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Particle size variations between bed load and bed material in natural gravel bed channels

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Abstract. Particle sizes of bed load and bed material that represent materials transported and stored over a period of years are used to investigate selective transport in 13 previously sampled, natural gravel bed channels. The ratio (D^*) of median particle size of bed material to the transport- and frequency-weighted mean of median bed load size decreases to unity with increasing drainage area, bank-full discharge, dimensionless stream power, and bed material sorting. In channels with high values of D^*, significant volumes of fine bed load are transported during discharges that are less than bank-full, which is commonly associated with general entrainment of the coarse pavement in many gravel bed channels. This indicates transport of fine bed load over a more stable substrate of coarser bed material. The apparent breakdown in equal mobility of the bed as a whole may be caused by areal segregation of poorly sorted bed material into superiorly sorted patches of varying mean size. Likely sources of selectively transported fine bed load include fine patches that have low entrainment thresholds and high virtual particle velocities. A simple sediment budget applied to measurements from three channels indicates that velocities of material from fine patches in pools relative to velocities of average bed material are high in low-order channels and decrease distally as more bed material that represents the bed as a whole is accessed for bed load by deeper annual scour.

Introduction

As a primary source of bed load transported in a natural gravel bed channel over a period of years, bed material is often assumed to have the same particle size distribution as bed load, discounting exceptionally coarse, immobile debris received directly from hillslopes. This equivalency is met by the equal mobility hypothesis [*Parker and Klingeman*, 1982; *Andrews*, 1983], which posits that the pavement of gravel bed channels is adjusted to provide transport of particles in proportion to their abundance by size in subsurface bed material. Equal mobility is an accurate approximation in some channels [*Parker and Klingeman*, 1982; *Andrews*, 1983; *Andrews and Erman*, 1986; *Kuhnle*, 1992], but in others, significant selective transport of finer sizes is apparent [*Komar*, 1987; *Ashworth and Ferguson*, 1989]. This motivates the question, How prevalent is equal mobility and in what types of channel is it violated?

Resolution of this question goes beyond the issue of equal mobility, because selective transport provides the potential for downstream fining of bed material. Thus the question of where bed load and bed material share the same size distribution bears on the relative influences of selective transport and particle attrition (abrasion and breakage) on the frequently observed downstream fining of streambed materials [*Krumbein*, 1941; *Bradley et al.*, 1972; *Adams*, 1979; *Shaw and Kellerhals*, 1982; *Ferguson and Ashworth*, 1991; *Parker*, 1991; *Kodama*, 1992; *Werrity*, 1992].

In this paper, I investigate differences in particle size distributions between bed load and subsurface bed material in 13 gravel bed streams from around the world. *Leopold* [1992] reported that sand is the dominant bed load size fraction in 12 natural gravel bed channels in the Rocky Mountains. Gravel, which composes the bars and riffles that form the primary features of these channels, is transported in small quantities mainly during bank-full discharges. As did Leopold, I found channels having relatively fine bed load, but as did *Parker et al.* [1982], I found others without differences in particle sizes. My primary goal was to explain these variations between channels. This led to the discovery of a trend of increasing fineness of bed load relative to bed material toward more proximal channels (those closer to their source). I present a possible mechanism for selective transport and illustrate it with a simple sediment budget approach applied to three channels of contrasting streamwise position. Finally, I discuss briefly how a general downstream decrease in selective transport can be related to downstream fining of bed material.

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Sources of Data

Bed load and bed material particle size distributions that were selected for this study represent materials transported and stored in a reach of natural channel over a period of years (Table 1). The 13 channels meeting data criteria described below ranged from 1.5 to 28,000 km^2 in drainage area and included a variety of gravel bed channels. Bank-full discharges ranged from 1.7 to 1700 m^3 s^{-1}, and stream gradients ranged from 0.0007 to 0.039. Median particle size of subsurface bed material ($(D_{50})_b$, excluding material finer than 1 mm) ranged from 6.4 to 73 mm. Braided, meandering, and sinuous channel patterns were represented. Most channels were bounded by floodplains or alluvial terraces and thus were able to adjust freely to discharge and sediment inputs. North Fork Caspar Creek was intermittently bordered by graywacke outcrops, Jacoby Creek by soft mudstone, and Redwood and Tom Mc-

Table 1. Characteristics of River Reaches Where Sediment Samples Were Gathered

River	Drainage Area, km^2	Channel Gradient	Bank-Full Discharge, $m^3 s^{-1}$	D_{50} of Bed Material,[a] mm	Channel Pattern[b]	Source of Data
Bambi Creek, Alaska	1.5	0.0082	1.7	14.7	A sinuous	*Sidle* [1988]; *Smith et al.* [1993]; R. D. Smith (personal communication, 1991)
Carl Beck, England	2.2	0.039	2.4	73	C sinuous	*Carling and Reader* [1982]; *Carling* [1989]; P. A. Carling (personal communication, 1991)
East Fork River, Wyoming	466	0.0007	20	6.4	A meandering	*Leopold and Emmett* [1976, 1977]; *Emmett* [1980]
Goodwin Creek, Mississippi	17.9	0.0033	90	14.2	A straightened meanders	*Kuhnle* [1992]; R. A. Kuhnle (personal communication, 1991)
Great Eggleshope Beck, England	11.7	0.010	5.6	67.7	A sinuous	see Carl Beck
Jacoby Creek, California	36.3	0.0063	9.0	20.6	A sinuous	*Lisle* [1989]; unpublished data
Ohau River, New Zealand	1250	0.0065	270	19.2	A braided	*Thompson* [1985]
North Caspar Creek, California	5.0	0.013	3.1	23.7	A sinuous	*Lisle* [1989]; unpublished data
Redwood Creek 1, California	600	0.014	430	9.1	A sinuous	*U.S. Geological Survey* [1979, 1981a, b, 1985]; *Lisle and Madej* [1992]
Redwood Creek 2	520	0.026	370	18.1	A sinuous	see Redwood Creek 1
Tanana River, Alaska	28,000	0.0008	1700	20.3	A braid/meander	*Burrows et al.* [1981]; *Burrows and Harrold* [1983]
Toklat River, Alaska	267	0.018	38	28.5	A braided	W. W. Emmett (personal communication, 1992)
Tom McDonald Creek, California	18	0.0060	3.6	10.8	A sinuous	*Smith* [1990]; R. D. Smith (personal communication, 1991) unpublished data
Turkey Brook, England	7.0	0.0086	13	16	A sinuous	*Reid and Frostick* [1986]

[a]For $D > 1$ mm.
[b]A indicates alluvial, bordered predominantly by floodplains and alluvial terraces; C indicates confined, bordered predominantly by bedrock or till.

