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# SURFACE PARTICLE SIZES ON ARMOURED GRAVEL STREAMBEDS: EFFECTS OF SUPPLY AND HYDRAULICS

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## ABSTRACT

Most gravel-bed streams exhibit a surface armour in which the median grain size of the surface particles is coarser than that of the subsurface particles. This armour has been interpreted to result when the supply of sediment is less than the ability of the stream to move sediment. While there may be certain sizes in the bed for which the supply is less than the ability of the stream to transport these sizes, for other sizes of particles the supply may match or even exceed the ability of the channel to transport these particles. These sizes of particles are called 'supply-limited' and 'hydraulically limited' in their transport, respectively, and can be differentiated in dimensionless sediment transport rating curves by size fractions. The supply- and hydraulically limited sizes can be distinguished also by comparing the size of particles of the surface and subsurface. Those sizes that are supply-limited are winnowed from the bed and are under-represented in the surface layer. Progressive truncation of the surface and subsurface size distributions from the fine end and recalculation until the size distributions are similar (collapse), establishes the break between supply- and hydraulically limited sizes. At sites along 12 streams in Idaho ranging in drainage area from about 100 to 4900 km$^2$, sediment transport rating curves by size class and surface and subsurface size distributions were examined. The break between sizes that were supply- and hydraulically limited as determined by examination of the transport rate and surface and subsurface size distributions was similar. The collapse size as described by its percentile in the cumulative size distribution averaged $D_{36}$ of the surface and $D_{73}$ of the subsurface. The discharge at which the collapse size began to move averaged 88 per cent of bankfull discharge. The collapse size decreased as bed load yield increased and increased with the degree of selective transport. 

KEY WORDS: armour; sediment supply; sediment transport; gravel

## INTRODUCTION

The surface of most gravel-bed streams is armoured: the median size of the grains at the surface is larger than the median size of the grains in the subsurface. Several interpretations have been proposed for the occurrence of an armour. One interpretation is that armour results when the supply of sediment is less than the amount the channel could transport such that the bed surface is winnowed of the most easily moved fine sediment (Little and Mayer, 1976; Shen and Lu, 1983; Dietrich *et al*., 1989; Lisle *et al*., 1993; and Buffington and Montgomery, 1999). Another interpretation is that armour results from a tendency for 'equal mobility' of various size fractions: larger grains become concentrated at the surface until their transport rate and abundance in the subsurface match (Parker and Klingeman, 1982; Andrews and Parker, 1987).

The suggestion that armour can develop from a limitation in sediment supply, as for instance below a dam (e.g. Leopold *et al*., 1964), was demonstrated experimentally by Dietrich *et al*. (1989). As the amount of sediment fed into a flume decreased, the bed surface coarsened absolutely and relative to the subsurface. The greater the reduction in supply, the greater was the relative difference between the median size of the surface and subsurface grains. They developed a simple quantitative model that showed how the degree of armouring, for a given boundary shear stress relative to that necessary for motion of the load, was inversely related to the ratio of sediment transport to transport capacity ($Q_*$). Kinerson (1990) was able to use the approach to estimate supply limitations at a number of field sites. Buffington and Montgomery (1999) used flume data to determine the

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sediment supply from the size of the surface grains relative to the predicted size of surface grains based on expected competence.

As was the case with Dietrich *et al.* (1989) and with most other workers, supply has been considered collectively: the aggregate of all sediment of all sizes. However, the sediment of a stream bed and the sediment supplied to a channel from the bed, banks and landscape are of various sizes. There are certain sizes of sediment for which the supply may be less than the amount of these sizes the stream could transport given the boundary shear stress. These sizes are winnowed from the bed. When winnowed, the surface size distribution is a truncated version of the subsurface particle size distribution, the difference being those sizes that have been preferentially removed. Gomez (1984) called this 'downstream winnowing' and differentiated it from 'vertical winnowing' which he argued was formed by equilibrium transport of all sizes (e.g. Parker and Klingeman, 1982). These preferentially removed sizes could be said to be 'supply-limited' in their transport and, as will be shown, are the finer fractions. On the other hand, there are other sizes of sediment for which the supply matches or even exceeds the amount of these particles the channel can transport. These sizes could be said to be 'hydraulically limited' in their transport and, as will be shown, are the coarser fractions.

Church *et al.* (1987) were perhaps the first to suggest that armours formed by winnowing could be identified by a comparison of the surface and truncated subsurface size distributions. In their work, they compared the median size of the subsurface size distribution truncated at 8 mm to the median size of the surface grains. There was general equivalence of the medians at a number of locations in the Fraser River consistent with creation of an armour layer by winnowing of finer sediment. For some sites, the median grain size remained coarser than that of the subsurface grains. They interpreted this to reflect spatial concentration of the coarser grains during equilibrium transport (Parker and Klingeman, 1982; Andrews and Parker, 1987). Lisle and Hilton (1999) compared surface and subsurface size distributions to characterize the finer matrix of particles that could be winnowed to create the coarser surface. They found the resulting size distribution of finer material to correspond with the size distribution of fines collected in pools.

In this study we examine the fractional transport rate of bed load, especially as compared to theoretical curves, at a dozen sites to illustrate supply limitation of certain particle sizes, but not all sizes. Then we show how the surface and subsurface size distributions can be compared to identify which sizes of particles are limited in their transport by the supply of sediment and which are limited in their transport by the shear stress required for entrainment.

