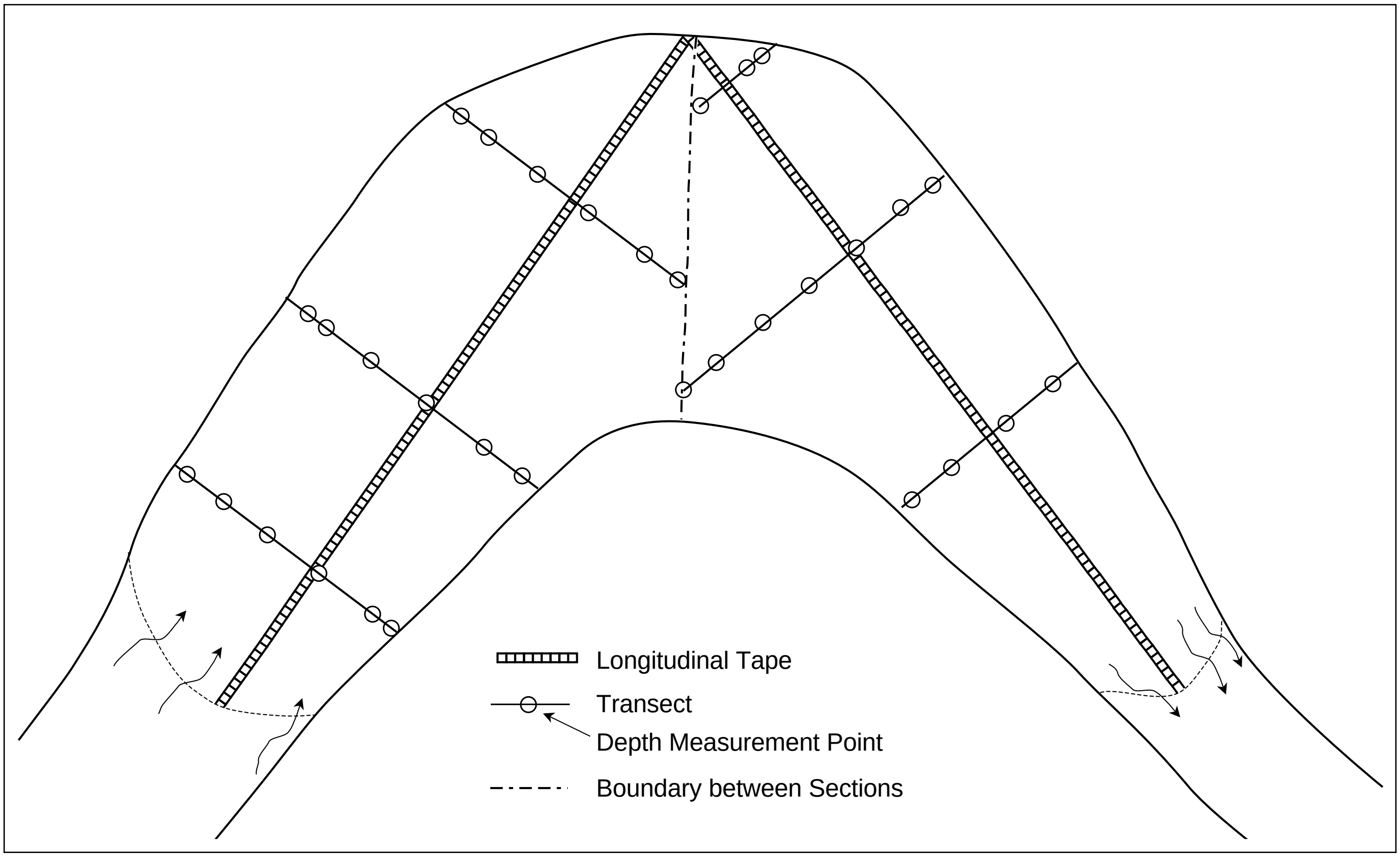

Figure 3—Measuring a pool with a bend. The longitudinal tape is strung in two straight segments, transects are located systematically along the tape, and a zero-area cross section is recorded at the location of the bend in the tape.

• If a pool has a deep, complex segment and another segment that is fairly long, simple, and shallow, the pool may be divided into two segments and the more complex segment sampled more intensely. A cross section at the boundary between segments makes the volume estimates for each more accurate.

