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VARIABILITY OF WOLMAN PEBBLE SAMPLES IN GRAVEL/COBBLE BED STREAMS

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Abstract. Wolman [1954] pebble sampling is the most commonly used method to estimate surface bed grain sizes in gravel-bed streams. A few studies documented different results between individual operators or repeated measurements within the same channel-reach obtained by this method. We tested potential differences in pebble sample distributions and related grain-size percentiles (D_{10}, D_{50} and D_{90}) between two fluvial geomorphologists and two almost inexperienced students in three channel-reaches and one gravel bar. None of sampled locations provided statistically consistent particle-size distributions and related percentiles when comparing measurements of all operators. The samples of experienced fluvial geomorphologists were most consistent for the channel-reaches with assumed widest range of particle sizes; a post-hoc test documented significant differences for the gravel bar and the lower plane bed reach. Medians of particle-size distributions for the gravel bar were equal for three of four operators; the fourth operator probably included also coarser particle population between the channel bed and bar. It implies that 100 sampled particles are most likely sufficient only for D_{50} estimations and homogenous sediment populations (i.e. well-sorted gravel bars). In any other case, much larger number of particles should be sampled in gravel/cobble bed streams to obtain narrower confidence limits of related grain-size percentiles.

Key words: Wolman sampling, bed sediments, mountain stream, flysch

INTRODUCTION

Information about grain-size characteristics of channel-bed sediments is necessary for many practical purposes, including hydraulic engineering and estimations of bedload transport by convent equations or descriptions of habitats for aquatic biota and related river restorations. Wolman [1954] sampling is the most commonly used method to obtain estimations of surface bed grain sizes in wadable gravel-bed streams and it has been

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applied in many conditions allowing direct measurements of individual grains by metric rule or template [e.g. Galia and Hradecký 2014, Radecki-Pawlik et al. 2014, Witkowski and Wysmołek 2015]. At the first stage, cross-sectional transects or a grid should be established to proportionally cover studied channel-reach. Then, at least 100 individual pebbles are picked and their intermediate b-axis is measured. The randomness of selected grains without any subjective preference of an operator could be achieved by fixed sampling points (e.g., regular intervals established by a tape) or the operator should select a grain beneath the tip of the toe of his boot without looking down.

The first limitation of pebble samples is their truncation at lower end due to inability to measure bed particles smaller than several millimetres [Kondolf and Lisle 2016]. However, some studies also documented that classic Wolman [1954] pebble counts or their later modifications [e.g Bevenger and King 1995] can lead to different results (i.e., medians, individual grain-size percentiles) between individual operators or repeated measurements within the same channel-reach. Rice and Church [1996] recommended measurements of at least 400 particles and usage of bootstrapping to obtain reliable estimations of grain-size percentiles and their standard errors. Wohl et al. [1996] cautioned against direct comparisons of grain-size distributions between channels or within a single channel through time if more than one operator performs the sampling. Daniels and McCusker [2010] demonstrated significant differences between individual operators at three sample sites as well as differences between replicated measurements by one operator even by using special sampling template. They also documented highest variability for higher grain-size percentiles > D_{50} and for low-order streams with more heterogeneous bed sediments. Kondolf [1997] criticized mixing grain-size populations from different channel units into a single sample, which naturally prevents from achievement of the same grain-size distributions by replicated measurements at one site. Bunte et al. [2009] identified notable differences between obtained grain-size characteristics due to sampling at different areas and cross-sections within the studied pool-riffle reach. Additional dissimilarities arose from different sampling techniques of modified pebble counts.

The aim of the study was to test potential differences in obtained pebble samples and related grain-size percentiles (D_{10}, D_{50} and D_{90}) between two experienced fluvial geomorphologists and two PhD students almost inexperienced in bed sediment sampling. We selected one stepped-bed channel-reach, two plane bed channel-reaches and a gravel bar as representative sampling locations. We hypothesise that (i) there will be greater differences in obtained pebble samples between individual operators in stepper-bed stream than on gravel bar consisted of relatively homogenous sediment and (ii) experienced operators will provide more consistent estimations of grain-size percentiles than non-geomorphologists.

