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Fine bed material in pools of natural gravel bed channels

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Abstract. Natural gravel bed channels commonly contain a fine mode of sand and fine gravel that fills voids of the bed framework of coarser gravel. If the supply of fine bed material exceeds the storage capacity of framework voids, excess fine material forms surficial patches, which can be voluminous in pools during low flow. Data collected in 34 natural channels in northern California and southern Oregon indicate the following. (1) Fine material on the bed surface can be readily winnowed and transported at high particle velocities, much of it in intermittent suspension. Fine material can dominate the bed material load in gravel bed channels, but its abundance on the bed surface is limited by its increasing mobility as hiding places among prominent particles are filled. (2) Fine material in pools is typically replaced many times per year. (3) The proportion V^* of residual pool volume filled with fine bed material correlates with annual sediment yield in channels whose parent material produces abundant sandy sediment. (4) Temporal and spatial changes in V^* appear to correspond to variations in the balance between sediment inputs and water discharge. These results suggest that V^* can be used to monitor and evaluate the supply of excess fine material in gravel bed channels and that samples of fine material in pools can characterize the fine, mobile mode of bed material load.

1. Introduction

The sediment load of a stream channel (the amount supplied and transported over a period of time) can be difficult to evaluate. Contributions from hillslopes can be quantified with erosion surveys and sediment budgeting, but uncertainty in routing makes it difficult to assess the load at any point in a channel network, and direct measurement of transport rates is notoriously difficult. Bed material typically furnishes the bulk of the annual bed load, especially in more distal channels, but the active volume that contributes to the load is highly variable and difficult to evaluate. It may be easier to detect variations in load by examining the mobility of the bed surface of gravel bed channels. Bed material in gravel bed channels characteristically includes a wide range of particle size, and the bed can become more or less mobile in response to changes in load by exposing finer or coarser components on the bed surface [*Dietrich et al.*, 1989].

In this paper, we focus on fine-grained bed material consisting mostly of sand and fine gravel that is transported in traction, saltation, or intermittent suspension in gravel bed channels. Fine bed material can be naturally delineated from the remainder of bed material (albeit with some uncertainty of division) because much of it is commonly transported and deposited selectively. Fine bed material is an issue in watershed management because it can have strong and pervasive effects on aquatic organisms and its concentration in streambeds is sensitive to watershed disturbance [*Cordone and Kelly*, 1961; *Everest et al.*, 1987; *Cederholm and Reid*, 1987; *Hicks et al.*, 1991]. The purpose of the research reported herein is to relate the particle size range of fine bed material to processes of transport and deposition and to improve methods to evaluate its in-channel supply. Practical methods to identify and measure selectively transported bed material would be useful, for example, to design the magnitude and duration of flow releases from reservoirs in order to flush fine sediment from streambeds downstream.

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Fine bed material is a component in heterogeneous gravel beds, but it can also appear as well-sorted surficial patches. It is commonly abundant enough to form a prominent fine mode in distributions of bed load and bed material. Typically, gravel particles of the coarser mode of the bed are in mutual contact and form a framework whose matrix is filled to varying degrees by finer material [*Carling and Reader*, 1982]. "Framework" and "matrix" populations are commonly evident in bimodal distributions of bed material or in skewed distributions if matrix particles are less abundant. Nevertheless, the partitioning of bed material by particle size has been uncertain because the behavior of intermediate particle sizes as matrix or framework materials is gradational and can be expected to vary from one channel to the next.

Significant transport of fine bed material held in the matrix depends on mobilization of the gravel armor, which commonly occurs at stages approaching bank-full [*Parker*, 1978; *Parker and Klingeman*, 1982; *Andrews*, 1984]. Once released by dislodged armor particles, fine bed material can be transported momentarily at high velocities but is soon trapped in hiding places on or in the gravel framework. Transport of fine bed material held in the matrix can be considered stream power dependent insofar as annual variations in transport appear to depend more on the duration and magnitude of stream power above the entrainment threshold of the mobile armor than on variations in the volume of fine bed material in the matrix.

However, fine bed material spanning a range of particle sizes can be selectively transported from a heterogeneous bed while exhibiting equal mobility for that size range [*Church and Wolcott*, 1991; *Wathen et al.*, 1995]. Similarly, tracer experiments show a rapidly weakening size dependency of virtual transport velocities with decreasing particle sizes less than the median size of bed material [*Hassan and Church*, 1992; *Ferguson and Wathen*, 1998].

Figure 1. Deposit of fine bed material in a pool of Bridge Creek, northern California. Fine material occupies approximately 20% of the residual pool volume.

Variations in channel topography and boundary shear stress can lead to sorting of bed material and formation of surficial patches of fine bed material that locally cover the gravel framework [*Lisle and Madej*, 1992; *Seal and Paola*, 1995; *Wiele et al.*, 1996]. Fine patches contain some of the first bed material to be entrained during rising stages, the most erodible at bank-full stages, and the last to be deposited during waning stages [*Andrews*, 1979; *Lisle*, 1979; *Meade*, 1985; *Sear*, 1996]. Important volumes of fine bed material in patches can be transported at stages below the entrainment threshold of the mobile armor and can be expected to be transported rapidly in saltation and intermittent suspension through a channel system [*Komar*, 1987; *Leopold*, 1992; *Lisle*, 1995; *Wathen et al.*, 1995; *Wilcock et al.*, 1996a]. Because of its high mobility, transport of fine bed material stored on the bed surface can be considered "supply-dependent" insofar as annual transport appears to depend more on the volume stored on the streambed than on the duration and magnitude of streamflow.

We propose that as the supply of fine bed material increases, the bed matrix becomes filled, and greater volumes of fine material become exposed on the bed surface to high boundary shear stress. The proportion of fine bed material that exceeds the storage capacity of the matrix can be regarded as "excess." During falling stages, excess fine bed material is winnowed from and overpasses immobilized gravel armors, where shear ... patches in

respond to variations in sediment supply [*Sawada et al.*, 1985; *Lisle and Madej*, 1992; *Wiele et al.*, 1996]. *Sawada et al.* [1985] measured major shifts in relationships between bed load transport and discharge that resulted from changes in storage of fine bed material in pools in a reach of a small step-pool channel. *Wiele et al.* [1996] model transient sand deposition in the Colorado River in the Grand Canyon downstream of a large input from the Little Colorado River. *Wilcock et al.* [1996b] propose to dredge pools in order to control volumes of fine bed material below a dam on the Trinity River, California.

In a previous paper [*Lisle and Hilton*, 1992], we proposed that a supply-dependent portion of fine bed material can be measured as the proportion of residual pool volume filled with fine bed material (V^*) (Figure 2). The strategy ~~is to~~ measure excess fine bed material where it is most abundantly stored and

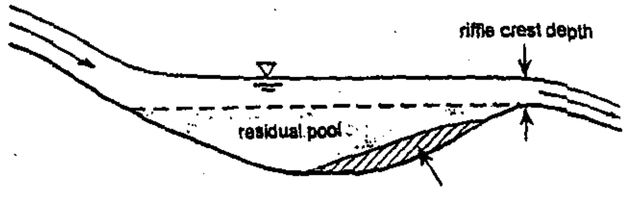

Figure 2. Definition sketch of V^*. In this longitudinal profile ... from the coarse substrate

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to scale by the available storage. In eight channels in the Trinity River basin of northern California, we show a positive correlation between V^* and categories of sediment yield that are based on available values of sediment yield and inventories of recent logging and road building. In 60 basins underlain by the Franciscan Formation in northwestern California, *Knopp* [1993] shows significantly lower values of V^* in channels draining basins that were either pristine or logged in the nineteenth century than in channels draining recently logged basins. *Hilton and Lisle* [1993] detail methods of measuring V^* and present sampling guidelines that are based on measurements of the variation of V^* between pools in a reach of channel.

In this paper we attempt to improve the utility of V^* to identify selectively transported, fine bed material and evaluate its supply. We use data from 34 channels to focus on the sedimentology of fine bed material and its storage in pools and the gravel bed matrix. We find that fine bed material in both of these storage reservoirs has a similar range in particle size. Fine bed material in pools is highly mobile and contributes disproportionately to the bed material load in relation to the total volume of fine material stored in the active bed. We provide more evidence that V^* responds to variations in sediment supply, but only where the supply includes abundant sandy material. We find no significant effects of pool type on V^* and minor effects of coarse, woody debris in pools. Finally, we examine annual variations of V^* in five channels.