## DESCRIPTION OF FIELD SITES AND METHODS

In central Idaho, the US Geological Survey and US Forest Service have collected flow discharge and bed load transport measurements that are relatively detailed over relatively long periods in a variety of basins of differing size (King *et al.*, in press). Each site has been the location of long-term measurement of streamflow for 12 to 86 years. Sediment measurements have been made at some sites annually for 12 or more years and at other sites for several years. The measurements were made in accordance with recommended methods (e.g. US Geological Survey, 1968). Annual floods during the years of bed load sampling included events with recurrence intervals above 8 years at all sites and from 15 to 25 years at 11 sites.

Flow velocity was measured with Price and Pygmy current meters for typically 60 seconds at typically 20 equally spaced points across the channel. The point measurements of velocity and local depth were integrated across the channel to give the streamflow (Hipolito and Leoureiro, 1988). Rating curves specifying the relationship between stage and water discharge were built for each site based upon tens to hundreds of stage–streamflow pairs.

Bed load was measured by the single equal width increment method (Edwards and Glysson, 1988). A square 7·6 or 15·2 cm Helley–Smith bed load sampler (Helley and Smith, 1971) with a 0·25 mm mesh collection bag was placed on the bed for a uniform period (30 or 60 seconds) at 10–25 equally spaced intervals across the channel. Typically two bed load samples were collected during each site visit. The Helley–Smith sampler was either hand-held or suspended from a cable or bridge. The larger sampler was typically used at higher discharges on the larger rivers. The range of measured flows extends from below mean annual discharge up to flood events with a minimum of a seven year recurrence interval. At seven of the 12 sites, bed load was measured at flow discharges with recurrence intervals in excess of ten years. Bed load samples reported herein were sieved at one-phi intervals.

The surface material was measured by the Wolman method (Wolman, 1954). Particles were selected for measurement of their intermediate axis (b-axis) at approximately equal-spaced intervals along four or five transects across the bankfull width of the channel. One of the transects in each set passed over the site where subsurface material was collected. Other transects were at 2 m intervals along the stream. The sampling interval across the channel was multiple grain diameters to avoid serial correlation (Church *et al*., 1987). The exact particle measured at each interval was chosen blindly. Particle size was measured and recorded to a millimetre. The size of particles finer than 2 mm in diameter was not measured but was recorded as less than 2 mm. A minimum of 100 particles (but often more) was measured for each set of traverses. Once sampling began along a transect, the entire transect was sampled. The total number of surface particles measured at sites ranged from 224 to 434.

The subsurface material was collected at a minimum of three locations with a '55-gallon' drum that was cut in half, had its end removed, and was placed on the bed. Sample weights ranged from 193 to 322 kg. Surface grains were removed to a depth of about the $D_{90}$ of surface grains and then the material below the surface was sampled. Subsurface material was sampled to a depth of at least two particle diameters and until the largest particle in the sample represented no more than 5 per cent of the total volume of the sample (Church *et al*., 1987). Once grain size data were analysed, the coarsest particle made up no more than 2 per cent of the total weight of any sample, and the average value was 1·3 per cent. The principal dimensions of grains coarser than 64 mm were measured with a ruler, while grains between 16 and 64 mm were wet-sieved in the field (Platts *et al*., 1983) and grains finer than 16 mm were sieved in the laboratory. Sieving was at one-phi intervals. As shown by Kellerhals and Bray (1971) the surface particle size measurements (grid-by-number) and subsurface particle size measurements (volume-by-weight) are directly comparable.

Other characteristics of the sites measured include channel slope and cross-stream geometry. Bankfull stage was determined from longitudinal surveys along the channel (Whiting *et al*., 1999). The bankfull discharge was determined from the stage–discharge curve for the gauge. Additional information on the sites is found in King *et al*. (in press), Moog and Whiting (1998) and Whiting *et al*. (1999).

## CHARACTERIZATION OF SITES AND SURFACE, SUBSURFACE AND BED LOAD SIZES

The channels described lie within the Snake River Basin. Drainage area to the sites ranges from 99 to 4947 km$^2$ and channel slope ranges from 0·0005 to 0·0268 (Table I). Bedrock geology includes the Idaho Batholith, volcanic rock, and metasedimentary rock (Maley, 1987). Bedrock is exposed locally in the bed and/or banks of several of the channels; nonetheless, all sites have substantial alluvium that allows for the development of

Table I. Characteristics of study sites

| Site | Drainage area (km$^2$) | Slope | $D_{50s}$ (mm) | $D_{50ss}$ (mm) | $\frac{D_{50s}}{D_{50ss}}$ | $D^*$ |
|---|---|---|---|---|---|---|
| Boise River | 2150 | 0·0038 | 76 | 23 | 3·3 | 8·3 |
| Little Slate Creek | 162 | 0·0268 | 102 | 24 | 4·2 | 3·8 |
| Lochsa River | 3056 | 0·0023 | 126 | 26 | 4·8 | 8·7 |
| Lolo Creek | 106 | 0·0097 | 68 | 20 | 3·4 | 5·9 |
| MF Red River | 129 | 0·0059 | 50 | 18 | 2·8 | 3·7 |
| North Fork Clearwater River | 3522 | 0·0005 | 95 | 23 | 4·1 | 6·1 |
| Rapid River | 280 | 0·0108 | 63 | 16 | 3·9 | 1·7 |
| Selway River | 4947 | 0·0021 | 173 | 24 | 7·2 | 10·2 |
| South Fork Payette River | 1181 | 0·0040 | 110 | 19 | 5·8 | 8·1 |
| South Fork Red River | 99 | 0·0146 | 106 | 25 | 4·2 | 4·9 |
| South Fork Salmon River | 855 | 0·0008 | 31 | 14 | 2·2 | 3·1 |
| Valley Creek | 381 | 0·0040 | 40 | 21 | 1·9 | 1·8 |

 

a self-formed channel. The channel architecture at sites is either riffle–pool or planar bed (Montgomery and Buffington, 1997). The basins are largely forested and disturbance in the basins has been relatively modest with the exception of the South Fork of the Salmon River which experienced large influxes of sediment in the mid-1960s and in the winter of 1996/97 during large flood events. The annual sediment yield (bed load) at the sites ranges from 0·51 to 12·40 t $km^{-2}$ $a^{-1}$.