STUDIED STREAMS

The Wolman samplings were conducted in the Čeladenka Stream and its upper tributary Magurka Stream (Fig. 1). Both represent typical gravel/cobble bed wadable streams of the Moravskoslezské Beskydy Mts, highest mountains of Czech flysch Western Carpathians. Three sampling locations were selected in Čeladenka including two plane

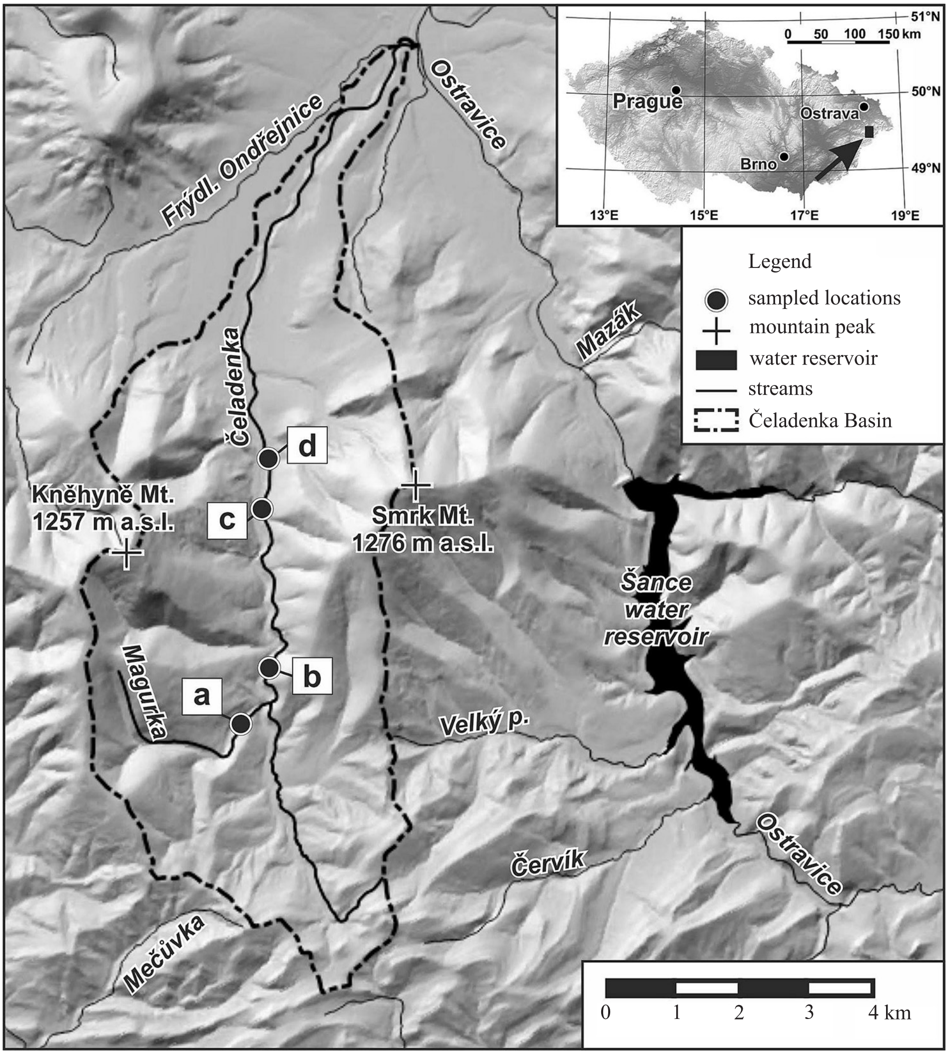

Fig. 1. Location of sampled channel-reaches: a – step-rapid (Magurka), b – plane bed UP (Čeladenka), c – plane bed DW (Čeladenka), d – gravel bar (Čeladenka)