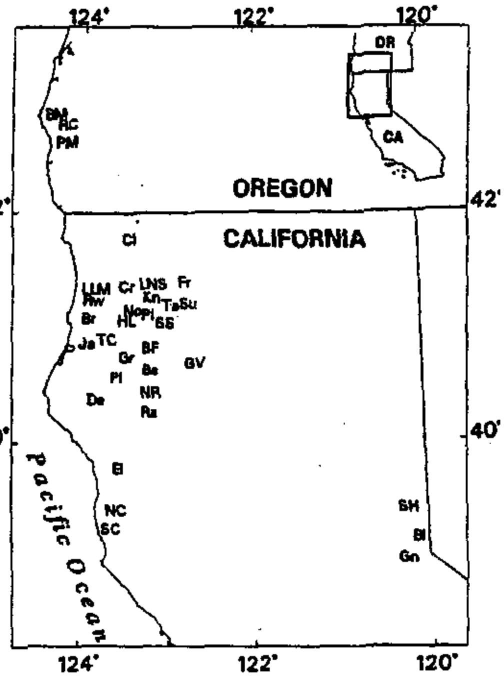

Figure 3. Location of study reaches. Abbreviations of channel names are defined in Table 1.

2. Study Sites

We collected data from natural gravel bed channels in northern California and southern Oregon that varied widely in size, form, parent material, and sediment production (Figure 3; Table 1). Drainage areas ranged from 3.8 to 520 km^2, and channel gradients ranged from 0.0026 to 0.045. Reach-mean values of V^* ranged from 0.027 to 0.50.

In order to investigate relationships between V^* and sediment supply, we selected 22 of the channels because they had available estimates of total annual sediment yield (suspended and bed load) for the past few decades. These channels provided a wide range in estimated sediment yield (3.1–2200 t km^{-2} yr^{-1}). However, matching values of sediment yield values and V^* was uncertain because sediment yield was computed for various time intervals and the reach in which V^* was measured did not always correspond to the downstream limit of the basin for which sediment yield was computed. Sediment yields averaged over recent decades may not accurately represent recent sediment supply conditions. For example, large floods in 1964 and the early 1970s contributed vast volumes of sediment to many channels in northern California and southern Oregon, but postflood routing of this sediment is poorly known. Furthermore, relating V^* to sediment yield is uncertain because the yield typically includes a wider range of particle sizes than is represented in fine material in pools. For these reasons, we do not claim to develop predictive relations, but instead use the degree of correlation to investigate relative influences of sediment yield and other variables.

Study reaches were 0.3–2.0 km or 40–170 channel-widths long and contained no major tributary junctions or other large lateral inputs of runoff or sediment. The channels had predominantly alluvial beds and banks, but many were in narrow valley bottoms and locally impinged on bedrock. Pools and riffles or steps were present, but regular meanders were not. Streambeds were extensively armored with gravel, cobbles, and boulders.

3. Methods

We detail methods to measure and compute V^* elsewhere [*Lisle and Hilton*, 1992; *Hilton and Lisle*, 1993] and describe them only briefly here. In each pool, we sounded water depths and probed the thickness of fine material with a steel rod along transverse profiles. We computed volumes of water and fine material within the boundaries of the residual pool, which lies below the elevation of the downstream riffle crest. We measured 8–24 pools in each reach, depending on variability of V^* and availability of pools. Most reaches were measured once, but five (Table 1) were measured annually for 6 years in order to investigate temporal variations. In this paper, we most frequently report the reach-mean value of V^*, which is an average of values for individual pools weighted by total pool volume (volume of residual water plus fine bed material).

We measured particle sizes of fine bed material in pools and in the subsurface in each reach. We used a pipe dredge to collect fine material in several pools in each reach. The probability of randomly selecting pools to sample was proportional to estimated volumes of fine bed material in each pool. We sampled subsurface material from recently active bars, alluvial fans, and logjam deposits which we chose to represent average bed load transported over a period of years. In most cases we collected enough material so that the largest particle was no more than 1% of the total sample weight; in coarse-bedded channels, we relaxed this criterion to 5%. Samples were typically >100 kg in total weight. In all but one case (Jacoby Creek), we sieved at $\frac{1}{2}\phi$ intervals down to 0.5 mm and retained the pan contents. Subsurface samples in Grouse, Jacoby, North Fork Caspar, and Redwood Creeks were obtained by stratified random sampling keyed to surface patches of bed material [*Lisle and Madej*, 1992].

There is uncertainty in representing bed load material by samples from the stream bed. Particle size of bed load aver-

Table 1. Characteristics of Study Reaches in Northern California and Southern Oregon

	Drainage Area, km^2	Stream Gradient	Sediment Yield,[a] $t\ km^{-2}\ yr^{-1}$	Sediment Yield Period	Parent Material[b]	V^* (s.e)[c]
		Fines-Rich Parent Materials				
Bear Creek (Be)[d]	20.0	0.042			g, ms	0.070 (0.04)
Bridge Creek (Br)	28.3	0.012	630	1954–1980	sch, ss	0.21 (0.03)
Crapo Creek (Cr)	44.5	0.040	1360	1965–1988	g, m	0.23 (0.02)
Decker Creek (De)	5.2	0.024			ss, sh	0.12 (0.03)
Elder Creek (El)	16.9	0.022			ss, sh	0.089 (0.011)
French Creek (Fr)	60.4	0.016	265	1990	g	0.33 (0.03)[e]
General Creek (Ge)	18.6	0.016	49	1975–1985	g	0.14 (0.02)
Grass Valley Creek (GV)	80.0	0.017	2240	1991	g	0.50 (0.16)
Grouse Creek (Gr)	140	0.016	1050	1960–1988	ss, sh, ms	0.26 (0.12)
Horse Linto Creek (HL)	97.0	0.018			ss, sh, ms, g	0.12 (0.05)
Jacoby Creek (Ja)	36.3	0.0063	180	1985	ss, sh	0.14 (0.02)
Little Lost Man Creek (LLM)	9.0	0.045	63	1980	ss, sh	0.17 (0.04)
Little North Fork, Salmon River (LNS)	50.2	0.028	144	1965–1988	g, m	0.046 (0.011)
North Fork, Caspar Creek (NC)	5.0	0.013	177	1963–1965	ss, sh	0.30 (0.03)
Pilot Creek #1 (Pi1)	54.3	0.0087			ss, sch, sh	0.16 (0.03)
Pilot Creek #2 (Pi2)	65.0	0.011			ss, sch, sh	0.40 (0.07)
Redwood Creek (RW)	520	0.0026			ss, sch, sh	0.24 (0.04)
South Fork, Caspar Creek (SC)	5.4	0.012	158	1963–1965	ss, sh	0.25 (0.03)
South Fork, Salmon River (SS)	88.3	0.028	175	1965–1988	g, m	0.22 (0.02)[f]
Sugar Creek (Su)	28.8	0.023	218	1990	g	0.15 (0.02)
Taylor Creek (Ta)	50.3	0.037	19	1965–1988	g, m	0.11 (0.02)
Three Creeks Creek (TC)	23.0	0.016			sch, ss	0.29 (0.05)
		Fines-Poor Parent Materials				
Bald Mountain Creek (BM)	18.6	0.024	130	1964–1986	css, ms, di	0.074 (0.001)
Big French Creek (BF)	99.0	0.019			m	0.040 (0.02)
Blackwood Creek (BW)	29.5	0.015	100	1975–1985	v	0.080 (0.014)
Clear Creek (Cl)	154	0.016			m	0.045 (0.006)
Knownothing Creek (Kn)	58.1	0.020	260	1965–1988	m, g	0.038 (0.011)
Nordheimer Creek (No)	81.3	0.016	147	1965–1988	m	0.029 (0.008)
North Fork, Rattlesnake Creek (NR)	22.0	0.044			ms	0.14 (0.03)
Plummer Creek (Pl)	37.8	0.036	83	1965–1988	ga, um, m	0.038 (0.015)
Purple Mountain Creek (Pu)	3.8	0.035	310	1964–1986	ms, di	0.049 (0.015)
Rattlesnake Creek (Ra)	120	0.013			ms, um	0.15 (0.08)
Red Cedar Creek (RC)	7.0	0.016	24	1964–1986	css, ms	0.027 (0.004)
Sagehen Creek (SH)	18.3	0.015	3.1	1954–1991	v	0.041 (0.013)

[a]Mean annual sediment yields are for clastic sediments, estimated from inputs over a period of years or from current erosion or transport rates (single dates). References for sediment yields are as follows: Bald Mountain, Purple Mountain and Red Cedar Creeks, C. Ricks (USDA Forest Service, Gold Beach, Oregon, personal communication, 1992); Blackwood and General Creeks, *Nolan and Hill* [1991]; Bridge Creek, M. A. Madej (Redwood National Park, Arcata, California, personal communication, 1992); Crapo, Knownothing, Nordheimer, and Plummer Creeks and South Fork Salmon River, *De la Fuente and Haessig* [1993]; French and Sugar Creeks, *Sommarstrom et al.* [1990]; Grass Valley Creek, *Bedrossian* [1991]; Grouse Creek, *Raines and Kelsey* [1991]; Jacoby Creek, *Lehre and Carver* [1985]; Little Lost Man Creek, *Tally* [1980]; North and South Forks, Caspar Creek, Redwood Sciences Laboratory, Arcata, California (unpublished data, 1996); Sagehen Creek, *Andrews* [1994].