• Cross sections or depth-measurement points or both may be added to adjust for irregularities in pool shape, such as large rocks, holes, or shoals.

• If most or all of the fines in a pool are in a few discrete deposits, their volume can be measured separately. The pool volume is measured using the basic systematic technique, as though fines in the discrete deposits were absent (fines depth measurements in the deposits are recorded as zero). The residual-pool volume of fine sediment in the deposits is then measured more intensively, and the volumes of the discrete deposits are added to the fine sediment volume measured in the rest of the pool.

Calculating V* and V*$_w$

V* is calculated as follows:

1. Calculate the residual cross-sectional area (the area deeper than the depth at the riffle crest) of fines and water in each cross section.
2. Set a zero-area cross section at the upstream and downstream ends of the pool.
3. Calculate the average residual cross-sectional area of fines and water between each pair of adjacent cross sections.
4. Multiply the average cross-sectional area for each pair by the distance between them.
5. Add the volumes of the water and fine sediment in all the segments to find the totals for the pool.
6. Calculate V* for the pool:

$$V^* = \frac{\text{residual fines volume}}{\text{scoured residual pool volume}}$$

where scoured residual pool volume = residual fines volume + residual water volume.

A sample data set with detailed instructions and examples of the calculations is shown in *appendix A.* Worksheets are available to do these calculations in Lotus 1-2-3 and in SQL*Calc.

V*$_w$ is the average of the V*'s for all the pools in a reach weighted by the scoured pool volume of each pool. Because V* is the ratio of fines volume to scoured pool volume, the weighted mean for the reach can be simply calculated as:

$$V_w^* = \frac{\Sigma\text{ (residual fines volume)}}{\Sigma\text{ (scoured residual pool volume)}}$$

The variance of the estimated residual water volume, fines volume, and V* for individual pools may be assessed by remeasuring a sample of the pools and treating each measurement as a random sample of all possible measurements of that pool. The variability of V*$_w$ for the reach can also be estimated, but since V* is a ratio of two estimates (fines volume and water volume), calculating the variability of the weighted mean is complex. A formula for estimating the variability of V^*_w is in *appendix B*, along with a process for testing for significant differences in V^*_w between reaches.

ACCURACY OF THE ESTIMATES

The accuracy of the estimated value of V^*_w for a reach depends on the accuracy of the estimates of V* for each pool and on the variability of V* between pools in the reach. To find out how precise our individual pool volume measurements were, we measured variability due to sampling and measurement error by repeating measurements of several pools. We also investigated how discharge at the time of measurement affected the measured surface elevation of the residual pool and consequent values of V*. To find out how variability between pools affected V^*_w, we studied the relationship between the estimated value of V^*_w and the variability of the estimate of V^*_w in 12 reaches, eight in the Trinity River watershed and four others in northern California.

Individual Pool Estimates

Nine pools in Trinity River tributaries were measured three times each in 1990, and six of these were remeasured two or three times each in 1991. For these duplicate measurements, we kept riffle-crest depth and pool length constant and varied the starting point for the systematic sample. The standard deviation of V* ranged from 0.00 to 0.08, and increased slightly with V*. Coefficients of variation ranged from 0 to 170 percent, with the higher values concentrated at very low values of V* *(figure 4)*. The coefficient of variation of V* in a pool was highly correlated to that of the fine sediment volume in that pool (r = 0.995). *Figure 4* also includes the coefficients of variation for five pools in the Salmon River, California, which were measured three times each in 1991. These measurements were taken a week apart, by different people, and riffle-crest depth and pool length varied somewhat between measurements. The standard deviations and coefficients of variation of those pools were similar to those of the other replicate measurements.