The 12 sites studied all have an armoured gravel or cobble bed (Table I). Median surface particle size ($D_{50s}$) at sites ranges widely from 31 to 173 mm. Median subsurface particle size ($D_{50ss}$) is similar between sites and ranges from 14 to 26 mm. The degree of armouring ($D_{50s}/D_{50ss}$) ranges from 1·9 to 7·2.

As noted above, the surface is coarser than the subsurface; the subsurface, in turn, is coarser than the bed load. Lisle (1995) defined the ratio $D^*$ as the median particle size of the subsurface grains compared to the median size of transport- and frequency-weighted bed load. Following Lisle, both the subsurface and bed load size distributions were truncated at a lower value to exclude grains that could be suspended (i.e. Sumer *et al*., 1996), in these cases, at 0·5 or 0·85 mm. The distributions also were truncated at an upper value of one-half the width of the sampler (usually truncated at 32 mm for a 3-inch sampler) to avoid the influence of the size of the orifice of the sampler as was done by Lisle. $D^*$ at the sites in Idaho ranged from 1·7 to 10·2. These values suggest that there is selective transport of the finer fraction (e.g. Ashworth and Ferguson, 1989).

## DIMENSIONLESS BED LOAD RATING CURVES

The potential for greater transport of bed load in general, and certain sizes of bed load in particular, can be demonstrated in dimensionless bed load rating curves by grain size. The dimensionless transport rate for size fraction i, $\phi_i$, is written as:

$$\phi_i = \frac{q_{s_i}}{\left[\left(\rho_s/\rho - 1\right)gD_i^3\right]^{0\cdot 5}}$$

following Einstein (1950) where $q_{s_i}$ is the volume flux of bed load by size fraction $i$, $\rho_s$ and $\rho$ are the sediment and fluid densities, respectively, $g$ is the gravitational acceleration, and $D_i$ is the particle diameter of the $i$th fraction. The dimensionless shear stress, $\tau^*$, is written as:

$$\tau^* = \frac{\tau}{(\rho_s - \rho)gD_i}$$

where $\tau$ is the total boundary shear stress. $\tau$ is taken here as the downslope component of the weight of the fluid, $\tau = \rho ghS$ where $h$ is the depth of flow and $S$ is the stream gradient over tens of channel widths. There was no attempt to remove form drag that reduces the total boundary shear stress to the grain shear stress. For these largely planar and relatively wide channels, the correction is small.

Figure 1 presents dimensionless sediment rating curves by one-phi size classes for the 12 sites. The bed load transport rate is weighted by the fraction of the particle size class on the channel bed (c.f. Ashworth and Ferguson, 1989). Following Ashworth and Ferguson (1989), the two envelope curves on Figure 1 encompass the theoretical transport capacity for several bed load equations (Meyer-Peter and Muller, 1948; Einstein, 1950; Parker, 1978).

Observed transport relations by size class at the study sites (Figure 1) are displaced below the theoretical curves (for which there is no supply limitation) at almost all shear stresses and for most grain sizes. In other words, there is less bed load transport at the sites than the theoretical curves would predict which is taken as evidence for supply limitation. Some workers (i.e. Ashworth and Ferguson, 1989) have ascribed the offset to the effect of hiding of the smaller fraction between the larger grains on the bed. While the effect of hiding is real, the larger issue is the relative absence of the finer grains: if the grains were just hiding, they would be found at the surface in the same quantities as found in the subsurface. The bed load transport rate for a particular size most closely approaches the theoretical curves at the highest shear stresses. At a site, the bed load transport rate for the largest grain sizes most closely approaches the theoretical curve. The observation that the larger size