[b]Parent materials generally producing abundant fine bed material: g, granitics; sch, schist; sh, shale; ss, sandstone. Parent materials generally producing modest or little fine bed material: css, competent sandstone; ga, gabbro; m, undifferentiated metamorphics; ms, metasediments; v, undifferentiated volcanics; um, ultramafics.

[c]Standard error of the weighted mean; formula is given by *Hilton and Lisle* [1993].

[d]Abbreviations are used in Figure 3.

[e]Data for some years furnished by J. Power (Klamath National Forest, Fort Jones, California).

[f]Data for some years furnished by R. Van de Water (Klamath National Forest, Fort Jones, California).

aged over the range of natural flows can be finer than that of subsurface bed material of gravel bed channels, particularly in ones such as those used in this study which have drainage areas of less than about 100 km^2 [*Leopold*, 1992; *Lisle*, 1995; *Toro-Escobar et al.*, 1996]. Bed load sizes can be regarded with greater confidence in Grass Valley, North Fork Caspar, Redwood, and Jacoby Creeks. We sampled deposits behind sediment traps in Grass Valley and North Fork Caspar Creeks. Subsurface sampling in Redwood Creek was intensive [*Lisle and Madej*, 1992], and subsurface material adequately represents bed load in this channel [*Lisle*, 1995]. Bed load was sampled directly in Jacoby Creek [*Lisle*, 1989, 1995], and the resulting size distribution was combined with detailed subsurface samples.

We used measurements of surface particle size and mean bank-full hydraulic conditions in a "reference subreach" to characterize the mobility of each reach. A reference subreach was the longest subreach available (usually >7 channel widths in length) that was uniform and straight in plan form and profile and lacked large elements of form roughness such as prominent outcrops, large boulders, or coarse woody debris. Gradients in reference subreaches approximately equaled average gradients of the study reaches. We measured surface particle sizes with pebble counts of ≥200 [*Wolman*, 1954] over the entire reference subreach (except in Grouse, Jacoby, North Fork Caspar, and Redwood Creeks, where multiple counts were done on patches selected by stratified random sampling [*Lisle and Madej*, 1992]). We measured mean bank-full channel dimensions

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Table 2. Particle Size Parameters of Bed Material and Fine Material in Pools

	Bed Material			Fine Material in Pools		
	Surface D_{50}, mm	Subsurface or Bed Load D_{50}, mm	Suspension Threshold D_S, mm	Percent Finer Than D_S	Percent Finer Than D_{50}	Percent Finer Than D_{90}
Fines-Rich Parent Material						
Bear Creek		8.5			1.1	8.7
Bridge Creek	72	16	4.2	82	1.1	7.1
Crapo Creek	122	11	11.4	83	1.1	2.9
Decker Creek		19			2.1	12
Elder Creek	227	21	9.8	79	3.4	15.6
French Creek		17			1.1	2.8
General Creek	52	17	6.1	68	2.1	20
Grass Valley Creek	86	1.5[a]	5.0	92	2.1	4.3
Grouse Creek	41	11	5.5	78	1.9	9.8
Horse Linto Creek	94	13	4.9	92	1.2	4.2
Jacoby Creek	40	16[b]	2.2	45	3.1	22
Little Lost Man Creek	106	15	7.9	77	2.6	14
Little North Fork, Salmon River		14			1.9	8.8
North Fork, Caspar Creek	22	9.2[a]	1.0	42	1.9	13
Pilot Creek #1[c]	46		2.3	35	3.9	16
Pilot Creek #2[d]	29		2.9	58	2.0	13
Redwood Creek	28	11	2.7	70	1.2	8.3
South Fork, Caspar Creek	47	6.8	2.2	34	4.8	18
South Fork, Salmon River		5.2			1.8	11
Sugar Creek		44			1.3	3.6
Taylor Creek		32			1.3	14
Three Creeks Creek	58	18	5.1	46	2.5	13
Fines-Poor Parent Material						
Bald Mountain Creek	75	8.0	6.1	51	6.0	21
Big French Creek		8.5			4.1	17
Blackwood Creek	49	24	3.5	53	3.0	26
Clear Creek		16			2.4	12
Knownothing Creek	129	44	4.0	58	3.1	14
Nordheimer Creek	105	30	4.5	47	5.1	23
North Fork, Rattlesnake Creek		25			6.4	30
Plummer Creek	126	25	10.1	71	5.9	16
Purple Mountain Creek	74	27	8.0	68	4.2	18
Rattlesnake Creek		26			5.6	22
Red Cedar Creek	61	32	3.0	23	10	35
Sagehen Creek[e]	58	6.5[b]	4.5	30	8.8	31

Bed load size distributions were obtained from samples in fresh bars, with exceptions as noted.
[a]Samples from deposits upstream of impoundments.
[b]Transport-weighted distributions from direct measurements of bed load transport (Jacoby from *Lisle* [1995]; Sagehen from *Andrews* [1994]).
[c]Reach is upstream of fine sediment source.
[d]Reach is downstream of fine sediment source.
[e]Particle size distributions from *Andrews* [1994].

by surveying three cross sections and a longitudinal profile of the channel thalweg, water surface, and bank-full margins.

4. Sedimentology of Fine Bed Material: Equivalency in Pools and Bed Matrix

The sedimentology of fine bed material is important to understanding its relation to sediment supply and transport characteristics. Here we use comparisons of particle size distributions of bed material, bed load, and fine bed material in pools as evidence that fine material is winnowed from the matrix of heterogeneous bed material and selectively transported and deposited in pools.

Particle size distributions of fine bed material in pools were similar to those of the fine mode of bed material load (Table 2; Figure 4). The median particle size of fine bed material in pools [$(D_{50})_{fp}$] fell within the range of coarse sand and granules and on average was one-seventh the D_{50} of bed load samples. At most study sites, particle size distributions of subsurface bed material or bed load either were skewed toward coarser fractions or were bimodal (Figure 4), signifying an abundant fine component of sand and fine gravel [*Kondolf and Wolman*, 1993; *Folk and Ward*, 1957] which is commonly transported selectively [*Wilcock*, 1993]. The modes were separated at particle sizes ranging from coarse sand to fine gravel. This is somewhat finer than D_{90} of fine bed material in pools (where D_{90} is the particle size for which 90% of the bed surface is finer), which commonly fell within the range of medium gravel and was as coarse as 35 mm.

Mobile armors were well winnowed of fine material. The median particle size of the bed surface, $(D_{50})_{sur}$, was commonly several times larger than that of bed load accumulations or samples of subsurface bed material that were selected to represent bed load and not the average subsurface material (Table 2). Armoring would have appeared to be weaker had we measured it with respect to average subsurface bed material,

