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An Improved Method for Size Distribution of Stream Bed Gravel

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Abstract. Random sampling of surface rocks on a gravel bar is biased toward larger sizes which, because of their area, are more likely to be picked up. Weighting can eliminate this bias. Data on average weight of a single rock are used to change numbers of rocks to weights, thus yielding size frequency data in general agreement with a sieved and weighed sample. The question of what to sample depends on the use to which the data are to be put, and is not treated in detail in this paper.

INTRODUCTION

For many geomorphologic studies it is important to determine the size distribution of coarse sediments. The usual sediment size distribution is obtained by weighing fractions of a sample held on sieves of different sizes. Results are presented as cumulative percentages by weight of the sample equal to or smaller than the chosen sieve sizes. These take the form of an S-shaped or ogee cumulative curve, from which median size, quartile sizes, and other parameters may be read.

For the geomorphologist working with coarse material, the sieve method is often impossible to use because the sample of required size cannot physically be carried to the laboratory or even sieved in the field. It is then necessary to use a method of counting the number of surface pebbles of various sizes, the sample being made up of a random selection of individual rocks within an area of several hundreds of square feet [*Wolman,* 1954]. Though this method or variants of it have been used for field studies [for example, *Hack,* 1957], it suffers from the important disadvantage of giving results not comparable with the usual sieved analysis. The counting method gives a size distribution of numbers of rocks, not their weights.

Two quite distinct questions arise. First is the matter of what to sample or how to obtain a sample. Second (and quite separate) is the matter of how to treat the data once obtained. The present paper is primarily concerned with the second of these questions under conditions faced by the geomorphologist or river engineer in describing river gravels for hydraulic and morphologic studies.

For such purposes there is a special significance attached to the pebbles or rocks exposed at the surface. The exposed surface grains affect and are affected by the character of the fluid flow. The surface counting method provides a measure of the fluid dynamic texture of the actual boundary surface.

This emphasis does not imply that the surface rocks constitute the only gravel population of concern nor that areal sampling of surface rocks is the only or even the most important description needed. For some purposes a bulk sample may be preferable but, as mentioned earlier, may be impractical to obtain. The present discussion, then, should be viewed merely as an attempt to improve the procedure for using one kind of gravel bar sample and not a treatment of the utility of various kinds of sampling procedures.

While it is important for comparative purposes to express size distributions in the same conventional terms of weight, it should be remembered that this convention was adopted for convenience. It is uncertain whether weight (proportional to number of grains times size^3), or aspect area (number times size^2), or ratio weight to area (number times size) may be the most basic to natural sorting processes.

The field counting method is biased toward the large sizes. Because the method consists of picking up a rock just touched by the finger, eyes averted or closed, the larger the rock the greater its probability of being touched relative to neighboring smaller individuals.

The method here described corrects these deficiencies in the previous scheme. Rocks are reported in terms of weight, and their number or frequency is weighted to counteract the probability of picking a large rather than a small rock.

To study river morphology, there is some advantage to the Bagnold method of plotting that is applicable to all sediment size distribution data but different from the usual cumulative curve [*Bagnold,* 1937, 1954].

FIELD PROCEDURE

In a river each gravel bar, riffle, pool, or other topographical unit includes subunits having somewhat different size distribution of pebbles. I will use the word river locale to characterize a geographic area within which the size distribution of surface rocks is, to the eye, the same. The purpose discussed here is to determine this size distribution.

Collection of the sample is similar to that described by Wolman. Within a river locale, an area to be sampled is visualized as divided into about 100 unit areas, and one rock from each will be chosen at random to comprise the sample. The operator walks along several parallel lines and, depending on the size of the area to be sampled, picks up a rock at each pace or each stride (a stride is defined as 2 paces, or the distance between two footprints of the same foot). He reaches down over his toe with a finger and the first rock touched is picked up for measurement. To avoid bias his eyes are averted or closed at the time his finger reaches the ground.

Each pebble thus picked up is measured with a scale across its *B* or intermediate axis. The *B* axis measurement is tallied in one of the size categories differing by $(2)^{1/2}$, and designated, in millimeters, 2, 2.8, 4, 5.7, 8, 11.3, 16, 22.6, 32, and so forth. As a convention, the size is recorded in the field opposite the number representing the lower end of the size category. Thus, if a pebble is in the range from 32 to 45 mm, it is listed as 32. This is comparable to sieving in that it would be held on a 32-mm sieve.

