United States Department of Agriculture

Forest Service

Rocky Mountain Research Station

General Technical Report RMRS-GTR-74

May 2001

Sampling Surface and Subsurface Particle-Size Distributions in Wadable Gravel- and Cobble-Bed Streams for Analyses in Sediment Transport, Hydraulics, and Streambed Monitoring

Kristin Bunte
Steven R. Abt

Abstract

Bunte, Kristin; Abt, Steven R. 2001. Sampling surface and subsurface particle-size distributions in wadable gravel- and cobble-bed streams for analyses in sediment transport, hydraulics, and streambed monitoring. Gen. Tech. Rep. RMRS-GTR-74. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 428 p.

This document provides guidance for sampling surface and subsurface sediment from wadable gravel- and cobble-bed streams. After a short introduction to streams types and classifications in gravel-bed rivers, the document explains the field and laboratory measurement of particle sizes and the statistical analysis of particle-size distributions. Analysis of particle parameters, including shape, density, and bulk density are also discussed. The document describes the spatial variability of bed-material particle sizes as well as the horizontal and vertical structure of particle deposits. The discussion of sampling procedures and equipment helps the user to make appropriate selections that support the sampling objective. Sample-size estimates may be obtained from empirical data or computed from statistical relationships between sample size and accuracy. The document explains a variety of methods, their usage and prerequisites. A detailed discussion of sampling schemes guides the user to select appropriate spatial sampling patterns necessary to produce representative samples.

Keywords: Particle-size analysis, spatial variability of bed-material size, sampling procedures, sampling equipment, sample size, spatial sampling schemes.

Authors

Kristin Bunte is a Fluvial Geomorphologist and Research Associate at the Engineering Research Center, Department of Civil Engineering, Colorado State University. She received M.S. and Ph.D. degrees in geography from the Freie Universität Berlin in Germany.

Steven R. Abt is Professor and Associate Dean for Research and Graduate Studies, College of Engineering, Colorado State University, and a Professional Engineer. He received M.S. and Ph.D. degrees in civil engineering from Colorado State University.

You may order additional copies of this publication by sending your mailing information in label form through one of the following media. Please specify the publication title and number.

Telephone	(970) 498-1392
FAX	(970) 498-1396
E-mail	rschneider@fs.fed.us
Web site	http://www.fs.fed.us/rm
Mailing Address	Publications Distribution Rocky Mountain Research Station 240 West Prospect Road Fort Collins, CO 80526

Sampling Surface and Subsurface Particle-Size Distributions in Wadable Gravel- and Cobble-Bed Streams for Analyses in Sediment Transport, Hydraulics, and Streambed Monitoring

Kristin Bunte
Steven R. Abt

Prepared in support of the National Stream Systems Technology Center mission to enable land managers to "secure favorable conditions of water flows" from our National Forests.

Preface

The Stream Systems Technology Center of the Rocky Mountain Research Station, U.S. Forest Service, initiated the generation of this compendium of methods because National Forest System streams are dominated by gravel caliber material and sound guidelines for characterizing the bed material of gravel- and cobble-bed streams are needed by hydrologists, fisheries and aquatic biologists, and geomorphologists. This project was initiated to meet Forest Service needs and at the same time provide an encyclopedia of approaches as a basis for the Federal Interagency Sedimentation Project Task Committee to adopt selected methods as standard approaches in the future. Work on this reference was initiated by an ad hoc team convened by Larry Schmidt of the Stream Systems Technology Center. The team included Ron Copeland, U.S.Army Corps of Engineers, Phil Zrymiak, Environment Canada, Randy Parker, U.S. Geological Survey, and Jim Fogg, Bureau of Land Management.

Streambed analysis and sampling in gravel-bed rivers have received increasing attention, especially over the last few years. Publishing activity reflects this trend. During the late 1970s and the 1980s, one or two papers were published per year on gravel-bed sampling procedures, sample size estimates, or sampling schemes. This number has risen to about five to seven papers per year during the 1990s. Despite the interest in the topic, a comprehensive compilation of these approaches is lacking and users need a reference to guide them through the multi-layered aspects of bed-material sampling.