Donald Creeks by schist, and Carl Beck is incised in bouldery till [*Carling and Reader*, 1982]. Reach 1 of Redwood Creek is in a long-term state of aggradation [*Varnum and Ozaki*, 1986].

I considered East Fork River a special case of selective transport because erosion of Tertiary sediments by irrigation return flow introduces large volumes of sand into a channel that is formed in glacial outwash gravels [*Andrews*, 1979]. Mixing of the two sediments in the vicinity of the bed load measurement site is inhibited by limited scour and fill of the gravel bed, and bed material contained a much greater fraction of sand (0.59) than the other channels (0.10–0.38). In some figures I identify the datum from East Fork River as an outlier.

Bed Load

I obtained bed load sizes from samples that have been collected across the bed with pit traps or Helley-Smith bed load samplers or obtained from deposits created by impoundments (Table 2). I considered bed load samples to be representative of the ambient load if discharges approaching bank-full or greater were sampled. I set the upper size limit of Helley-Smith samples at 32 mm to avoid effects of selective rejection of particles by the sampler, which has an orifice width of 76 mm.

I set the lower grain size limit of bed load, as well as that of subsurface bed material, at 1 mm to exclude material that was transported predominantly in suspension. Suspendible sizes are excluded to lessen the influence of sediment that is introduced from outside of the channel and passes with limited storage in bed material. Truncation at 2 mm, a more conservative upper limit of suspension, did not change qualitatively the results of comparisons with bed material size. However, particles larger than 1 mm were probably suspended at least intermittently in some channels. I evaluate suspension thresholds in greater detail in a later section.

One can confidently obtain bed load size distributions that represent long-term averages from careful and extensive sampling in deposits formed by impoundments. More often, however, one must obtain them from samples of moving bed load taken over short and widely spaced time intervals. Where data were available (Table 2), I weighted particle size distributions from individual bed load samples ($f_j(D)$) by rate ($(q_s)_j$) and frequency of corresponding water discharge class (p_k) to compute an average particle size distribution, $F(D)$. Weighting distributions of individual samples by rate and discharge frequency reproduced distributions of accumulated bed load and removed the bias of sampling bed load during high or low discharges disproportionally to their frequencies. I grouped individual bed load distributions into 10 corresponding discharge classes and computed rate-weighted particle size distributions $[\bar{f}_k(D)]$ for each class,

$$\bar{f}_k(D) = \frac{\sum_{j=1}^{n} (q_s)_{jk} f_{jk}(D)}{\sum_{j=1}^{n} (q_s)_{jk}}$$

and the overall average as

Table 2. Data Used in Comparisons of Size Distributions of Bed Load and Subsurface Bed Material

	Bed Load					Bed Subsurface			
River	Sampling Method[a]	Sizes Sampled, mm	Total Sample Size, kg	Maximum Q Sampled Q/Qbf[b]	Frequency Weighted?	Sampling Scheme[c]	Sizes Sampled, mm	Total Sample Size, kg	Percent Truncated ($D > 1$ mm)[d]
Bambi Creek	HS	1–32	256	1.5	yes	bulk grid	>1	180	2
Carl Beck	pit	>1	>1000	1.6	yes	FC random	>1	130	22[e]
East Fork River	trap	>1	1200	1.7	yes	bulk grid	>1	200	0
Goodwin Creek	HS	1–32	3200	0.9	yes[f]	10 bulk, 1 point	>1	50	10
Great Eggleshope Beck	pit	>1	>1000	1.4	yes	FC random	>1	70	23[e]
Jacoby Creek	HS	1–32	300	3.8	yes	bulk random	>1	1000	39
Ohau River	delta	>1	900	1	yes	bulk	>1	120,000	0
North Caspar Creek	pond, pit	>1	159	2.0	yes	bulk random	>1	280	0
Redwood Creek 1	HS	1–32	70	0.87	no	bulk random	>1	3000	12
Redwood Creek 2	HS	1–32	100	0.88	no	bulk random	>1	5000	31
Tanana River	HS	1–32	470	1.2	yes	bulk grid	>1	2000	27
Toklat River	HS	1–32	154	0.8	no	bulk random	>1	148	47
Tom McDonald Creek	HS	1–32	54	3.5	no	bulk random	>1	184	28
Turkey Brook	pit	>2	500	1.3	no	bulk, 1 site	>2	30–60	0

[a]HS, Helley-Smith sampler.
[b]Ratio of largest discharge during which bed load was sampled and bank-full discharge.
[c]Grid, evenly spaced samples across transects; FC, frozen core.
[d]Size range to fit bed load size range.
[e]Truncated at 128 mm because of limited bed load sample size in larger particle size classes.
[f]Computed by R. A. Kuhnle (personal communication, 1991).

$$F(D) = \frac{\sum_{k=1}^{m} p_k(\bar{q}_s)_k \bar{f}_k(D)}{\sum_{k=1}^{m} p_k(\bar{q}_s)_k} \qquad (1)$$

where $(\bar{q}_s)_k$ is the mean bed load transport rate for a discharge class. For Carl Beck and Great Eggleshope Beck, I used the duration of flow events during which bed load was trapped in pit samplers in place of frequency and along with transport rate to compute weighted-average distributions.

In cases where flow frequency data were not available, I weighted individual distributions by transport rate alone. I assumed that bed load sampling programs did not cause important deviations from those that would be designed according to frequency of bed load transport rate. Frequency-weighted and non-frequency-weighted bed load size distributions in individual channels showed no important or consistent differences.

Subsurface Bed Material

All of the subsurface bed samples used in this study were gathered as bulk samples. Subaerial samples pose no problem: After the surface layer is removed a sample is dug out of the bed using a shovel or excavator. Subaqueous samples are more problematic. In large rivers such as the Tanana where water depths are great, bed material samples must be taken with a dredge, which also incorporates potentially coarser surface material. In shallower streams one can obtain subaqueous samples by removing material from inside a cylinder worked into the streambed [*McNeil and Ahnell*, 1964] or freezing a core around one or more probes driven into the streambed and injected with liquid nitrogen or carbon dioxide [*Walkotten*, 1976; *Everest et al.*, 1980; *Carling and Reader*, 1982]. The cylinder method is more likely to accurately represent the existing bed material. Differences between cryogenic cores and bulk samples are inconsistent, but cryogenic cores tend to oversample particles coarser than about 50 mm [*Young et al.*, 1991]. However, an experimental set of cryogenic cores taken by Carling, whose study reaches Great Eggleshope and Carl Becks are part of this study, is finer grained than bulk samples taken in the same location (P. A. Carling, personal communication, 1991).