After a rock is measured and tallied, it is cast away. The sample is considered complete when about 100 rocks have been measured.

In areas containing rocks too large to be picked up physically, the *B* axis measurement is made on the rock lying in place. Usually the smallest or *C* axis is perpendicular to the surface, so a measurement of the smaller of the two axes exposed is considered to be the *B* axis.

The pickup method fails for sizes less than 2 mm and cannot be used for sand. If the finger touches a place where the local grain size is in the sand size, or finer, the measurement is entered in a category of <2 mm. The procedure for computing and plotting is applicable to fine grains, but the small size fraction must be taken to the laboratory for sieving and weighing. The combination of the counted particle data with a sieved sample of the fine grain component is possible using percentage by weight of the combined sample, but when this is necessary the problem of choice of the sample is severe. A single river bar is often composed of surface material of gravel or cobble size in the upstream portion, changing gradually or abruptly to sand or finer materials at the downstream tip. The distribution itself is evidence that depositional factors are quite different in the two zones of the bar and should be sampled separately. It is also usual for the surface particle size distribution to be quite different from that immediately below the surface. The method of computing and plotting the data does not solve the ubiquitous problem of what sample is required for the particular investigation. The present paper deals primarily with the method and adds emphasis to the necessity for care and thought in approaching the more complicated matter of sample selection and interpretation.

TRANSLATION OF ROCK NUMBERS INTO WEIGHTS

Some of the difficulties involved in comparing line transect and other types of sampling with results of sieve analysis are indicated by a rather large literature, recent examples of which are *Van der Plas* [1962] and *Friedman* [1965]. There is the additional problem of transformation of number frequency to weight frequency, which for fine grained materials has been explored both in theory and in practice by *Sahu* [1964]. For the special problem faced by geomorphologists and river engineers who must describe coarse materials by some simple field method, the present paper may provide a useful tool even if it does not overcome the sampling difficulties.

The specific gravity of the most common rocks varies within narrow limits, say between 2.5 and 2.8. Compared with the variation of shape and size of particles which fall within a category of sieve sizes, the variation in specific gravity is usually not important. It is possible for many purposes to use an average weight of a single pebble of a given size category.

The natural subrounded gravel and cobbles, mostly quartzite and other metamorphics, found in streams draining into the Green River system on the western flank of the Wind River Mountains, Wyoming, were used to define the curve shown in Figure 1. It is an empirical relation of pebble size to average weight. The sizes were determined by sieving; for the largest rocks, squares of wire were made 45, 64, 90, and 128 mm on a side so that large rocks could be measured as if they were being sieved. Weights are averages for various samples; average values plotted represent the total weight divided by the number of rocks in the sample. The data plotted in Figure 1 included 78 weighed fractions comprising 3100 individual rocks.

In Table 1 the average weights of the different size classes is given, and these are multiplied by the observed number of rocks to provide an estimated total weight in each size class.

ADJUSTMENT FOR ROCK DIAMETER

The probability of the operator touching a given rock increases with the exposed area of rock. Therefore the large rocks tend to be picked up too frequently relative to their numerical frequency. This increased probability is proportional to the projected area or therefore to the square of the mean diameter. The number of rocks in each size class should therefore be weighted by a factor inversely proportionate to the square of the diameter of the B axis.

Having the estimated total weight of each size fraction in the pebble count sample, the values are adjusted by dividing by the square of the mean diameter of the B axis applicable to each size class. The percent of the total is the percentage by weight represented in each size class after adjustment for the bias toward large sizes represented in the original numbers of rocks counted.