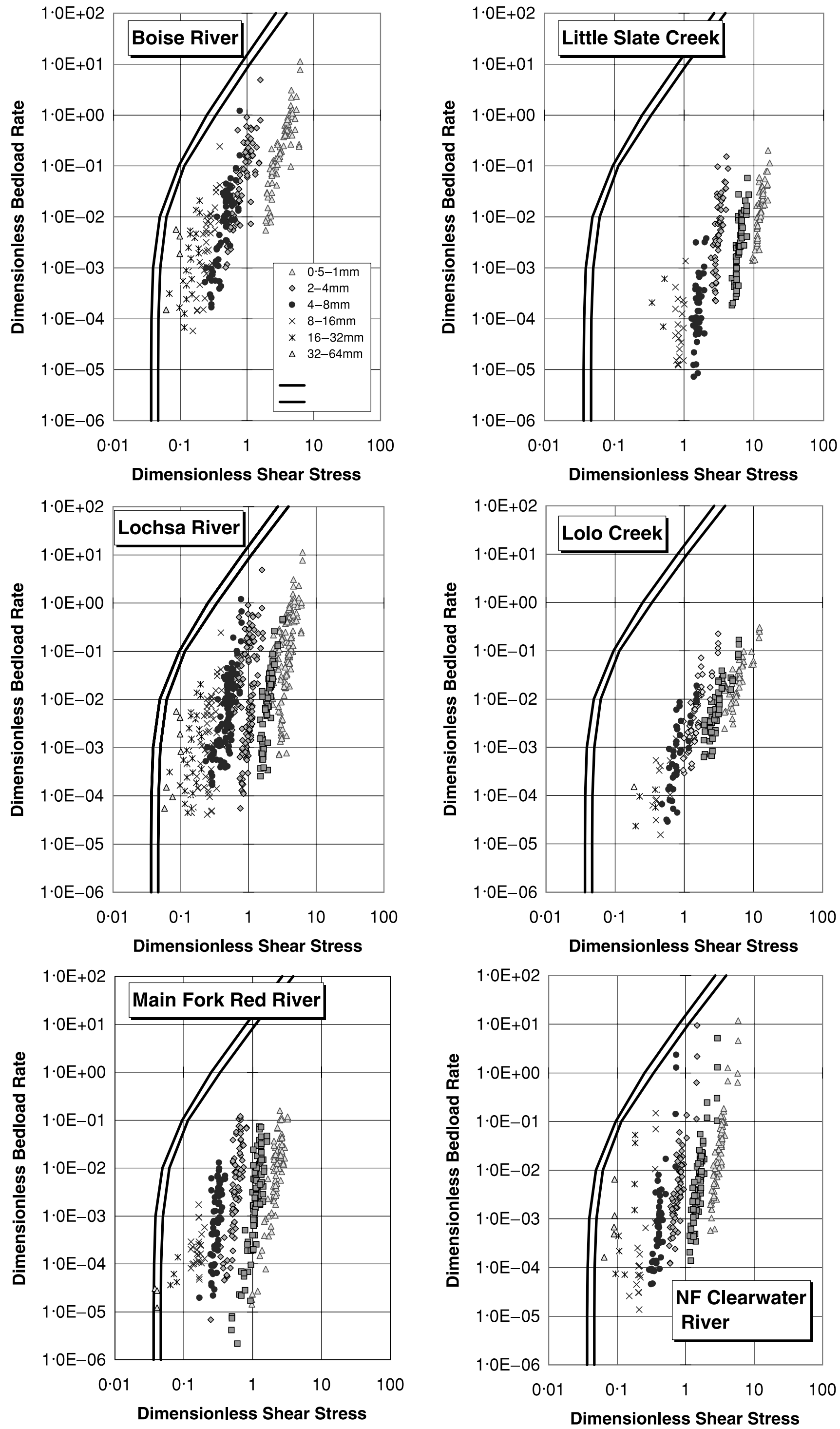


Figure 1. Dimensionless bed load rating curves by particle size class (one-phi interval) for the 12 sites. The two envelope curves encompass the theoretical transport for many bed load equations. The bed load transport rate is weighted by the fraction of the particle size class on the channel bed

