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SURFACE GRAIN SIZE VARIATION WITHIN GRAVEL BARS: A CASE STUDY OF THE RIVER OPAVA, CZECH REPUBLIC

Abstract: Babej J., Máčka Z., Ondrejka P. & Peterová P., *Surface grain size variation within gravel bars: a case study of the River Opava, Czech Republic.* (IT ISSN 0391-9838, 2016)

Grain size variation across surfaces of three gravel bars was studied at the River Opava. Sediment sorting at the scale of individual gravel bars is still an imperfectly explained phenomenon. The aim of the study was to examine the relation of grain-size pattern to within bar position (lateral and longitudinal distance to thalweg and elevation above channel bottom) and vegetation cover. Grain size analysis was performed by combination of grid count and dry sieving of fine fractions at sample plots aligned to transects crossing the bar surfaces. Descriptive statistics have been computed (median, sorting, skewness, kurtosis) and data were analysed by means of correlation (Spearman rank correlation), principal component analysis (PCA), and redundancy analysis (RDA) to elucidate the effect of controlling variables upon the grain size spatial pattern. Median grain size was found to be weakly correlated to lateral and longitudinal distance to thalweg. Sediment coarsening with increasing elevation above the channel bottom, probably mediated by vegetation, was detected. Vegetation coverage proved to be a factor explaining much of the variability in data. Grain size median and sorting were both affected by vegetation coverage. RDA analysis revealed that vegetation coverage, elevation above the channel bottom, and lateral distance to thalweg were the variables most affecting the grain size pattern (altogether explaining 33.1% of data variability). However, the role of particular variables differed between gravel bars. Field evidence from the studied river reach suggests that variables controlling within bar grain size variability are strongly site specific.

Key Words: gravel-bed river, gravel bar, grain size, sediment sorting, the River Opava, Czech Republic.

Shrnutí: Babej J., Máčka Z., Ondrejka P., Peterová P. & *Zrnitostní variabilita povrchové vrstvy štěrkových lavic: případová studie z řeky Opavy, Česká Republika.* (IT ISSN 0391-9838, 2016)

Tento příspěvek se věnuje variabilitě v zrnitosti povrchových sedimentů tří říčních lavic na řece Opavě. Zrnitostní diferenciace sedimentů v prostorovém měřítku individuálních korytových forem je dosud nedořešenou otázkou. Příspěvek řeší vztahy mezi zrnitostí sedimentů, pozicí v rámci lavic (vzdáleností podél lavice, od proudnice a výškou nad dnem) a pokryvností vegetací. Zrnitostní analýza byla provedena jako kombinace metody *grid count* a sítování jemnozrnných frakcí za sucha, vzorkovány byly plochy rozložené podél příčných transektů lavicemi. Pro vzorky byly spočítány popisné statistiky (medián, vytřídění, šikmost a špičatost), pro objasnění vlivu kontrolních proměnných na prostorovou diferenciaci zrnitosti sedimentů byl použit korelační počet (Spearmanův koeficient pořadové korelace), analýza hlavních komponent (PCA) a redundanční analýza (RDA). Byla nalezena pouze slabá korelace mediánu zrnitosti k podélné vzdálenosti a příčné vzdálenosti k proudnici. Bylo zaznamenáno hrubnutí sedimentů s výškou nad dnem koryta, pravděpodobně podmíněné přítomností vegetace. Pokrytí vzorkovacích ploch vegetací se ukázalo být proměnnou vysvětlující nejvíce variability v datech, ovlivněn byl jak medián zrnitosti, tak vytřídění sedimentů. Redundanční analýza ukázala, že prostorová diferenciace zrnitosti povrchových sedimentů lavic byla nejvíce ovlivněna pokryvností vegetace, výškou nad dnem a příčnou vzdáleností od proudnice (společně vysvětlovaly tyto proměnné 33,1% variability v datech). Role těchto proměnných se nicméně mezi jednotlivými lavicemi lišila. Terénní výsledky ze zkoumaného říčního úseku naznačují, že faktory ovlivňující zrnitostní diferenciaci na povrchu štěrkových lavic se místo od místa liší.

Klíóvá Slova: štěrkonosný tok, štěrková lavice, zrnitost, vytřídění, řeka Opava, Česká Republika.

INTRODUCTION

Gravel bars in rivers are depositional features that display patchy nature of textural variation across their surfaces (Wolcott & Church, 1991; Seal & Paola, 1995; Verdu & *alii*, 2005). Patchiness arises from complex depositional history involving sorting of heterogeneous sediments by various imperfectly known mechanisms operating at various spatial scales (Powell, 1998). Patterns of sediment sorting in rivers were commonly interpreted as a textural response to local differences in flow competence (boundary shear

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stress). However, the concept is being revisited and debate continues on effectiveness of selective entrainment, transport and deposition of sediment mixtures (Hoey & Ferguson, 1994; Batalla & Martín-Vide, 2001; Mao & Surian, 2010). Our contribution focuses on evaluation of selected variables that might influence the grain-size heterogeneity across bank-attached gravel bars in river channels.

Size segregation of river bed material occurs at various spatial scales. The downstream reduction in the bed surface grain size is the most obvious manifestation of the sorting process. Discontinuities in exponential decline of grain sizes in river-length scale arise from tributary inputs and valley slope failures (Knighton, 1980; Pizzuto, 1995; Rice & Church, 1998; Rice, 1999). Reach scale patterns of sediment sorting are associated with geomorphological organization of river channels. Riffle-pool sequences and point bars are examples of longitudinal and lateral patterns of bed material sorting. The riffle sediments are commonly coarser and better sorted than those in adjacent pools (Keller, 1971; Lisle, 1979). Bed material sorting also occurs at the grain scale. Most gravel-bed rivers develop a surface layer (armour), one or two grain diameters thick, that is relatively coarse in comparison with the sand and gravel mixture beneath (Dietrich & *alii*, 1989; Parker & Sutherland, 1990). Differentiation of grain sizes around obstacles changing flow pattern was also described (Naden & Brayshaw, 1987; Euler & Herget, 2012).