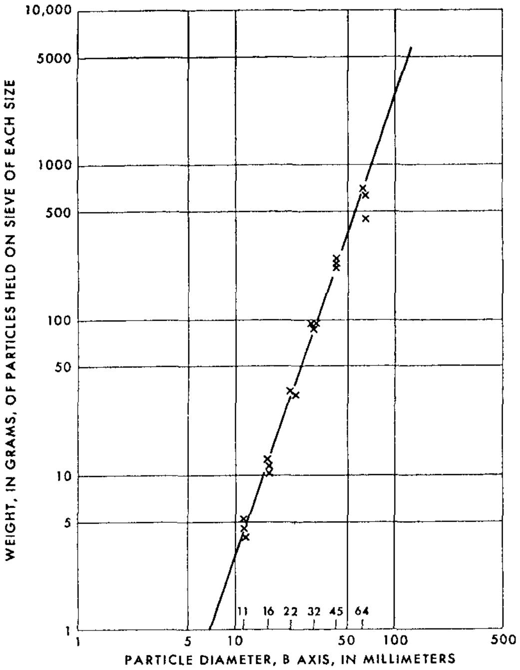

Fig. 1. Weights of individual rocks held on sieve of each size.

The schemes for plotting size distribution data of sediments are legion, and each has advantages for some purposes. It is without prejudice to the well-known work of Pettijohn, Krumbein, and other eminent sedimentologists when I say that for river studies I have found the method of plotting proposed by *Bagnold* [1954, p. 107–124] to be very useful. Other river geomorphologists [*Sundborg*, 1967] find the standard methods are best but with some minor variations introduced. My preference for the Bagnold method stems in part from the fact that it gives visual emphasis to a river problem of importance, namely, that rivers carrying coarse material seem to lay down sediments having sorting characteristics quite uniform on each limb of the size curve, but the two limbs are different.

The plot consists of the first differential or slope of the usual cumulative curve of percentage versus particle sizes, but the percentage by weight represented in a given size class has been divided by the log diameter interval, that is log $(2)^{1/2}$ in the case of my data.

The reason for dividing the percentage by the log diameter interval is that no special set of sieves needs to be used. A sieve sequence usually chosen to bear some ratio of grain diameters (often 2 or $(2)^{1/2}$) is not necessary.

TABLE 1. Size Distribution Data, Gravel Bar, Right Bank, Pole Creek below Hoot Owl Bridge, at Station 37 + 50 near Pinedale, Wyoming, June 21, 1967 (sample of two randomly selected areas 1 foot square, all surface particles; pebble count from same part of bar over an area 10 × 20 feet)

	Random Pebble Count in a 10 × 20 Foot Area, Data							Combined Sample from Two 1 × 1 Foot Areas Using All Surface Rocks Exposed in Each				
Sieve Opening Held On, mm	No. of Rocks	Average Weight of One Rock, gms	Estimated Total weight, gms	Mean Diameter Squared, mm^2	$\sum wt/d^2$, gms/mm^2	Percent of Total, %	$\frac{\text{Percent}}{\log (2)^{1/2}}$	No. of Rocks	Total Weight, gms	Percent of Total, %	$\frac{\text{Percent}}{\log (2)^{1/2}}$	Mean Size Sieve Opening, mm
256		40,000		92,000								303
180		15,000		45,800								214
128		5,600		23,100								152
90		2,100		11,500								107
64	2	700	1400	5,770	0.243	5.7	38	1	777	6.2	41	76
45	11	255	2800	2,920	0.959	22.6	150	10	2,949	23.4	156	54
32	20	94	1880	1,445	1.300	30.6	204	47	4,380	34.8	232	38
22.6	18	34	612	718	0.854	20.1	134	69	2,320	18.4	123	26.8
16	12	12	144	360	0.400	9.4	63	107	1,330	10.6	71	19.0
11.3	15	4.5	68	179	0.380	9.0	60	132	613	4.9	33	13.4
8	5	1.6	8	90	0.089	2.1	14	90	154	1.2	8	9.5
5.6	1	0.52	1	44	0.023	0.5	3	82	45	0.4	3	6.6
4		0.21		22				128	24	0.2	1	4.7
Total	84		6913		4.248	100.0		666	12,592	100.1		

The interval between sieves is arbitrary and must be eliminated to make the shape of the plotted graph independent of the interval chosen. If more categories of size are desired in any part of the total range, extra sieves can be added without changing the shape of the final plotted curve. The ratio of percentage weight to log diameter interval is plotted on a log scale. The plotting position on the abscissa scale is for each size class the geometric mean size of the interval.