Effect of Discharge on V*

Because we measure only within residual pools, the measured water and fine-sediment volumes (and thus V*) should not vary with discharge. If the riffle crest is always measured in the same place, the riffle-crest depth will increase exactly as much as the water surface of the pool rises, the elevation of the surface of the residual pool (riffle-crest elevation) will be constant, and the same volume will be measured at any discharge. However, because locating the riffle crest and selecting the section to measure are somewhat subjective, there is some potential for error. Systematic errors could occur if the measured riffle-crest elevation is consistently affected by discharge and if V* is consistently affected by riffle-crest elevation. To determine whether discharge affects riffle-crest elevation, we measured riffle-crest elevation (water-surface elevation minus the measured riffle-crest depth) at three pools in Jacoby Creek at four different flow levels. Elevations were measured at extremely low base flows, normal summer base flows, and flows significantly above summer base flows. To find out whether riffle-crest elevation affects V*, V*'s calculated at different riffle-crest depths were compared for sample pools from five creeks in northern California.

Measured riffle-crest elevations in Jacoby Creek tended to be higher at low flows than at high flows, possibly because the width of the minimum flow channel was underestimated at high flows. Riffle-crest elevations did change less than water-surface elevations, however. Maximum changes in water-surface elevation ranged from 0.10 to 0.20 m, whereas changes in riffle-crest elevation ranged from 0.01 to 0.07 m. Maximum changes in residual elevation were equivalent to 10 percent, 25 percent, and 70 percent of the riffle-crest depth of the respective pools at moderately low flows.

To evaluate the effect of an error of this magnitude in riffle-crest elevation on V*, we calculated V* using a riffle-crest depth equivalent to 150 percent of the original value (measured at moderately low flows) in 19 pools. Original values of V* ranged from 0.01 to 0.62. The deeper riffle-crest depths resulted in smaller residual pools, which had higher V* values in 18 of the 19 cases. The mean percent change in V* was 13 percent (16 percent if the negative change was omitted), which corresponded to a mean absolute change in V* of 0.05.

Variability in V^*_w

We calculated the standard error of the estimate of V^*_w for all of the reaches we measured using the formula in *appendix B*. We then modified the formula to predict the number of samples (pools) required to

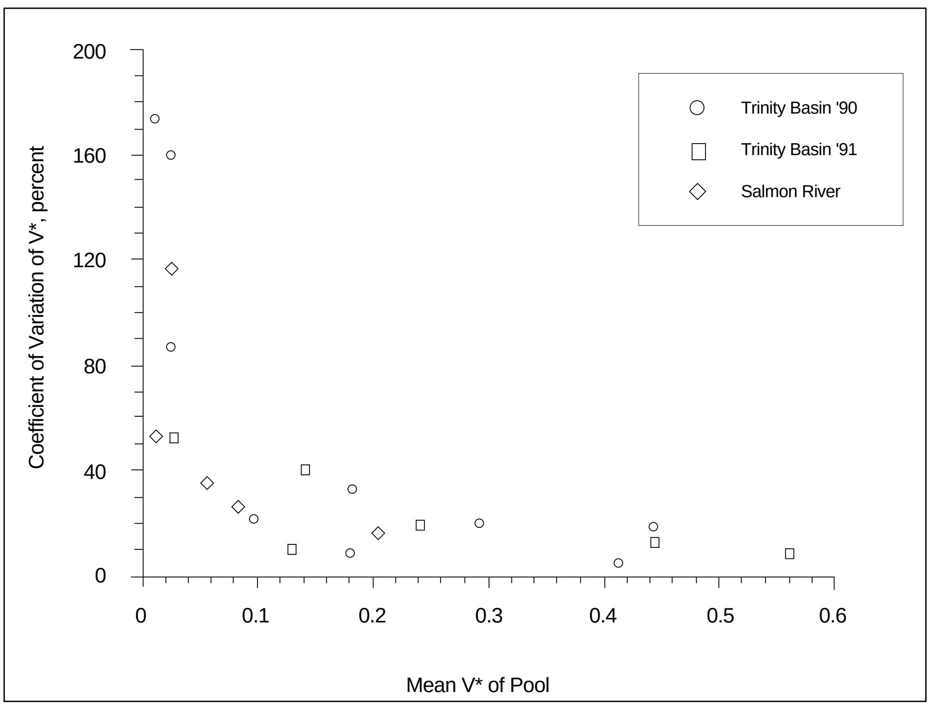

Figure 4—Variability of the estimate of V*, from multiple measurements of V* on pools in Trinity River tributaries in 1990 and 1991 and in the South Fork Salmon River in 1991. The coefficient of variation is the percentage ratio of the standard error of the mean to the mean value of V* for each set of measurements.

achieve a standard error of 20 percent of V^*_w for each reach. The standard errors of our reaches, each of which included 10 to 20 pools, ranged from 0.01 to 0.06 and averaged 17 percent of the value of V^*_w. The calculated sample size necessary to obtain a 20 percent error in V^*_w ranged from 4 to 26 pools and generally decreased as V^*_w increased. Exceptions were reaches in Grouse Creek, which had extremely irregular pools due to the presence of very large boulders, and in North Fork Caspar Creek, which had irregular pools caused by large woody debris. These two reaches had high standard errors and required higher sample sizes.