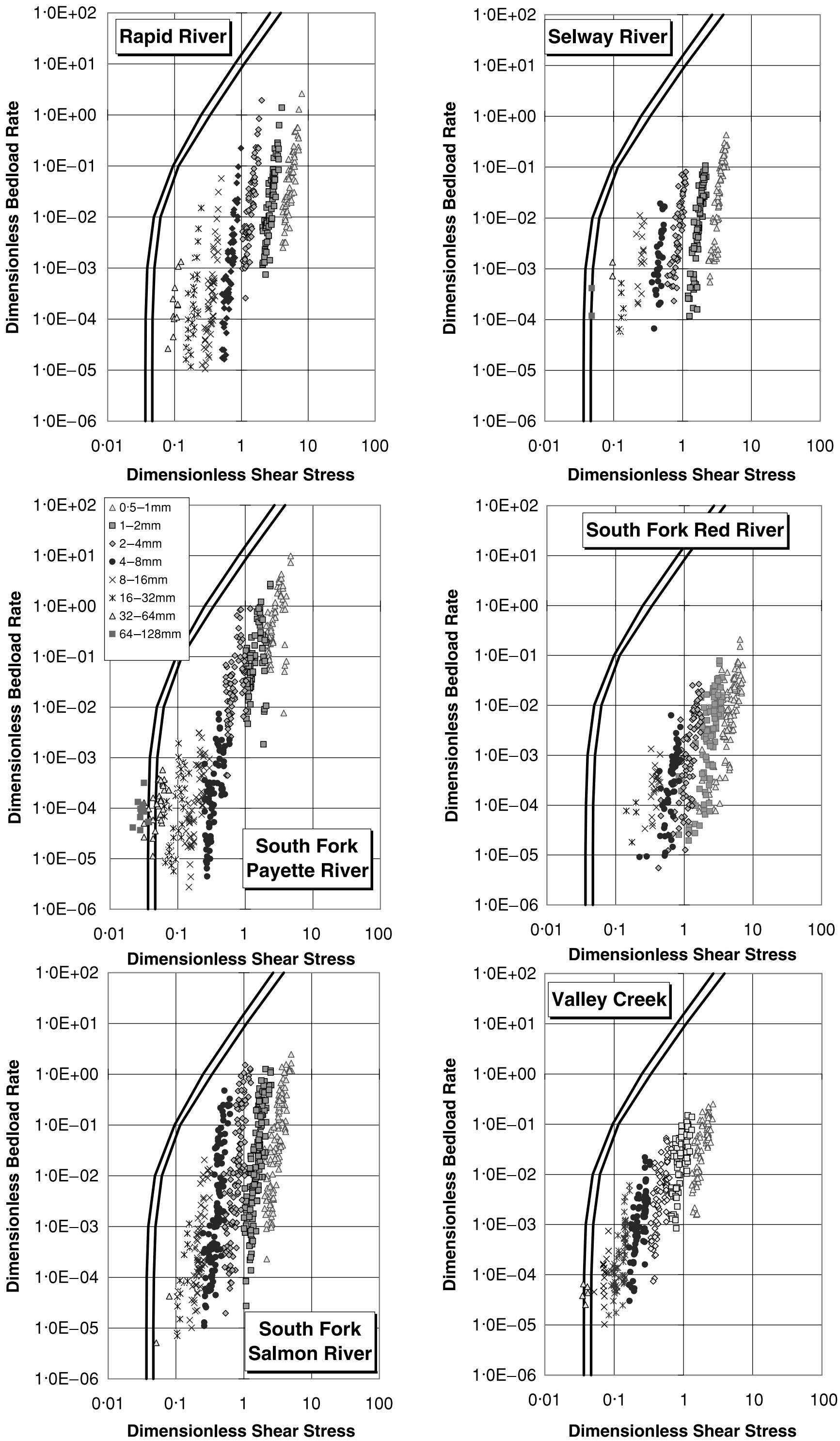


Figure 1. (*Continued*)

Table II. Characterization of the collapse size

| Site | Particle size approaching envelope curves (mm) | Collapse size (mm) | Surface per cent finer than collapse size | Subsurface per cent finer than collapse size | Per cent Qbf at initial motion of collapse size |
|---|---|---|---|---|---|
| Boise River | 32–64 | 54 | 39 | 73 | 95 |
| Little Slate Creek | >32 | 63 | 38 | 76 | 111 |
| Lochsa River | 32–64 | 63 | 26 | 74 | 89 |
| Lolo Creek | >32 | 45 | 34 | 71 | 115 |
| MF Red River | 32–64 | 38 | 42 | 68 | 108 |
| NF Clearwater River | 32–64 | 54 | 23 | 72 | 78 |
| Rapid River | >64 | 45 | 41 | 72 | 65 |
| Selway River | 64–128 | 108 | 32 | 86 | 90 |
| SF Payette River | 64–128 | 63 | 26 | 83 | 100 |
| SF Red River | >32 | 38 | 19 | 60 | 70 |
| SF Salmon River | 32–64 | 54 | 64 | 80 | 78 |
| Valley Creek | 32–64 | 32 | 42 | 62 | 53 |
| Mean | | | 36 | 73 | 88 |
| Range | | 32–108 | 19–64 | 60–86 | 53–115 |

classes lie closer to the theoretical curves suggests that supply limitations decrease, or even disappear, for the coarser fractions.

The smallest size class that lies approximately along the theoretical curve is reported in Table II. For all the sites, this corresponded to the 32–64 mm, 64–128 mm, >32 mm or >64 mm size class (reported for some as greater than a value because observed transport for these sizes was non-existent or was on too few occasions to determine which sizes lay approximately along the theoretical curve). Those values reported in Table II are taken to represent approximations of the break between finer particles whose bed load transport rate is governed by the supply of such size material and the applied stress (supply-limited sizes) and those coarser particles whose transport is governed by the applied stress (hydraulically limited sizes).

## DETERMINATION OF SUPPLY AND HYDRAULICALLY LIMITED PARTICLE SIZES

The supply- and hydraulically limited fractions can be distinguished also by comparing the sizes of particles in the surface and subsurface layers. Particles for which the transport capacity of the stream exceeds the supply of such particles will be winnowed from the bed surface and thus under-represented in the bed surface as compared to the subsurface. Sizes for which the supply approximately matches the stream's transport capacity should be similarly represented at the bed surface as in the subsurface once account is made of the winnowed grains.

Figure 2 provides an example from Lolo Creek of the procedure by which the supply- and hydraulically limited fractions can be differentiated by a comparison of the surface and subsurface size distributions. Figure 2a presents the initial size distributions of the surface and subsurface. Figure 2b shows the modified surface and subsurface size distributions reflecting the truncation of both samples at a lower value of 2 mm and the truncation of the surface size distribution at an upper value of 140 mm, the size of the coarsest grain common to both the surface and subsurface. Figure 2c–i shows the surface and subsurface size distributions as the finer material is removed at progressively narrower phi increments (1 phi, 1/2 phi, then 1/4 phi) and the size distributions recalculated. Figure 2j plots both the sum of the differences between the surface and subsurface size distributions at various values of the lower truncation normalized by the number of increments over which the two distributions were compared, as well as the squared sum of the differences normalized by the number of increments over which the distributions were compared. The surface and subsurface distributions were compared at the various intervals between the lower and upper value of truncation: these points are shown on the plots.

 