In the example (Table 1 and Figure 2), the percentage-by-weight values are divided by the log of the ratio of the sieve size diameters in the size class. For example, the sieve opening of 64 mm is larger than the next smaller sieve, 45 mm, by the ratio $(2)^{1/2}$. The log $(2)^{1/2}$ is 0.150. Therefore the percentage by weight in the size class 45–64 mm, 22.6, is divided by 0.150 to give 150. The latter number is plotted on the ordinate (Figure 2) at an abscissa value of 54 mm, the geometric mean of the interval 45–64 mm, or $(2)^{1/4} \times 45$.

In the case that sieves or class intervals for measurement are chosen in a regular ratio, then the denominator in the heading of column 8 is a constant as shown, in this case log $(2)^{1/2}$. If the ratio of size classes varies, then a different denominator is used for each size class, as shown in the example used by *Bagnold* [1954, p. 114].

The resulting graph can be defined by three coefficients, the slopes of the two limbs, and the size at which the curve peaks. In regularly sorted materials, the two limbs are nearly straight lines over most of their plotted length, but compared with dune sand the coarse limb is generally short in riverbed materials. The straight portion of each limb is extended upward to intersection (dashed lines, Figure 2) and the 'peak size' is read directly on the abscissa scale at the intersection.

The 'coarse grade coefficient' is the slope of the right limb, measured as the linear height per unit horizontal linear distance. Because the coarse limb slopes downward to the right, its slope is always negative but for simplicity is written without sign. The slope of the straight portion of the fine grain limb is called the 'small grade coefficient.'

A measure of degree of sorting or grading is the sum of the reciprocals of these coefficients which *Bagnold* [1937, p. 256] called w, the 'width of a sand,' or of the sample.

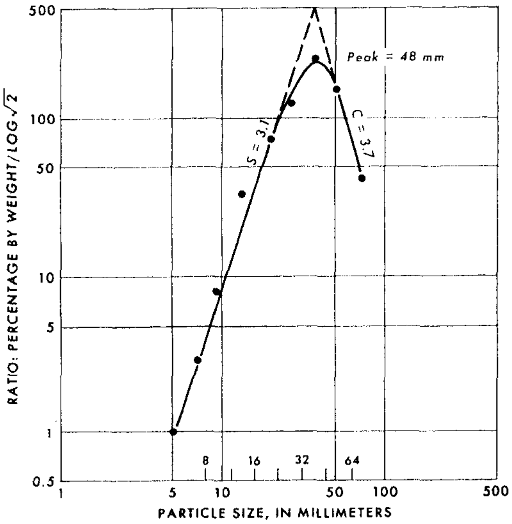

Fig. 2. Particle size distribution, gravel bar of Pole Creek below Hoot Owl Reach at station 37+50 near Pinedale, Wyoming.

These *coefficients* have a specific meaning. Since each of the two limbs approximates a straight line on the log-log plot, the percentage weight frequency approximates a definite power of the diameter. Thus if the coarse grade coefficient is c and the small grade coefficient is s, then along each limb of the graph the percentage weight varies respectively as d^{-c} and d^{s}.

SOURCES OF VARIANCE

The samples of gravel used as an illustration were taken from river bars recently exposed on a falling river stage after the annual peak due to snowmelt in the mountains in the upstream parts of the basins. It is possible that at time of peak flow the surface layer may have contained a wider tail of fine particles than is shown in the samples from the exposed bars. These fines may have been washed out with the decreasing load in transport as the water stage fell.

Differences between a sample sieved and weighed in the laboratory and one measured in the field may arise from several sources. The measurement of the B axis with a scale may give a somewhat different size distribution from that obtained by sieving the same rocks. To test this, samples collected by random pebble count method were measured both by ruler and by sieving. The samples were collected by the

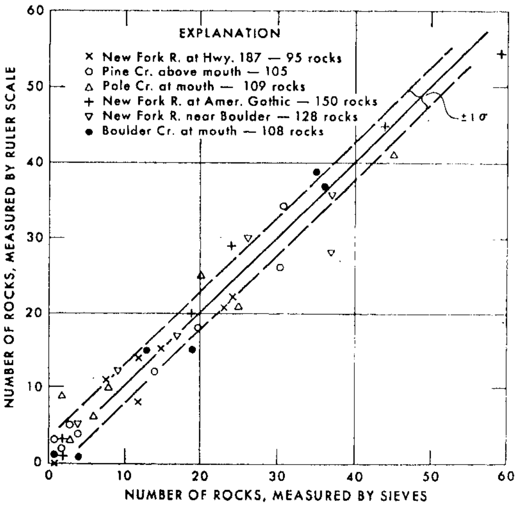

Fig. 3. Comparison of number of rocks in a given size class as determined by sieving and by measurement by ruler scale.

