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THE VOLUME OF FINE SEDIMENT IN POOLS: AN INDEX OF SEDIMENT SUPPLY IN GRAVEL-BED STREAMS[1]

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ABSTRACT: During waning flood flows in gravel-bed streams, fine-grained bedload sediment (sand and fine gravel) is commonly winnowed from zones of high shear stress, such as riffles, and deposited in pools, where it mantles an underlying coarse layer. As sediment load increases, more fine sediment becomes available to fill pools. The volume of fine sediment in pools can be measured by probing with a metal rod, and, when expressed as the fraction (V^*) of scoured residual pool volume (residual pool volume with fine sediment removed), can be used as an index of the supply of mobile sediment in a stream channel. Mean values of V^* were as high as 0.5 and correlated with qualitative evaluations of sediment supply in eight tributaries of the Trinity River, northwestern California. Fine-sediment volume correlated strongly with scoured pool volume in individual channels, but plots of V^* versus pool volume and water surface slope revealed secondary variations in fines volume. In sediment-rich channels, V^* correlated positively with scoured pool volume; in sediment-poor channels, V^* correlated negatively with water-surface slope. Measuring fine sediment in pools can be a practical method to evaluate and monitor the supply of mobile sediment in gravel-bed streams and to detect and evaluate sediment inputs along a channel network.

(KEY TERMS: fine sediment; sediment supply; pools; channel condition; bedload; erosion; sedimentation; water quality monitoring.)

INTRODUCTION

One of the greatest hindrances to assessing downstream effects of land-use practices on stream channels in mountainous areas is a lack of understanding of how channels respond to changes in sediment supply. In some cases, changes in runoff and hillslope erosion rates can be evaluated and predicted with acceptable precision and accuracy, but their influence on channel form and process remains problematic. This gap in knowledge prevents development of general predictive models linking sediment supply to changes in habitats of aquatic organisms.

A characteristic of a gravel-bed channel receiving large sediment inputs relative to its transport capacity is an abundance of fine sediment on its bed surface (Platts and Megahan, 1975; Lisle, 1982). (For now, fine sediment is loosely defined as some mixture of silt, sand, and fine gravel that is sorted from coarser fractions during certain phases of sediment transport.) This may reflect increased erosion of soil and weathered colluvium which typically contain large fractions of fine-grained material. Fine sediments tend to have high transport velocities and can be flushed rapidly from streams. Therefore, their high concentration on a streambed can indicate widespread, chronic supplies or recent, local inputs of fine sediment (Platts and Megahan, 1975). Abundant fines on the bed surface may also indicate a reduction of bed-surface particle size in response to an increase in sediment supply alone: that is, without a change from the grain size of material previously carried by the stream (Dietrich *et al.*, 1989). Lastly, fine-sediment abundance can indicate a reduction in transport capacity without a compensating decrease in sediment supply. By a brief inspection at low flow, an experienced geomorphologist, hydrologist, or fishery biologist can gain an impression of the fine-sediment abundance on the bed surface. However, a practical and reliable technique of measuring the supply of mobile sediment in a channel has been lacking.

We present a new method for measuring the fraction of the volume of pools filled with fine sediment. Mobile sediment tends to be concentrated in pools; thus, the fraction of pool filling serves as an index of the supply of mobile sediment in natural, gravel-bed channels. We describe how pool filling is related to the overall supply of sediment in the channel as a whole.

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After describing the method, we provide a qualitative trial by comparing the fraction of pool filling from eight study reaches to assessments of their sediment loads. Finally, we explore the factors that cause variations in fine-sediment volume between pools of a given channel.

THEORETICAL BACKGROUND

A channel in equilibrium, that is, one that neither aggrades nor degrades over time, has a capacity to transport a limited volume of sediment given its existing hydrologic regime and the caliber of sediment delivered from its basin (Mackin, 1948). It is difficult to apply the concept of transport capacity to practical problems, however, because of the difficulty in measuring and accurately predicting bedload transport rates in gravel-bed streams. Also, response to sediment load is complex. When sediment supply to a channel increases, adjustments may include changes not only in bed elevation and channel geometry, but also in bed roughness (Leopold and Bull, 1979; Lisle, 1982).

In a flume experiment, Dietrich *et al.* (1989) demonstrated that, without corresponding changes in bed elevation, bed-surface material can be made coarser by reducing rates of sediment supply. They conclude that, as sediment supply increases, fine particles become more abundant on the bed surface which then becomes less resistant to transport. Particle size of sediment on the bed surface relative to that transported as bedload or stored in the bed can contribute to a measure of the degree to which a channel's transport capacity is fulfilled by its load. When transport capacity is fulfilled, particle size of the bed surface would equal that of bedload or subsurface material, which is assumed to represent bedload. On this basis, Kinerson (1990) calculated bedload transport rates at bankfull flow from two alternative median particle sizes: that of the bed surface and subsurface. The ratio of computed rates for each of six stream channels in California correlated with qualitative assessments of sediment load.

Measuring the particle size of bedload and bed material can become difficult, however, where large cobbles or boulders comprise a significant proportion of bed material or spatial variations in particle size are great. This motivated us to find another manifestation of bed-surface fining in response to increases in sediment load.

According to the model of Dietrich *et al.* (1989), fine sediment can be expected to be abundant at high flow [illegible] of the bed of a channel containing a large [illegible] size of the sediment supplied (Figure 1). During waning flows, fine sediment is selectively transported from zones of relatively high boundary shear stress, such as riffles, and deposited in zones of low shear stress, such as pools, where they mantle a coarser substrate (Lisle and Madej, in press). Increases in fine-sediment volume in pools can be caused either by an enrichment of the load with fine sediment, or, according to our application of the concept of Dietrich *et al.* (1989), by an increase in the load with no change in the mixture of grain sizes. Our strategy is to use the filling of pools by fine sediment, which can be easily measured with a probe, as an index of the availability of mobile sediment in a stream channel.

METHODS

Study Sites

The volume of water and fine sediment in pools was measured in reaches of eight stream channels in the Trinity River basin in northwestern California (Figure 2). These streams were chosen to represent drainages with a wide spectrum of sediment loads. The channels and their basins are typical of those found in the Klamath Mountains, where rates of uplift and erosion are high relative to elsewhere in the conterminous United States (Judson and Ritter, 1964; Janda and Nolan, 1979). The basins are steep, densely dissected, and forested with mixed conifers and deciduous trees. Study reaches were selected to have channel gradients gentler than adjacent reaches. It was assumed that such reaches tend to store relatively large volumes of sediment and, thus, would be sensitive to changes in sediment inputs. All study reaches have well-developed riffle-pool sequences, flow through narrow valley bottoms, and are partially confined by bedrock at the base of hillslopes. The streambed surfaces are predominantly covered by a layer of gravel, cobbles, and boulders. Drainage areas range from 20 to 140 km^2, gradients of the study reaches range from 0.013 to 0.044 (Table 1).