The work presented is intended to fill this gap. Obviously attempting to comprehensively synthesize a rapidly evolving technology is impossible. This effort represents our knowledge at this point in time. Consequently, the user must exercise judgment in applying the approaches provided herein to specific sampling projects. To make the best choice of methods, the user should have knowledge about gravel-bed rivers and the processes forming them. The selection of a sampling program (where, how, and how much to sample) significantly influences the outcome.

Acknowledgments

This publication was made possible through a partnership between the Rocky Mountain Research Station, National Stream Systems Technology Center and the Colorado State University, Engineering Research Center. The authors appreciate the helpful contributions and assistance of John Gray, Tom Lisle, Sue Hilton, Dave Dawdy, Paul Bakke, Mike McNamara, Mark Weinhold, Mohammed Samad, and Pete Klingeman. A special thanks to John Buffington, John Potyondy, and John Ritter for their significant effort in carefully reviewing this document and to Kurt Swingle and Louise Kingsbury who helped edit the final manuscript.

Contents

Copyrighted Materials

We would like to thank the following publishers, individuals, and organizations for granting permission to reproduce, quote, or modify the following figures as needed. We have made every effort to contact those we believe to be the original sources to obtain these permissions. If there have been any accidental errors, omissions, or misattributions we apologize to those concerned.

Geological Society of America, for **Fig. 1.1**; taken from Figs. 2 and 3 on p. 600 and 601 in: Montgomery, D.R. and J.M. Buffington, 1997. Channel-reach morphology in mountain drainage basins. *Geological Society of America Bulletin* 109 (5): 596-611.

Elsevier Science , for **Fig. 1.2**; taken from Fig. 1 on p. 174 in: Rosgen, D.L., 1994. A classification of natural rivers. *Catena* 22: 169-199.

John Wiley and Sons, for **Fig. 2.3** and **Fig. 2.4**; taken from Fig. 3.3 on p. 51 in: Church, M., D.G. McLean and J.F. Walcott, 1987. River bed gravels: sampling and analysis. In: *Sediment Transport in Gravel-Bed Rivers.* C.R. Thorne, J.C. Bathurst and R.D. Hey (eds.).

American Society of Civil Engineers, for **Fig. 2.5**; taken from Fig. 1 on p. 844 in: Hey, R.D. and C.R. Thorne, 1983. Accuracy of surface samples from gravel bed material. *Journal of Hydraulic Engineering*, 109 (6): 842-851.

Society for Sedimentary Geology, for **Fig. 2.10**; taken from Fig. 1 on p. 940 in: Ibbeken, H., 1974. A simple sieving and splitting device for field analysis of coarse grained sediments. *Journal of Sedimentary Petrology* 44(3): 939-946.

Society for Sedimentary Geology, for **Fig. 2.15**; taken from Fig. 3 on p. 1218 in: Ibbeken, H., 1983. Jointed source rock and fluvial gravels controlled by Rosin's law: a grain size study in Calabria, South Italy. *Journal of Sedimentary Petrology* 53(4): 1213-1231.

Springer Verlag, for **Fig. 2.18**; taken from Fig. A-1 on p. 585 in: Pettijohn, J.F., P.E. Potter, and R. Siever, 1972. *Sand and Sandstone*. Springer Verlag, New York, Heidelberg, Berlin, 619 pp.

American Geophysical Union, for **Fig. 2.21**; taken from Fig. 6 on p. 1183 in: Sambrook Smith, G.H., A.P. Nicholas and R.I. Ferguson, 1997. Measuring and defining bimodal sediments: Problems and implications. *Water Resources Research* 33 (5): 1179-1185.