sampling method described earlier, picking up a rock after each stride. The rocks were measured by ruler but were saved instead of discarded. The samples were then taken to the laboratory and sieved to determine how many rocks were held on each sieve size. The total number or rocks involved was 695, and their sizes varied from 8 to 90 mm. The results of the two types of size determination are plotted on Figure 3 where each point represents a group of rocks in the same sample and of the same size class.

The two dashed lines represent the confidence limits one standard deviation away from the line of equal numbers. As can be read from the graph, the standard deviation is slightly larger than one rock. That is to say, there is a 66% chance that the number of rocks in a given size class determined by a ruler measurement will differ from the number determined by sieves by about ±1.

Perhaps a more practical measure of variance is the comparison of estimated total weight of a pebble count sample and the same rocks sieved and weighed. This comparison includes both the variance due to the measurement of size with a ruler, and the application of an average weight for particles in each size class.

Figure 4 presents the estimated weights and actual weights determined after sieving for 52 subsamples comprising 991 individual rocks. The dashed lines show a confidence limit of one standard deviation on each side of the line of perfect agreement. The variance is about ±30%. Thus, if a sample consisting of rocks in a variety of size classes is classified by size in the field with a ruler and the weights of each size class estimated, two-thirds of these weights will lie within ±30% of the weights determined by sieving and weighing.

Because the final graph is a plot of percentage by weight of the total sample represented by each size class, the usefulness is not restricted by the errors involved in estimating weights and sizes. Three size distribution graphs are plotted in Figure 5, showing typical comparison of size distribution by pebble count and that from sieving and weighing the same rocks. Comparison of the quantities depicting those graphs is shown in Table 2. The variance between the two methods is less than between river locales or sedimentation units.

DIFFERENCE WITHIN A RIVER LOCALE AND AMONG RIVERS

Sampling of all the materials in a stream bed, buried as well as surficial, gives different results from a surface-only sample. There are geologic and stratigraphic reasons why such a sample may be desired, but for geomorphic purposes of describing the bed relative to its hydraulic characteristics and the load first entrained, the surface material is important.

The surface of a bar is winnowed of fine grains and a larger percentage of fines, especially sand, occurs at a depth of 1-grain diameter below the surface. Samples of surface particles cannot be expected to be the same as samples taken only a few diameters below the surface.

Figure 6 shows size distribution curves for four depths on the same gravel bar. The surface rocks have, as in previous examples, more or less linear limbs. The difference between the random pebble count sample and a sample consisting of all the material in the top 1 inch is not the result of greater depth, for the peak size of surface material in this example is nearly the same. Rather the pebble count did not collect the sand grains hidden under and among the gravel. Thus, the top 1-inch sample (Figure 6) is similar to the pebble count except for the