Gravel bars are the result of interaction between channel geometry, water flow, sediment transport and deposition (Bridge, 1993). Generally speaking, the overall picture of bar surface grain sizes is a result of material segregation by size during entrainment, transport and deposition. At entrainment, sorting occurs because of size-dependent differences in particle weight, packing, and pivot angle. During deposition, "like-seeks-like" phenomenon (Moss, 1963), congestion sorting (Iseya & Ikeda, 1987) or particle overpassing (Allen, 1983), and the shape of the hydrograph (Hassan & *alii*, 2006) may be involved in sorting processes. During transport, sorting of bed load depends on local flow patterns controlled by channel topography, sediment transport and supply rates (Brayshaw & *alii*, 1983; Ashworth, 1996; Thompson & *alii*, 1999; Buffington & Montgomery, 1999).

Evidence on grain-size variation across bar surfaces is still inconsistent. While some studies indicated downstream fining of surface sediments on unit bar surfaces (Smith, 1974), other studies showed the downstream coarsening of sub-armour layer (Lunt & Bridge, 2004). Downbar and downstream fining is generally considered as characteristic of medial bars in braided rivers (Bluck, 1982; Ashworth & Ferguson, 1986). Point bars in meandering rivers commonly fine laterally from the outer bank to the inner bank and, at least in some cases, longitudinally from barhead to bartail (Bridge & Jarvis, 1976, Parker & Andrews, 1985). On compound bars the situation is further complicated because their primary elements (i.e. unit bars) are arranged in complex vertical and horizontal patterns reflecting complicated depositional/erosional histories. Grain size across river bars may also be affected by structure and temporal evolution of riparian vegetation (Edwards & *alii*, 1999).

Knowledge of sediment sorting patterns is important for understanding depositional processes in channels and floodplains (Bravard & Peiry, 1999), boundary roughness (Robert, 1990), and formation and maintenance of aquatic and riparian habitats (Petts & *alii*, 2000). Large body of work has been done on longitudinal variation of bed material grain size at reach and river-length scales (e.g. Schumm & Stevens, 1973; Rice, 1999; Surian, 2002; Brumer & Montgomery, 2003; Rengers & Wohl, 2007). On the contrary, the variability of grain size at bar scale has been the subject of fewer studies despite the observed within-bar grain-size differences (Rice & Church, 2010).

In this paper, aspects of grain-size variation across bar surfaces are analysed and bar-scale patterns are discussed in relation to local controlling variables potentially affecting the deposition process. Grain-size variation is examined with respect to longitudinal position on the bar, lateral distance from the thalweg, and elevation above the channel bottom. Vegetation density (coverage) was also considered as a factor affecting the grain-size pattern. Since majority of the channel network in the Czech Republic is engineered, the River Opava was chosen as a convenient candidate for the gravel bar grain-size analysis; the major flood of 1997 (with recurrence interval 500 years) destroyed the regulated channel and exposed gravelly sediments in many river sections.

STUDY AREA

Three bank-attached bars in the upper course of the River Opava (Czech Republic) have been selected for the analysis. The Opava is a major river draining the eastern margin of the Sudeten Mountains (region of Hrubý Jeseník and Nízký Jeseník Mts.) in the north-eastern part of the Czech Republic (fig. 1). The Opava is a left-side tributary of the River Oder with the drainage area of 2,089 km^2 and the length of 109 km. River reach with the studied bars is located between river km 100.2 and 101.6, with an upstream drainage area of 196.9 km^2. The Opava primary sources are mountain torrents: Černá Opava, Střední Opava and Bílá Opava Rivers that drain the highest elevations of the Hrubý Jeseník Mts. Bedload of the Opava comes from weathering of metamorphic rocks (gneiss, schist, phyllite) of Proterozoic and Paleozoic age, that outcrop in the upper part of the watershed. The vegetation of gravel bars is dominated by herbaceous species (*Galium rivale*, *Petasites hybridus*, *Phalaris arundinacea*, *Poa palustris*, *Urtica dioica*) and juvenile shrub species (*Alnus incana*, *Salix fragilis*). Herbaceous vegetation is denser and higher (up to 80% coverage and 2 m height) in lower part of gravel bars. In the higher part with lower moisture availability, the vegetation coverage decreases along with vegetation height. Shrubs are irregularly scattered in a small amount. Mean annual discharge at the Karlovice gauging station, located 4.2 km upstream from the study river reach, is 2.6 m^3/s. The highest discharge approximately of 320 m^3/s was recorded during 500-year flood in 1997 (Řehánek, 2002). The extreme flood of 1997 markedly transformed the engineered channel that has been regulated regularly since the mid-19th century. The channel was considerably widened in many river sections and extensive gravel bars formed during the flood event.