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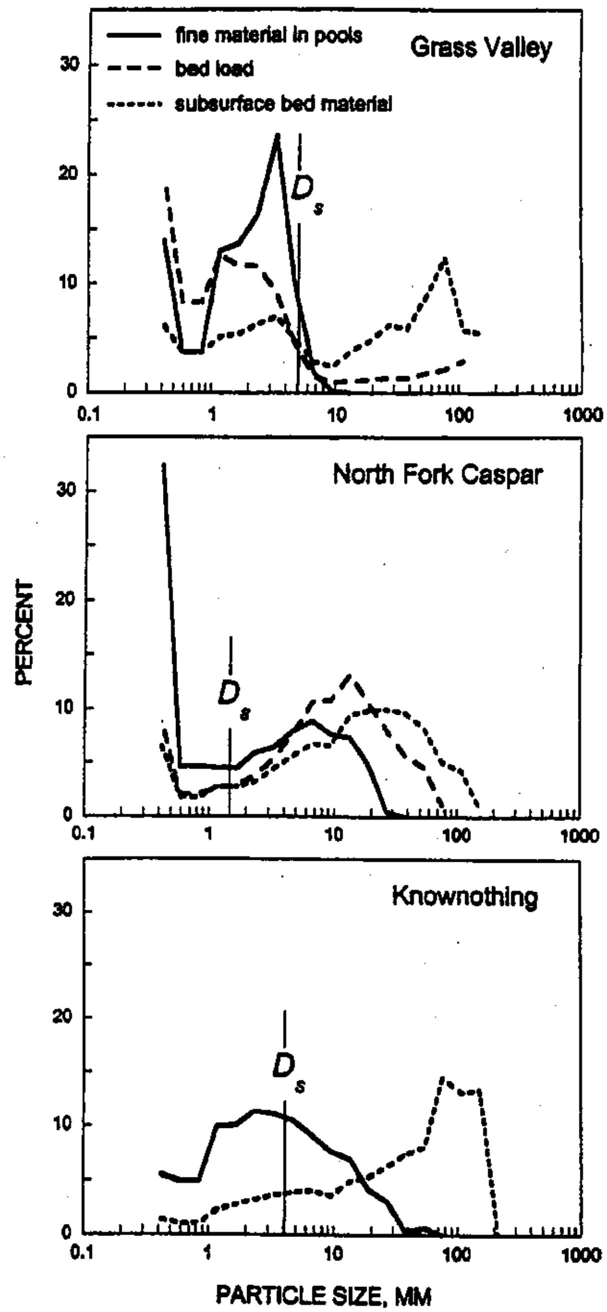

Figure 4. Representative particle size frequency curves for bed load deposits and fine bed material in pools from various parent materials (Knownothing, high-grade metamorphics and granitics; General and Grass Valley, granitics; Jacoby and North Fork Caspar, sandstone and shale; Redwood, schist, sandstone, and shale). D_S is the estimated threshold of intermittent suspension. The finest size range is for particles <0.5 mm. Values of V^* are shown below each channel name. Particle size distributions for some of the other channels are shown by *Lisle and Hilton* [1992]; truncated bed load size distributions for Jacoby and Redwood Creeks are shown by *Lisle* [1995]).

which can be expected to be coarser than bed load in upland channels [*Lisle*, 1995].

To examine whether fine bed material in pools represents matrix material winnowed from the gravel bed, we compared their respective size distributions. We assumed that mobile armors could be produced by winnowing away matrix material from exposed subsurface bed material. This leads to an analytical separation of subsurface distributions into surface and matrix distributions: Winnowing of a unit volume of subsurface material would create a smaller volume of surface material by selectively removing some of the finer fractions, resulting in a subsurface distribution that completely overlaps a reduced surface distribution (Figure 5a). To produce this overlap, we matched the coarse limbs of the surface and subsurface distributions by making the proportion of the modal value of the surface distribution $[(f_M)_{sur}]$ equal to that of the same particle size of the subsurface $(f_{Msur})_{sub}$; we then reduced the rest of the surface distribution proportionately:

$$(f_i)'_{sur} = \frac{(f_i)_{sur}(f_{Msur})_{sub}}{(f_M)_{sur}}$$

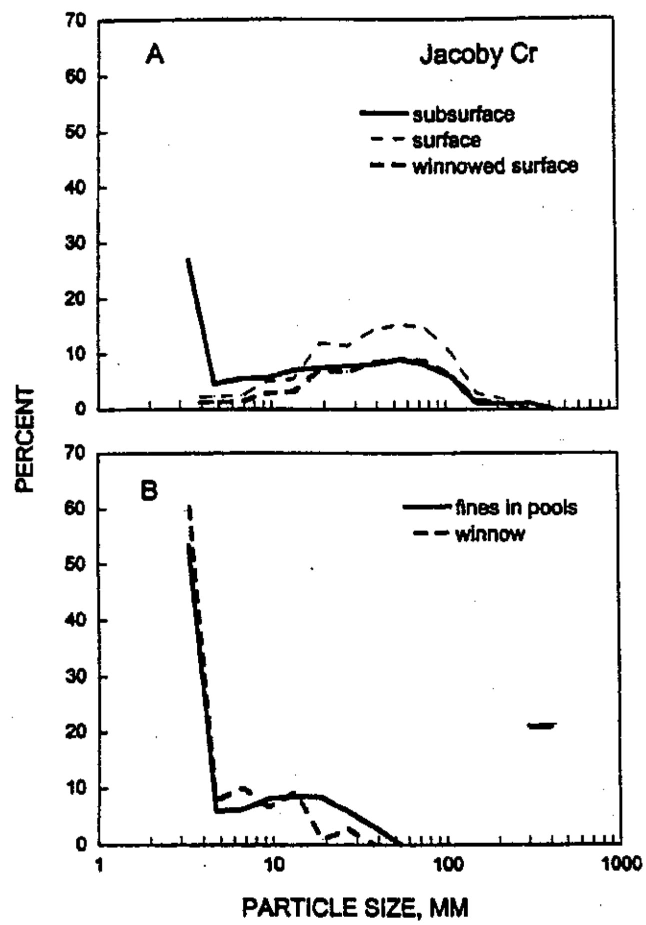

Figure 5. Particle size distributions of fine bed material from pools and matrix material estimated from surface and subsurface size distributions for Jacoby Creek, illustrating a "good fit." The finest size range is for particles <4 mm. (a) Subsurface, surface, and winnowed surface. The matrix is calculated by subtracting the winnowed surface from the subsurface. (b) Fine bed material in pools and estimated matrix.

Table 3. Comparisons of Particle Size Distributions of Fine Sediment in Pools and Matrix Material Calculated From Surface and Subsurface Distributions

	$(f_{<4})_P - (f_{<4})_{mx}$	$(\phi_{50})_P - (\phi_{50})_{mx}$	$(\phi_{90})_P - (\phi_{90})_{mx}$	$\Sigma\ (f_i)'_{mx}$
Bald Mountain[a]	−0.07	0.3	−0.7	0.78
Blackwood	−0.30	—	1.4	0.28
Bridge	0.47	—	−2.8	0.64
Elder	0.12	—	−2.9	0.72
General	0.24	—	−0.9	0.65
Grouse[b]	0.23	—	−1.4	0.27
Jacoby[a,b]	−0.09	—	0.8	0.41
Knownothing	0.31	—	−2.3	0.50
Nordheimer[a]	0.10	−0.7	−0.6	0.36
North Fork Caspar[a,b]	−0.18	—	0.5	0.28
Plummer[a]	−0.01	−0.1	−0.7	0.39
Purple Mountain[a]	0.09	−0.3	−0.8	0.58
Red Cedar[a]	−0.06	0.1	0.1	0.45
Redwood[a,b]	0.14	—	−0.4	0.28
Sagehen[a]	−0.07	0.5	0.3	0.44
South Fork Caspar[a]	−0.02	0.1	−0.1	0.70

Here $(f_{<4})_P - (f_{<4})_{mx}$ is the difference in fractions of particles <4 mm in diameter between pool sediments and calculated matrix material, $(\phi_{50})_P - (\phi_{50})_{mx}$ is the difference in D_{50} (phi units), and $(\phi_{90})_P - (\phi_{90})_{mx}$ is the difference in D_{90} (phi units).

[a]"Good" fit.

[b]Intensive stratified-random sampling of bed material.

where the prime signifies that the summation, $\Sigma\ (f_i)'$, over all sizes is less than 1. The size distribution of the winnowing product (matrix material) for sizes smaller than the modal surface size was found from the difference,

$$(f_i)'_{mx} = (f_i)_{sub} - (f_i)'_{sur}$$

The summation, $\Sigma\ (f_i)'_{mx}$, over all size fractions is the estimated proportion of matrix material in subsurface material. Most values of $\Sigma\ (f_i)'_{mx}$ exceeded an upper limit of storage capacity that would be provided by the porosity (approximately 0.4) of an ideal gravel framework in grain-to-grain contact (Table 3). The high values of $\Sigma\ (f_i)'_{mx}$ thus suggest a more open framework or an overestimation of the minimum particle sizes included in the framework. However, had we chosen to sample average subsurface material instead of the finer bed load deposits, subsurface material would have appeared to contain less matrix material.