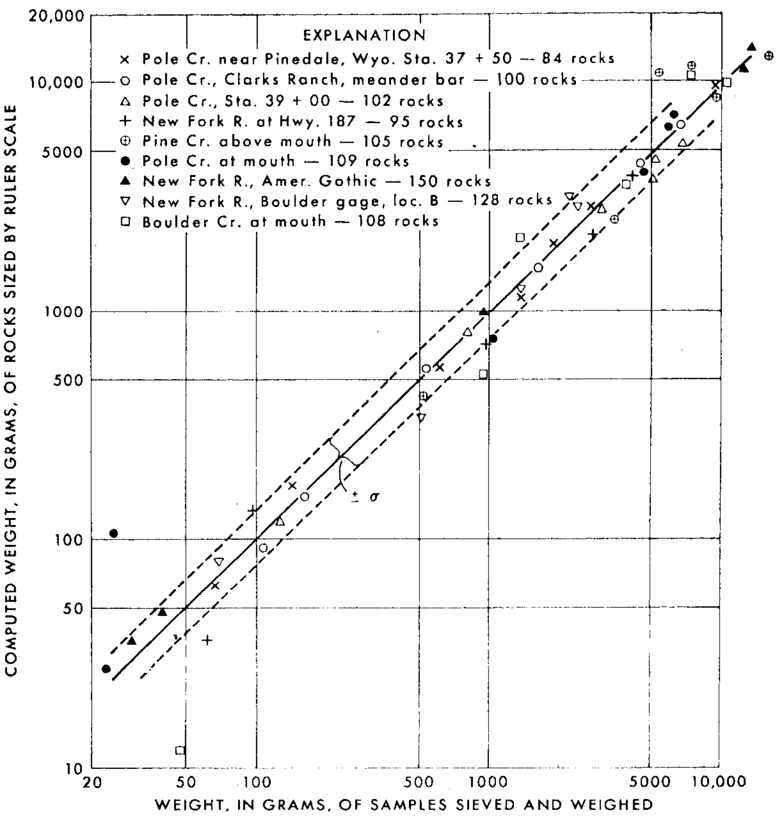

Fig. 4. Comparison of weights of 52 samples of gravel determined by (1) sieving and weighing and (2) measuring of size class by ruler scale then multiplying the number of rocks by average weight of a single rock.

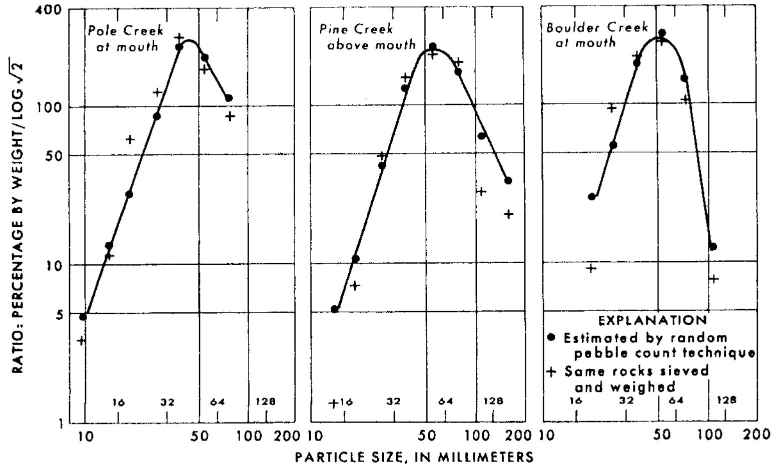

Fig. 5. Size distribution of the same sample by two techniques; data represent samples from three rivers near Pinedale, Wyoming.

TABLE 2. Comparison of Coefficients of Size Distribution Graphs Derived by Random Pebble Count Technique and Results of Sieving and Weighing the Same Rocks (data plotted in Figure 3)

		Boulder Creek at Mouth	Pine Creek above Mouth	Pole Creek at Mouth
Estimated	Peak size, mm	50	50	44
Weighed		50	50	39
Estimated	*C*	6.7	2.0	1.8
Weighed		6.0	3.1	1.8
Estimated	*S*	3.4	3.5	3.0
Weighed		5.0	4.4	3.3
Estimated	*W*	0.44	0.79	0.89
Weighed		0.37	0.55	0.86

Peak size. Read off particle size scale at intersection of the two limbs of the graph.

C, coarse grade coefficient, the slope of the coarse limb.

S, small grade coefficient, the slope of the limb for smaller sizes.

W, width of the sample, equals $1/c + 1/s$.

inclusion of a long tail of the small grade limb.

In the analysis of dune sand, Bagnold showed that double peak curves could be attributed to a mixture of sands derived from different processes or different sedimentation environments. The same seems to apply to riverbed materials. When the curves are double peaked or the limbs deviate importantly from straight lines, it probably means more than one source for the deposit, or more than one process.

Figure 6 includes a sample from which the surface inch was removed and the material taken from the layer between 1 and 3 inches below the surface. Also is plotted a bulk sample representing the surface down to a 6-inch depth. All four samples are within the same locale.

The samples that go deep contain a larger percentage of sand than the surface. Also the fine grade is not straight, and I infer that various processes have contributed to the deposition.