Sediment loads were categorized prior to field work as low, moderate, high, or extreme based on bedrock erosivity, area and intensity of logging and road building, and narratives of watershed specialists of the U.S. Forest Service and U.S. Fish and Wildlife Service who are involved with management of these streams (Table 1). Inherent erosivity of bedrock varies widely. The least erosive is fine-grained, competent metamorphic rock found in Big French, Horse Linto, and Rattlesnake Creeks. Occurring within Three Creeks and Grouse Creek basins are highly erosive, complex

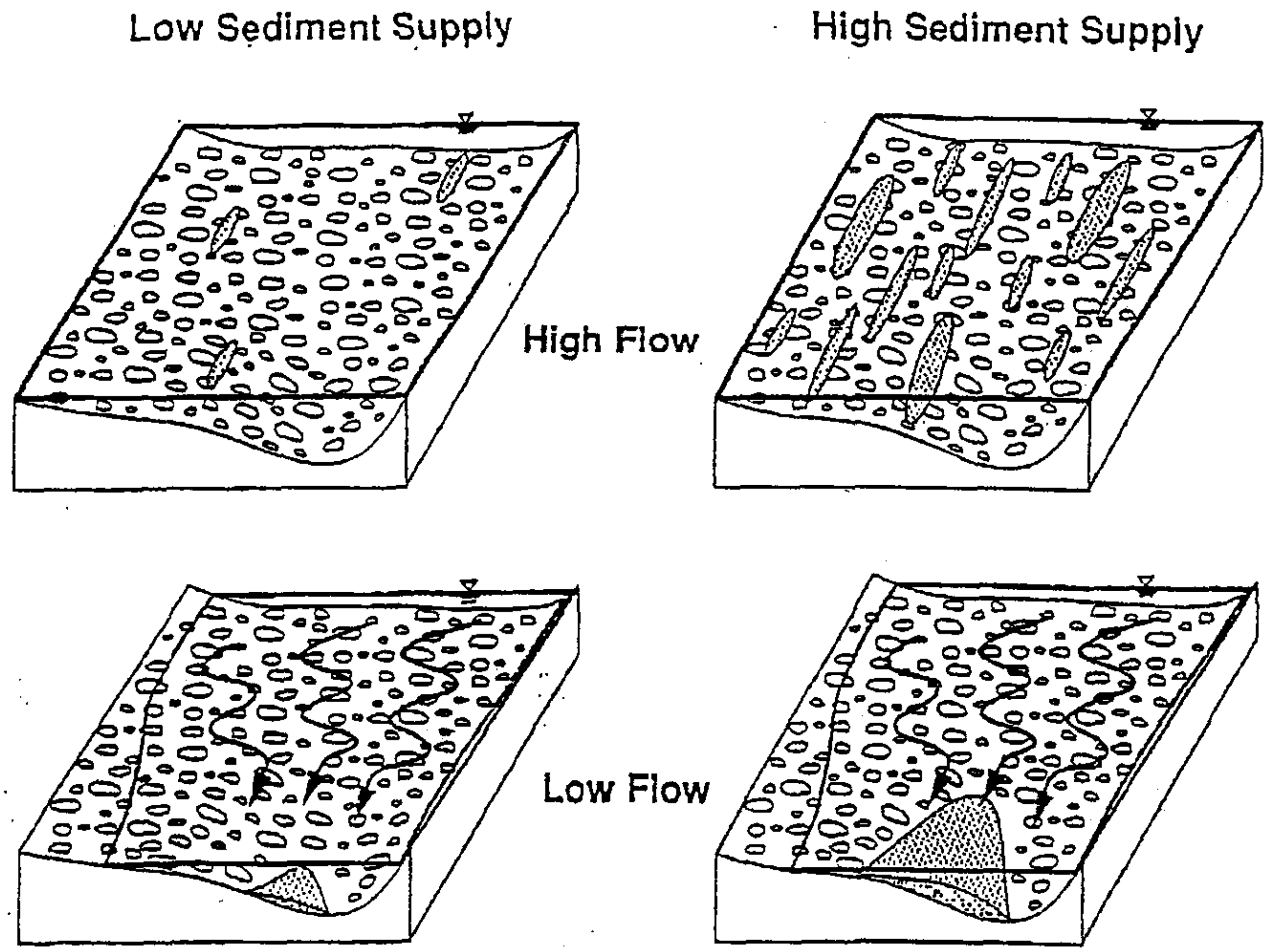

Figure 1. Conceptual Model of Filling of Pools with Fine Sediment During Waning Stages in Gravel-Bed Channels with High and Low Sediment Supplies. At high stages, fine sediment, as well as coarse gravel (arrows), are transported over much of the channel. At low flow, the flow over riffles (curved lines), converges into pools and carries fine sediment winnowed from the bed surface.

suites of highly sheared bedrock marking the boundary between Klamath-Mountain and Franciscan terranes. Deeply weathered granitic rocks in Bear and Grass Valley Creeks probably have the greatest potential for producing fine sediment. Intensity of land use also varies widely. Big French and Bear Creeks have had almost no human disturbance, while the entire basin of Grass Valley Creek has been logged in the past 40 years.

A sediment budget by Kelsey *et al.* (1989) provides a detailed analysis of the amount of sediment entering Grouse Creek from 1960 to 1988. Sediment delivered to the channel over the 29-year period totaled 30,600 m^3/km^2 or 1050 m^3/km^2yr, which ranks high among measured sediment yields for basins in northwestern California (Janda and Nolan, 1979). Streamside landslides contributed 77 percent, mostly during or shortly after a large flood in December 1964. Roads and hillslope erosion of logged areas directly contributed 21 percent, and an additional but unknown proportion can be attributed to indirect effects and other management activities. Managed areas have contributed sediment chronically up to the end of the study period.

Grass Valley Creek is the greatest contributor of fine sediment deposited over a 50-km reach of the Trinity River downstream of Lewiston Dam (California Department of Natural Resources, 1970). Seventy percent of the production is attributed to logging and road building on private land (Bureau of Reclamation, 1986). Most of the logged area was tractor-yarded, which creates widespread disturbance of the protective organic mat overlying the highly erosive, weathered granite. Estimates of annual sediment yield range from 930 to 1400 m^3/km^2 (Soil Conservation Service, 1981; Bureau of Reclamation,

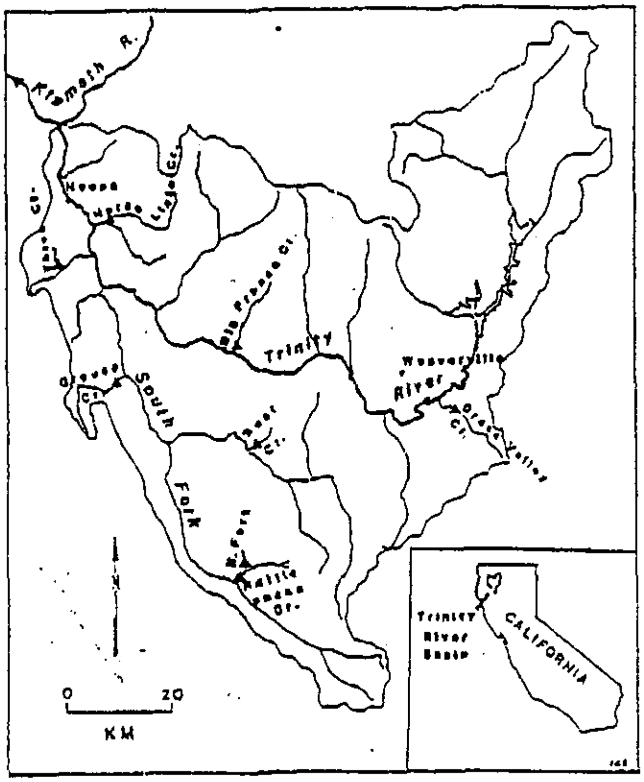

Figure 2. Trinity River Basin and the Tributaries Used in This Study.