A "good fit" between size distributions of fine bed material sampled in pools and those computed as matrix material is defined by criteria that include the fine, central, and coarse parts of the distributions: (1) a difference between fractions of material finer than 4 mm (the lower size limit of pebble counts) that is less than 0.2; (2) a difference in D_{50} that is less than 1 ϕ; and (3) a difference in D_{90} that is less than 1 ϕ. In some cases, the coarsest fractions of the surface distribution were not represented in the subsurface distribution; thus the coarse limb of the subsurface distribution did not fully overlap that of the reduced surface distribution. Another limitation of this comparison is that particles no smaller than 4 mm can be sampled in pebble counts, and 4 mm was commonly coarser than much of the matrix material. As a result, the fit according to criterion 2 could not be evaluated for most cases.

Eleven of sixteen channels showed a good fit, according to our criteria, between particle size distributions of fine bed material sampled in pools and those computed for matrix material (Figure 5b; Table 3). Of the intensively sampled channels (Grouse, Jacoby, North Fork Caspar, and Redwood Creeks) all but Grouse Creek showed a good fit. In light of uncertainties due to sampling and estimating matrix sizes, we conclude that this comparison indicates a likely correspondence and exchange of particles between fine bed material in pools and matrix material.

5. Transport and Storage of Fine Bed Material

5.1. Suspension Threshold

Bed material load is commonly transported in either traction or intermittent suspension, depending on particle size and stream power. Determining modes of transport of fine sediment is important to evaluating its mobility, because suspension or saltation tend to cause high transport velocities and low residence times in the channel.

We evaluated the suspendibility of fine bed material in pools by estimating the proportion carried in suspension at bank-full stage. We estimated the particle size at the threshold of intermittent suspension according to the suspension criterion, $w_s = u^*_g$ (where w_s is particle settling velocity, $u^*_g = (\tau_b/\rho)^{1/2}$, τ_b is mean bank-full boundary shear stress, and ρ is fluid density) [*Middleton*, 1976]. We assumed that $\tau_b = \rho g \bar{d} S$ (where g is gravitational acceleration, $\bar{d}$ is mean bank-full depth, and S is channel gradient) approximates the boundary shear stress exerted on bed particles. This assumption should be reasonably accurate, since τ_b was computed from parameters measured in straight, uniform channels lacking large form roughness. In many of these channels, however, form drag around boulders and large cobbles created a tendency to overestimate stress on bed particles over much of the bed and thus to overestimate the average maximum size of suspendible particles. On the other hand, locally high turbulence and boundary shear stress can be expected to suspend coarser particles than would be predicted from mean hydraulic variables. However, the estimation of a suspension threshold is less sensitive to errors in measuring shear stress than is an estimation of transport rates of particle size classes, because the former increases with increasing shear stress to the power of 0.5, while the latter increases to a power of approximately 1.5.

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We estimated D_S, the threshold diameter of suspension, by applying values of w_s to Figure 8 of *Dietrich* [1982]. Settling velocity depends partly on particle shape, which is quantified in Dietrich's analysis by the Corey shape factor, CSF = $c(ab)^{-1/2}$, where a, b, and c are the long, intermediate, and short axes, respectively, of the particle. We gave CSF a value of 0.7.

The results indicate that important fractions of fine bed material in pools were transported in at least intermittent suspension during events of bank-full or greater magnitude. From 23 to 92% of fine bed material in pools was finer than D_S, which ranged from 1 to 11 mm, and D_{50} was most commonly less than D_S (Table 2). Although sizes nearly equal to D_S could be intermittently suspended at bank-full flow, much is likely to drop out of suspension and be selectively transported in traction at lesser stages, particularly in traveling from riffles to pools. Particles not far above the suspension threshold can be expected to be transported in saltation. In either case, transport velocities can be expected to be substantially higher than those of coarser fractions.

5.2. Residence Time of Fine Bed Material in Pools

If most fine bed material in pools were scoured and filled annually, then its residence time would be short, and its volume would register annual variations in sediment supply. Measurements of scour in one of the study reaches and in previous studies indicate this to be the case. We planted 24 scour chains [*Leopold et al.*, 1964] in two pools of Three Creeks Creek in January 1993 and recovered them the following summer after a period in which peak discharges were no greater than approximately one-half bank full. The scour chains recorded deep scour, commonly below the gravel substrate. Fourteen chains showed scour at or below the base of fine sediment. The average depth of scour was 1.4 times the original thickness of fine sediment, or, counting only scour to the base of the fine sediment, 0.75 times fine-sediment thickness. Similarly, *Andrews* [1979] and *Lisle* [1979] measured scour of sandy bed material down to a gravel substrate in pools during sub-bank-full discharges in the East Fork River, Wyoming. Pools scoured and filled as waves of sandy bed load migrated downstream during the annual nival flood [*Meade*, 1985]. *Lisle et al.* [1997] used bed surface particle sizes measured at low flow and local boundary shear stresses calculated with a quasi three-dimensional flow model to estimate the spatial distribution of dimensionless boundary shear stress at bank full stage,

$$\tau^* = \frac{\tau_b}{g(\rho_s - \rho)(D_{50})_{sur}}$$

(where ρ_s is sediment density) in Redwood, Grouse, and Jacoby Creeks. Local values of τ^* over fine patches in pools greatly exceeded entrainment thresholds, while values averaged over each reach barely exceeded conventional thresholds, suggesting that fine bed material was stripped from pools during high flow.

Using the reservoir approach of *Dietrich et al.* [1982], we roughly estimated a replacement frequency of the volume of fine bed material stored in pools in a reach by dividing median volume by the approximate annual transport rate of fine bed material. We estimated annual transport rate by summing the products of the annual yield of bed material and the proportion of each fraction <32 mm in the subsurface samples. We assume that all fine bed material is transported through each pool and exchanges uniformly with the sediment stored there. For 19 channels the median replacement frequency in each reach was at least 5 year^{-1} and as much as 30 year^{-1}. These values indicate that fine bed material passes quickly through pools, and thus volumes stored can be sensitive to annual changes in sediment supply unless passage is so quick that annual inputs are essentially flushed. Annual measurements of V^* (presented later) indicate that fine bed material in pools commonly responds to annual variations in sediment supply.

5.3. Significance of Fine Bed Material in Pools to Sediment Transport and Storage

The significance of fine bed material in pools to channel-wide sediment transport and storage depends on its volume and mobility relative to that of bed material in the remainder of the channel. *Lisle* [1995] uses particle size distributions and active bed volumes of fine bed material in pools and subsurface material from Redwood, Jacoby, and North Fork Caspar Creeks to demonstrate that finer patches of bed material can contribute disproportionately to bed load through higher transport velocities. *Lisle* [1995] estimates that as much as one half of bed material load is contributed from fine bed material in pools from North Fork Caspar Creek, but in Redwood Creek this contribution is overwhelmed by the contribution from subsurface material that undergoes deep annual scour and fill. The actual contribution of fine bed material in pools to bed load in the other channels is difficult to evaluate in this manner, however, because data on annual depths of scour are unavailable. Furthermore, estimates in all cases are highly uncertain because the mobility of numerous other patches of bed material in areas other than pools can also be expected to be highly variable.

Grass Valley Creek represents a case where fine bed material clearly dominates bed material load in an otherwise coarsely armored channel. Widespread erosion associated with extensive logging and road construction on deeply weathered granite produced one of the highest rates of sediment yield [*Frederikson, Kamine, and Associates*, 1980] and the highest values of V^* (0.50) of basins used in this study. The channel is moderately steep (S = 0.017) and mostly armored with coarse gravel, cobbles, and boulders. Samples of subsurface material from bars were much coarser than samples of bed load deposits taken from behind a sediment retention dam near the mouth (Figure 4). Both bed load and fine bed material in pools were dominated by sand and fine gravel and roughly conformed to the fine mode of the subsurface samples. Voluminous sandy material from recent erosion apparently overpassed a relatively stable armor.

The volume of fine bed material stored in pools can be scaled to channel size by dividing the total volume of fine bed material in pools in a reach by bank-full width and reach length. The resulting value y_{fp} is the average thickness of fine bed material in pools as if it were spread over the entire channel. Values of y_{fp} averaged 0.7 cm and never exceeded 2 cm (n = 17), which would be insufficient to cover prominent particles on the bed surface, assuming a uniform distribution of fines. If such a layer of fine bed material were present on the bed surface (whether it originated from pools or from the subsurface of a mobilized bed), its thickness would be limited by the increased vulnerability of fine particles to shear stress as they filled spaces around prominent particles. Therefore a balance between supply and transport of fine material on the bed surface is likely to be achieved before prominent particles are buried. Low values of y_{fp} are consistent with a limitation in the thickness of fine material that can be available for transport on the bed surface during high flow, and subsequently winnowed and deposited in pools during waning flows.