Society for Sedimentary Geology, for **Fig. 2.22**; taken from Figs. 3 and 4 on p. 66 and 67 in: Krumbein, W.C., 1941. Measurement and geological significance of shape and roundness of sedimentary particles. *Journal of Sedimentary Petrology* 11 (2): 64-72.

University of Chicago Press, for **Fig. 2.23**; taken from Figs. 2 and 6 on p. 119 and 123 in: Sneed, E.D. and R.L. Folk, 1958. Pebbles in the lower Colorado River, Texas: a study in particle morphogenesis. *Journal of Geology* 66: 114-150.

Society for Sedimentary Geology, for **Fig. 2.24**; taken from Plate 1 in: Krumbein, W.C., 1941. Measurement and geological significance of shape and roundness of sedimentary particles. *Journal of Sedimentary Petrology* 11 (2): 64-72.

Society for Sedimentary Geology, for **Fig. 2.25**; taken from Figs. 1 and 2 on p. 932 in: Crofts, R.S., 1974. A visual measure of single particle form for use in the field. *Journal of Sedimentary Petrology* 44 (3): 931-934.

Press Syndicate of the University of Cambridge, for **Fig. 2.27**; taken from Fig. 7.1 (top) on p. 112 in: Julien, P., 1995. *Erosion and Sedimentation*. Cambridge University Press, Cambridge.

Press Syndicate of the University of Cambridge, **Fig. 2.28**; taken from Fig. 7.1 (bottom) on. P. 112 in: Julien, P., 1995. *Erosion and Sedimentation*. Cambridge University Press, Cambridge

John Wiley and Sons, for **Fig. 3.1**; taken from Fig. 11.6 (top) on p. 302 in: Church, M. and D. Jones, 1982. Channel bars in gravel-bed rivers. In: *Gravel-bed Rivers. Fluvial Processes, Engineering and Management*. R.D. Hey; J.C. Bathurst and C.R. Thorne (eds.).

Newbury Hydraulics Ltd., for **Fig. 3.3**; taken from Fig. 3.9 on p. 76 in: Newbury, R.W. and M.N. Garboury, 1993. *Stream Analysis and Fish Habitat Design. A Field Manual*.

John Wiley and Sons, for **Fig. 3.4**; taken from Figs. 11.1 and 11.4 on p. 295 and 299 in: Church, M. and D. Jones, 1982. Channel bars in gravel-bed rivers. In: *Gravel-bed Rivers. Fluvial Processes, Engineering and Management*. R.D. Hey; J.C. Bathurst and C.R. Thorne (eds.).

John Wiley and Sons, for **Fig. 3.5**; taken from Figs. 2 and 4 on p. 634 and 636 in: Thompson, A., 1986. Secondary flows and the pool-riffle unit: a case study of the processes of meander development. *Earth Surface Processes and Landforms* 11: 631-641.

American Geophysical Union, for **Fig. 3.6**; taken from Fig. 26 on p. 1379 in: Dietrich, W.E. and J.D. Smith, 1984. Bedload transport in a river meander. *Water Resources Research* 20 (10): 1355-1380.

John Wiley and Sons, for **Fig. 3.7**; taken from Fig. 6.9 on p. 215 in: Whiting, P., 1996. Sediment sorting over bed topography. In: *Advances in Fluvial Dynamics and Stratigraphy*, P.A. Carling and M.R. Dawson (eds.).

Blackwell Science, for **Fig. 3.8**; taken from Fig. 6.6 on p. 134 in: Church, M., 1992. Channel morphology and typology. In: *The Rivers Handbook*, Vol. 1. P. Calow and G.E. Petts, eds.

John Wiley and Sons, for **Fig. 3.9**; taken from Fig. 8 on p. 258 in: Sear, D.A., 1996. Sediment transport processes in pool-riffle sequences. *Earth Surface Processes and Landforms* 21: 241-262.