DISCUSSION

The main factor affecting the variability of the estimate of V* for a pool seems to be the amount of fines in the pool. In pools with moderate to high values of V* (V* >0.10), most (80 percent) of the standard deviations were less than 20 percent of the mean V* for the pool. In pools with lower V* values, the standard deviations ranged up to 170 percent of V*. Although it is not practical to expect the same percent errors in these pools as in those with higher V* values (because a small percent of a small number is a very small number), it may still be important to measure V* in these pools more precisely than in pools with a higher proportion of fine sediment. Error in V* was strongly correlated with error in fines-volume measurement, and fine sediment does tend to be measured less intensively when it occupies a small proportion of the area of the pool. Therefore, we strongly recommend increasing sampling intensity in areas of fines or measuring fine-sediment deposits separately, or both, particularly where fine-sediment deposits occupy a small proportion of the surface area of the pool or when it is important to measure low values of V* accurately.

Estimates of the maximum possible error in V* due to variations in discharge (13-16 percent of V* measured at moderately low flow) were slightly less than the 18 percent average measurement error for replicate measurements at a constant discharge. However, measurement error from systematic samples with a random start is random, whereas errors due to changes in water depth appear to be consistent and thus have the potential to bias V^*_w. We recommend measuring at moderately low flows. Riffle-crest depths can be difficult to measure accurately at very low flows when the pattern of the flow is affected by surface rocks. At moderately high flows the water surface over a pool is likely to slope appreciably and affect pool volume measurements. For monitoring over time, comparisons will be more accurate if V^*_w is measured at a consistent stage or discharge. Similarly, comparisons between reaches will be more reliable if all reaches are measured at nearly the same relative flow. If this is not possible, allowance should be made for the possibility that values of V^*_w measured at high base flow could be elevated relative to those measured at low flow.

Our estimates of the variability of V^*_w include the effects of measurement errors in V* but do not include any possible bias due to variations in discharge, since all pools in a reach were measured at approximately the same discharge. The desired standard error of V^*_w depends on the precision required to detect changes in a reach, deviations from a reference value, or differences between reaches. We found that the standard errors from measuring 10-20 pools per reach enabled us to distinguish fairly well between reaches, and the sample size calculations indicated that fewer pools would probably have been enough in most reaches. The calculated sample size *(figure 5)* is not necessarily the number of pools that should be measured in each reach, since the percent error in V^*_w needed to distinguish between reaches will depend on both the value of V^*_w (a 20 percent error is a large range of V^*_w values when V^*_w is high and a small range when V^*_w is small) and on the closeness of the values being compared. The sample size calculation does, however, indicate the relative sampling intensity required to be able to measure reaches with high standard errors at the same precision as reaches with lower variability between pools. We recommend evaluating the irregularity of the pools and the variation in V* before and during data collection in a reach. If all of the pools in a reach have similar values of V*, then differences between the estimates of V* caused by measurement error could have a significant effect on the variance of the estimate of V^*_w, and V^*_w can be best estimated by measuring a few (6-10) pools accurately. For most reaches we recommend measuring 10-15 pools, and if the value of V* varies widely between pools, the best strategy might be to measure as many pools as possible (20 or more), perhaps with less sampling intensity on each. If V* is highly variable but the number of pools available

