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Granulometry and morphometry of river sediments – sand and gravel studies in the Sava River (Zagreb, Croatia)

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Abstract

Morphometry of pebbles from the Sava River gravel sampled in the Zagreb City area revealed shape distributions along the observed waterway. Predominant carbonate pebbles have disc and sphere shapes implying mainly distant sources. Distributions of pebble shapes in sandstones and other minor lithologies indicate local and distant sources. Granulometry of the Sava River sand sampled in the same area and obtained by dry sieving and laser granulometry showed a predominately fine and medium sand deposition. Medium sand increased downstream, probably due to artificially channelized riverbed in the urban area. Fine sand prevails further downstream in a more meandering river area.

Keywords: river sediments; granulometry; morphometry, Sava River, Zagreb

1. Introduction

Morphometric analysis of the gravels often aims to describe weathering, transporting and depositional processes (**Müller, 1967; Tucker, 1988**). Holocene alluvial sediments deposited in the Sava River alluvial terraces near the City of Zagreb (Croatia), are especially suitable for this purpose. These sediments were used for a case study that analyses morphometric characteristics of gravel pebbles, aiming to describe transport and depositional mechanisms. Contribution of eroded material from the local sources, brought from the nearby hills and Medvednica Mountain, was compared to the contribution of material from the upstream sources. The research was performed at selected sites along the Sava River watercourse.

Granulometric analysis of the sand bodies deposited at riverbanks of the Sava River was also undertaken. Sava River flows partly through the Zagreb city area, and its natural grain size distribution consequently has been changed. Zagreb City arose between Medvednica Mt. and the Sava River, channelized and embanked after the 1964. flood. Natural grain size distribution in sand bodies is now restricted to several sites at the riverbanks. Further downstream Sava River re-establishes its natural meanders.

The Sava River follow transition in the underlying geomorphology and riverbed changes accordingly. In the high-relief area upstream, riverbed is shallower and mainly gravels are deposited. West of Zagreb as well as downstream towards the east, river morphology transitions to a predominantly meandering form. Recently, watercourse in the urban city area has been highly regulated and embanked after the major flooding of the City of Zagreb in 1964. Deposits of the meandering Sava River system are nowadays mainly exploited in gravel pits. For the Middle Pleistocene gravels in the area west of Zagreb it was determined that predominant sandstone pebbles originated from a nearby source area (Medvednica Mt. and surrounding hills), and for the overlying Holocene gravels predominantly carbonate lithology of the Alpine provenance is determined **(Barudžija et al., 2020)**.

2. Methods

Several field and laboratory procedures were performed to obtain morphometric characteristics of the gravel pebbles. Representative sites for sampling gravel were chosen at nearby gravel pits, Sava riverbanks and riverbed gravel bars (red dots in **Figure 1**).