1986). Although this value is similar to that for Grouse Creek, Grass Valley Creek is ranked higher in sediment production because it has produced more sediment recently.

Relative Volume of Fine Sediment in Pools

We measured residual water volume (Bathurst, 1981; Lisle, 1986; 1987) and fine-sediment volume in all of 13 to 21 pools in each study reach during the annual summer drought. We defined a pool as an area which

- had a nearly horizontal water surface (slope <0.0005) during low flow,
- occupied the main part of the channel, and
- had a maximum residual depth equal to at least twice the water depth at the downstream riffle crest during low flow.

Residual depth at a point in a pool is defined as that corresponding to minimum flow, when surface flow barely spills over the downstream lip of the pool (riffle crest); it is calculated by subtracting water depth at the riffle crest measured during low flow from water depth at a point in the pool (Figure 3A). The advantage of using residual values to quantify depths or volumes in pools is that the measurements are substantially independent of discharge because the datum for residual depths is the bed elevation at the riffle crest. The relative volume of fine sediment in a

TABLE 1. Characteristics of Study Basins and Stream Reaches (streams are listed in order of perceived sediment supply).

	Drainage Area (km^2)	Reach Slope	Bedrock*	Land-Use History
Big French	99	0.019	meta	1.5% logged; mostly wilderness
Bear	20	0.042	2/3 wgr; 1/3 msed	1% logged since 1960
Horse Linto	97	0.018	sed; msed	4% logged since 1960
Rattlesnake	120	0.013	msed; umaf	11% logged since 1960; residential development on 10% of basin
North Rattlesnake	22	0.044	msed; umaf	41% logged since 1960
Three Creeks	23	0.016	sheared sed and umaf	25% logged since 1960; abandoned road bed along channel
Grouse	140	0.016	sheared sed; msed; mlg	41% logged since 1960; extensively tractor yarded
Grass Valley	80	0.017	wgr	28% logged since 1980; 84 percent logged 1960-1980; road density = 1.98 km/km^2

*Meta = undifferentiated metamorphic rocks; wgr = weathered granite; msed = metasediments; umaf = ultramafics; sed = sandstone and shale; mlg = melange. All rocks are of Mesozoic age.

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pool, V^*, is the fraction of scoured pool volume occupied by fine sediment.

$$V^* = V_f/(V_f + V_r)$$

where V_f = fine-sediment volume and V_r = residual pool volume. Scoured pool volume ($V_f + V_r$) is the residual volume of a pool if the fine sediment were removed (Figure 3A). The mean value for the reach, $\overline{V}^*$, is a weighted average of the V^*'s for all of the pools in the reach. Since the weighting factor for each pool is its scoured volume, the weighted mean for the reach can be calculated simply as:

$$\overline{V}^* = \frac{\sum (V_f)}{\sum (V_f + V_r)}$$

where V_f and V_r are the fine-sediment and residual pool volumes for each pool.

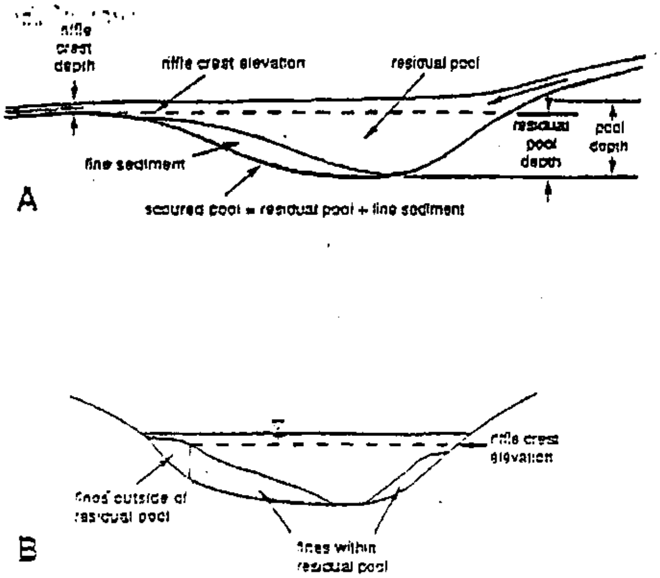

Figure 3. (A) Longitudinal Section of a Pool Showing Delineation of Fine-Sediment and Residual Pool Volumes. (B) Cross Section of a Pool Showing Fine Sediment Falling Inside and Outside of Residual Pool Boundaries.

We computed residual volume from 15 to 50 soundings along four to eight taped transects perpendicular to a tape stretched along the pool axis. Measurement intensity was greater for complex pools and those with large areas of fine sediment. Riffle-crest depth was an average of several soundings in the thalweg, which was usually indistinct, where the nearly horizontal water surface broke at the head of the downstream riffle. Error in measuring riffle-crest depth was highest where there were large cobbles and boulders. Establishing the riffle-crest datum is somewhat affected by discharge at the time of measurement, but we consider this effect to have been small since all measurements were taken at low flows.

We measured fine-sediment thickness and water depth with a graduated steel rod 1.2 cm (0.5 in) in diameter. We measured the depth of the fines to the underlying coarse layer by probing with the rod, in some cases tapping it with a hand sledge. Abrupt changes in resistance to penetration and the sound and feel of the rod as it passed from sand and fine gravel to imbricated coarse gravel and cobbles made the interface apparent. We spaced transects and probings more closely over isolated thick deposits of fine sediment.

Some fine sediment was deposited higher than the riffle crest and was, therefore, outside of the residual area of the pool (Figure 3B). We chose to disregard this portion in calculating reported values of V^*, because the limits of fine sediment outside of the residual pool areas were ambiguous in some cases. Inclusion of this portion would have increased our values of volume of fine sediment 17 percent, on average, and as much as 100 percent in individual pools. Values of V^* would have increased 20 percent, on average, and as much as 280 percent in individual pools. Relative contributions of fine sediment outside of residual pools to the total showed no obvious correlation with channel characteristics.