I considered subsurface samples to be representative if individual sampling locations were randomly selected or evenly distributed across the bed. I required minimum total sample weight for bed load and subsurface bed material to meet a bulk sample standard chosen from *Church et al.* [1987] that the largest stone (estimated as the upper limit of the largest size range of sieved bed material) compose no more than 5% of the total sample weight. In most cases, this criterion was considerably exceeded.

I compared bed load and bed material size distributions over the same particle size range to avoid complications from sampling limitations (mostly of bed load) and immobile bed material. Truncation of size ranges resulted in the elimination of 0–47% of bed material (Table 2) and an unknown proportion of bed load. I describe effects of truncation in the following section.

Bed Load and Bed Material Particle Size Distributions

Bed load was finer than subsurface bed material in about one half of the channels used in this study (Figure 1). I represented differences between bed load and bed material size distributions by the ratio (D^*) of median size of bed material ($(D_{50})_b$) to the weighted average median size of bed load ($(\bar{D}_{50})_l$). Values of D^* ranged from 0.90 to 3.3; five channels had values greater than 2.0 (Table 3).

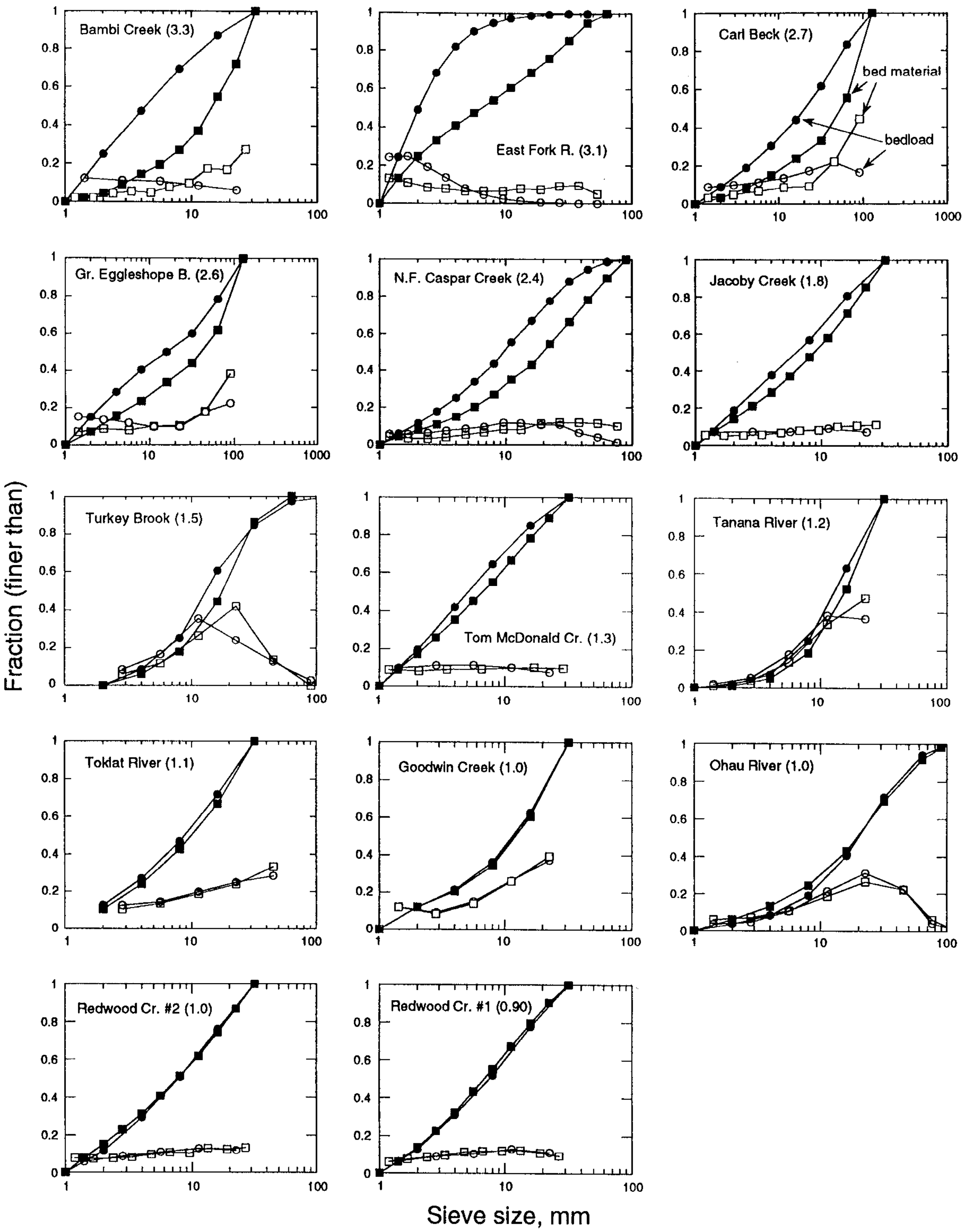

Figure 1. Particle size distributions for subsurface bed material and mean bed load weighted by transport rate and discharge frequency (when available). Cumulative fractions are represented by solid symbols, and fractions are represented by open symbols. In cases where bed load contains fewer size classes, bed load distributions were made comparable to bed material distributions by multiplying each bed load fraction by the ratio of number of bed load classes to number of bed material classes. In each case, distributions were truncated if necessary so that bed load and bed material were both represented over the full size range. Channels are arranged in order of decreasing D^* given in parentheses.

The required truncation of size distributions at 32 mm in some channels apparently reduced values of D^* in those channels where D^* was greater than unity, because coarser particles were increasingly underrepresented in bed load as the size range was extended upward. For example, all bed load sizes (1–90 mm) were represented in the value of D^* for North Fork Caspar Creek. If the sizes were truncated at 32 mm, then the value of D^* would fall from 2.38 to 1.28. Among the five channels where $D^* > 1.2$ and sizes larger than 32 mm were represented, truncation to 32 mm would reduce values of D^* by an average of 12% per 10% of bed material truncated.