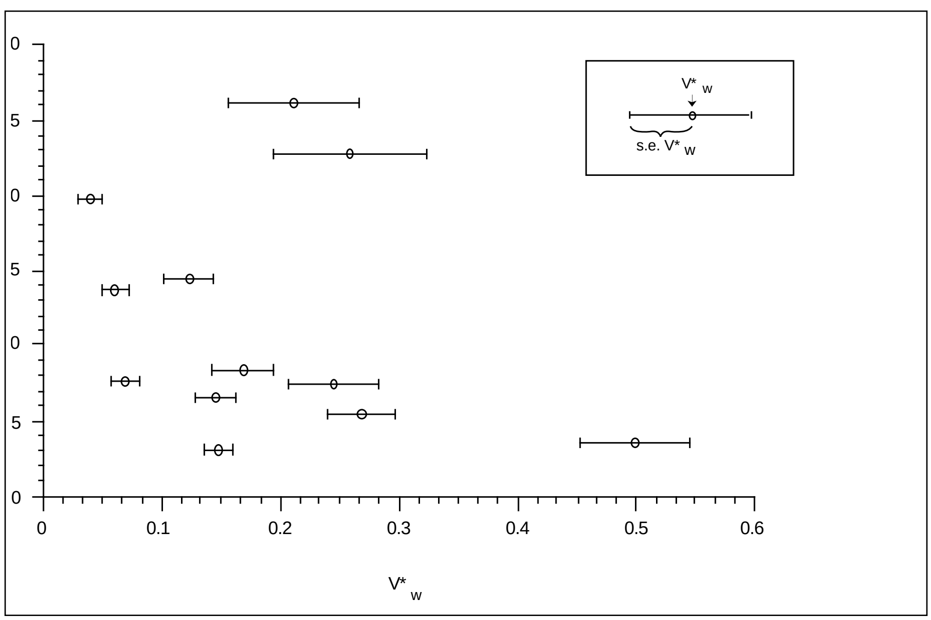

Figure 5—Predicted sample sizes necessary to limit the error in V^*_w to 20 percent of the value of V^*_w for that reach, calculated for 12 reaches. Our estimate of V^*_w for each reach is shown with our standard error of the estimate for that reach, which was based on 10-20 pools.

in the reach is limited (by sediment sources, changes in slope, etc.), putting more effort into sampling each pool will at least reduce the measurement-error component of the total variability. If the objective is to monitor a reach over time, and if the structure of the pools in a reach is fairly stable, accurate measurements of a few major pools at approximately the same discharge each year may give the best information.

SUMMARY OF RECOMMENDATIONS

To minimize variability of the estimates and eliminate potential bias, we make the following recommendations:

Fine Sediment Measurements

• When fine-sediment deposits occupy a third or less of the pool substrate area, increase measurement intensity in fine-sediment deposits, either by decreasing the distance between depth-measurement points or by making separate measurements of deposits.

Discharge Levels

• Measure all pools at moderately low flows.

• If a reach is being monitored over time, measure at approximately the same discharge each year.

• If reaches are being compared, measure all reaches at approximately the same relative flow.

Sample Size

• If all pools in a reach have similar values of V*, measure 6-10 pools relatively intensively.

• If V* varies somewhat (V* for all pools is within 20-30 percent of the mean), measure 10-15 pools.

• If V* is highly variable (some V*'s of 0.4 or more and others 0.1 or less), measure as many pools as possible, up to 20 or so.

• If the objective is to monitor changes over time in a single reach, and if the pools in the reach are structurally stable, intensive measurement of a few pools (4-5 minimum) may minimize variability and provide additional information about changes in individual pools.

APPENDIX A

Calculating Residual Pool Water Volume, Fine-Sediment Volume, and V*

Follow these basic steps to compute residual-water and fine-sediment volumes for a pool:

1. Calculate cross-sectional areas of the water and fine sediment in the residual pool at each cross section.
2. Assume a zero-area cross section at the beginning and end of the pool. Calculate water and sediment volumes in cells between each pair of adjacent cross sections, including the zero-area cross sections at the endpoints.
3. Sum residual-water and fine-sediment volumes for all of the cells to compute total volumes.