We estimated measurement error by repeating measures of residual and fine-sediment volume three times in nine pools in each of three different streams. The number and spacing of soundings were held constant, while starting points for the longitudinal positions of transects and for soundings along each transect were selected randomly. The coefficient of variation of V^* for each pool ranged from 5 percent to 170 percent. Most high values were associated with mean values of V^* less than 0.05. For larger V^* values, the coefficient of variation had a relatively constant value of approximately 18 percent. The coefficient of variation of V^* was highly correlated with the coefficient of variation of fines volume ($r^2 = 0.99$).

We describe these methods in greater detail and provide more sampling guidelines in a forthcoming paper (Hilton and Lisle, in preparation.)

Particle Size Distributions

A definition of fine sediment in gravel-bed channels based on a fixed particle-size range is inappropriate because the behavior of particles of a given size depends on the entire particle-size distribution of the streambed. Instead, we define fine sediment as the material composing the matrix among the gravel framework (Carling and Reader, 1982). It is mostly absent in winnowed surface layers, but commonly forms distinct deposits elsewhere. Its particle-size distribution varies between streams, but most commonly includes some mixture of sand and fine gravel. Practically speaking, it is easy to distinguish fine and coarse sediment in pools.

We sampled bed material in bars and fine sediment in pools in order to determine the size fraction of bedload that was responsible for filling pools. Bar samples were chosen to represent the bulk of the bedload transported in the channel. We scraped the surface layer from bar surfaces at four to six locations in each reach and obtained samples totalling approximately 100 kg. Using standard sieve intervals at multiples of $\sqrt{2}$ mm, we sieved the combined samples down to 11.2 mm in the field and sieved subsamples of the finer fractions in a laboratory. We used a pipe dredge to take ten samples of approximately 400 ml each of fine sediment in each of four to six pools in each study reach. Samples were taken along transects and were spaced closely where fine sediment was thick. We sieved all of the fine-sediment samples in the laboratory using the same sieve sizes we used for the bed material samples.

RESULTS

Spatial Distribution of Fine Sediment in Pools

Fine sediment was deposited nonuniformly in pools and bore little relation to water depth. Deposits were thick under eddies and backwaters, around the periphery of pools, and behind large boulders. Deposits were commonly absent under the thalweg. Figure 4 shows the distribution of fine sediment in a relatively simple pool in Three Creeks Creek. The bed was swept clean of fine sediment along the axis of the pool deep. At a flow slightly less than the threshold of entrainment of bed-surface particles, we observed surface flow trajectories over the large deposit to the right of the thalweg to be deflected as much as 30° from the centerline of the channel. Secondary flow cells such as this apparently swept fine sediment from areas of converging flow at the head of the pool toward lateral areas of diminishing flow velocity and boundary shear stress, where the sediment was deposited. Fine sediment occupied 30 percent of the scoured volume of this pool.

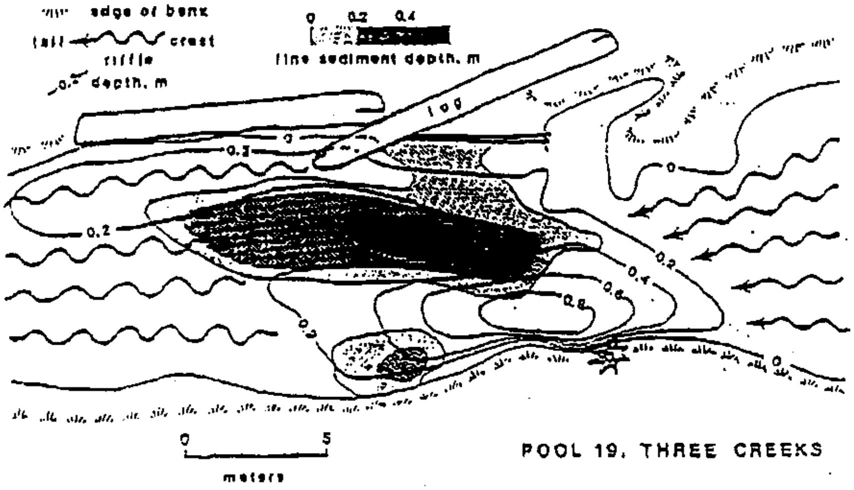

Figure 4. Representative Pool in Three Creeks Creek at Low Flow Showing Water Depths and Fine-Sediment Accumulation.

Comparison of Fine-Sediment Volume Between Streams

The weighted mean value of V* for each creek, $\bar{V}^*$, corresponded in general to qualitative rankings of sediment production in the basins (Figure 5). Grass Valley Creek contained the most fine sediment ($\bar{V}^*$ = 0.50) and ranked highest in sediment production; Big French Creek contained the least fine sediment ($\bar{V}^*$ = 0.04) and ranked lowest. Values of fine sediment volume for the remainder fell in approximate order of sediment production. Since V* was a ratio of two variables, we used the delta method (Bishop *et al.*, 1975) to derive a formula to estimate the variance of the weighted mean. Standard deviations calculated using this formula averaged 15 percent of $\bar{V}^*$ and varied from 8 percent (Rattlesnake Creek) to 25 percent (Grouse Creek).

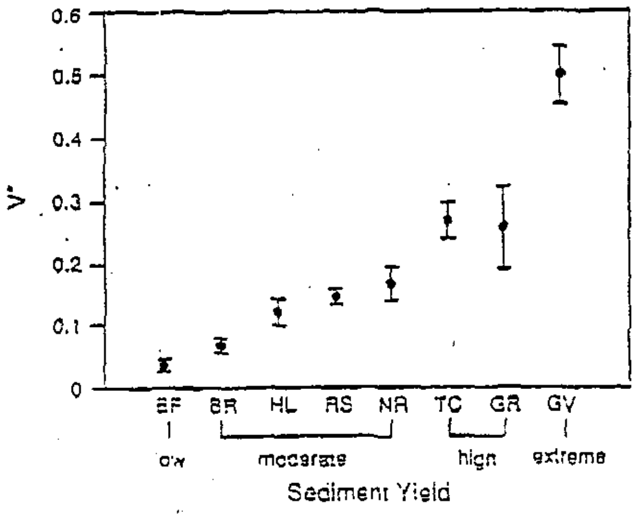

Figure 5. Relation Between Percent of Pool Volume Filled with Fine Sediment (V*) and Qualitative Category of Basin Sediment Yield. Brackets show ±1 standard error of the mean. Streams are plotted in order of ranking of sediment yield. Values of V* for Bear Creek did not include pools affected by the mine; values for North Fork Rattlesnake Creek did not include an anomalously large pool. BF = Big French, BR = Bear, HL = Horse Linto, RS = Rattlesnake, NR = North Rattlesnake, TC = Three Creeks, GR = Grouse, GV = Grass Valley.

Scoured pool volume per unit channel area increased with bankfull discharge (Figure 6), but did not correlate with sediment production. (We used floods with a recurrence interval of 1.2 years [annual series, estimated using Young and Cruff (1967)] to approximate bankfull discharge.) For example, both Big French and Grass Valley Creeks, which have the highest and lowest sediment production, had relatively low scoured pool volumes. Plots (not shown) of frequency and median volume per unit length of individual pools versus drainage area also showed no correlation with sediment production. Sediment production apparently affected the volume of sediment stored, therefore, and not the total potential volume of storage in pools. On the other hand, residual pool volume was reduced by as much as one-half in the most highly disturbed basins.