bed channel-reaches and one forced gravel bar upstream retention check-dam (Fig. 2). The bankfull width of evaluated plane bed reaches was about 6 m and the mean channel gradient varied between 0.015–0.020 $m \cdot m^{-1}$. The channel gradient along sampled gravel bar was 0.007 $m \cdot m^{-1}$ and the dimensions of the bar were 40 m in length and 8 m in width. The sampled location in Magurka had step-rapid character following the channel-reach classification of flysch-based headwaters [Galia and Hradecký 2014]. It had also slightly higher channel gradient (0.025 $m \cdot m^{-1}$) when compared to Čeladenka and the bankfull width was 4.5 m. Studied channel-reaches were located in Godula Member, which produces the coarsest sandstone particles in the context of flysch rock structures of the Moravskoslezské Beskydy Mts. Despite this fact, local bed sediments have prominently low proportion of boulder fraction > 256 mm, which predisposes to intensive bedload transport during floods and low stability of channel beds [Galia et al. 2015]. Small-magnitude, but relatively frequent debris flows were identified along the Čeladenka Stream and its tributaries, which represent important inputs of coarse sediments into channel network [Šilhán 2014, Galia and Škarpich 2015].

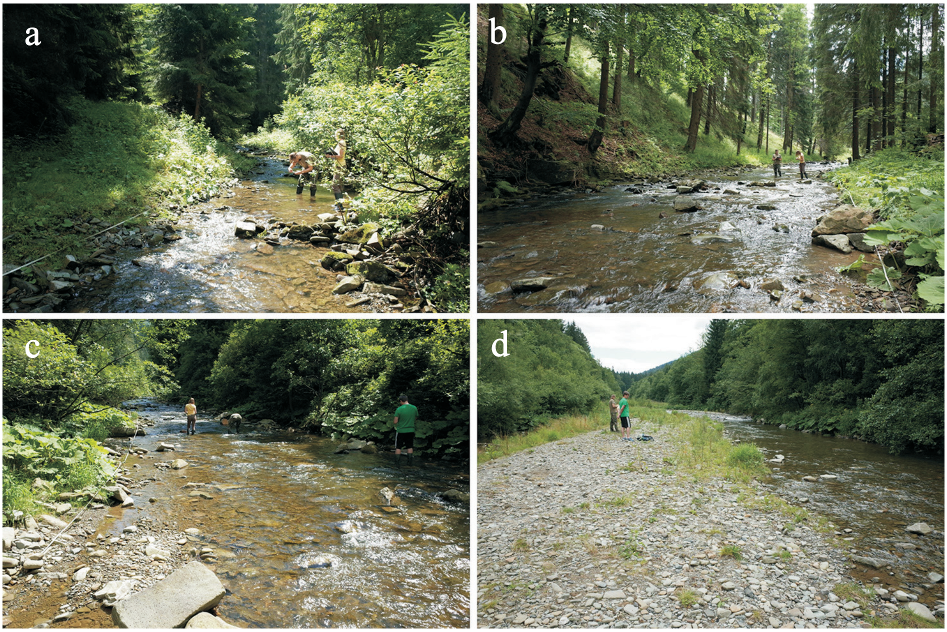

Fig. 2. Sampled locations (upstream views): a – step-rapid (Magurka), b – plane bed UP (Čeladenka), c – plane bed DW (Čeladenka), d – gravel bar (Čeladenka)

METHODS

Fieldworks were performed during low flow conditions of June 2016 allowing easier sampling of bed material and safety movement in the wadable channel. Two fluvial geomorphologists well-experienced in pebble samplings (E1, E2) and two PhD students of geography (S1, S2) conducted samples at four identical locations (two plane beds, one step-rapid and one gravel bar) including 100 randomly selected and measured grains. The students were briefly instructed in the field about sediment sampling methodology. Sampled channel-reaches were 30 m long and relatively consistent in grain-size populations without channel units with notably larger or smaller bed material. The pebble sampling was applied by blind selections and measurements of particles beneath the tip of the toe of operator's boot, when sampled transect covered entire length of channel-reach and bankfull width. The sampling on the gravel bar was taken by all operators in its middle part to prevent from additional inaccuracy by measurements of various grain-size populations, which are usually presented on bars. Measurements of intermediate b-axis were performed by stainless steel tapes in millimetres (accuracy ±0.5 mm). In the case of selected boulder which cannot be easily taken from the river bed, the intermediate axis of boulder was measured in the original position most accurately as possible.