Bed material size distributions in all channels were negatively skewed, as were, necessarily, bed load distributions in channels showing no difference in particle sizes. Negative skewness is common in gravelly bed material [*Kondolf and Wolman*, 1993] and indicates a fine component that is abundant enough to impose a fine tail on the overall distribution but not enough to impose recognizable bimodality [*Folk and Ward*, 1957]. In channels with $D^* > 1.5$, bed load distributions were skewed negatively (Carl Beck) or positively (Bambi Creek) or were symmetrical (North Caspar) or bimodal (Great Eggleshope Beck). These attributes, especially departures from the negative skewness of bed material, can indicate an enrichment of bed load by fine material [*Komar and Carling*, 1991].

In the cases where $D^* > 1.5$, proportions of bed load fractions exceeded those of corresponding bed material fractions at least up to the midpoint of the range of particle sizes; differences existed not only in the sand-granule size range but also in gravel. Although I truncated bed load sizes at a minimum of 1 mm to eliminate much of the suspended sediment, intermittent suspension of coarser particles may have affected discrepancies in particle sizes of sampled material that I used to represent bed load and bed material.

To evaluate the suspendibility of size fractions of bed material, I used a suspension criterion, $w_s = u_g^*$ (where w_s is the particle settling velocity; $u_g^* = (\tau_g/\rho)^{1/2}$; τ_g is the boundary shear stress exerted on surface particles: and ρ is fluid density) to estimate the largest particle size ($(D_{ss})_{max}$) in suspension at bank-full stage. I computed u_g^* from a skin friction equation

Table 3. Particle Size Distribution Data

	D^*	$(D_{ss})_{max}$, mm	D', mm
Bambi Creek	3.3[a]	···	9.0
Carl Beck	2.7[b]	2.0	45
East Fork River	3.1	0.61	6.5
Goodwin Creek	1.0[a]	0.63	···
Great Eggleshope Beck	2.6[b]	0.52	11
Jacoby Creek	1.8[a]	1.8	6.0
Ohau River	1.0	···	···
NF Caspar Creek	2.4	1.7	16
Redwood Creek 1	0.90[a]	1.5	···
Redwood Creek 2	0.97[a]	3.1	···
Tanana River	1.2[a]	1.2	···
Toklat River	1.1[a]	2.6	···
Tom McDonald Creek	1.3[a]	0.48	5.0
Turkey Brook	1.5	···	13

D^* is the ratio of median grain sizes of subsurface bed material and bed load. $(D_{ss})_{max}$ is the estimated diameter of largest suspended particles at bank-full flow. D' is the particle diameter at intersection of bed load and bed material frequency distributions in cases where bed load is finer than bed material.

[a]Here, $1 < D < 32$ mm.

[b]Here, $1 < D < 128$ mm.

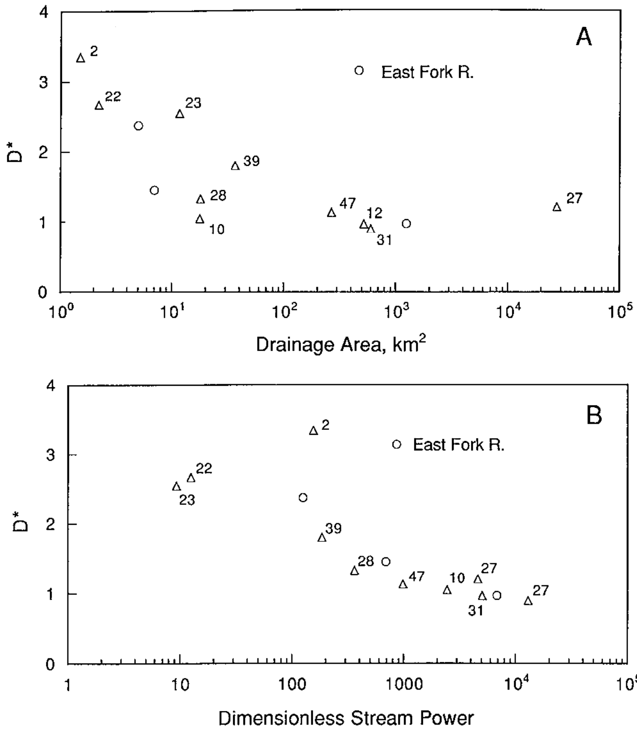

Figure 2. Value of D^* from mean weighted bed load size distribution versus (a) drainage area and (b) dimensionless stream power. Triangles denote sites where particle size distributions were truncated, and values give percent of bed material excluded by truncation; circles denote sites without truncation.

$$U/u_g^* = 3.26 + 5.75 \log (d/D_{84})$$

where U is mean velocity, d is depth, and D_{84} is the particle size greater than 84% of surface particles. I estimated values of w_s from 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) [*Corey*, 1949]:

$$\mathrm{CSF} = c/(ab)^{1/2}$$

where a, b, and c are the longest, intermediate, and shortest axis, respectively, of the particle. CSF was given a value of 0.7.

In all cases the value of $(D_{ss})_{max}$ (0.48–3.1 mm) was substantially smaller than the value of the diameter (D') corresponding to the intersection of distributions (5.0–45 mm) (Figure 1, Table 3). This indicated that intermittent suspension of bed material collected and counted as part of the bed load was not an important cause for differences between bed load and bed material particle size distributions.

Variation of D^* With Basin and Channel Characters

The ratio D^* decreased down to unity with three parameters (drainage area, bank-full discharge, and dimensionless stream power) that commonly increase in value downstream. Values of D^* approached unity at a drainage area of approximately 100 km² (Figure 2a) or a bank-full discharge of approximately 50 m^3 s^{-1} (not shown). The channels in which *Leopold* [1992] found bed load to be finer than bed material have drainage areas more or less than 100 km², but in some sites long-term bed load sizes are uncertain because of sampling at less than bank-full stages. Bed load was trapped over 3–5 years, how-

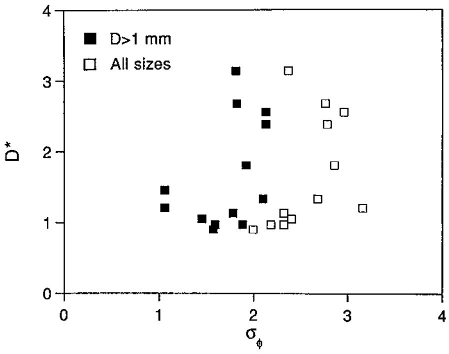

Figure 3. Value of D^* from mean weighted bed load size distribution versus σ_ϕ.

ever, in sites on Coon and East Fork Encampment Creeks (drainage areas of less than 20 km^2).

Values of D^* also decreased with increasing dimensionless stream power,

$$\Omega^* = \frac{\rho Q_{bf} S}{(\rho_s - \rho) g^{1/2} (D_{50})_b^{5/2}}$$

where g is gravitational acceleration, S is the channel gradient, and ρ_s is the density of sediment (Figure 2b). As a measure of transport capacity scaled by particle size, Ω can be used to quantify the potential for scour which, as will be proposed later, can control the potential for sorting of bed material.