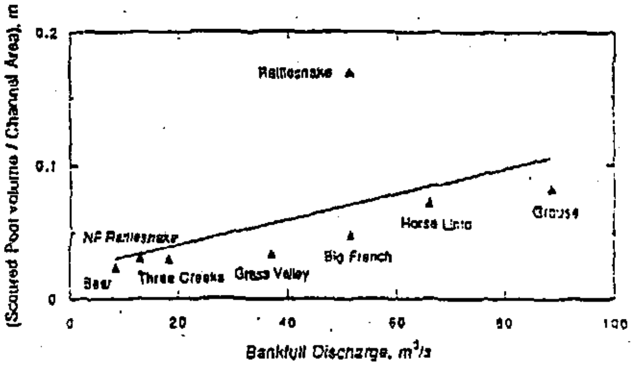

Figure 6. Plot of Scoured Pool Volume Per Channel Area Versus Bankfull Discharge. A recurrence interval of 1.2 years is used to estimate bankfull discharge.

Particle Size of Fine Sediment in Pools

Particle size of sediment in pools ranged from sizes finer than medium sand up to coarse gravel (<64 mm) (Figure 7). Most of the material consisted of coarse sand to medium gravel (0.5 to 16 mm). Median particle sizes ranged from 1.1 to 6.4 mm. Fine-sediment size distributions correspond to the fine mode of bimodally distributed bedload size distributions in Big French, Grass Valley, and Horse Linto Creeks. In three channels with the highest values of $\bar{V}^*$ (Grass Valley, Three Creeks, and Grouse), grain size of fines in pools was relatively small, both in terms of median grain size (2.1, 2.3, and 1.9 mm) and ratio of median grain size of fines to that of bedload deposits (0.15, 0.13, and 0.13). In three channels with low values of $\bar{V}^*$ (Big French, North Fork Rattlesnake, and Rattlesnake), grain sizes of fines in pools was relatively large (D_{50} of 4.1, 6.4, and 5.6 mm; ratio to D_{50} of bedload deposits of 0.48, 0.25, and 0.22). Grain size of pool fines in Horse Linto Creek, which had a low value of $\bar{V}^*$, was relatively small, but corresponded to the fine mode of a pronounced bimodal distribution of bedload. The finest material filling pools was in Bear Creek. This can be attributed to the introduction of

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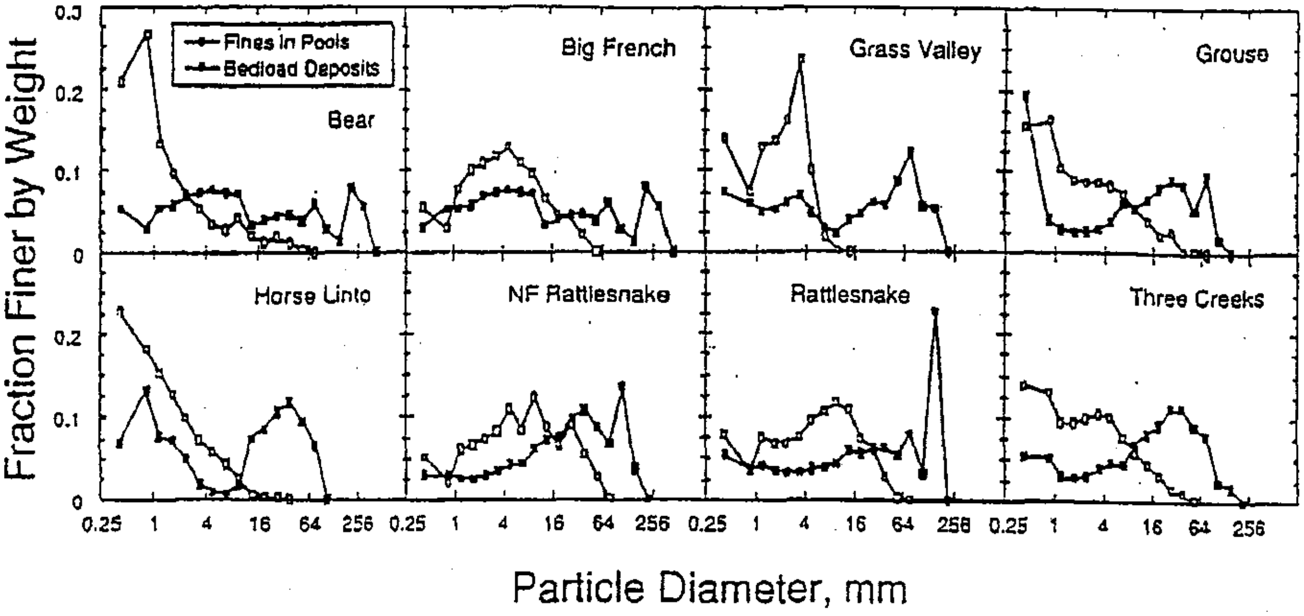

Figure 7. Grain-Size Distributions of Fine Sediment in Pools and Bedload Deposits. The finest size class corresponds to all material passing a 1-phi (0.5 mm) sieve.

eroded soil from hillslopes adjacent to the study ready, as described below.

Downstream Variations in Fine-Sediment Volume

Measurements of fine sediment in pools of Bear Creek led to the detection of a local sediment source – an illegal mining operation upslope, but out of sight of the channel – and quantified the extent and volume of deposition. The relative volume of fine sediment in pools increased sharply immediately below the mine, and then attenuated rapidly within the next 100 m or subsequent three pools (Figure 8). Although fine sediment had been winnowed from most of the affected area of the coarse, steep channel, it was still apparent in pools. Values of V* were among the lowest of the study reaches upstream of the mine and among the highest immediately downstream.

Grouse Creek provide a case study of the influence of channel gradient on fine-sediment storage. The upper half of the study reach was steep (water surface slope = 0.032) and contained numerous large boulders (2-4 m) derived from adjacent landslides and rockfalls; the lower half had a gentle gradient (0.0081) and contained fewer larger boulders (≥ 4 m). No large sources of sediment had entered the channel within the reach; thus, sediment supply appeared uniform. Fine-sediment volume and scoured pool volume increased from the upper, steeper reach to the lower, gentler reach, but V* showed no significant change (Figure 9). Thus, slope apparently did not affect the fraction of available storage filled by fine sediment.