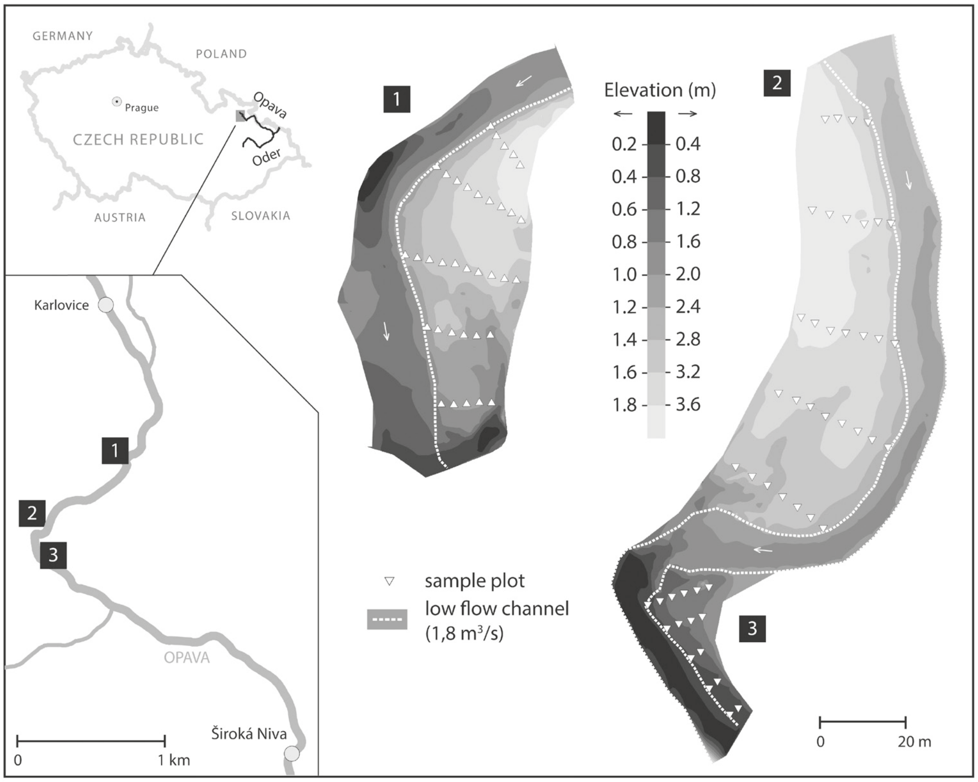

FIG. 1 - Location of studied gravel bars in the River Opava watershed, and 3D models of gravel bars with sample plots indicated.

METHODS

Sampling of surface sediment was performed along transects predominantly perpendicular to the thalweg, five transects were measured at each gravel bar. Along each transect, sampling plots with 1 m^2 area were established, altogether 83 sites were sampled. The number of plots varied, depending on the length of transects and the overall heterogeneity of gravel bars. Morphological parameters of the channel and studied bars are summarized in table 1.

Particle size distribution was determined by the combination of two methods, Wolman pebble count and dry sieving, because of obvious bimodality of grain-size distribution (the first maximum is in sandy fraction and the second one in fraction 32-64 mm). First, the percentage coverage of fractions larger than 16 mm was visually estimated. Then, 25 clasts larger than 16 mm were randomly withdrawn, and the b-axis was measured.

TABLE 1 - Information about morphology of the channel, studied gravel bars and number of sample plots

	Bankfull channel width [m]	**Bankfull channel depth [m]**	**Channel gradient [‰]**	**Bar area [m²]**	**Mean bar width [m]**	**Maximum bar width [m]**	**Number of sample plots**
Gravel bar 1	90.0	2.1	4.1	1763.5	20.8	29.9	35
Gravel bar 2	81.7	2.7	5.1	2595.9	22.9	29.3	32
Gravel bar 3	32.1	3.5	2.5	307.3	9.1	17.7	16

Albeit the original recommendation of Wollman (1954) was to collect 100 particles, and for appropriate estimation of grain-size median measuring of 60 particles was suggested by Brush (1961), lower number of grains was measured beacause of practical reasons. Firstly, the aim of the study was to record grain-size variability within small channel bedforms (bars). That dictated the sampling design with large number of small plots (1 m^2) to reflect transverse and longitudinal gradient in grain sizes. Small area of plots brings about the limited number of particles available for sampling as referred by Bunte & Abt (2001). Secondly, sampling was primarily targeted to detect the differences between individual plots, rather than to express precisely their grain-size distributions. For such a purpose even visual characterization of surface sediments in gravel-bed rivers may be an acceptable procedure as presented by Latulippe & *alii* (2001). In this point, the sampling strategy with lower number of measured grains was adopted similarly to works of Church & Kellerhals (1978) and Galia & Škarpich (2013, 2015).

Particles with a mesh size below 16 mm were sampled for dry sieving with a Retsch AS 200 sieve shaker. According to the recommendation of Ettema & *alii* (1984), the depth to which the samples were taken is equal to the length of c-axis of the largest clast in a sample plot. Samples were taken from several spots (at least five, corners and centre of a plot, in some cases more to obtain required weight of a sample) to ensure the representativeness of the sampling and mixed. The overall sample weight varied according to the diameter of the largest clast as recommended by Church & *alii* (1987).

Kallerhals & Bray (1971) give recommendations for converting grain size distributions determined by pebble count and sieving of volumetric sample. Method for merging pebble count and volumetric sampling data is described in Bunte & Abt (2001), and for pebble count and aerial sampling in Fripp & Diplas (1993). In our case, a new way of combination the results from the pebble count and sieving method was used. First, percentages of grain size fractions were calculated for both pebble count and sieving. Then, the overall grain-size distribution was determined as a weighted average from both methods, whereby the aerial coverage of the fractions above and below 16 mm was used as a weighting criterion. For 25 plots the whole surface layer was removed and sieved to perform validation of the combined pebble count/sieving method.

The following parameters were recorded to characterize each plot: longitudinal distance along the bar, lateral distance from the thalweg, elevation above the channel bottom, and vegetation coverage. The position of each sampling plot within the gravel bar was determined with the total station Topcon GPT 9000. Surface of the bars and adjacent channel bottom were also surveyed with total station and detailed 3D model of gravel bars was constructed. The values of hydraulic radius and channel gradient were calculated for every respective channel reach.