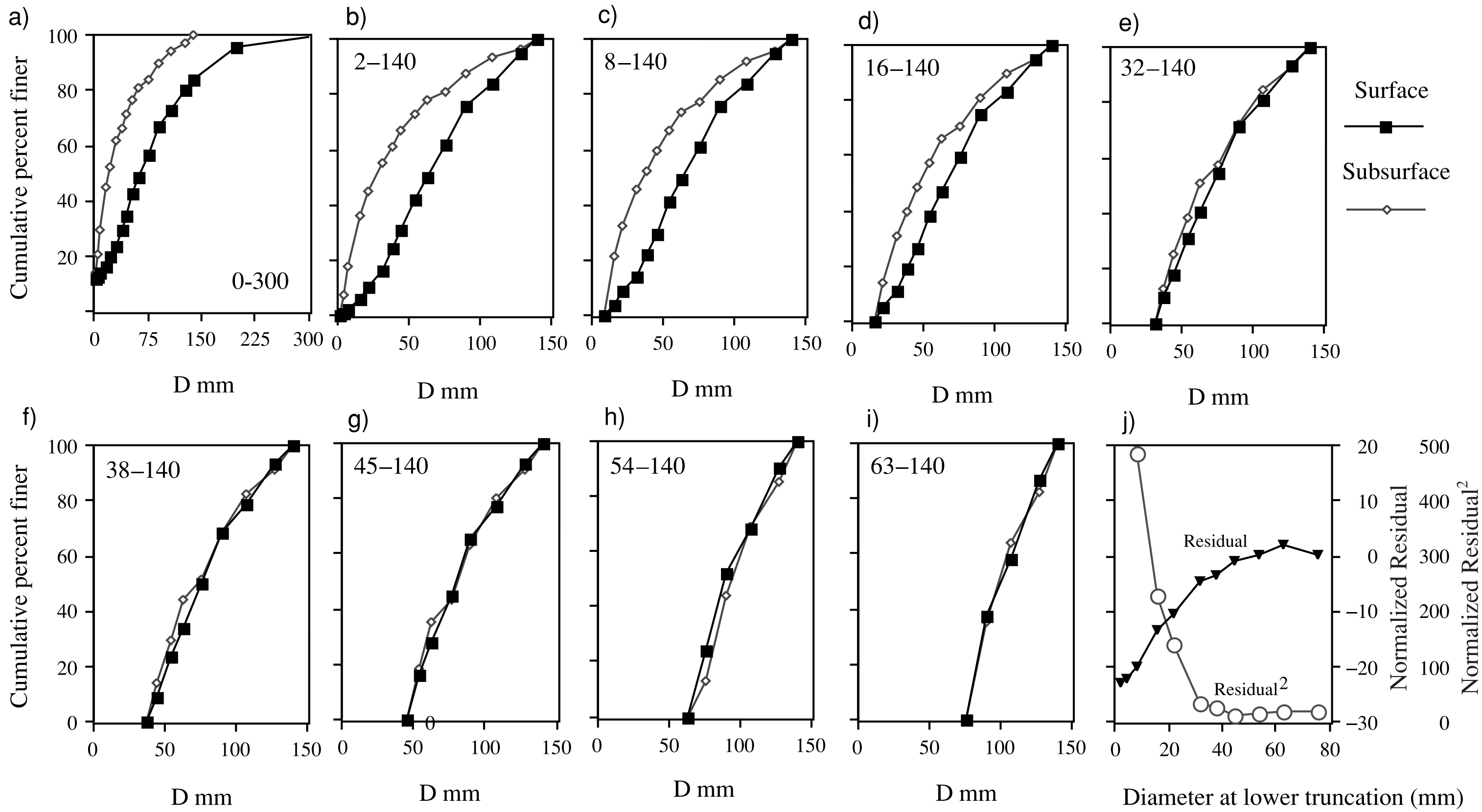


Figure 2. Example from Lolo Creek of the procedure by which the supply- and hydraulically limited fractions can be differentiated by a comparison of the surface and subsurface size distributions: (a) initial size distributions of the surface and subsurface; (b) modified surface and subsurface size distributions both truncated to sizes above 2 mm and less than 140 mm; (c) like (b) but sizes 8 to 140 mm; (d) like (b) but sizes 16 to 140 mm; (e) like (b) but sizes 32 to 140 mm; (f) like (b) but sizes 38 to 140 mm; (g) like (b) but sizes 45 to 140 mm; (h) like (b) but sizes 54 to 140 mm; (i) like (b) but sizes 63 to 140 mm; (j) the sum of the differences between the surface and subsurface size distributions at various values of the lower truncation and the squared sum of the differences both normalized by the number of increments over which the distributions were compared

The surface at Lolo Creek, as for all sites reported herein, is coarser than the subsurface (Figure 2a). Considering only the gravel (>2 mm) and particle sizes finer than 140 mm, the surface size distribution is still coarser than the subsurface (Figure 2b). As progressively larger material is removed at increments and the size distributions recalculated, the surface and subsurface size distributions become visually similar by 32 mm (Figure 2e). The distributions are most similar when the fraction finer than 45 mm is removed (Figure 2g). In other words, the surface and subsurface size distributions collapse to a common distribution when only grains equal to or coarser than 45 mm are included. Continued removal of finer material at 1/4 phi increments above 45 mm does not dramatically alter the similarity of the two distributions. Both the sum of differences and sum of squared differences in the percentiles at measured intervals (normalized by the number of intervals of comparison) drop to small values at 45 mm and values remains small for larger sizes (Figure 2j).

We interpret the similarity of the surface and subsurface size distributions at and above 45 mm, in the case of Lolo Creek, to reflect at least the partial removal of sizes finer than 45 mm from the surface relative to the subsurface. Thus, selective erosion has winnowed (at least partially) the bed surface of grains finer than 45 mm. Those particles winnowed from the bed are capable of being transported by the flow at a greater rate than they are supplied. These particles can be said to be supply-limited in their transport. Those particles found in similar proportions in the surface and subsurface (once winnowed grains are accounted for), in this case particles with diameters of 45 mm and coarser, are transported at a rate commensurate with their supply from upstream. Their transport can be said to be hydraulically limited. The observed transport of sizes smaller than 64 mm is less than the capacity (Figure 2) which is consistent with the inferences from comparison of the surface and subsurface size distributions.

The same procedure was used to determine the break between supply- and hydraulically limited particle sizes (collapse size) at the other sites in Idaho. The collapse size ranges from 32 to 108 mm at the sites (Table II).