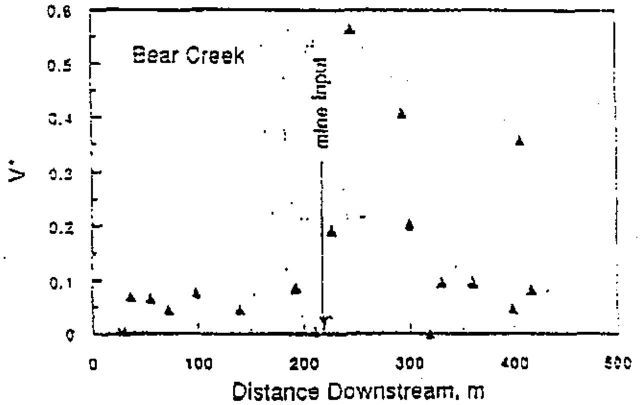

Figure 8. Downstream Variation of Relative Volume of Fine Sediment (V*) in Bear Creek. "Mine input" indicates location of fine-sediment input from a mine.

We measured fine-sediment volume in randomly selected traverses covering 24 percent of the entire

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bed surface (not just pools) of Grouse Creek in order to evaluate the proportion stored in pools. The residual area of pools held 44 percent of the total fine sediment on the bed in the upper reach, 80 percent in the lower reach, and 75 percent overall. The mean-cross sectional area of fine sediment stored outside of residual pools equalled 0.23 m^2 (s.e.=0.09 m^2) in both reaches. Thus, overall, a large majority of fine sediment on the bed surface was stored in the large pools of the lower reach. Elsewhere, fine sediment was stored in small pockets along streambanks, on bars, and around boulders, large woody debris, and riparian vegetation.

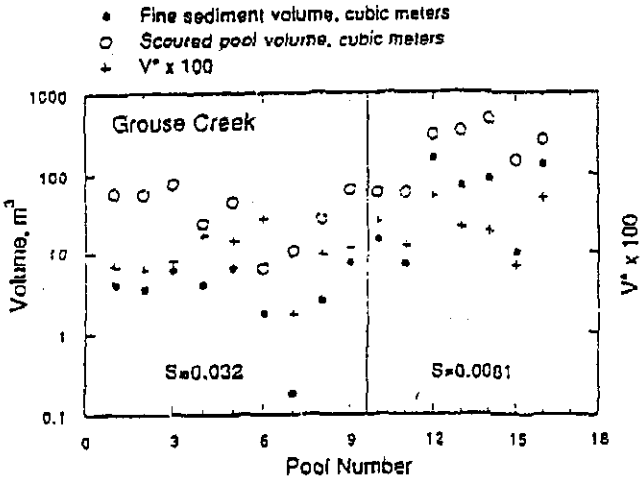

Figure 9. Downstream Variation of Fine-Sediment Volume, Scoured Pool Volume, and Relative Fine-Sediment Volume (V*) in Grouse Creek. Pools in downstream order are partitioned by a decrease in slope demarking upper, steeper and lower, more gentle segments.

In other streams, downstream variations in fine sediment in pools were due apparently to variations in storage capacity of individual pools, and not to downstream variations in sediment supply or channel morphology.

Variation in Fine-Sediment Volume Between Pools

In each stream channel, a linear regression between fine-sediment volume in pools and scoured pool volume was significant ($p<0.01$; Table 2). Residual plots from these regressions showed no obvious departures from linearity, except for North Fork Rattlesnake Creek, where an anomalously large pool contained little fine sediment. This pool may have been enlarged recently by damming of its outlet by debris, and we eliminated it from our sample. We determined a joint confidence region (alpha = 0.05) for the regression of fine sediment volume versus scoured pool volume for each stream to determine if it was different from a function passing through the origin and having a slope equal to $\bar{V}^*$. Only Grass Valley Creek, which had a negative intercept, showed a significant difference.

TABLE 2. Coefficients of Determination (r^2) for Fine-Sediment Volume (V_{fs}) in Pools Versus Scoured Pool Volume (V_{sp}), V* Versus Scoured Pool Volume, and V* Versus the Log of Local Water Surface Gradient ($\log S_{ws}$).

	$V_{fs} = f(V_{sp})$ r^2	$V^* = f(V_{sp})$ r^2	$V^* = f(\log S_{ws})$ r^2
Big French	0.50***	0.00	0.10
Bear[a]	0.80***	0.44**	0.17
Horse Linto	0.64***	0.02	0.55**
North Rattlesnake[b]	0.65***	0.01	0.02
Rattlesnake	0.96***	0.24**c	0.42**
Three Creeks	0.77***	0.04	0.20*
Grouse	0.68***	0.29**	0.21*c
Grass Valley	0.98***	0.46***	0.11

*Significant at a probability $0.05<p<0.10$.
**Significant at a probability $0.01<p<0.05$.
***Significant at a probability $p<0.01$.
[a] Pools downstream of mine input are excluded.
[b] Anomalously large pool is excluded.
[c] Variable does not make an additional significant contribution to explanation of variation of V*.

In most cases, variance in fine sediment volume, as well as fine-sediment volume itself, increased as scoured pool volume increased. In many cases, variations in V* of individual pools were wider for smaller pools than for larger pools. This may be due to a high inherent variability in deposition of small volumes of fine sediment, which are typical of small pools. Differences in measurement error between large and small pools were not a factor apparently, because replicate measurements showed no relation between variance of V* within a pool and pool size.

Less striking, but nonetheless apparent, influences on fine-sediment volume in some streams were revealed in plots of V* versus scoured pool volume (Figure 10A) and estimated water surface slopes (S_{ws}) over pools at moderate flow (Figure 10B). We used S_{ws} at moderate flow as an index of the scouring potential of the flow when fine sediments are transported into pools. This slope is estimated by the average water-surface slope measured at low flow from one channel-width distance upstream of the pool downstream to the riffle crest. V* was negatively correlated ($0.01<p<0.05$) with log S_{ws} in Horse Linto and Rattlesnake Creeks, whose pools were filled less than

15 percent on average with fine sediment (Table 2). In Bear Creek above the mine, Grass Valley Creek, and Grouse Creek, V^* was not significantly correlated with log S_{ws}, but was positively correlated ($0.01<p<0.05$) with scoured pool volume. These channels can be characterized as having either high values of V^* (Grass Valley and Grouse) or small grain size of fine sediment (all three). In Rattlesnake Creek, V^* was also correlated with scoured pool volume, but was more strongly correlated with log S_{ws}, and scoured pool volume did not have a significant effect when the effect of S_{ws} was accounted for. Considering all channels and higher levels of significance, V^* correlated better with scoured pool volume than log S_{ws} in channels with high sediment loads and small particle size of fine sediment in pools; the opposite was true for channels with low sediment loads and coarse sediment in pools.