The median grain size, sorting, skewness and kurtosis were calculated in Gradistat 8.0 software considering the logarithmic Folk and Ward graphical measures (Folk & Ward, 1957, Blott & Pye, 2001). Geodetic surveys by total station were processed in ESRI ArcGIS 10.3 software to compile digital terrain models of bars. To produce the models, first, a triangular irregular network (TIN) was created from elevation points. TIN was then converted to a raster terrain model using the natural neighbour algorithm. Natural neighbour is a method of interpolation based on Voronoi tessellation that produces a smooth terrain approximation (Sibson, 1981). Digital terrain models were used to calculate the channel width, depth and slope. Further, the average and maximum width and area of emerged portion of bars related to the low flow channel conditions (discharge of 1.8 m^3/s) were calculated.

Data were analysed in R-project 3.2.1 software (R Core Team, 2013). To compare the results of grain size analysis acquired by combination of pebble count and dry sieving with the results of dry sieving of the whole surface layer at 25 plots, the Wilcoxon sign rank test for dependent samples was used (p=0.05). For determination of the correlation between grain-size and controlling variables (lateral and longitudinal distance from thalweg, elevation above the channel bottom, vegetation coverage, grain size median, sorting, skewness and kurtosis) Spearman's rank correlation was chosen due to non-normal distribution of most variables. To show the similarities (or dissimilarities) between sample plots according to their grain-size, the principal component analysis (PCA) ordination diagram was constructed with plots and grain-size fractions included, then, the controlling and grain-size variables were passively projected into the ordination diagram as well ("vegan" package, Oksanen et al. 2013). The axes of the PCA diagram, that illustrate the non-random variability, were selected by function evplot (broken stick model) (MacArthur, 1957, a script from Borcard & *alii*, 2011). Subsequently, the coordinates of the plots of PCA analysis were correlated (Spearman's rank correlation) with controlling variables.

The effect of environmental factors on grain-size distribution at sample plots was tested by redundancy analysis (RDA) ("vegan" package, Oksanen & *alii*, 2013). The data from all gravel bars were tested as a whole and also individually. Controlling variables were chosen by forward selection method. The suitability of an explanatory model consisting of selected variables was tested with Monte Carlo permutation tests (number of permutations 9999). Further, the partial effect of controlling variables (after removing the variability explained by other variables) was investigated by using variability decomposition ('vegan' package, Oksanen & *alii*, 2013; Borcard & *alii*, 1992). For testing differences in grain size median and vegetation coverage between the gravel bars Tukey and Kramer (Nemenyi) test with Tukey-Dist approximation for independent samples was used ("PMCMR" package, Pohlert, 2015). The difference in sorting of plots with <50% and >50% vegetation coverage was tested by Wilcoxon sign rank test for independent samples.

RESULTS

There is no statistically significant difference between grain-size distribution determined by merging of pebble count and sieving and grain-size distribution determined by sieving of the whole surface layer (Wilcoxon sign rank test for dependent samples, p=0.05). Visual examination of data reveals that percentage proportion of fractions <16 mm and >16 mm at sampling plots correspond well with the results of combined pebble count/sieving method. Proportion of the individual factions 16-32 mm, 32-64 mm and 64-128 mm corresponded well in plots with higher proportion of fraction below 16 mm (relative deviation was less than 12%), which have limited number of particles. These plots account for almost half of the total number of sampling plots. Higher deviations were observed in plots in which proportion of fraction more than 16 mm was greater than 50% (mean relative deviation of 10-40%). In this case, the higher relative deviations were observed predominantly if one fraction had a low proportion (≤5%). Thus, the relative deviation was indeed higher, but the absolute deviation was still relatively low.

An overview of descriptive statistics for controlling and grain size variables may be found in table 2. The relationship between controlling variables (longitudinal and lateral distance to thalweg, elevation above the channel bottom, vegetation coverage) and median grain-size, sorting, kurtosis and skewness was first examined by means of correlation (see table 3). The strongest correlation was found between the median grain size and vegetation coverage (r=-0.73). The negative value of correlation coefficient indicates that with increasing vegetation coverage the median size decreases. This result suggests the influence of vegetation on fining of surface sediments on gravel bars. Next, the value of grain-size median decreases with increasing longitudinal and lateral distance from thalweg (weak correlation). Figure

TABLE 2 - Descriptive statistics of controlling and grain size variables

	Mean	**Median**	**Minimum**	**Maximum**	**Lower quartile**	**Upper quartile**
Vegetation coverage (coverage) [%]	55	65	5	95	25	85
Lateral distance from thalweg (dist_lat) [m]	16.77	15.69	3.20	34.30	9.89	22.80
Longitudinal distance from thalweg (dist_long) [m]	45.02	42.70	8.10	90.80	27.40	63.10
Elevation above channel bottom (elevation) [m]	1.01	0.99	0.22	1.90	0.70	1.31
Sorting	2.158	2.168	0.179	4.136	1.464	2.772
Skewness	-0.480	-0.390	-2.774	1.930	-0.642	-0.120
Kurtosis	0.940	0.920	-0.530	2.020	0.551	1.230
Median [mm]	24.657	23.763	0.142	76.995	4.000	39.061

TABLE 3 - Spearman's correlation coefficients for controlling and grain size variables

	coverage	**dist_lat**	**dist_long**	**elevation**	**sorting**	**skewness**	**kurtosis**	**median**
coverage		0.29**	0.31**	-0.17	0.33**	0.35**	-0.07	-0.73***
dist_lat	0.29**				0.13	0.02	0.07	-0.25*
dist_long	0.31**				0.02	0.40***	0.19	-0.33**
elevation	-0.17				0.09	-0.48***	-0.02	0.26*
sorting	0.33**	0.13	0.02	0.09				
skewness	0.35**	0.02	0.40***	-0.48***				
kurtosis	-0.07	0.07	0.19	-0.02				
median	-0.73***	-0.25*	-0.33**	0.26*				

p-values: *<0.05, **<0.01, ***<0.001

2 gives an overview of the changes in the median according to lateral and longitudinal distance. However, median in certain cases increased with increasing elevation above channel. In such cases, an opposite trend in vegetation coverage was recorded (vegetation coverage decreased upwards), a weak positive correlation between sorting and vegetation coverage was found as well.