It can be seen that different depths even within the same locale give results which differ among themselves more than differences due to the estimating process.

Table 3 presents the four coefficients read from plotted curves for a variety of rivers. Included also is a sample of windblown sand. The peak size of these samples in the river materials varies from 0.28 mm to 150 mm. The sorting, measured by the width of the sample, is not correlated with peak size. The smaller values of *w* represent well sorted materials characterized by a narrow range of sizes.

The poorest sorted, as well as the best sorted, materials in the table are the bed sands of the Mississippi River. Several of the Mississippi River samples have a secondary peak. The very coarse material in the Yellowstone River sample is relatively well sorted despite the large value of peak size, 150 mm.

With the exception of the curves with double peaks, which are not uncommon, most of the data I have obtained from riverbeds have straight limbs, as had been found for dune sand; that is, the percentages of different sizes vary logarithmically about a peak size. The river data differ from dune sand principally in that in the former the coarse grade limb is shorter. That is, extremely large sizes relative to the peak size are missing. The attempts I have made to incorporate the use of the largest single rock in a locale have not given an improvement in the method so far described.

The logarithmic distribution (straightness of each limb) and similarity in slopes of these limbs among such a wide variety of sediments implies that the sorting process itself has a mechanism which leads to these characteristics.

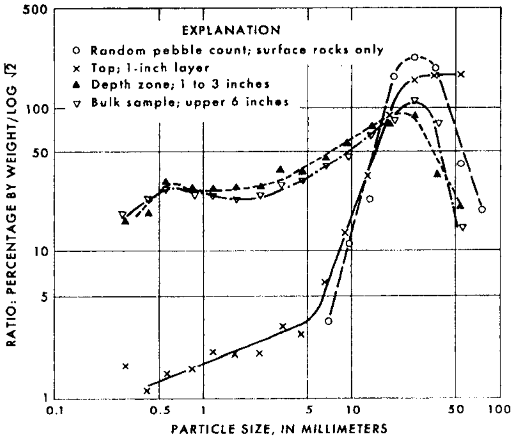

Fig. 6. Size distribution of four sampling zones in the same locale of a single gravel bar, Pole Creek at straight reach and Clark Ranch near Pinedale, Wyoming.

TABLE 3. Samples of Riverbed Materials from Different Environments Expressed as Bagnold Coefficients

Location	Peak Size, mm	Coarse Grade Coefficient, *C*	Small Grade Coefficient, *S*	Width of the Sample, *W*	Second Peak, mm
Mississippi River bed material					
2 miles below Cairo, Illinois*	0.47	0.52	3.2	2.23	
98 miles below Cairo*	0.54	0.72	1.10	2.30	25
350 miles below Cairo*	0.40	2.4	3.1	0.74	10
500 miles below Cairo*	0.50	1.8	5.4	2.41	
Above head of passes	0.28	8.1	7.3	0.26	0.03
Ephemeral arroyos, semiarid area, near Santa Fe, New Mexico					
Ancha Chiquita near Rancho Montozo	0.88	1.2	2.1	1.31	
Tributary to Hermanas Arroyo near Las Dos	0.52	0.51	3.5	2.29	
Gravelly streams of moderate size at base of Wind River mountains near Pinedale, Wyoming					
New Fork 2 miles south of Pinedale	38	3.4	4.5	0.51	
Pine Creek 1/8 mile south of Pinedale	42	2.7	4.2	0.61	
Pine Creek at mouth	32	1.5	3.2	0.98	
Boulder Creek at mouth	50	6.7	3.4	0.44	
Large rivers in western mountain region					
Yellowstone River at Billings, Montana	150	3.1	1.9	0.85	
Green River near Daniel, Wyoming	65	2.2	3.1	0.77	
Blown sand in desert dunes, Libya [*Bagnold*, 1954, p. 120]	0.50	4.6	1.7	0.80	

* From U. S. Waterways Experimental Station Paper 17, [*U. S. Army Corps of Engineers*, 1935].

The theoretical nature of the mechanism has already been explored initially by *Bagnold* [1956, p. 284]. Further theoretical work is needed, as it holds promise of yielding a general explanation of the sorting process in relation to sediment transport theory.

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