John Wiley and Sons, for **Fig. 3.10**; taken from Fig. 13.3 on p. 285 in: Lisle, T.E. and M.A. Madej, 1992. Spatial variation in armouring in a channel with high sediment supply. In: *Dynamics of Gravel Bed Rivers*. P. Billi, R.D. Hey, C.R. Thorne and P. Tacconi (eds.).

Blackwell Science for **Fig. 3.11**; taken from Fig. 6.4 a on p. 130 in: Church, M., 1992. Channel morphology and typology. In: *The Rivers Handbook*, Vol. 1. P. Calow and G.E. Petts, eds.

American Geophysical Union, for **Fig. 3.13**; taken from Fig. 1 b on p. 1904 in: Buffington, J.M. and D.R. Montgomery, 1999a. A procedure for classifying textural facies in gravel-bed rivers. *Water Resources Research* 35 (6):1903-1914.

John Wiley and Sons, Inc., for **Fig. 3.14**; taken from Fig. 3.1 on p. 47 in: Church, M., D.G. McLean and J.F. Walcott, 1987. River bed gravels: sampling and analysis. In: *Sediment Transport in Gravel-Bed Rivers*, C.R. Thorne, J.C. Bathurst and R.D. Hey (eds.).

Geological Society of America, for **Fig. 3.16**; taken from Fig. 1 on p. 105 in: Whiting, P.J., W.E. Dietrich, L.B. Leopold, T.G. Drake, and R.L. Shreve, 1988. Bedload sheets in heterogeneous sediment. *Geology* 16: 105-108.

John Wiley and Sons, for **Fig. 3.18**; taken from Fig. 9.2 in: Todd, S.P., 1996. Process deduction from fluvial sedimentary structures. In: *Advances in Fluvial Dynamics and Stratigraphy*. P.A. Carling and M.R. Dawson (eds.),

Canadian Society of Petroleum Geologists, for **Fig. 3.19**; taken from Fig. 2 on p. 79 in: Brayshaw, 1984. Characteristics and origin of cluster bedforms in coarse-grained alluvial channels. In: S*edimentology of Gravels and Conglomerates*. E.H. Koster and R.J. Steel, (eds.), Canadian Society of Petroleum Geologists, Memoir 10: 77-85.

John Wiley and Sons, for **Fig. 3.20**; taken from Fig. 9 a on p. 129 in: Bunte, K. and J. Poesen, 1994. Effects of rock fragment size and cover on overland flow hydraulics, local turbulence and sediment yield on an erodible soil surface. *Earth Surface Processes and Landforms* 19: 115-135.

John Wiley and Sons, for **Fig. 4.12**; taken from Fig. 2 on p. 62 in: Ibbeken, H. and R. Schleyer, 1986. Photo sieving: a method for grainsize analysis of coarse-grained, unconsolidated bedding surfaces. *Earth Surface Processes and Landforms* 11: 59-77.

John Wiley and Sons, for **Fig. 4.13**; taken from Fig. 3 on p. 62 in: Ibbeken, H. and R. Schleyer, 1986. Photo sieving: a method for grainsize analysis of coarse-grained, unconsolidated bedding surfaces. *Earth Surface Processes and Landforms* 11: 59-77.

American Geophysical Union, for **Fig. 4.15**; taken from Figs. 3 and 4 on p. 1906 and 1907 in: Buffington, J.M. and D.R. Montgomery, 1999a. A procedure for classifying and mapping textural facies in gravel-bed rivers. *Water Resources Research* 35 (6): 1903-1914.

American Society of Civil Engineers, for **Fig. 4.19**; taken from Fig. 9 on p. 964 in Diplas, P. and J.B. Fripp, 1992. Properties of various sediment sampling procedures. *Journal of Hydraulic Engineering* 118 (7): 955-970.

National Council of the Paper Industry for Air and Steam Improvement, for **Fig. 4.28**; taken from Fig. 15.3 on p. A-16 in: National Council of the Paper Industry for Air and Stream Improvement (NCASI) 1986. A comparison of four procedures for determining streambed substrate composition. Technical Bulletin 481. Source: Walkotten, W.J., 1976. An improved technique for freeze sampling streambed sediments. U.S.D.A. Forest Service Research Note PNW-281, 11 pp.