As mentioned above, the impact of controlling variables on grain-size median was assessed using correlation coefficients. However, median is only a measure of central tendency and does not reflect the overall nature of grain-size distribution and variability in values of individual grain-size fractions. For this reason, the sampling plots were depicted in the PCA ordination diagram based on the percentages of grain size fractions (fig. 3). Using the broken stick model, it was found that the amount of non-random variability in the data is represented by the first two PCA axes (fig. 4); wherein the first axis captures 51% and the second axis 20% of variability. It is evident from the ordination diagram that samples from the gravel bar 1 are grouped in cluster on the right side of the diagram. In this cluster, samples with low values of median (significant correlation with first axes, r=-0.86) and high values of vegetation coverage (r=0.79) are included. Using the Tukey Kramer test, it was found that the bar 1 is indeed significantly different (p=0.05) from the other two bars with respect to grain size and vegetation coverage. Differences in the channel geometry at three respective sites may be seen on figure 2b, where bars' longitudinal and transverse profiles are presented. River reach with bar 3 deviates markedly from other two sites; the channel is narrower and deeper (width to depth ratio 12.8 compared with 31.8 and 29.6). No statistically significant difference was found between gravel bars 2 and 3, although the grain-size median is higher and vegetation coverage is lower on the third bar than on the second one (fig. 5). The statistically significant difference in sorting was found between the plots with vegetation coverage lower and higher than 50%.

Redundancy analysis (RDA) with forward selection was used to clarify which controlling variables and how significantly affect the grain size composition. When data from all three gravel bars were analysed together, the statistically significant variables were: vegetation coverage, elevation above the channel bottom and lateral distance to thalweg. Explanatory model based on these three variables was statistically significant (p=0.001). All three parameters together explained 33.1% of variability in grain-size composition. The greatest amount of variability was explained by vegetation coverage (30%), markedly less variation in data was explained by elevation above the channel bottom (2%) and lateral distance from thalweg (1%) (tab. 4). Further, it was found by variance decomposition that a considerable proportion of the explained variation is shared with other variables in the case of vegetation coverage. When shared variability is eliminated, this factor explains 22.2% of variation in grain-size composition (see in table 4 individual adjusted R^2). RDA has been also done separately for all gravel bars because of differences in both median and vegetation coverage (Tukey Kramer test). The vegetation coverage was the most influential variable for all bars and explained about 26% variability.

From other explored variables, longitudinal distance to thalweg was significant in explaining part of data variability for the bar no. 1 (8.6% of variability), and elevation above the channel bottom for the bar no. 3 (14% of variability). Therefore, it is evident that some variables may have more marked impact on grain-size distribution at the spatial scale of individual bars.

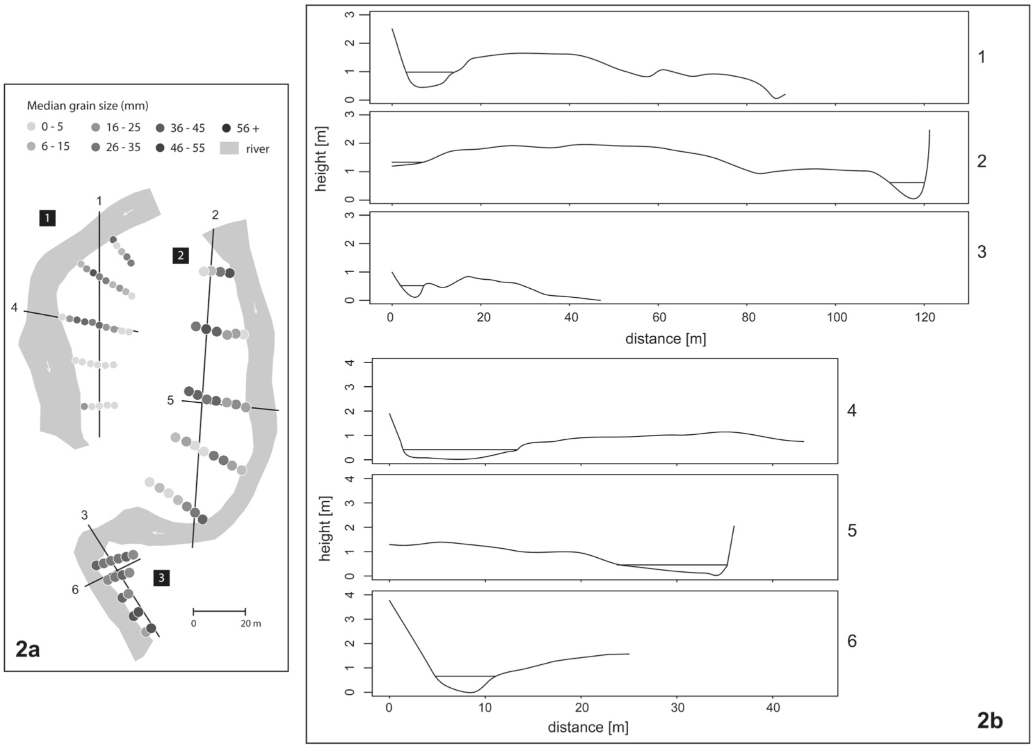

FIG. 2 - a) Variation of median with respect to position on a bar, b) longitudinal profiles (number 1, 2 and 3, direction: upstream to downstream) and cross-sectional profiles (number 4, 5 and 6, direction: right bank to left bank) with depiction of low flow channel (1.8 m^3/s).