Values of D^* greater than unity signify a breakdown in equal mobility and the onset of selective transport. Selective transport can be caused by bed material that is so poorly sorted or strongly bimodal that equal mobility of bed material can no longer be maintained by particle sorting and arrangement on the bed surface [*Wilcock*, 1992]. I calculated alternative values of the standard deviation (σ_ϕ) of bed material size distribution from (1) particles coarser than 1 mm and (2) all particle sizes. I assumed in case 1 that particles finer than 1 mm do not affect selective transport of larger sizes; I assumed in case 2 that they do so by helping to create transport surfaces over which coarse particles are rapidly transported [*Iseya and Ikeda*, 1987].

High values of σ_ϕ were a common (if not exclusive) trait of channels with high values of D^*, which suggests an effect of bed material sorting on selective transport (Figure 3). Equal mobility was apparently maintained up to values of σ_ϕ roughly equal to 2, in agreement with the upper limit approximated by *Paola and Seal* [1995] from experimental and field-derived values.

All streambeds in this study would be classified as "very poorly sorted," considering case 2 values of σ_ϕ [*Folk*, 1968]. However, sampling of relatively homogeneous patches of bed material in four of the channels by methods described by *Lisle and Madej* [1992] showed that sorting was better within patches than in the bed as a whole, especially in channels (Jacoby and North Caspar) with high values of D^* (Table 4). Values of mean σ_ϕ for patches varied over a relatively narrow range between channels and were less than the approximate upper limit corresponding to equal mobility. This suggested a greater likelihood of maintaining equal mobility within individual patches than in the bed as a whole.

Variation of $(D_{50})_l[(D_{50})_b]^{-1}$ With Discharge

Variations of bed load particle size with discharge revealed aspects of the mechanism behind sorting of bed material. Bed load transported at low discharges was generally finer than that transported at discharges near bank-full or greater (Figure 4). In keeping with previous reports of variations of bed load particle size with water discharge [*Carling*, 1988; *Komar and Carling*, 1991], I represented median particle size of individual bed load samples as ratios to $(D_{50})_b$, the inverse of ratios presented in the previous section. Some bed load samples at very low discharges were coarse (e.g., East Fork River and Jacoby Creek), but these samples were small and influenced by a few pebbles that may have been disturbed by the sampler. Channels with high values of D^* were characterized by (1) values of $(D_{50})_l[(D_{50})_b]^{-1} < 1$ at all discharges (e.g., Bambi Creek and East Fork River) and (2) persistence of low values of $(D_{50})_l[(D_{50})_b]^{-1}$ into discharges of one-half bank-full or greater (e.g., North Fork Caspar and Jacoby Creeks). Similar plots for Great Eggleshope and Carl Becks [*Carling*, 1988, Figure 8] show both of these characteristics.

Relative contributions of different discharges to fractional and total bed load volumes over a period of years depended on associated transport rates and frequencies (Figure 5). (In these plots, summing weighted fractional transport rates, as represented by the histograms across the full range of discharge, yielded the weighted-mean bed load size distribution according to (1).) In Bambi Creek, low discharges (when bed load was particularly fine grained) were responsible for large proportions of the total bed load transported, but bed load was finer than bed material over the full range of sampled discharges, and D^* was correspondingly high. In Jacoby Creek, which had a lower value of D^*, low discharges contributed little to total bed load transport, and bed load was as coarse as bed material at discharges near bank-full and greater.

Therefore a salient aspect of selective transport was that important volumes of bed load were transported below bank-full discharge, which commonly corresponds to general entrainment of the coarse surface layer or pavement in many gravel bed channels [*Andrews*, 1984; *Andrews and Smith*, 1992]. If pavements were maintaining equal mobility of their underlying bed material, then the source of this bed load must have been other than the average pavement representing much of the bed surface of these channels.

Selective Transport by Sorting and Uniform Scour

The channels in this study that displayed selective transport of fine material are not known to be aggraded or degraded or to have received recent supplies of fines from upstream. A

Table 4. Bed Material Sorting Data

	σ_ϕ	$\overline{(\sigma_\phi)_i}$ (s.d.)	n
Jacoby	1.92	1.68 (0.38)	49
North Fork Caspar	2.13	1.82 (0.25)	16
Redwood 1	1.57	1.53 (0.22)	45
Redwood 2	1.88	1.84 (0.22)	31

Data presented are sorting of mean bed material (σ_ϕ); mean sorting of bed material patches [$\overline{(\sigma_\phi)_i}$] and its standard deviation (s.d.); and number of patches sampled (n).