American Fisheries Society, for **Fig. 4.30**; taken from Fig. 1 on p. 854 in: Rood, K. and M. Church, 1994. Modified freeze-core technique for sampling the permanently wetted streambed. *North American Journal of Fisheries Management* 14: 852-861.

Chapman & Hall, for **Fig. 4.31**; taken from Fig. 4-5 on p. 54 in: Lewis, D.W. and D. McConchie, 1994. *Analytical Sedimentology*.

American Society of Civil Engineers, for **Fig. 4.32**; taken from Fig. 5 on p. 1170 in: Kellerhals, R. and D.I. Bray, 1971. Sampling procedures for coarse fluvial sediments. *Journal of the Hydraulics Division, ASCE,* 97 (HY8): 1165-1180.

American Society of Civil Engineers, for **Fig. 4.36**; taken from Fig. 2 on. p. 541 in: Fraccarollo, L. and A. Marion, 1995. Statistical approach to bed-material surface sampling. *Journal of Hydraulic Engineering* 121 (7): 640-545.

John Wiley and Sons, for **Fig. 5.1**; taken from Fig. 2.4 on p. 11 in: Gilbert, R.O., 1987. *Statistical Methods for Environmental Pollution Monitoring*. Van Nostrand Reinhold, New York, 320 pp.

American Geophysical Union, for **Fig. 5.4**; taken from Fig. 4 on p. 2630 in: Marcus, W.A., S. Ladd and J. Stoughton, 1995. Pebble counts and the role of user-dependent bias in documenting sediment size distributions. *Water Resources Research* 31 (10): 2625-2631.

Society for Sedimentary Geology, for **Fig. 5.8**; taken from Fig. 5 on p. 658 in: Rice, S. and M. Church, 1996b. Sampling surficial fluvial gravels: the precision of size distribution percentile estimates. *Journal of Sedimentary Research* 66 (3): 654-665.

Society for Sedimentary Geology, for **Fig. 5.10**; taken from Fig. 7 on p. 660 in: Rice, S. and M. Church, 1996b. Sampling surficial fluvial gravels: the precision of size distribution percentile estimates. *Journal of Sedimentary Research* 66 (3): 654-665.

Society for Sedimentary Geology for **Fig. 5.11**; taken from Fig. 8 on p. 661 in: Rice, S. and M. Church, 1996b. Sampling surficial fluvial gravels: the precision of size distribution percentile estimates. *Journal of Sedimentary Research* 66 (3): 654-665.

John Wiley and Sons, for **Fig. 5.19 a-c**; taken from Fig. 2 on p. 1066 in: Ferguson, R.I. and C. Paola, 1997. Bias and precision of percentiles of bulk grain size distributions. *Earth Surface Processes and Landforms* 22 (11): 1061-1078.

John Wiley and Sons, for **Fig. 5.20** taken from Fig. 7 on p. 1073 in: Ferguson, R.I. and C. Paola, 1997. Bias and precision of percentiles of bulk grain size distributions. *Earth Surface Processes and Landforms* 22 (11): 1061-1078.

John Wiley and Sons, for **Fig. 5.21 a-c**; taken from Fig. 5 on p. 1070 in: Ferguson, R.I. and C. Paola, 1997. Bias and precision of percentiles of bulk grain size distributions. *Earth Surface Processes and Landforms* 22 (11): 1061-1078.

John Wiley and Sons, for **Fig. 5.22 a-c**; taken from Fig. 7 on p. 1073 in: Ferguson, R.I. and C. Paola, 1997. Bias and precision of percentiles of bulk grain size distributions. *Earth Surface Processes and Landforms* 22 (11): 1061-1078.