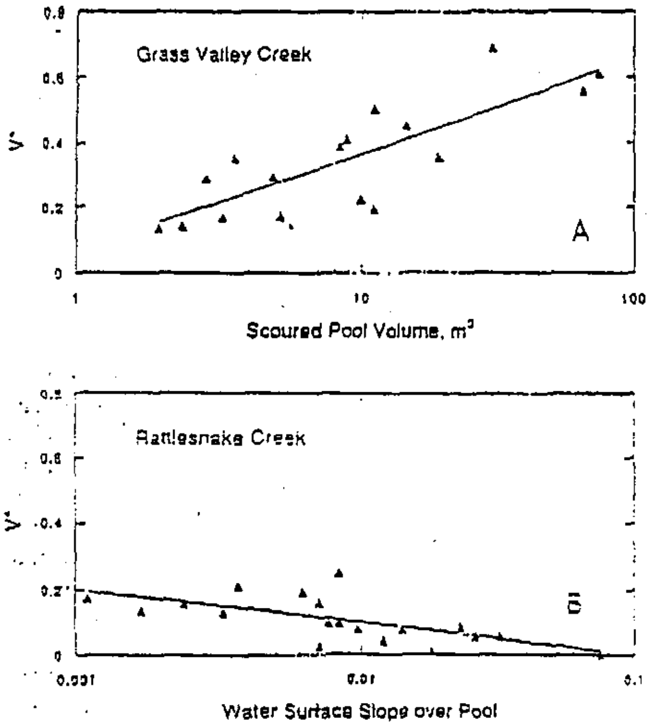

Figure 10. Variation of Relative Volume of Fine Sediment (V^*) with (A) Scoured Pool Volume in Grass Valley Creek, and (B) Water Surface Slope at Low Flow Over Pools in Rattlesnake Creek.

DISCUSSION

Conceptual Model for Accumulation of Fine Sediment in Pools

Andrews (1979) and Lisle (1979) observed that sand in pools of the East Fork River, Wyoming, was scoured at approximately bankfull discharge, exposing a coarse gravel bed. At or near this stage, mean boundary shear stress in pools equalled or exceeded that in riffles and exceeded the critical shear stress of entrainment of all particle sizes on the bed. As the stage dropped, boundary shear stress in pools became less than that in riffles, and pools refilled with selectively transported sand (Lisle, 1979). Keller (1971) observed a similar pattern of variation in near-bottom velocities in another channel. Using these observations, we offer a conceptual model for the accumulation of fine sediment in pools and the factors that control how much fine sediment is deposited.

As the stage drops below bankfull, pools begin to fill with fine sediment winnowed from riffles and other areas of the bed where boundary shear stress exceeds that in pools (Lisle and Madej, in press). Although some fine sediment is deposited in pools, boundary shear stress along the major sediment pathways in pools is sufficient to maintain continued transport downstream. At each stage, the volume of fine sediment deposited in a pool reflects a balance between local sediment transport capacity and the influx of sediment from upstream (Laursen, 1952). Transport capacity is afforded by the high-velocity flow converging into the pool, which is analogous to a wall jet impinging at a shallow angle on the bed of the pool. Filling of the pool during a steady discharge, for example, would be hindered by an increase in boundary shear stress under the jet as depth decreases.

Transport of fine sediment from pool to pool is interrupted when boundary shear stresses in pools are insufficient to transport sediment onto riffles. In the final stage of deposition, much of the remainder of fine sediment on riffles is winnowed and deposited in pools.

Fine-sediment volume in pools can vary widely because of complex factors influencing deposition. Eddies and zones of flow separation are characteristic of pools. Sand is often suspended intermittently, carried by eddies into "dead zones," and deposited to great depths during waning stages (Rubin *et al.*, 1990). Such areas are created by channel bends or large obstructions including boulders, bedrock projections, and large woody debris. Thus, the mean hydraulic variables used to characterize the capacity of flow to transport or store fine sediment in pools cannot be expected to explain all of the variation in

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fine-sediment volume in pools of a particular stream. However, a continuum of hydraulic conditions over the range of sediment-transporting flows is responsible for both the scoured volume of a pool and the volume of fine sediment stored. Some correlation between fine-sediment volume and the volume and flow conditions in a pool can be expected.

Consider the same stream channel, once with a low sediment supply and once with a high supply. Filling of its pools with fine sediment during recessional stages of a flood hydrograph would cease at the same critical shear stress measured in its pools, regardless of sediment supply, provided particle sizes of fine sediment remained equal. Filling would cease at different flow rates, however, depending on sediment supply. In the case of low sediment supply, critical shear stresses would be reached in deeply scoured pools at moderate flow; in the case of high supply, they would be reached in shallow, filled pools at low flow.

With the exception of Bear Creek, the material filling pools in Trinity River tributaries with low sediment supplies was coarser than that in those with high supplies. Bear Creek had a meager sediment load and very fine-grained material filling pools, but the mine contributed fine-grained material directly to the study reach. Perhaps, in high-supply channels, proportionately more sand and silt are produced from active soil erosion and abrasion of frequently mobilized bed materials than in low-supply channels. From theoretical considerations of sediment transport, however, the influence of particle size of pool-filling material on volume of fill is ambiguous.

In channels with abundant supplies of sediment, e.g., Grass Valley Creek, V^* correlated with scoured pool volume. In such channels, fine-sediment transport is prolonged into stages in which the scouring mechanism becomes weak. Variations in resulting residual volume between pools with large and small scoured volumes are relatively small (Figure 11A), because variations in scour potential are limited at low flow. As a result, low-energy zones that become filled with sediment are proportionately larger in large pools than in small pools. We term fine-sediment deposition in pools of these channels "volume-limited" because fine sediment can occupy a smaller proportion of the scoured volume of small pools than that of large ones.

In channels with meager sediment supplies, e.g., Rattlesnake Creek, V^* correlated with local stream gradient which indexes local transport capacity when fine sediment is deposited in pools. In such channels, filling ceases at a moderate flow when the scouring mechanism remains strong. Variations in scour strength can cause large variations in V^* from pool to pool (Figure 11B). Differences between average values in V^* for large pools versus those for small pools tend to be small, however, because of the continuum in scouring potential and the small difference between flows which scour pools to an underlying coarse layer and those during which filling ceases. The potential for deposition of fine sediment is roughly proportional to scoured pool volume, but differences in scour potential cause large variations in deposition between pools of a given size. We term fine-sediment content in these channels "jet-limited" because the strength of the submerged jet tending to scour a pool apparently limits the relative volume of fine sediment deposited.

The volume of water providing habitat for fishes and other aquatic organisms in a pool depends partly on the volume of the pool basin created during general transport of the streambed and partly on secondary filling of the pool by fine material that is selectively transported as flows wane. Sediment supply to our study streams apparently influenced the latter, but not the former, unless the scoured pool volume of sediment-rich channels has been inherited from a previous period of low sediment supply. Local channel conditions such as the size and spacing of large obstructions and bends that induce scour (Lisle, 1986) may override sediment-load effects on the scoured volume of pools. In Grouse Creek, for example, pools were frequently associated with large blocks of landslide debris. The pools were filled as much as 50 percent by fine sediment, but the presence of the blocks greatly enhanced total pool volume, and some large pools were scoured around the largest blocks. However, no conclusions can be made on the effects on scoured pool volume by sediment inputs more voluminous than we encountered. Large sediment inputs leading to widespread aggradation and channel instability can severely reduce pool volume without the occurrence of secondary filling by fine sediment.