What proportion of fine material in the active bed (including the depth that is annually mobilized) is stored in pools? Surficial patches of fine bed material are found elsewhere on the channel, but they comprise, for example, only about one-quarter of the total volume of fine surface material in Jacoby and Grouse Creeks [*Lisle and Hilton*, 1992]. Another large reservoir of fine bed material is the matrix of the active bed in areas other than pools. We estimated the average thickness of fine material stored in gravel interstices of the active bed, y_{fb}, by multiplying the proportion of matrix material in subsurface bed material, $\Sigma\ (f_i)'_{mx}$, by a characteristic annual scour depth, which was assigned a value of $2(D_{90})_{sur}$. (Scour depths for North Fork Caspar, Jacoby, and Redwood Creeks were measured directly with scour chains and frequent surveys [*Lisle*, 1989, 1995; *Madej*, 1996]). The proportion of the total fines in the active bed that is stored in pools is $y^*_{fp} = y_{fp}(y_{fp} + y_{fb})^{-1}$. Although large errors in our estimate of the thickness of the active bed could affect values of y^*_{fp}, pools apparently stored a small proportion of fine bed material in the active channel. Values of y^*_{fp} averaged 0.05 and were no greater than 0.2 in 16 channels that had data available.

In summary, the volume of fine bed material stored in pools was apparently limited by the volume that can accumulate on the bed surface, and as a result, a small proportion of the total volume of fines in the active channel was stored in pools. Nevertheless, the exposure of fine material on the bed surface (mostly in pools) to high tractive forces during high flow results in higher transport velocities and promotes contributions to the bed material load that are disproportionate to the volume stored [*Lisle*, 1995].

6. Influences on the Relative Volume of Fine Bed Material in Pools (V^*)

6.1. Parent Material and Sediment Supply

A comparison of two nearby channels with contrasting parent materials and disturbance-related sediment supplies illustrates the influence that parent material can have on the abundance of fine bed material in channels. Blackwood and General Creeks both drain portions of the west side of the basin of Lake Tahoe, California, and were selected by the U.S. Geological Survey to measure erosion and sediment yield [*Hill et al.*, 1990; *Nolan and Hill*, 1991]. Blackwood Creek basin has undergone a variety of disturbances, including logging, road building, mining, grazing, and wildfire. Its average annual sediment yield (1975–1985) is 100 t km^{-2} yr^{-1}. General Creek basin, in contrast, is contained in a state park and disturbed little by land use; its annual sediment yield for the same period is 49 t km^{-2} yr^{-1}. On the basis of sediment yields alone, one would expect V^* to be higher in Blackwood Creek than in General Creek, but the opposite was true: V^* values were 0.080 and 0.14, respectively. A likely explanation is a difference in particle size of erosional products. Blackwood Creek basin is mostly underlain by extrusive and pyroclastic volcanics, metamorphic rocks, and surficial deposits derived from these lithologies. Because of the texture of these rocks, they produce predominantly suspended sediment and gravel, and relatively little sand. General Creek is underlain by granitic rocks, which produce abundant sand and fine gravel when weathering breaks the bonds between coarse crystals. We propose that a sediment input into General Creek would include so much fine sediment that newly available storage capacity in the gravel framework would be quickly filled and a large excess would be stored in pools, whereas in Blackwood Creek, more introduced fine sediment would be stored in interstices of the gravel framework.

Three types of parent material contributed large proportions of sand and fine gravel to some of our study basins: (1) weathered granitics; (2) highly fractured and friable sandstones and shales of the Franciscan Formation, which break down along dense fractures and surfaces of primary sand grains; and (3) schist, which breaks along dense foliations. The abundance of fine sediment produced by these lithologies was expressed by a prominent fine mode in bimodal bed load particle size distributions (Figure 4) and by values of V^* mostly greater than 0.1 (Table 1).

In contrast, weathering of ophiolites of the Klamath Mountains (high-grade metamorphic rocks, diorite, gabbros, and ultramafics), volcanic rocks (basalts and andesites) and well-indurated sandstone apparently produce smaller proportions of sand and fine gravel. Values of V^* for these lithologies were mostly less than 0.1 (Table 1). Metasediments apparently produced moderate concentrations of fine bed material, as fine sediments were represented only by the tail in the unimodal bed load distributions (e.g., in Knownothing Creek; see Figure 4).

Correlations of V^* with sediment yield depended strongly on parent material. With all parent materials considered together, V^* correlated significantly but weakly with total average annual sediment yield (Figure 6a; Table 4). The correlation was better taking fines-rich lithologies alone, while V^* in channels draining fines-poor lithologies was consistently low over a range of low to moderate sediment yields.

Fines-rich lithologies also created a smaller particle size of fine bed material in pools ($(D_{50})_{fp}$ = 2.0 mm; σ = 1.0 mm) than fines-poor lithologies ($(D_{50})_{fp}$ = 5.4 mm; σ = 2.3 mm). Fine bed material in pools produced from weathered granitics were typically coarse sand regardless of sediment yield, but in other parent materials, $(D_{50})_{fp}$ tended to be smaller in basins with higher sediment yields (Figure 6b). Two explanations are possible: (1) Erosive parent materials in this study area produce finer (and greater) fractions of sand and fine gravel than less erosive parent materials. (2) Under low supplies, the finer fractions of fine bed material are selectively transported and depleted. Consistent values of $(D_{50})_{fp}$ in granitic basins indicate that lithologic controls cannot be ruled out.

6.2. Pool Type

An hypothesis that V^* varied between step pools (those commonly formed in steep reaches by plunging over boulders and coarse woody debris) and bar pools (those formed in gentler reaches as part of a bar pool sequence) was not supported by our data. Many of the study reaches contained both types of pool. To test for this difference, we normalized the data using the arc sine transformation [*Zar*, 1974] and then computed the normal deviate of V^* for each pool in each reach,

$$Z = \frac{V^*_i - \overline{V^*}}{s}$$

where V^*_i is the value for each pool, $\overline{V^*}$ is the reach average (unweighted), and s is the sample standard deviation of V^*_i.

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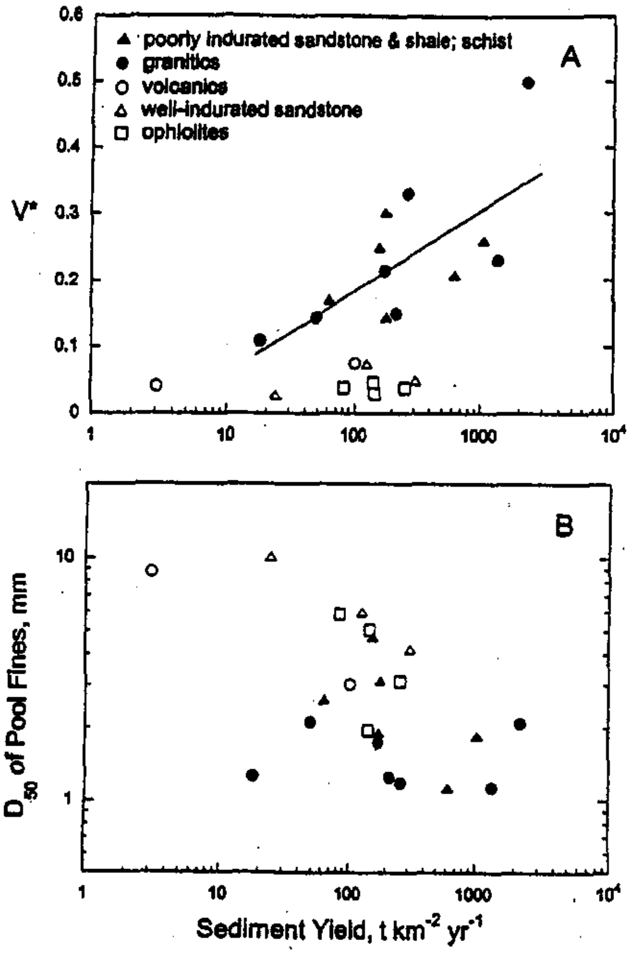

Figure 6. (a) V^* and (b) median particle size (D_{50}) of fine bed material in pools versus mean annual sediment yield per drainage area. Solid symbols represent parent materials that typically produce abundant sand and fine gravel as weathering products; open symbols represent those that produce little such material.

The data set included 185 bar pools and 67 step pools in 20 channels. A comparison of frequency distributions of Z showed no significant difference in mean values of Z between the two kinds of pool (Student's t test, assuming unequal variances; $P(Z_{\text{bar}} \neq Z_{\text{step}}) = 0.47$; not significant at $\alpha = 0.05$).