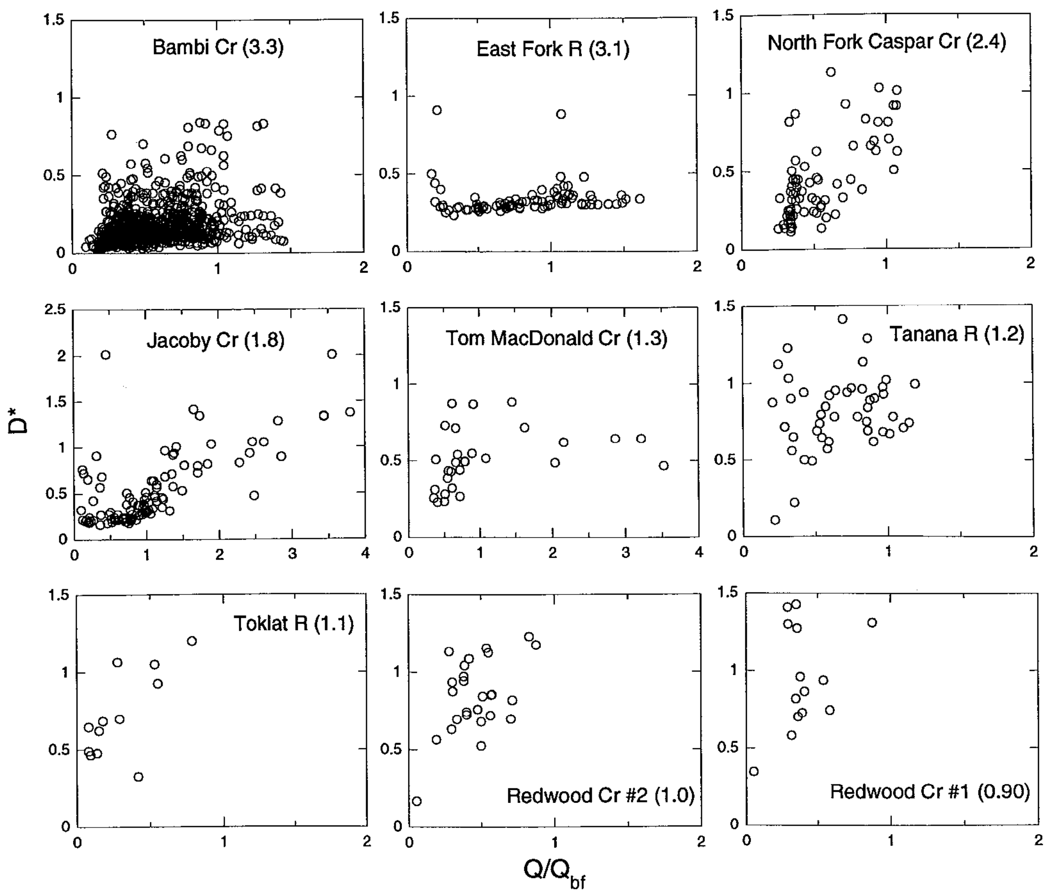

Figure 4. Values of $(D_{50})_l[(D_{50})_b]^{-1}$ for each bed load sample versus ratio of discharge to bank-full discharge. Channels are arranged in order of decreasing D^* given in parentheses.

possible mechanism for bed load being finer than bed material is the rapid downstream movement of material stored in relatively well sorted, surface patches of fine-grained material [*Emmett et al.*, 1983; *Meade*, 1985; *Lisle and Madej*, 1992; *Paola and Seal*, 1995]. Bed load transport rate of a size fraction over a period of years is a function of its concentration in bed material and its virtual transport velocity (averaged over periods of rest and motion). An apparent enrichment in fine material in bed load can be created in part by superior virtual transport velocities. I present data relevant to this mechanism from three channels below and discuss more evidence and implications later.

Role of Scour and Fill

Limited annual scour below the pavement of many small, coarsely bedded channels may provide the conditions for selective transport of bed material. Conversely, selective transport of surficial bed material would have a lesser effect on long-term caliber of bed load if deep thicknesses of bed material over much of the channel were accessed by annual scour and fill.

Repeated cross-sectional surveys at North Caspar, Jacoby, and Redwood Creeks provided a basis for comparing the depth of annual scour and fill between channels with contrasting values of D^* (2.4, 1.8, and 1.0 respectively). *Lisle* [1989] resurveyed cross sections after storm flows in North Caspar and Jacoby Creeks and measured maximum scour depth with scour chains. Depth of bed material annually incorporated into bed load transport (the active bed thickness) is defined as the mean difference between the highest bed elevations and maximum scour depths measured along cross sections [*Lisle*, 1989]. In reaches 1 and 2 of Redwood Creek, I quantified active bed thickness by cross-sectionally averaged absolute values of scour and fill that were measured from annual surveys of cross sections in or near the study reaches [*Varnum*, 1984; *Varnum and Ozaki*, 1986; *Potter et al.*, 1987]. Active bed thickness in Redwood Creek represented a minimum value because it did not include additional scour that commonly occurs during high flows. Scour chains that were planted 6 km downstream of reach 1 recorded an average scour depth greater than 2 m over one year ending in 1982, and soundings during stream gaging during a single high-flow event in 1980 showed scour and fill of up to 1 m deep across the entire bed in a section 6 km upstream of reach 1 and in section within reach 2 [*Madej*, 1995].

Mean active bed thickness, expressed as a multiple of bed surface D_{84} or the approximate thickness of the pavement, equaled 0.4 in North Caspar Creek, 4 in Jacoby Creek, 8–12 in Redwood Creek, reach 1, and 4–8 in Redwood Creek, reach 2 (Table 5). On an annual basis, most bed material was mobilized only within the pavement layer of North Caspar Creek, within a few pavement layer thicknesses in Jacoby Creek, and within many pavement layer thicknesses in Redwood Creek (especially in consideration of the inadequacy of scour measurements). This comparison suggests a relationship between decreasing difference in bed load and bed material particle size and increasing depth of annually mobilized bed material.

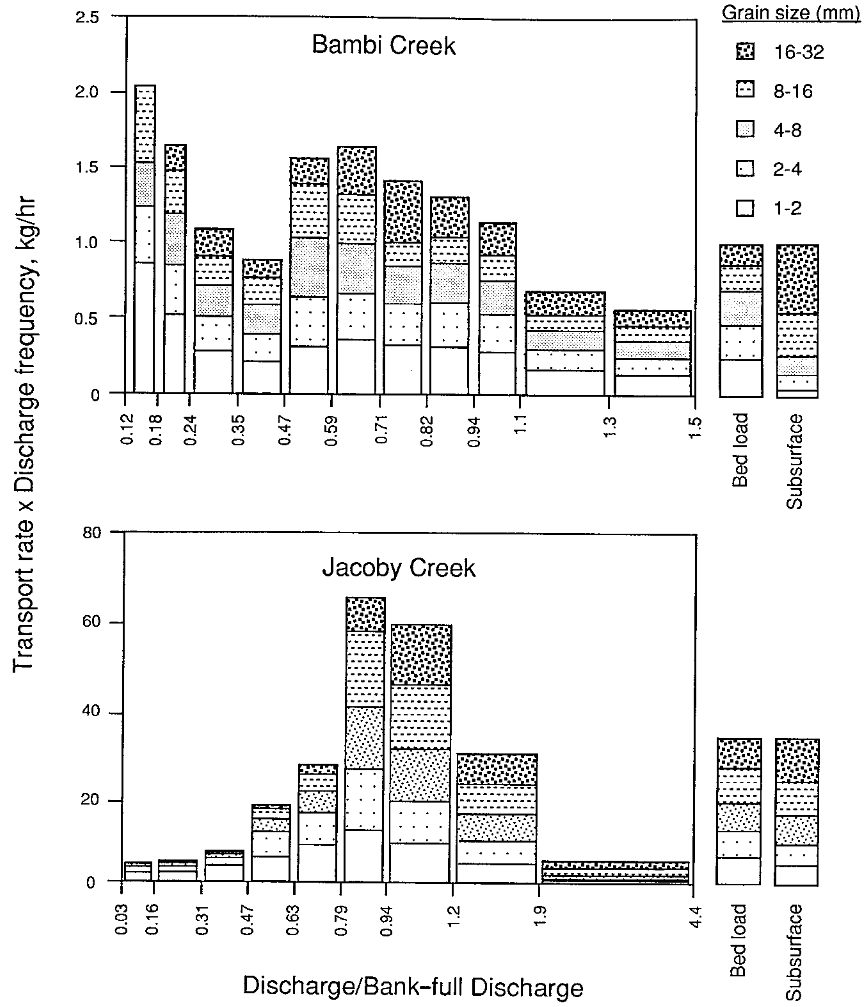

Figure 5. Discharge frequency weighted, mean fractional bed load transport rates versus discharge class, Bambi and Jacoby Creeks. Transport rates were adjusted for unequal discharge ranges to display rates for equal ranges.