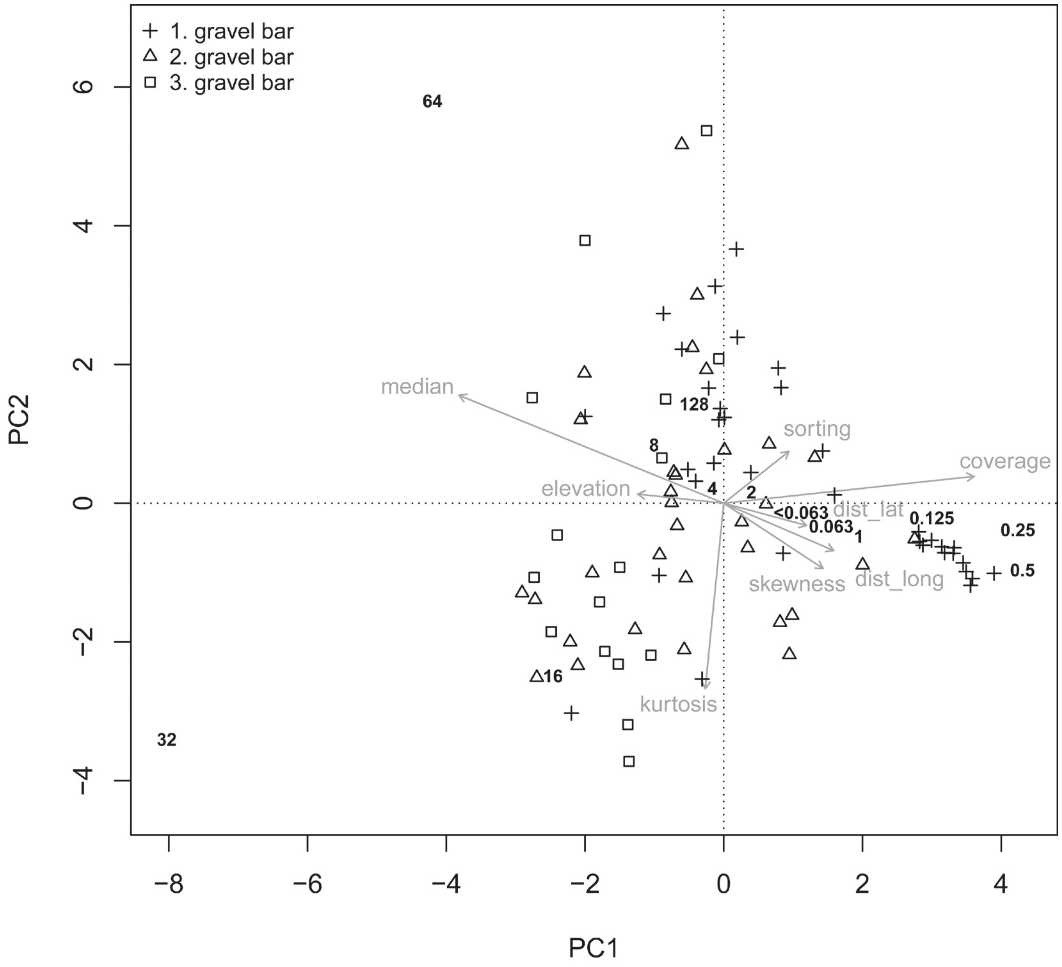

FIG. 3 - Principal component analysis – ordination diagram of sample plots, grain size classes (numbers in the ordination diagram denote the upper limit of size class, e.g. 0.125 = 0.063-0.125 mm) and variables, which have statistically significant correlation with PCA axis.
PC1: coverage: 0.79***, dist_lat: 0.27*, dist_long: 0.33**, elevation: -0.27*, median: -0.86***, sorting: 0.35**, skewness: 0.42***; PC2: kurtosis: -0.61***. p-values: *<0.05, **<0.01, ***<0.001.