6.3. Coarse Woody Debris

Another hypothesis that coarse woody debris (CWD) in pools tends to increase V^* was supported. This hypothesis originated from observations of finer bed surface textures associated with CWD in gravel bed channels [*Buffington*, 1995]. To test an effect on V^*, we assigned pools to three categories based on abundance of CWD lying within the residual margins and high water stages: (1) none; (2) CWD (>10 cm in diameter) covering <10% of pool area; (3) CWD covering >10% of pool area. Mean values of Z for categories 1 and 2 equaled −0.06 and together were significantly different than the mean value (0.25) for category 3 (Student's t test; $n_{1-2} = 250$; $n_3 = 64$; $P(Z_{1-2} \neq Z_3) = 0.022$; significant at $\alpha = 0.05$). This indicates that V^* in pools in category 3 had a V^* value $0.31s$ higher than those in categories 1 or 2. Although these differences are significant for our sample of pools, increases in V^* due to CWD would probably go undetected in an individual reach. For example, in a channel with $\overline{V^*} = 0.20$, abundant CWD added to a pool can be expected to increase V_i^* to 0.24, on average, given a characteristic variability ($s = 0.12$) in such a reach. However, an increase of this magnitude would just equal the standard error of the mean (0.04) from a sample of 10 pools, which is a common sample size.

6.4. Spatial and Temporal Variations of V^*

Examining variations in V^* in a single channel can reveal relations to sediment supply while avoiding the confounding effects of parent material in comparing different channels. Spatial variations indicate a potential use of V^* to detect, evaluate, and monitor the movement of a large sediment input along a channel. *Lisle and Hilton* [1992] document a local increase in V^* from <0.1 to >0.5 downstream of an illegal mining operation in Bear Creek. In another case, a severe fire in the Pilot Creek basin in 1987 resulted in inputs of schist regolith from three small tributaries that enter the main channel within a 1-km reach. In 1994 the input of sand and fine to medium gravel was obvious both from its abundance and lithology. V^* increased from 0.16 (standard error SE = 0.03) in the reach just upstream of the tributaries to 0.40 (SE = 0.07) in the reach downstream. After the 1997 flood, differences were less: V^* in the upstream reach remained approximately constant at 0.14 (SE = 0.03), while V^* in the downstream reach decreased to 0.20 (SE = 0.02).

We monitored annual variations in five channels over a four- or five-year period (Figure 7). Measurements of V^* recorded changes not only in the volume of pool fines, but also in residual pool volume with fines removed ("scoured-pool volume"; see Figure 2). Each case is described below:

6.4.1. French Creek. This basin is predominantly underlain by deeply weathered granitic soils that produce sandy sediments. Large chronic inputs were reduced by an erosion control program from 1991 to 1994, which mainly targeted roads (J. Power, report filed with Klamath National Forest, Fort Jones, California, 1995). During this period, fines volume decreased by more than one half as scoured-pool volume remained essentially unchanged. Values of V^* decreased to approximately one-third the initial value. However, a large rain-generated flood in January 1997 (recurrence interval = 14.5 years in trunk stream) caused fines volume and V^* to nearly double.

6.4.2. North and South Forks of Caspar Creek. The upper basin of Caspar Creek has been administered as an experimental watershed since 1963 [*Ziemer*, 1981, 1990], and detailed records of flow and sediment production are available to evaluate effects of logging and road building [*Ziemer*, 1996]. Suspended sediment discharge during storm flows is monitored at gaging stations, and bed load is collected in debris

Table 4. Regression Equations and Statistics

Equation	n	r^2	P
$V^* = 0.117 \log G_B - 0.098$	22[a]	0.37	0.003
$V^* = 0.121 \log G_B - 0.054$	13[b]	0.47	0.009
$(F_f)_{sur} = f(V^*)$	23	0.06	0.27
$(F_f)_{sur} = f(\log G_B)$	17	0.08	0.26
$(F_f)_{sur} = -0.229 \log \tau_b + 0.74$	17	0.46	0.003

[a]Including all parent materials.
[b]Including parent materials producing abundant fines.

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basins that are surveyed annually. The basin is predominantly forested with redwood that was first logged in the late nineteenth century and early twentieth century. The South Fork basin (5.4 km^2) was selectively logged in 1971–1973; 48% of the North Fork basin (5.0 km^2) was clear-cut in 1989–1991.

The recent logging in the North Fork increased the magnitude of small to moderate peak flows, increased suspended sediment yield by 89%, but did not affect bed load yield [*Lewis*, 1998]. An increase in V^* in the North Fork from 1991 to 1993 may have signaled the increase in fine sediment supply. However, both North and South Forks show a decrease in V^* after 1994, perhaps in response to flushing by large peak flows in 1993, 1995, and 1997. The recurrence intervals of these flows were larger in the North Fork than the South Fork, which may have caused an unmatched increase in scoured-pool volume in the North Fork.

6.4.3. Little Lost Man and Three Creeks. These channels have similar flow regimes, drain erodible terrane with similar lithologies, and have had moderate to high values of V^* (0.10–0.33). Both have been relatively undisturbed in recent decades: Little Lost Man Creek drains an old growth redwood forest, and Three Creeks was most recently logged in the 1960s. They provide case histories of the effects of moderately high floods on V^* under stable sediment transport regimes. Peak flows measured in Little Lost Man Creek can be expected to approximate in magnitude those in Three Creeks, which is ungaged. Recurrence intervals of annual peak flows in Little Lost Man Creek were <2 years in water years of 1992–1994 but were 2.4, 4.8, and 6.3 years (n = 18) in 1995, 1996, and 1997 (R. Klein, personal communication, Redwood National Park, Arcata, California). During the latter period, V^* decreased to its lowest value in both channels. Apparently, high runoff during these storm flows favored flushing of fine bed material over inputs of new material. Volumes of fine bed material in pools decreased as scoured-pool volume remained roughly constant.

In summary, V^* in five channels changed progressively over a period of years, suggesting gradual shifts in the balance between sediment input and transport. Changes in sediment input and transport were not well documented, but changes in V^* were consistent with available evaluations of watershed condition and peak flow events. A decrease in V^* in most of the channels during the latter half of the period was associated with a series of moderately high peak flows that apparently caused a net flushing of fines. Such variations could have been caused by annual variations in the relative frequency of flows that selectively transport fine material, particularly during the recessional flows leading up to the annual low-flow season when V^* was measured.

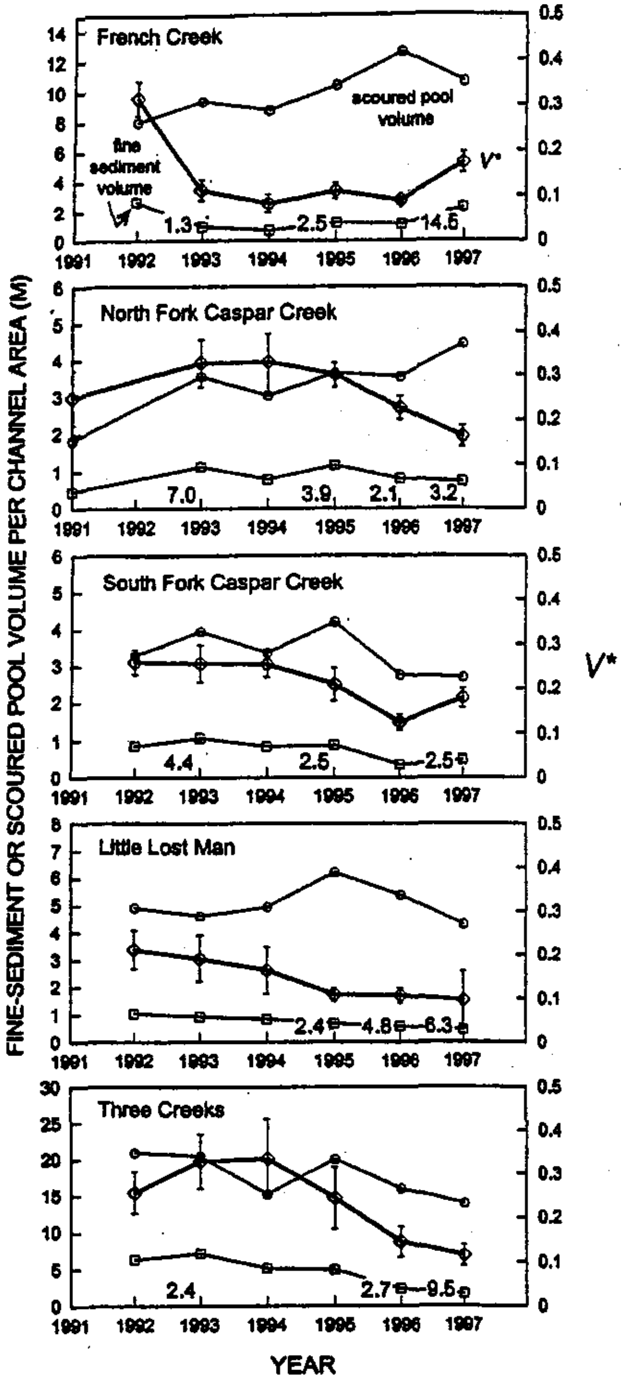

Figure 7. Annual variations in mean scoured-pool volume, fine-sediment volume, and V^* in five channels. Values above x axis are recurrence intervals of peak flows (partial duration series, excluding those <2 years) in study stream or nearby gaging station (French Creek: Scott River at Fort Jones (DA = 1800 km^2); Three Creeks: Redwood Creek near Blue Lake (DA = 188 km^2).