The following example of the calculations uses the data from a very small pool. In this example, d = water depth, d_{rc} = riffle-crest depth, and y_f = fine-sediment thickness. These are the data:

riffle-crest depth (d_{rc}) = 0.10 m; total length of pool = 12.0 m

cross section #1 at 2.4 m

distance (m)	0	0.5	1.5	2.5	2.7
d (m)	0.10	0.50	0.88	0.40	0.10
y_f (m)	0	0	0.02	0.02	0

cross section #2 at 6.4 m

distance (m)	0	1	2	3	4	5	6	6.2
d (m)	0.06	0.62	0.74	1.12	0.96	0.70	0.56	0.10
y_f (m)	0.04	0.10	0.02	0.01	0	0	0	0

cross section #3 at 10.4 m

distance (m)	0	0.8	1.8	2.8	3.8	4.6
d (m)	-0.02	0.08	1.08	1.14	0.94	0.10
y_f (m)	0.12	0.10	0.14	0.06	0.04	0

The first step is to compute depths of the water and fines in the residual pool. The residual water depth, d_r, is the water depth minus the riffle crest depth. The residual fine-sediment thickness, y_{rf}, is the thickness of the fine sediment below the riffle crest *(figure 1)*. If the water depth at any location is less than the riffle crest depth, the fines thickness at that location is reduced by a corresponding amount. That is, $d_r = d - d_{rc}$ and IF $d < d_{rc}$, THEN $y_{rf} = y_f - (d_{rc} - d)$, ELSE $y_{rf} = y_f$. After these calculations, the data look like this:

cross section #1

distance (m)	0	0.5	1.5	2.5	2.7
d_r (m)	0	0.40	0.78	0.30	0
y_{rf} (m)	0	0	0.02	0.02	0

cross section #2

distance (m)	0	1	2	3	4	5	6	6.2
d_r (m)	-0.04	0.52	0.64	1.02	0.86	0.60	0.46	0
y_{rf} (m)	0	0.10	0.02	0.01	0	0	0	0

cross section #3

distance (m)	0	0.8	1.8	2.8	3.8	4.6
d_r (m)	-0.12	-0.02	0.98	1.04	0.84	0
y_{rf} (m)	0	0.08	0.14	0.06	0.04	0

The next step is to compute cross-sectional areas of water and fine sediment. We start by calculating the width w_i, average residual depth $(d_r)_i$, and average fine-sediment thickness $(y_{rf})_i$ of each segment of the cross section (between two adjacent measurement points).

cross section #1

segment number	1	2	3	4
w_i (m)	0.5	1	1	0.2
$(d_r)_i$ (m)	0.20	0.59	0.54	0.15
$(y_{rf})_i$ (m)	0	0.01	0.02	0.01

cross section #2

segment number	1	2	3	4	5	6	7
w_i (m)	1	1	1	1	1	1	0.2
$(d_r)_i$ (m)	0.24	0.58	0.83	0.94	0.73	0.53	0.23
$(y_{rf})_i$ (m)	0.05	0.06	0.015	0.005	0	0	0

cross section #3

segment number	1	2	3	4	5
w_i (m)	0.8	1	1	1	0.8
$(d_r)_i$ (m)	-0.07	0.48	1.01	0.94	0.42
$(y_{rf})_i$ (m)	0.04	0.11	0.10	0.05	0.02

In each segment, the cross-sectional area of residual water $(a_r)_i$ equals $(d_r)_i \times w_i$, and cross-sectional area of fine sediment $(a_{rf})_i$ equals $(y_{rf})_i \times w_i$. Negative average water depths are set equal to zero. This gives us:

cross section #1

segment number	1	2	3	4
$(a_r)_i$ (m^2)	0.10	0.59	0.54	0.03
$(a_{rf})_i$ (m^2)	0	0.01	0.02	0.002

cross section #2

segment number	1	2	3	4	5	6	7
$(a_r)_i$ (m^2)	0.24	0.58	0.83	0.94	0.73	0.53	0.046
$(a_{rf})_i$ (m^2)	0.05	0.06	0.015	0.005	0	0	0

cross section #3

segment number	1	2	3	4	5
$(a_r)_i$ (m^2)	0	0.48	1.01	0.94	0.336
$(a_{rf})_i$ (m^2)	0.032	0.11	0.10	0.05	0.016

The total cross-sectional area of residual water, A_r, and fine sediment, A_{rf}, of each cross section equals the sum of the corresponding segment areas. Cross sections are added to upstream and downstream ends of the pool and given areas of zero.