## DISCUSSION

Those particle sizes identified in the analysis of the sediment rating curves by size class as being transported at a rate less than is possible given the boundary shear stress (displaced below the envelope curves) (Figure 1) correspond in general to the grains that are under-represented in the surface of the streambeds. Figure 3 compares

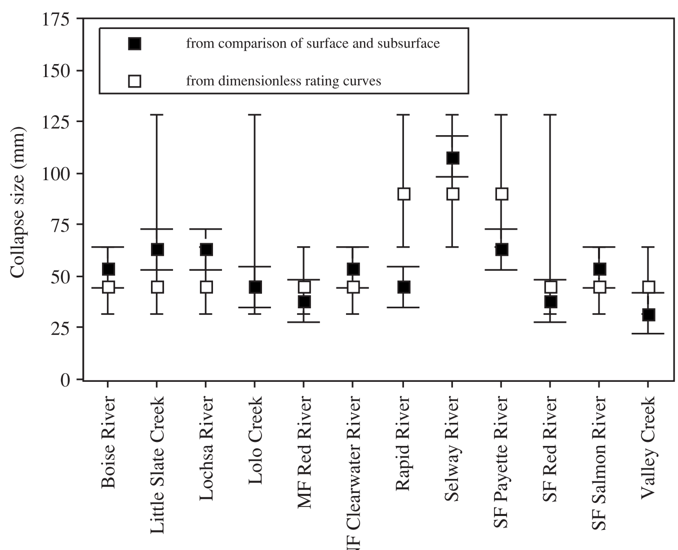


Figure 3. A comparison of the estimates of the upper limit of the supply-limited grain sizes from analysis of the dimensionless bed load rating curves and the comparison of the surface and subsurface size distributions. The geometric mean of the size class approaching the envelope curves is shown by the open square with the error bars at the sieve intervals. For those sites where the value is greater than a particular size, the midpoint of the next size interval is plotted and the upper bound is set at 150 mm. The solid square is the collapse size identified by comparing the surface and subsurface size distributions. The error bars (wide) for the collapse size are arbitrarily set at ±10 mm

 

for each site the finest size class whose dimensionless transport rate approaches the theoretical curve, which should be a lower limit on the size of hydraulically limited particles, with the finest particle size represented in the surface and subsurface similarly (collapse size), which should be an upper limit on supply-limited particles. The two estimates overlap at 11 of the 12 sites.

The break between supply- and hydraulically limited particle sizes as determined from the comparison of the surface and subsurface size distributions (collapse size) is finer than the median surface grain (except at the South Fork Salmon River) and coarser than the median subsurface grain. The collapse size corresponds on average to the $D_{36}$ of the surface size distribution (range: $D_{19}$ to $D_{64}$) and the $D_{73}$ of the subsurface size distribution (range: $D_{60}$ to $D_{86}$) at sites (Table II).

The flow discharge associated with initial motion of the collapse size averages 88 per cent of the bankfull discharge (range: 53 to 115 per cent) (Table II). The approximate flow discharge associated with the initiation of movement of the collapse size particle at sites was calculated by three methods (P. J. Whiting, 2000, unpublished report). By one method, a relationship was developed between the upper limit of the size class of the largest particle in each bed load sample for the years 1994–1997 and the corresponding flow discharge (c.f. Whiting *et al.*, 1999, figure 9). By another method, a relationship was developed between the size of the largest particle in samples from 1995–1997 (as a ratio to the median size of the surface grains) and the dimensionless shear stress calculated from the depth–slope product. The shear stress was in turn related to flow discharge. The third method relied upon the relationship between the size of coarsest particle collected in bed load samples from 1995–1997. The coefficient in the relation was modified so that the line passed through the instantaneous peak discharge in 1997 and the largest particle moved in 1997 as determined from field observations. The reported value for the critical discharge for the movement of the collapse size is the average of the three values.

Observations from one of the study sites in Idaho illustrate the effect of supply on the surface size distribution. In the winter of 1996/97 (after collection of most of the data presented herein), the basin of the South Fork of the Salmon River experienced numerous debris flows. Downstream of the debris flows, sediment deposits were dominated by sand and fine gravel. From limited bed load data collected after the floods, we estimate that the bed load at least doubled. Immediately after the floods, the armour along the stream as described in Tables I and II largely disappeared, as the surface became much finer with the influx of sand and finer gravel from hillslopes. Prior to the flood and landslides, we interpreted the collapse size of 54 mm to indicate that sizes less that 54 mm were supplied at a rate that was less than the capacity of the South Fork Salmon River hence the bed was winnowed of these sizes. Calculations of the collapse size using the surface particle size distribution measured after the floods give a collapse size of 4 mm. The influx of large volumes of material less than 54 mm eliminated the supply deficiency (at least for sizes greater than 4 mm) and the bed surface size distribution approached that of the subsurface as determined earlier. More recently, the channel bed has coarsened again as is consistent with the decrease in the sediment supplied from the landscape.

In a separate study of sediment supply, Moog and Whiting (1998) identified clockwise hysteresis in the relationship between flow and bed load transport (of all sizes greater than 0·85 mm) at the five sites with the smallest drainage area. Higher bed load transport was observed prior to the first annual exceedence of a flow discharge corresponding to about one-half bankfull. Moog and Whiting (1998) concluded that by about one-half bankfull discharge rising flows largely exhausted the supply of easily moved finer sediment provided since the last high flows by tributaries, slope wash, bank collapse, freeze–thaw cycles and bed disturbance. While this earlier paper considered hysteresis in the aggregate of all bed load sizes (thus did not identify a particle size that was limited in supply), the results and conclusions are consistent with the supply limitations presented herein.