7. Discussion and Conclusions

Unsteady and nonuniform hydraulic forces acting on heterogeneous particle sizes in gravel bed rivers result in size-selective transport and deposition. As a result, fine bed material can be stored not only in the matrix of the gravel bed, where its mobility is limited by the hiding effects of larger particles, but also in surficial patches, where it is highly mobile. As the fine component becomes increasingly abundant in the bed material load, hiding places in the gravel framework become filled, and excess fine material becomes available for transport on the bed surface. Characteristics of the transport and storage of excess fine sediment indicate that it is a highly mobile component of bed material load and that its abundance is supply-dependent:

1. Particle size distributions of fine sediment vary between parent materials, but in most channels, much of the fine sediment is finer than a suspension threshold computed from

mean hydraulic variables at bank-full stage. This indicates that when exposed to hydraulic forces on the bed surface, fine sediment can be readily winnowed from energetic areas of the bed surface and transported at high velocities in intermittent suspension and saltation.

2. Fine sediment in pools is typically replaced many times per year.

3. V^* correlates with measured annual sediment yield in 20 channels whose parent material produces abundant sandy sediment.

4. Temporal and spatial changes in V^* appear to correspond to qualitative variations in the balance between sediment inputs and water discharge.

Similarities in particle size distribution between fine bed material in pools, the fine mode of bimodal distributions of bed material, and fine material winnowed from gravel armors (as estimated by subtracting surface distributions from subsurface distributions) suggest that the source of fine bed material in pools is the winnowing of matrix material from armors during waning stages of sediment transport events. Thus a size distribution representing both selectively transported excess fines and matrix material can be found directly by sampling fine bed material in pools.

Pools are the largest storage reservoirs of excess fine sediment but the volumes stored are apparently limited by the high mobility of fine sediment on the bed surface. As hiding places on a gravel armor are filled with fine material, greater exposure of the fines to tractive forces tends to increase its transport rate and promote more rapid flushing downstream. Thus if the volume of fine bed material that we measured in pools were spread evenly over the bed, gravel particles would still be prominent in the flow and offer some degree of hiding for fine material on the bed surface, even in the extreme case of Grass Valley Creek, which had the highest value of V^* in our study and whose bed material load was dominated by fine material. Similar conditions are described by *Leopold* [1992] for channels in the Rocky Mountains. Furthermore, much less fine material is stored in pools than is annually scoured from subsurface material. This suggests that as more excess fine bed material accumulates on the bed surface, it is transported at rates increasingly greater than those of other bed material and contributes more disproportionately to the bed material load. Thus the relative volume of fine bed material in pools (V^*) can be a sensitive measure of the relative load of fine bed material. At the crudest scale, the presence of significant fine bed material in pools should indicate significant selective transport of fine bed material.

We estimated a mean frequency of replacement of fine material in pools that ranged from 5 to 30 years^{-1}. This suggests a potential for excess fines to be rapidly flushed from gravel bed channels. However, we observed relatively conservative annual variations of V^* in some cases, and larger variations in other cases where there were annual changes in supply from the watershed. Taken together, these results indicate that V^* is sensitive to variations in supply, but that sediment routing causes variations over a characteristic time scale of about 1 year.

However, V^* may not register variations in sediment supply consistently, because particle size distributions of sediment inputs can affect the amount of excess fine sediment that remains on the bed surface. Low V^* can indicate either small inputs of fines-rich sediment or large inputs with enough coarse sediment to hide the fine fraction in the matrix. The latter case typifies channels in basins whose parent materials produce scant sandy sediment.

V^* may also be limited in channels with relatively well sorted bed material, which is usually associated with a low upper limit of particle size and a reduced capacity for hiding smaller particles. Poor sorting promotes selective transport [*Wilcock*, 1992; *Lisle*, 1995] and formation of bed surface patchiness [*Paola and Seal*, 1995] and would thereby create the conditions to segregate fine bed material and collect it in pools. Our channels had poorly sorted bed material, so we were not able to investigate effects of sorting on V^*. However, our study reach in Redwood Creek has a large channel with relatively well sorted bed material, a fine bed surface (D_{50} = 28 mm), and a moderately high value of V^* (0.24). In another reach downstream with an even finer surface (D_{50} = 15 mm), V^* was unmeasurable because fine bed material in pools could not be distinguished clearly and probed. This suggests that downstream fining of bed material broke down the sorting processes by which fine bed material accumulates as large surficial patches.

Excess fine bed material may also be limited by the relative frequency of flows that selectively transport bed material. For a given supply of fine material, less would be expected to remain on the bed if events that selectively transport bed material increased in frequency in relation to larger events that could entrain the armor layer or contribute fine sediment from the watershed. A likely contrast would be between snowmelt-dominated hydrologic regimes (with relatively low variation in runoff) and rainfall-dominated regimes (with high variation) [*Pitlick*, 1994]. Most of the channels in this study had rainfall-dominated regimes. Only three channels, (Blackwood, General, and Sagehen Creeks) had important spring snowmelt hydrographs; the highest value of V^* among these was 0.14, which is moderate. The effect of flow frequency on bed material size distributions deserves further research.

In cases where V^* is insensitive to variations in sediment supply, responses may be more likely to be found in the mobility of the bed surface [*Dietrich et al.*, 1989; *Lisle et al.*, 1993] or pool frequency and volume [*Lisle*, 1982; *Madej and Ozaki*, 1996; *Wood-Smith and Buffington*, 1996].

As a tool for waterway managers, V^* can serve as a sensitive measure of the relative supply of excess fine sediment in gravel-bed channels. Given a poorly sorted, gravel bed channel with excess fine material, V^* appears to be affected mainly by sediment supply. V^* is essentially independent of pool volume, hydraulic conditions at the reach scale [*Lisle and Hilton*, 1992], pool type (step pools and bar pools), and volumes of coarse woody debris at least within a modest range. Most user bias can be eliminated from measurements, and with an adequate sample size (commonly ~10 pools), important changes in fine sediment in a reach of channel can be detected with conventional levels of statistical significance [*Hilton and Lisle*, 1993].

For reconnaissance, one can use visual estimates of V^* to evaluate the relative abundance of excess fine bed material. Our experience is that in a channel with $V^* \leq 0.1$, fine bed material in pools is characteristically confined to small and discontinuous deposits in eddies; outside of pools, a fine mode may not be evident among surface interstices. In such cases, fine sediment supply would probably not be a critical issue; nor would V^* be an appropriate monitoring parameter unless large inputs of fine material were anticipated. A channel with $V^* \geq 0.2$ characteristically has large patches of fines occupying much of the area of pools; fine patches are evident else-

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where in the channel, and surface interstices may be noticeably filled. However, ecologically important supplies of fine sediment may not be clearly evident on riffle armors, which can be effectively winnowed even in sediment-rich channels [*Lisle and Madej*, 1992].

Particular ranges of V^* cannot provide universal standards of channel condition, however, because V^* depends not only on rates of sediment input, but also on the fraction of fine sediment from sediment sources, which varies with parent material. One cannot use V^* to adequately interpret channel condition with respect to sediment supply without referring to time trends in sediment inputs and/or the range of values of V^* associated with the particular type of parent material. For this reason, there is more certainty in interpreting temporal or streamwise variations of V^* in a single channel than in interpreting variations between channels. Therefore V^* may be most useful as a monitoring parameter. In any application, the interpretation of a parameter of channel condition is much improved with knowledge of past and present conditions and characters of the watershed.

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