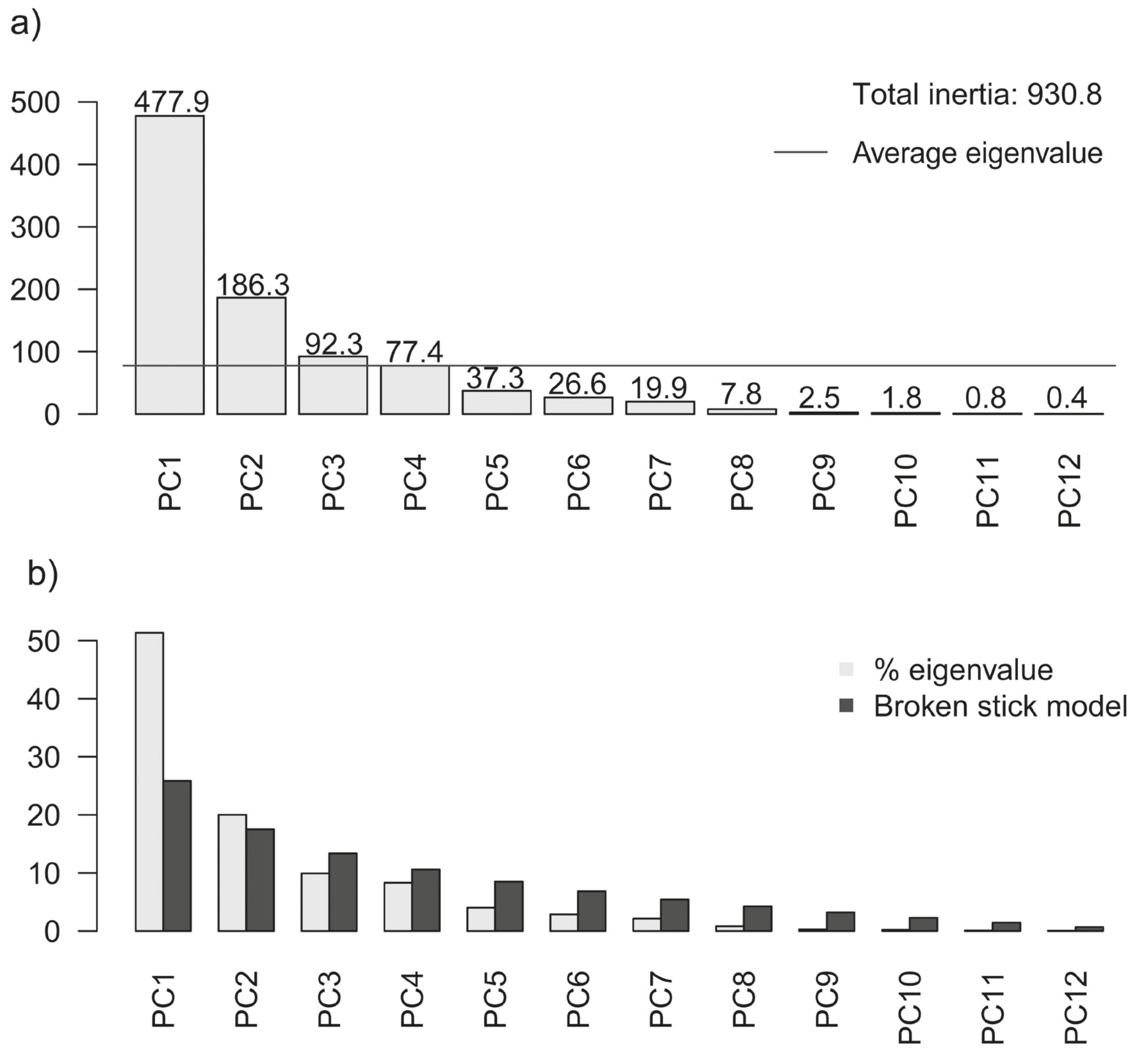

FIG. 4 - Results from broken stick model; a) eigenvalues for PCA axis, b) comparison of eigenvalues for PCA axis with broken stick model.

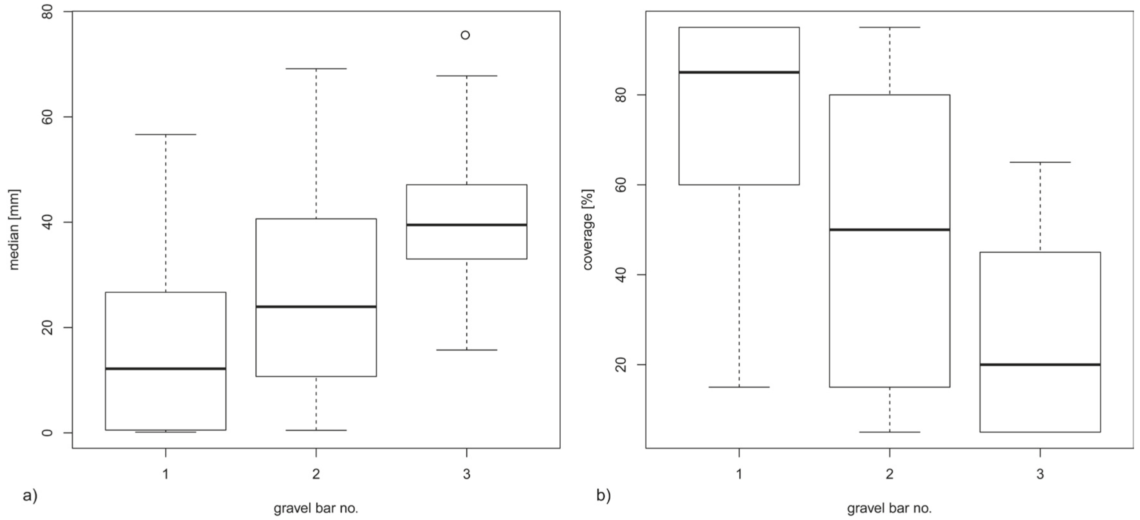

FIG. 5 - Comparison of median (a) and vegetation coverage (b) for three studied gravel bars.

TABLE 4 - Variation partitioning of controlling variables (coverage of vegetation, elevation above channel, lateral distance to thalweg, longitudinal distance to thalweg), adjusted R^2 for variables without shared variation (first column) and with shared variation (second column) between variables, adjusted R^2 for variables included in explanation model (third and fourth column)

	Individual adjusted R^2 (without shared variation)	Total adjusted R^2 (with shared variation)	Adjusted R^2 (explanation model)	Cumulative adjusted R^2 (explanation model)
coverage	0.2223	0.3005	0.3005***	0.3005
elevation	0.0280	0.0354	0.0204**	0.3209
dist_lat	0.0111	0.0290	0.0104*	0.3313
dist_long	0.0043	0.0552	-	-

p-values: *<0.05, **<0.01, ***<0.001

DISCUSSION AND CONCLUSION

This study has sought to test, by statistical means, the hypothesis that within-bar grain-size variation depends on the position at the bar surface and vegetation coverage. The structure of the data reveals complexity that may not be elucidated by straightforward relations, nonetheless, the results of the study are pointing to some regularities in spatial pattern. The number of gravel bars investigated is rather small, however, we sampled the bar surfaces in unprecedented detail; similar studies of within-bar variability are virtually lacking with only a few exceptions (e.g., Rice & Church, 1998; Rice & Church, 2010). Three levels of variability may be distinguished when analysing the data: differences between individual gravel bars, within-bar variation, and within-sample plot variation.