Wildland Hydrology, for **Fig. 6.7**; taken from Fig. 5-18 on p. 5-27 in: Rosgen, D.L., 1996. *Applied River Morphology*.

American Society of Civil Engineers, for **Fig. 6.9**; taken from Fig. 8 and 9 on p. 1114 in: Crowder, D. W. and P. Diplas, 1997. Sampling heterogeneous deposits in gravel-bed streams. *Journal of Hydraulic Engineering* 123 (12): 1106-1117.

American Society of Civil Engineers, for **Fig. 6.10**; taken from Fig. 7 on p. 1113 in: Crowder, D. W. and P. Diplas, 1997. Sampling heterogeneous deposits in gravel-bed streams. *Journal of Hydraulic Engineering* 123 (12): 1106-1117.

Kristin Bunte and Steven Abt
Fort Collins, May, 2001

List of Notations and Units

a	Particle *a*-axis, the longest axis	mm
a	Coefficient	—
a, β	Confidence levels	—
b	Particle *b*-axis, the intermediate axis	mm
b	Coefficient	—
A	Area	m^2, mm^2
A_p	Area covered by one particle	m^2, mm^2
A_s	Sampling area	m^2, mm^2
B	Bimodality index (Wilcock 1993)	—
B^*	Bimodality index (Sambrook Smith et al. 1997)	—
c	Particle *c*-axis, the shortest axis	mm
C	Corey shape factor, similar to particle sphericity ψ	—
b_m	Mean particle *b*-axis size	mm
$b_{m(sq)}$	Mean *b*-axis size of particles retained on a square-hole sieve	mm
$b_{m(rd)}$	Mean *b*-axis size of particles retained on a round-hole sieve	mm
d	Diameter (e.g., of a freeze core)	m
d_p	Penetration depth of adhesive in areal sampling	mm
d_{Smin}	Minimum sampling depth	cm
D	Particle size or particle sieve size	mm
D_{cm}	Particle size of the coarse mode of a distribution	mm
D_{ci}	Particle size of the center of the ith size class	mm
D_{dom}	Dominant large particle diameter within an area of concern (reach)	mm
D_e	Vertical extent of particle embedded or buried below the bed	mm
D_f	Height with which a particle protrudes above the bed	mm
D_{fm}	Particle size of the fine mode of a distribution	mm
D_{gm}	Geometric mean particle size of a distribution	mm
D_i	Particle size of the ith size class	mm
D_{ic}	Center of class particle size computed from the geometric mean of the upper and lower border of the size fraction (equal to logarithmic mean, or arithmetic mean of particle sizes in ϕ-units)	mm ϕ
$D_{i(sq)}$	Particle size of the ith size class on a square-hole sieve	mm
$D_{i(rd)}$	Particle size of the ith size class on a round-hole sieve	mm
D_m	Mean particle size of a distribution	mm
D_{max}	Largest particle	mm
D_{mc}	Particle size of the weight midpoint of a sieve class; i.e., particle size that halves the particle mass per size class	mm
D_{min}	Smallest particle	mm
D_{mode}	Mode of particle size distribution	mm
D_n	Nominal particle diameter, $(a \cdot b \cdot c)^{1/3}$	mm
D_p	p^{th} percentile of a particle-size distribution	mm
D_{pass}	Smallest sieve size through which a particle passed	mm
$D_{pass(i)}$	Smallest sieve size passed by all particles of the *i*th size class	mm
D_{pm}	Mean of p^{th} percentile obtained from several subsamples	mm
D_{ret}	Largest sieve size that retained a particle	mm
$D_{ret(i)}$	Largest sieve size retaining all particles of the *i*th size class	mm
D_s	Size of sieve opening	mm
D_t	Total vertical extent of a particle	mm
D_{50}	Median particle size of a distribution	mm
D_{84}	84^{th} percentile of a particle-size distribution (subscript number refers to percentile)	mm
D_{84m}	Mean particle size of the D_{84} in subsamples	mm
e	Void ratio, ratio of volume of voids to total volume	—
$e_{\%Dm}$	Percentage error around the mean particle size in mm (D_m)	mm
$e_{\pm\phi m}$	Absolute error around the mean particle size inϕ-units (ϕ_m)	ϕ