Kruskal-Wallis one way analysis of variance was used for testing whether non-parametric samples of individual operators originate from the same distribution. Post-hoc Fischer LSD test determined which samples were significantly different from others. Additional confidence limits 100(1-α)% were calculated for D_{10}, D_{50} and D_{90} without assuming normality of the population, because obtained pebble samples did not fit into the criteria of normality reflecting Kolmogorov-Smirnov test. All statistical tests were performed at 0.05 significance level.

RESULTS

Obtained D_{10}, D_{50} and D_{90} grain-size percentiles together with confidence limits (p = 0.05), arithmetical mean and standard deviation of all samples are displayed by Table 1, whereas graphical illustrations of collected samples (median, second and third quartile and outliers) provides Figure 3. The confidence limits of D_{10}, D_{50} and D_{90} of experienced operators were overlapped for all evaluated samples. This was not the case of PhD students, when their confidence limits of D_{50} were not intersected for step-rapid reach. There existed differences in the confidence limits even for the finest particles D_{10} between experienced operators and PhD students: E2 > S1 in the case of plane bed UP and E1 > S1 in the step-rapid morphology. It implies that S1 student overestimated fine particles in heterogeneous, generally coarse sediment mixtures of steep mountain streams. On the other hand, E2 experienced operator sampled coarser material in the gravel bar, which resulted into significant difference between the confidence limits for D_{90} of E2 and S2 operators. For medians, at least one PhD student produced considerably finer D_{50} confidence limits than E1 operator (plane bed UP and step-rapid), and E2 operator (gravel bar).

We consequently tested if samples of individual operators originate from the same distribution for each of the sampled locations. In disagreement with our first hypothesis, all collected samples of four operators were significantly different with $p = 0.0065$ for plane bed DW, $p = 0.0028$ for plane bed UP, $p = 0.0006$ for gravel bar and $p < 0.0001$ for step-rapid. Obtained particular differences between individual operators are shown in Table 2. Post hoc test did not produce any significant differences between the samples obtained by PhD students. On the other hand, differences between experienced operators were obtained in one plane bed channel and on sampled gravel bar. Thus also our second hypothesis was rejected, when relatively inexperienced operators provided generally more consistent samples than fluvial geomorphologists often performing pebble counts.

Table 1. Obtained grain-size percentiles, arithmetical means and standard deviations by experienced operators (E1, E2) and PhD students (S1, S2)

	Plane bed UP				Plane bed DW				Step-rapid				Gravel bar			
	E1	E2	S1	S2	E1	E2	S1	S2	E1	E2	S1	S2	E1	E2	S1	S2
D_{10}, mm	25.1	20.1	27.1	19.1	28.0	27.3	26.1	22.2	26.3	22.1	20.0	24.1	19.0	21.9	21.0	21.0
$D_{50,}$ mm	65.5	63.0	52.5	45.0	73.0	83.0	55.0	54.5	63.0	67.0	39.5	52.5	36.5	49.0	35.0	34.5
D_{90}, mm	168.7	205.0	126.4	127.5	172.7	238.7	164.0	151.1	169.0	178.8	108.2	110.0	77.2	91.1	75.0	59.1
Ar. mean, mm	86.0	91.7	73.6	64.1	88.0	111.1	79.5	78.7	79.5	84.9	64.7	65.0	44.5	53.0	40.3	36.7
St. dev, mm	78.3	78.0	77.3	62.5	62.2	94.6	73.7	71.2	52.6	61.1	95.5	41.7	24.7	28.7	20.1	15.8
*D_{10} LCL, mm	19	14	25	16	17	16	19	15	22	17	16	20	16	13	16	17
*D_{10} UCL, mm	28	23	32	23	34	33	32	28	34	28	21	29	21	23	24	23
*D_{50} LCL, mm	57	54	45	37	59	59	45	42	63	57	32	45	33	39	31	29
*D_{50} UCL, mm	77	76	60	53	87	104	68	77	77	84	44	60	43	55	39	38
*D_{90} LCL, mm	132	158	92	103	136	179	118	120	137	137	85	98	68	82	56	52
*D_{90} UCL, mm	277	260	255	160	224	325	250	252	216	225	232	130	96	102	85	65

* Calculated lower and upper confidence limits for individual grain-size percentiles.