cross-section #	0	1	2	3	4
location (m downstream)	0	2.4	6.4	10.4	12
A_r (m^2)	0	1.26	3.90	2.77	0
A_{rf} (m^2)	0	0.032	0.130	0.308	0

To compute the water and fine sediment volume in each cell of the pool, between each two adjacent cross sections, we calculate the average cross-sectional areas of residual water $(A_r)_j$ and fine sediment $(A_{rf})_j$ and the length (l_j) for each cell. The cell in the upstream end of the pool, for example, has an average residual area equal to one-half of the area of the first cross section downstream.

cell number	1	2	3	4
l_j (m)	2.4	4.0	4.0	1.6
$(A_r)_j$ (m^2)	0.63	2.58	3.33	1.38
$(A_{rf})_j$ (m^2)	0.016	0.081	0.219	0.154

The volumes for each cell, $(V_r)_j$ and $(V_{rf})_j$, are the average areas times the length, and the total for the pool is the sum of the volumes of all the cells.

cell number	1	2	3	4	total
$(V_r)_j$ (m^3)	1.5	10.3	13.3	2.2	27.4
$(V_{rf})_j$ (m^3)	0.04	0.32	0.88	0.25	1.48

Finally we calculate V* as: $\dfrac{\text{total fines volume}}{(\text{total fines} + \text{total residual pool volume})} = 0.051$

and we're done!

APPENDIX B

Estimating the Variance of the Estimate of V^*_w

The formula we used for estimating the variance of V^*_w was developed using the Delta method[5] for estimating the variance of a variable that is a function of other variables. The variance of V^*_w for a reach is calculated as:

$$\widehat{Var}\left(V_w^*\right) \cong n\left(\sum_{i=1}^{n} f_i + \sum_{i=1}^{n} w_i\right)^{-4}\left[\left(\left(\sum_{i=1}^{n} f_i\right)^2 \sigma_w^2 + \left(\sum_{i=1}^{n} w_i\right)^2 \sigma_f^2\right) - 2\sum_{i=1}^{n} f_i \sum_{i=1}^{n} w_i\left(\operatorname{cov}(f,w)\right)\right]$$

where f_i is the fines volume and w_i is the residual pool water volume of the *i*th pool in the reach, and $\widehat{cov}(f,w)$ is the covariance of the fines volume and the water volume in the reach. The covariance is calculated as:

$$\widehat{cov}\ (f,w) = \frac{\sum_{i=1}^{n}\left(f_i - \bar{f}\right)\left(w_i - \bar{w}\right)}{n-1}$$

The covariance can be obtained from many statistical programs by printing a variance-covariance matrix.

The calculated variance can be used to test for significant differences in V^*_w between two reaches by assuming that the test statistic,

$$\frac{V_{w1}^* - V_{w2}^*}{\sqrt{\widehat{Var}\left(V_{w1}^*\right) + \widehat{Var}\left(V_{w2}^*\right)}},$$

has a standard normal distribution.

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END NOTES AND REFERENCES

[1]Lisle, Thomas E.; Hilton, S. 1992. *The volume of fine sediment in pools: an index of sediment supply in gravel-bed streams.* Water Resources Bulletin 28(2): 371-383.

[2]Bathurst, James C. 1981. *Discussion of "Bar Resistance of Gravel-bed Streams" by G. Parker and A.W. Peterson*. Journal of the Hydraulics Division, American Society of Civil Engineers 107(HY10): 1276-1278.

[3]Lisle, Thomas E. 1987. *Using "residual depths" to monitor pool depths independently of discharge*. Res. Note PSW-394. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 4 p.

[4]Carling, Paul A.; Reader, N.A. 1982. *Structure, composition and bulk properties of upland stream gravels.* Earth Surface Processes and Landforms 7:349-365.

[5]Bishop, Yvonne M.M.; Feinberg, S.E.; Holland, P.W. 1975. *Discrete multivariate analysis: theory and practice.* Cambridge, MA: The M.I.T. Press, p. 487.

The Authors:

Sue Hilton and **Thomas E. Lisle** are hydrologic technician and hydrologist, respectively, with the Station's Hillslope Processes, Fishery Resources, and Stream Environment Research Work Unit in Arcata (1700 Bayview Drive, Arcata, CA 95521-6098).