$e_{\%\phi m}$	Percentage error around the mean particle size in ϕ-units (ϕ_m)	ϕ
$e_{\pm Dp}$	Absolute error around the mean particle size for the p^{th} percentile in mm.	mm
$e_{\pm \phi p}$	Absolute error around the mean particle size for the p^{th} percentile in ϕ-units	ϕ
E	Embeddedness	—
$E\%$	Percent cobble embeddedness	%
F	Particle form factor distinguishing between platy, bladed and elongated particle shapes	—
f	Frequency by weight or number of a particle-size class	
$f_{\%}$	Percent frequency by weight or number of a particle-size class	%
$G_{\phi i}$	Frequency of an equivalent Gaussian distribution of ϕ_i	—
$G_{\%i}$	Percent frequency of an equivalent Gaussian distribution of ϕ_i	%
g	Acceleration due to gravity = 9.81	m/s^2
i	ith size class	—
k	Total number of size classes	—
K	Particle size of the bottom particle	mm
ku	Arithmetic kurtosis of a distribution	—
ku_g	Geometric kurtosis of a distribution (hypothetical)	—
l	Length (e.g., of a freeze core)	m
L_{Di}	Frequency of an equivalent lognormal distribution of D_i	—
$L_{\%i}$	Percent frequency of an equivalent lognormal distribution of D_i	%
m	Mass	g, kg
m_{Dmax}	Mass of the D_{max} particle size	g, kg
m_{mi}	Mean weight of particles retained on the ith size class	g, kg
m_i	Mass of particles retained on the i^{th} size class	g, kg
m_s	Mass of all particles contained in a sample	g, kg
m_{ss}	Mass of all particles contained in a subsample	g, kg
m_{tot}	Mass of all particles contained in the total sample	g, kg
$m_{\%i}$	Percent frequency of particle mass for the i^{th} size class	%
$m_{\%cmi}$	Percent frequency of particle mass for the i^{th} size class that is part of the coarse mode of the distribution	%
$m_{\%fmi}$	Percent frequency of particle mass for the ith size class that is part of the fine mode of the distribution	%
n_{emb}	Number of embedded particles	—
n_{exp}	Number of particles exposed on the bed surface	—
n_i	Number of particles retained for ith size class	—
n	Total number of particles per sample	—
$n_{\%\ exp}$	Percent of particles exposed on the bed surface	%
n_i	Number of particles retained in the ith size class	—
n_{ph}	Number of particles contained within a photographed area	—
n_r	Number of particles at the reference site	—
n_s	Number of particles at the study site	—
n_{tot}	Total number of samples	—
n_2	Second sample	—
$n_{\%i}$	Percent frequency of particle numbers for the i^{th} size class	%
$\Sigma n_{\%i}$	Cumulative percent frequency of particle numbers for the i^{th} size class = p_i	%
p	Porosity, ratio of volume of voids to total volume	—
$p_{i,a\text{-}w}$	Weight fraction (m_i/m_{tot}) of the i^{th} size class of an area-by-weight particle-size distribution	—
$p_{i,0}$	Weight fraction (m_i/m_{tot}) of the i^{th} size class of a volume-by-weight size-distribution converted from an area-by-weight distribution	—
$p_{i,v\text{-}w}$	Weight fraction (m_i/m_{tot}) of the i^{th} size class of a volume-by-weight particle-size distribution	—
p_s	Proportion of fines in bed material at a study site	—