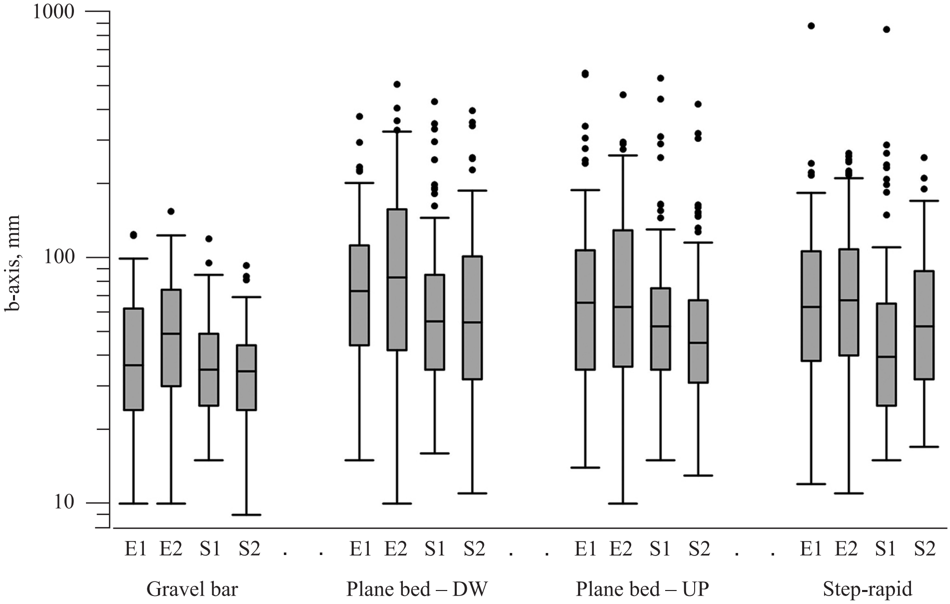

Fig. 3. Grain-size distributions obtained by Wolman pebble counts by four different operators E – experienced fluvial geomorphologists, S – PhD students of geography

Table 2. Significantly different pairs of samples corresponding to Post-hoc Fischer LSD test ($p = 0.05$)

Locality	Different samples
Plane bed UP	E1>S2; E2>S2
Plane bed DW	E2>E1; E2>S1; E2>S2
Step-rapid	E1>S1; E1>S2
Gravel bar	E2>E1; E2>S1; E2>S2; E1>S2

DISCUSSION

Observed differences between samples indicated that 100 measured particles would be insufficient to produce reliable particle-size distributions of bed sediments in mountain gravel/cobble bed streams. Similar conclusions were documented by Daniels and McCusker [2010] for coarse bed substrates of I.-IV. order streams, when standardised sampling template was used to minimise systematic bias caused by inaccurate measurements of particle b-axis. Rice and Church [1996] recommended measuring at least 400 particles and the application of bootstrapping to obtain reliable estimations of grain-size percentiles and related standard errors. Grain-size distributions rarely follow normal distribution curve and the application of unconventional approach (e.g. binomial probabilities, bootstrapping) is convenient [Fripp and Diplas 1993]. In our case, calculated additional confidence intervals following non-uniform distribution covered impractical wide range of values especially for D_{90} percentile. It supports that a large number of particles should be measured in coarse substrates to obtain reliable estimations of higher grain-size percentiles.