Virtual Transport Velocities of Fine and Coarse Bed Load

I applied a simple model to the four channels used above to evaluate differences in virtual transport velocity between particles originating from (1) coarse patches that on the whole represent the average particle size distribution of the bed and (2) fine patches in pools (Figure 6). Fine sediment that is stored in pools during low flow and scoured at high flow can account for most of the volume of unarmored fine sediment in streambeds [*Andrews*, 1979; *Emmett et al.*, 1983; *Meade*, 1985; *Lisle and Hilton*, 1992; *Hassan*, 1993]. In Jacoby Creek, pool fines constituted 73% of the total overlying the bed pavement. I made the simplifying assumption that material from a patch was not sorted during transport and traveled at the same velocity. I began by evaluating the relative contribution from each patch by finding through trial and error the mixture that produced a size distribution resembling bed load (Figure 7):

Table 5. Mean Active Bed Thickness and Data Related to Two Bed Load Constituents

	y_b (s.d.), m	$y_b/(D_{84})_b$	p_b	V_f/By_b	w_f/w_b
North Caspar	0.12 (0.050)[a]	1.7	0.5	0.012	90
Jacoby	0.32 (0.12)[a]	3.8	0.9	0.027	4
Redwood 1	>1.7[b]	>53	...	...	...
Redwood 2	>0.7[c]	>13	1 (0.98)[d]	<0.017	...

Data presented are mean active bed thickness (y_b), its standard deviation (s.d.) and its ratio to dominant bed material size ($y_b/(D_{84})_b$); fraction of subsurface bed material (p_b) that would be needed to mix with fine sediment in pools in order to replicate bed load size distribution; fraction of active bed material ($V_f/(By_b)$) that was contained in fine patches in pools; and computed ratio (w_f/w_b) of transport velocity of fine sediment in pools to that of average bed material.

[a]From scour chains and cross-section surveys between high flow events [*Lisle*, 1989].

[b]From variations in bed elevation measured during discharge measurements 2 km upstream, 1974–1982 [*Madej*, 1995].

[c]From scour and fill measurements made with scour chains, some of which were lost [*Madej*, 1995].

[d]Value in parentheses is computed from y_b, assuming $w_f = w_b$.

$$f(D)_l = (p_b)f(D)_b + (1 - p_b)f(D)_f \quad (2)$$

where $f(D)$ is an average particle size distribution, subscripts b and f denote average bed material and fine sediment in pools, respectively, and p_b is the proportion of average bed material contributed to bed load.

I expressed the transport rate of either constituent i in terms of its relative particle velocity,

$$q_{si} = q_s f_i u^*_{pi} \quad (3)$$

where u^*_{pi} is relative particle velocity, which is equal to the ratio of the constituent particle velocity to the mean for all particles. The fraction of constituent i in bed load is $p_i = q_{si}/q_s$. Substituting p_i into (3) and rearranging led to an expression that the fraction of a constituent in bed load is proportional to its relative transport velocity:

$$p_i/f_i = u^*_{pi} \quad (4)$$

Substituting terms for the two constituents into equation (4), I expressed p_b in terms of transport rates from the two sources:

$$p_b = \frac{(u_p)_b V'_b}{(u_p)_b V'_b + (u_p)_f V_f} \quad (5)$$

where $(u_p)_b$ and $(u_p)_f$ are particle velocities of the respective constituents. The volume of bed material per unit channel length that is incorporated seasonally into bed load from coarser patches (V'_b) was approximately equal (as will be shown) to active bed volume V_b, represented by the product of average depth of scour (y_b) and channel width (B) (Figure 6). I assumed that the entire volume per unit channel length of fines overlying a coarser substrate in pools (V_f) contributes to bed load [*Lisle and Hilton*, 1992].

Substituting these identities and rearranging (5) yielded the ratio of transport velocities:

$$\frac{(u_p)_f}{(u_p)_b} = \frac{By_b(1 - p_b)}{p_b V_f} \quad (6)$$

The relative volume of fine patches was evaluated by $V_f(By_b)^{-1}$.

I computed values of $(u_p)_f[(u_p)_b]^{-1}$ for North Fork Caspar, Jacoby, and Redwood Creeks from measured variables on the right-hand side of (6). In reaches where bed material was sampled, particle sizes of pool fines and fines volumes of 12–21 pools were measured according to the methods of *Hilton and Lisle* [1993]. Total fines volume was divided by the length of the reach that included the measured pools.

Although this model and the data to support it are crude, the high values of $(u_p)_f[(u_p)_b]^{-1}$ for North Fork Caspar and Jacoby Creeks indicated that particle velocities of fine sediment in pools were significantly higher than those of bed material, and thus fine patches contributed to bed load disproportionately to their volume ($V_f(By_b)^{-1}$), which is very small (Table 5). Because $f(D)_b = f(D)_l$ in Redwood Creek, the contribution of pool fines to bed load according to this model was zero, $p_b = 1$, and $(u_p)_f[(u_p)_b]^{-1} = 0$. If $(u_p)_f[(u_p)_b]^{-1} = 1$ (a minimum value), p_b would equal 0.98, which confirmed that any contribution of pool fines to bed load would be unmeasurable. The association of values of $(u_p)_f[(u_p)_b]^{-1}$ with the characteristics of these channels indicated that selective transport by this mechanism tended to decrease with increasing potential for scour, which at least here corresponded with larger, more distal channels.

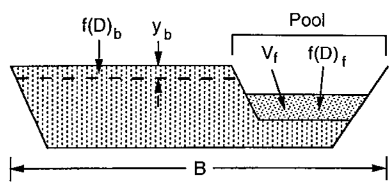

Figure 6. Cross-sectional model of a channel depicting bed load sources from fine sediment in pools and coarser bed material. The parameters are defined for (2) and (6).