CONCLUSIONS

Measurement of the relative volume of fine sediment stored in pools provides a practical method to inventory the volume of mobile sediment stored in a reach of gravel-bed channel. Weighted averages of ratios of fine-sediment volume to scoured pool volume correlated well with qualitative assessments of sediment yield for eight tributary basins of the Trinity River, California. The method can also be used to detect and evaluate inputs of sediment along a channel network. The method is practical because it (1) measures the most active component of channel-stored sediment and is thus sensitive to changes in contributions from the watershed; (2) quantifies a sediment-related effect on an important component of aquatic habitat; and (3) is easily accomplished in

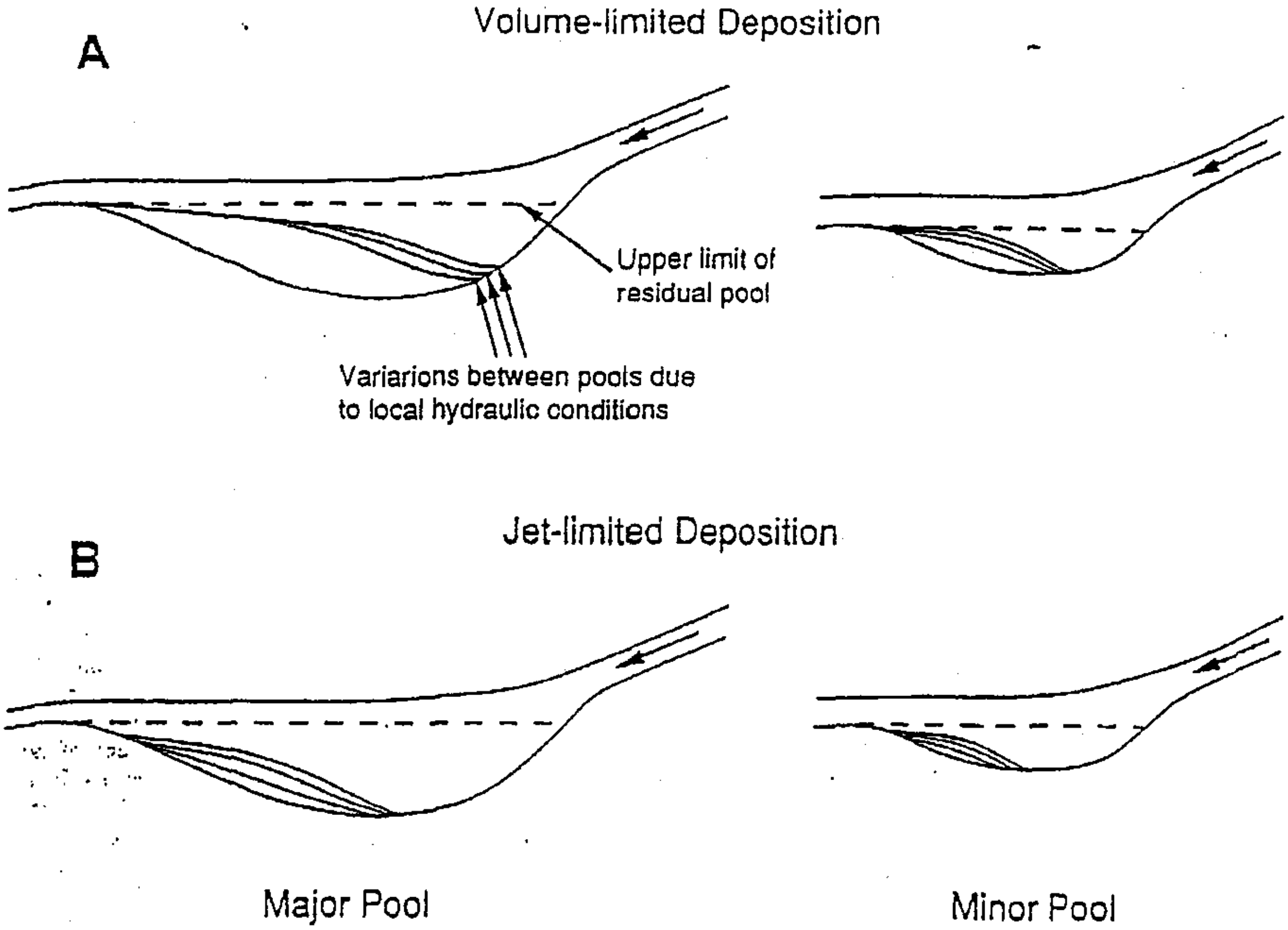

Figure 11. Models for Volume-Limited (A) and Jet-Limited (B) Deposition of Fine Sediment in Pools.

small- to moderate-sized stream channels. Because sediment storage is measured in consistent hydraulic environments, the relative areas of pools and riffles in inventoried reaches does not confound comparisons between stream channels or in individual reaches over time as areas change.

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and excerpt from a scientific article, "Effects of Fines in Salmonid Redds" -- Chapman, illustrates the threshhold phenomenon and effect on embryo survival of fine sediments:

Percent Survival of Salmonid Embryos
vs.
Percent of Fine Sediments

THRESHHOLD and AREA OF DRASTIC
DECREASE IN EMBRYO SURVIVAL

"Research generally supports the hypothesis that survival declines in substrates as quantities of fine sediments increase. Fines tend to reduce gravel permeability and pore space, as well as dissolved oxygen in water available to embryos, thus influencing incubation success."

from Transactions of the American Fisheries Society, "Critical Review of Variables Used to Define Effects of Fines in Redds of Large Salmonids"
by D.W. Chapman
Volume 117, Number 1, January 1988

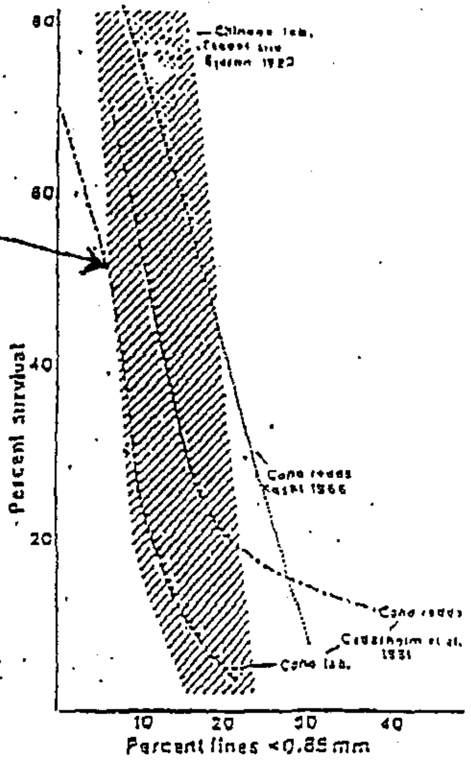

FIGURE 5.—Survival of salmonid embryos to emergence in relation to fines smaller than 0.85 mm in diameter. Data provide comparisons of coho salmon survivals in laboratory (lab.) and field (Cederholm et al. 1981), of coho salmon in two different streams (Koski 1966; Cederholm et al. 1981), and of chinook salmon in gravels with a range of percentages of particles less than 9.5 mm in diameter (shaded area: Tappel and Bjornn 1983).