Experienced operators provided more consistent samples in naturally more heterogeneous sediment mixtures (step-rapid and upper plane bed reach). By contrast, E2 operator sampled significantly coarser material on the gravel bar than other operators. This disproportion could be caused by sampling of the population of coarser cobbles close to the water surface (i.e. in boundary between the channel bed and bar), which could be omitted by other operators. E1 operator produced significantly coarser arithmetical mean and D_{90} than S2 operator on this gravel bar, but medians (D_{50}) were practically equal for E1, S1 and S2 operators (34.5–36.5 mm). It implies that at least particle-size median could be reliably obtained on gravel bars by measurements of 100 particles, but uniform grain-size population should be included in a single sample [see Kondolf 1997 and Kondolf and Lisle 2016 for further discussion].

CONCLUSIONS

None of sampled locations provided statistically consistent particle-size distributions and related percentiles when compared measurements of all operators. In general, inexperienced operators provided relatively consistent samples with systematic overestimations of finer particles except the step-rapid channel-reach, where their obtained confidence limits of D_{50} did not intersect. The same situation was also observed for D_{10} and upper plane bed channel-reach. Experienced fluvial geomorphologists were surprisingly most consistent in sediment sampling in the step-rapid morphology and upper plane bed channel with assumed widest range of particle sizes. Their confidence limits calculated for D_{10}, D_{50} and D_{90} were overlapped in all sampled locations, but post-hoc testing documented significant differences for the gravel bar and lower plane bed reach. Obtained medians of particle distributions for the gravel bar were practically equal for three of four operators; the fourth operator probably included coarser particle population in the transitional area between the bed and bar sediments, which resulted into coarser D_{50} and D_{90}. It implies that one hundred sampled particles are most likely sufficient only for D_{50} estimations and homogenous sediment populations of gravel bars. In any other case, much larger number of particles should be sampled in gravel/cobble bed streams to obtain narrower confidence limits of related grain-size percentiles as recommended previous studies.

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ZMIENNOŚĆ POBIERANIA PRÓBEK ŻWIRU METODĄ WOLMANA ZE ŻWIROWEGO LUB ZBUDOWANEGO Z OTOCZAKÓW DNA STRUMIENI

Streszczenie. Pobieranie prób metodą Wolmana [1954] jest metodą najczęściej używaną do oceny rozmiaru powierzchniowych osadów dennych w strumieniach o dnach żwirowych. Badania przyniosły różne wyniki u poszczególnych badaczy w rezultacie pomiarów powtarzanych w tych samych korytach przy użyciu tej metody. Prześledzono potencjalne różnice w rozkładzie próbek żwirowych i powiązanych percentylach wielkości ziarna (D_{10}, D_{50} and D_{90}) pomiędzy dwoma geomorfologami rzecznymi oraz dwoma prowadzącymi badania studentami niemal bez doświadczenia w trzech odcinkach koryt i jednym progu żwirowym. Przy porównaniu ustaleń wszystkich badaczy biorących udział w doświadczeniu stwierdzono, że żadna z badanych lokalizacji nie zapewniła statystycznie jednolitych rozkładów rozmiaru cząstek i odpowiadających im percentyli. Próbki doświadczonych geomorfologów rzecznych były bardziej spójne dla odcinków rzek ze stwierdzonym najszerszym zakresem rozmiaru cząstek; testy wykonane po przeprowadzeniu analizy wariancji udokumentowały znaczne różnice dla progu żwirowego oraz niższego poziomu odcinka koryta. Mediany rozkładów cząstek dla progu żwirowego były takie same dla trzech spośród czterech badaczy; czwarty uczestnik eksperymentu prawdopodobnie uwzględnił także grubsze cząstki osadzone między korytem a progiem. To sugeruje, że 100 próbek najprawdopodobniej wystarczy jedynie w przypadku oceny D_{50}

oraz osadów jednorodnych (tj. dobrze sklasyfikowanych progów żwirowych). W każdym innym przypadku, aby otrzymać zawężone granice pewności powiązanych percentyli wielkości ziarna, należałoby zgromadzić znacznie większy zasób cząstek ze żwirowych/otoczakowych koryt strumieni.

Słowa kluczowe: pobieranie próbek metodą Wolmana, osady denne, górski potok, flisz

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