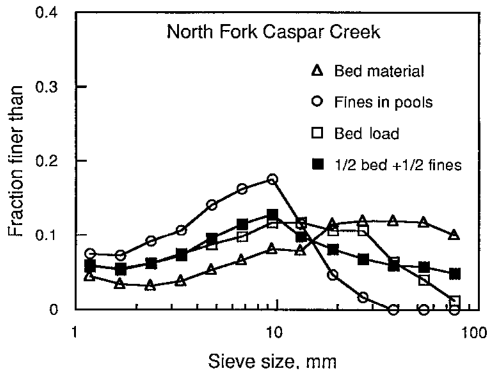

Figure 7. Particle size distributions for subsurface bed material, fine sediment in pools, weighted mean bed load, and a mixture (composed of equal parts each) of bed material and pool fines that was selected to most closely resemble bed load, North Fork Caspar Creek.

Discussion

Selective Transport of Fine-Grained Patches of Bed Material

Differences in particle size between bed load and bed material in some of the channels investigated in this study indicated significant selective transport of fine bed material. A likely mechanism for selective transport is the lateral and longitudinal sorting of bed material into patches that include those of fine material which are readily entrained and move rapidly downstream [*Paola and Seal*, 1995; *Seal et al.*, 1993; *Lisle and Madej*, 1992]. This is consistent with three of the major results of this investigation.

First, selective transport was most prevalent in steep, coarse-bedded, low-order channels where annual scour of bed material was limited. Many dominant bed surface particles of such channels commonly remain immobile until discharges exceed bank-full severalfold [*Hayward*, 1980; *Best and Keller*, 1986; *Grant et al.*, 1990], and measurements in three channels illustrated that bed scour scaled by bed particle size commonly becomes limited as one progresses toward headwaters. Limited annual scour tends to increase the relative contribution of fine bed load overpassing less mobile, coarser bed material to the long-term yield of bed load. Conversely, deeper scour and greater mobility of much of the streambed in higher-order channels leads to domination of bed load sources by those that better represent the bed as a whole.

Second, in channels showing high values of D^*, important volumes of fine bed load were transported at stages below those usually associated with general entrainment of pavements that characterize gravel bed channels. This further supports a hypothesis of early entrainment of a fine-grained component of bed load that passes over a more stable bed of coarser material.

Third, fine-grained patches of bed material with apparently low entrainment thresholds are described in five channels in this study, as well as in other natural channels [*Andrews*, 1979; *Emmett et al.*, 1983; *Meade*, 1985; *Seal and Paola*, 1995; *Lisle and Madej*, 1992; *Lisle and Hilton*, 1992]. For example, fines in pools apparently include some of the first bed material to be entrained during rising stages and the last to be deposited during waning stages [*Jackson and Beschta*, 1982; *Lisle and Madej*, 1992]. Particle sizes within any patch may be equally mobile [*Paola and Seal*, 1995; *Lisle and Madej*, 1992], but material from fine patches can be mobilized earlier in a flood hydrograph and scoured more deeply during higher stages and selectively transported over the bed, leading to a size distribution of bed load that is finer than the average for the bed as a whole. Such fine patches described in three channels used in this study contain small but significant volumes of material relative to the volume of bed material subject to annual scour, particularly in low-order channels.

Other Selective Transport Mechanisms

The first two results summarized above are also consistent with selective entrainment of fine particles from a pavement typifying a channel as a whole, in apparent violation of the equal mobility approximation. The coincidence of high values of D^* with a wide spread in bed material particle size distributions supports the supposition that equal mobility can break down where the range in particle size is large. However, *Paola and Seal* [1995] argue that the response of natural gravel streambeds to such a breakdown is to organize disparate particles into relatively well-sorted patches of contrasting mean size that allow local achievement of equal mobility. This hypothesis is supported by the relatively narrow sorting of patches that was measured in four channels used in this study.

Another explanation for the apparent selective transport observed in this study is that some of the fine material that enriches bed load, particularly in low-order channels, is introduced into the channel and rapidly transported past a sampling section without intermediate storage in bed material. However, enhanced transport of finer bed material included sizes that were transported predominantly by traction, not suspension, and storage of fine bed load in the channel is probably at least seasonally important.

Last, particle attrition can create differences between sizes of bed load and bed material even though they are sampled at the same site. Weathering weakens particles stored in the bed, and they are most likely to break soon after entrainment [*Adams*, 1979; *Kodama*, 1992], although particle breakage during extracting and sieving bed material would tend to negate this effect to an unknown degree. Nevertheless, as a measure of selective transport of bed material, values of D^* that are computed from the full range of active bed material should be regarded as maximum.

Implications for Downstream Fining

Selective transport represents the potential for downstream fining of bed material, for deposition of selectively transported bed load would create a bed finer than that from which it originated. Trends of decreasing D^* with drainage area, bankfull discharge, and dimensionless stream power indicate a decreasing potential downstream for downstream fining of bed material due to selective transport and deposition. This trend is consistent with *Werrity*'s [1992] determination of decreasing rates of downstream fining in the Dunajec River, Poland (a pattern which fits the *Sternberg* [1875] law) due to selective transport alone.

The condition of bed load being finer than bed material in a reach of channel implies that under conditions approaching equilibrium, virtual particle velocities of finer constituents of active bed material are greater than those of coarser constituents. A crude sediment budget for three channels used in this study suggested that this velocity difference can be manyfold in low-order channels and less in more distal channels. Greater equalization of particle velocities in a reach downstream would promote bed-material fining while diminishing the potential for fining further downstream. Deep scour that has been observed in the beds of distal channels would tend to equalize particle velocities by incorporating large volumes of all sizes of bed material in annually activated bed load and by promoting mixing of fine and coarse constituents during a wide range of transporting events.

Conclusions

1. The average particle size of bed load transported over a period of years can be finer than that of subsurface bed material in natural gravel bed channels. This difference manifests selective transport and a violation of the equal mobility hypothesis as applied to a channel as a whole.

2. Differences between bed load and bed material tend to diminish for more distal channels.

3. Channels exhibiting selective transport are characterized by low depths of scour and significant transport of fine bed load at discharges less than those that are commonly associated with entrainment of the coarse pavement in many gravel bed channels. These indicate transport of fine bed load over a more stable substrate of coarser bed material.

4. Likely sources of selectively transported fine bed load include fine patches on the streambed that have low entrainment thresholds and high virtual particle velocities. These and coarser patches are relatively well sorted and may individually maintain equal mobility.

5. A downstream decrease in selective transport, which provides the potential for downstream fining, is consistent with decreasing rates of downstream fining due to selective transport in natural gravel bed channels.

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