p_r	Proportion of fines in bed material at a reference site	—
$p_{v,0}$	Porosity, ratio of volume of voids to total sediment volume (bulk)	—
p	Probability associated with z_p values	—
p	Percentile (in decimals)	—
p_i	Percentile of a cumulative distribution for i^{th} size class (in decimals)	—
p_{Ai}	Percentile for i^{th} size class of an areal sample	—
p_{Gi}	Percentile for i^{th} size class of a grid sample	—
p_{ri}	Percentile for i^{th} size class of a sample using a rigid combination method	—
p_{fi}	Percentile for i^{th} size class of a sample using a flexible combination method	—
P	Particle roundness index	—
P_m	Mean particle roundness index for a deposit	—
P_{cm}	Proportion of sediment contained in the coarse distribution mode	mm
P_{fm}	Proportion of sediment contained in the fine distribution mode	mm
P_{1m}	Proportion of sediment contained in the primary distribution mode	mm
P_{2m}	Proportion of sediment contained in the secondary distribution mode	mm
q	Number of subsamples	
r	Number of replicate samples for a given sample or subsample size	—
r	Largest radius of a circle that can be inscribed into a corner of a particle	mm
R	Largest radius of a circle that can be inscribed into the entire particle	mm
R_{Di}	Frequency of an equivalent Rosin distribution of D_i	—
$R_{\%i}$	Percent frequency of an equivalent Rosin distribution of D_i	%
s	Sample standard deviation, or sorting coefficient of an approximately normal distribution	mm or ϕ
s_{Dm}	Standard deviation of the mean particle size in subsamples	mm or ϕ
s_{50}	Standard deviation of the median particle size D_{50} in subsamples	mm or ϕ
s_g	Geometric standard deviation or sorting coefficient of a sample distribution	—
sk	Arithmetic skewness of a distribution	—
sk_g	Geometric skewness of a distribution	mm, mm^2
s_p	Standard error around percentile p	mm or ϕ
s_R	Sorting coefficient for a Rosin distribution	mm or ϕ
s_I	Sorting coefficient as computed by Inman (1952)	ϕ
S	Particle compactness	—
V	Volume (e.g., of a freeze core)	m^2
V_s	Volume of sediment without pores	m^3, liter
V_t	Total volume of sediment	m^3, liter
V_v	Volume of voids or pores in sediment	m^3, liter
z_p	Values of the x-axis of a true, bell-shaped normal distribution	—
Φ	Pivot angle, angle of repose, intergranular friction angle	°
ϕ	Particle size unit = $-\log_2(D)$	ϕ
ϕ_m	Arithmetic mean particle size of a distribution	ϕ
ϕ_i	Particle size in ϕ-units of the i^{th} size class	ϕ
ϕ_{ci}	Particle size in ϕ-units of the center of the i^{th} size class	ϕ
ϕ_{m1}	Particle size of the primary distribution mode	ϕ
ϕ_{m2}	Particle size of the secondary distribution mode	ϕ
ϕ_{50}	Median particle size of a distribution	ϕ
ϕ_{84}	84^{th} percentile of a particle-size distribution (subscript number refers to percentile)	ϕ
ϕ_p	p^{th} percentile of a particle-size distribution	ϕ
γ	Specific weight $\rho \cdot g$	$g/cm^2 \cdot s^2$, $kg/m^2 \cdot s^2$
μ	Distribution mode	mm or ϕ
π	Dimensionless constant, 3.141	—

ρ	Density	g/cm^3, kg/m^3
ρ_f	Fluid density	g/cm^3, kg/m^3
ρ_s	Density of a sediment particle	g/cm^3, kg/m^3
ρ'_s	Submerged particle density	g/cm^3, kg/m^3
ρ_b	Sediment bulk density	g/cm^3, kg/m^3
ρ_{sub}	Subsurface sediment bulk density	g/cm^3, kg/m^3
σ	Standard deviation of the population distribution	any unit
Σ	Sum	any unit
ψ	Particle size unit, $= \log_2(D) = -\phi$	ψ
ψ	Particle sphericity	—
ψ_r	Effective particle settling sphericity	—