The streams in Idaho each had collapse sizes that were relatively large: coarse gravel or cobbles. Data from Lisle (1995; pers. comm., 1998) and Kinerson (1990) were analysed to establish how variable the collapse size might be. These streams are Jacoby Creek, Lagunitas Creek, North Caspar Creek, Prairie Creek, Redwood Creek, and Sagehen Creek in northern California. The determination of particle size was similar to that employed in Idaho. The collapse size was determined in a manner identical to that described earlier. Collapse sizes for the streams in northern California corresponded to 16 and 90, 5·6 and 8, 5·6 and 4, and 5·6 and 32 mm, respectively. The collapse size ranged from $D_0$ to $D_{80}$ of the surface size distribution. For some of

 

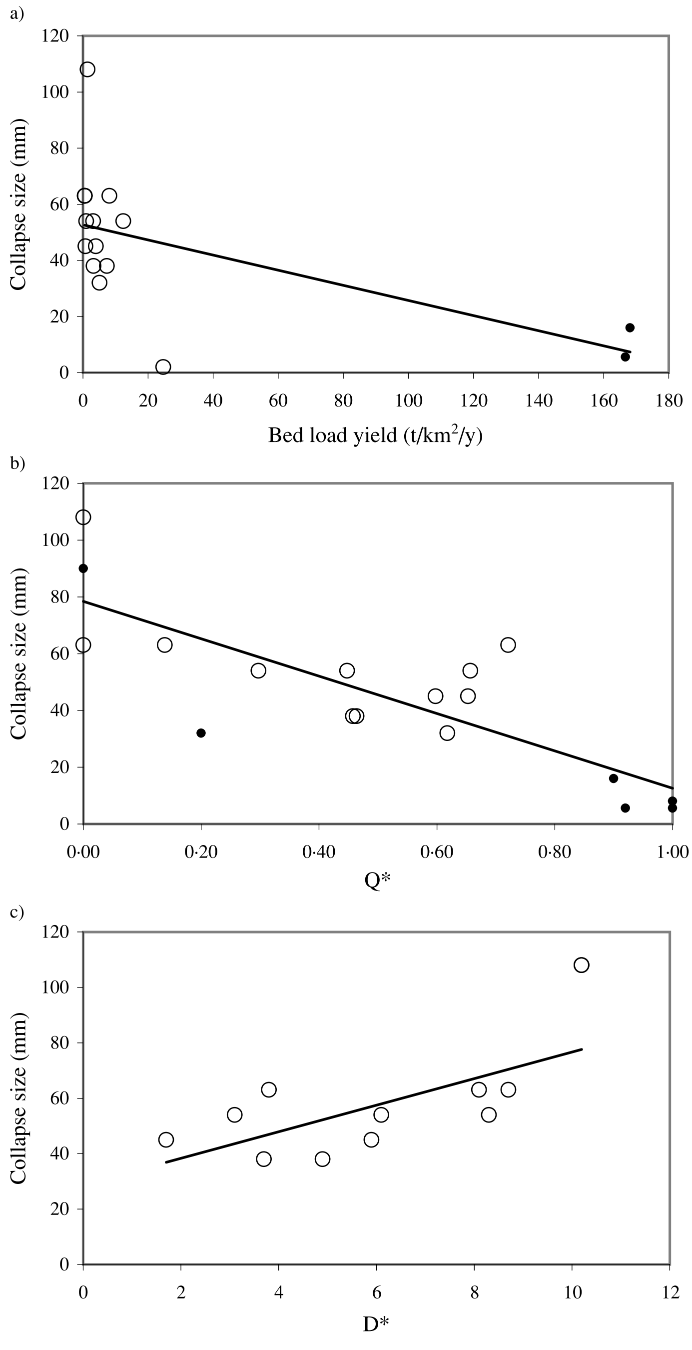


Figure 4. The collapse size decreases with the bed load yield (a) and with $Q_*$, the degree of supply limitation (b). The collapse size increases with $D_*$, the degree of selective transport (c). Open circles represent the data from Idaho and the smaller filled circles represent data from elsewhere as described in the text

these sites, the bed load transport or estimated transport relative to capacity ($Q_*$) (Dietrich *et al*., 1989) was known.

The data from Idaho and other sites indicate that the collapse size decreases as the bed load yield increases ($r^2 = 0{\cdot}34$) (Figure 4a) and decreases as $Q_*$ increases ($r^2 = 0{\cdot}70$) (Figure 4b). The collapse size increases with $D_*$, the degree of selective transport ($r^2 = 0{\cdot}45$) (Figure 4c).

 

## CONCLUSIONS

The examination of the bed load transport by size fraction and the relationship between the size of surface and subsurface grains suggest that the hypothesis that the surface armour develops when the transport capacity exceeds the supply can be taken further to identify those sizes for which the supply is less than the potential transport and those sizes for which the supply approximates the potential transport. The ability to differentiate these different populations of material in a channel extends our understanding of the effect of changing fluxes of material from the landscape (total and by size) and its influence on channel form and process. For example, increasing the supply of the finer material (supply-limited sediment) is not likely to lead to channel aggradation because the stream has some capacity to transport more material of these sizes, whereas increasing the supply of coarse material (hydraulically limited sediment) is likely to lead to channel aggradation because the channel is already transporting these sizes at capacity. Further, in situations where the upstream supply has been eliminated leading to the loss of gravel suitable for spawning, such analyses can aid in the development of gravel replenishment strategies.

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