Between bar differences in median grain size are shown on figure 5. Noticeable downstream coarsening is evident from the box-plots. Comparison of surface grain sizes between three respective bars shows that the bar 3 is covered with the coarsest material and that it differs distinctly from other two bars. However, statistically significant difference has been found by Tukey Kramer test only to more distant bar 1 that is probably caused by the immediate upstream proximity of bar 2 (see fig. 1). Distinctive between-bar variability is present regardless of spatial proximity of bars that are spread within only 1.4 km long river reach. Downstream coarsening may not be explained as a result of lateral input of coarse material, because the Opava is lacking any tributaries and noticeable cut-banks in this reach.

Instead, we presume that channel dimensions and morphology may be of importance (see figures 1 and 2b). Bars are situated on the convex side of channel bends; whereas bars 1 and 2 are stretched along gradual channel bends, the much smaller bar 3 is located at the sharp bend, where the channel direction changes abruptly. Whereas the channel morphology at bars 1 and 2 is somewhat similar (width to depth ratio of bankfull channel is 31.8 and 29.6 respectively), the bar 3 differs significantly (width to depth ratio only 12.8). The mean width of the channel is 34 and 34.7 m in reaches with bar 1 and 2, mean channel depth is 1.2 m in both reaches. On the other hand, the mean channel width and depth are 21 m and 1.7 m respectively in the reach with bar 3. Hydraulic radius is rather variable along the reaches; it drops from 0.9 to 0.3 along bar 1, from 0.6 to 0.3 along bar 2, and from 0.6 to 0.2 along bar 3. Correspondingly, mean bed shear stress varies with changing cross profile along the bars (bar 1: 11.2-36.2 N/m^2, bar 2: 17.7-30.2 N/m^2, bar 3: 5.5-14.8 N/m^2). Lower values of mean shear stress along bar 3 are conditioned by twice lower channel gradient compared to bars 1 and 2. The sudden drop of channel capacity behind the sharp channel bend between bars 2 and 3 may cause increase in water level, flow velocity and shear stress during high flows, thus, causing coarsening of surface sediment on bar 3.

Traditional views of sediment sorting across bar surfaces suggest downbar fining from barhead to bartail, lateral fining from thalweg to channel bank, and vertical fining from channel bottom to bar top (e.g. Smith, 1974; Bluck, 1982; Ashworth & Ferguson, 1986). This pattern is related to the variation of boundary shear stress with flow depth across the channel bottom. In this respect, our study brings ambiguous results. Statistically significant, albeit weak, negative correlation was found between grain size and longitudinal and lateral distance to thalweg. Relation of grain size to elevation above the channel bottom showed to be reversed than expected, i.e. grain-size median increases with increasing elevation above the channel. We suppose this may be explained by decreasing vegetation coverage in upwards direction on bar surfaces. The role of position within the bar surface has been further examined by redundancy analysis (RDA). Here, the nature of discovered relationship depends on the way how data was treated. If sample plots from three bars were grouped to a single dataset, the variability in data was best explained by elevation above the channel bottom and lateral distance from thalweg. If RDA was applied separately for individual bars, the role of positional variables became less obvious (for bar 1 longitudinal distance, this is also evident from figure 2a, and for bar 3 elevation above the channel bottom were significant).

Quite surprisingly, the density of vegetation proved to be the factor explaining much of the variability in data. Role of vegetation in affecting grain-size of sediments in rivers was recently investigated by Petts & *alii* (2000), Gurnell & *alii* (2008) or Corenblit & *alii* (2009). These studies propose sediment fining as a result of increased hydraulic roughness brought about by vegetation. Our results indicate that vegetation may not only promote sediment fining, but also influences sediment sorting. Sorting varied considerably between sample plots from moderately well sorted to very poorly sorted sediments (Folk & Ward, 1957). During transport of bed load over vegetated bar surfaces, both coarse and fine material is trapped and sediments become less sorted. Relation of sorting to vegetation coverage is supported, firstly, by positive correlation (see table 3), secondly, by statistically significant difference in sorting of plots with <50% and >50% vegetation coverage (Wilcoxon sign rank test for independent samples, p=0.001). However, the effect of vegetation on sediment deposition is variable and unstable in time as described in the concept of biogeomorphological succession (Gurnell & *alii*, 2008; Corenblit & *alii*, 2009).

Bar surface disturbance by floods is another factor with relevance for explaining surface pattern. Entire channel was reworked during the extreme flood in 1997 (500-year recurrence interval). Major floods occurred subsequently in 2001, 2006, 2007, 2009 and 2010 with respective recurrence intervals 10, 5, 50, 30 and 5 years (data from gauging station Karlovice operated by Czech Hydrometeorological Institute). These flows with higher stream power and, thus, transport capacity may deposit coarser particles in the higher part of the bars. As the flood flow decreases, the largest particles do not move any longer and are deposited, whereas the finer particles still continue to move and are eventually washed away by the receding flood flows. Presumably, joint effect of fluctuating flows (floods) and surface roughness linked with the presence of vegetation should be considered when interpreting bar surface grain size.

Results presented here deviate from general model of sediment sorting on gravel bar surfaces represented by downstream and transverse/bottom-up fining of surface sediments. The field evidence suggests that controls of within bar grain-size variability are rather site specific at the studied gravel bars. Whereas at some bars the position of sample plots (elevation above the channel bottom or distance from thalweg) was found to be significant, at other bars it was not the case. Other variables, in our case channel geometry, vegetation coverage and flood history may disrupt an expected pattern of sediment sorting across bar surfaces. More field based studies would be of use for identification of such “disturbing” factors.

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