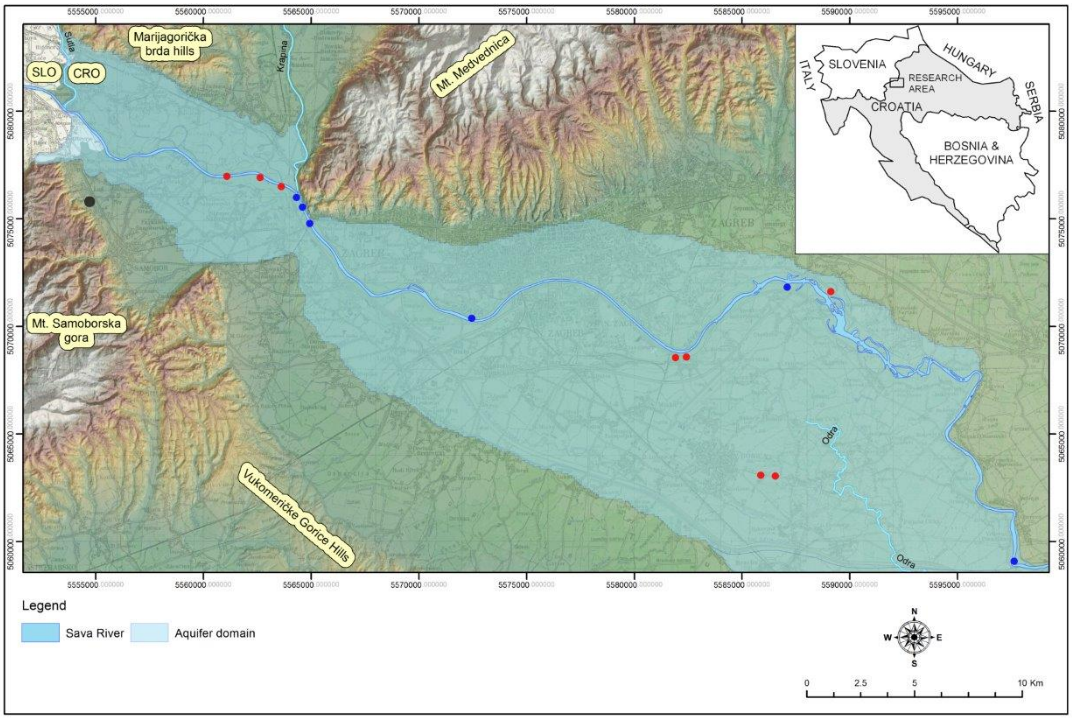

Figure 1: Sampling sites: gravel pebbles for morphometry (red dots); and sand samples for granulometry (blue dots)

Statistically representative sets of 300 pebbles of various sizes were taken from the >6 mm separated fractions of each sample. Pebbles were also determined by their lithology as lithotypes. Direct measurements of three perpendicular geometrical axes on the pebbles were made with Vernier calliper on all selected pebbles, according to well-established procedure **(Zingg, 1935; Krumbein, 1941; Muller, 1967**). According to their b/a and c/b ratios, basic grain shape names were attributed: disc, sphere, blade or rod (**Table 1**). Measurements and notations are reliable with less than 1% of outliers, which are excluded as measurement errors. The original method (**Zingg, 1935**) upgraded by (**Muller, 1967**) to characterize and classify pebble shapes has been applied. Flatness ratios, defined by **Equation 1**:

$$F = (a + b) / 2c \qquad (1)$$

Where are:

a - the longest diameter/length,
b - the middle diameter/width,
c- the shortest diameter/height.

were further calculated for each selected pebble. They usually vary for gravel pebbles between 1.2 and 5.

Table 1: Basic types of pebble shapes (**Zingg, 1935**)

	b/a	c/b	Shape
I.	>2/3	<2/3	disc
II.	>2/3	>2/3	sphere
III.	<2/3	<2/3	blade
IV.	<2/3	>2/3	rod

Riverbed sand sampling sites for granulometric analysis (blue dots in **Figure 1**) were chosen at riverbanks, in sandy point bar sedimentary bodies. The following analytical procedures were performed on the collected samples: granulometric analysis by dry sieving and granulometric analysis by laser granulometry in the Laboratory for Geological Materials (LaGeMa) at the RGN Faculty, University of Zagreb, according to procedures from **Müller, 1967** and **Tucker, 1988**. Samples were air-dried, quartered to cca 100 g, and sieved manually through the set of sieves. Each fraction is weighed, with the accuracy of > 99%. Laser granulometric analysis is performed with a Malvern Panalytical Mastersizer 3000 device, operating on the laser diffraction principle (**URL 1**).

Standard granulometric parameters were read off directly from a cumulative granulometric curve, or calculated from standard equations (**Müller, 1967** and **Tucker, 1988**):

(1) Median (Md), grain size value on a cumulative granulometric curve at the 50th percentile (at 50%).

(2) Mean (M), average grain size value, calculated from grain size values at the 16th (Φ16), 50th (Φ50) and 84th (Φ84) percentile (**Equation 2**):

$$M = \frac{\Phi_{16}+\Phi_{50}+\Phi_{84}}{3} \quad (2)$$

Where are:

*Φ*n – grain size at the nth percentile,
M – mean grain size.

(3) Mode is the value in the middle of the most represented class (class with the largest number of grains).

(4) Sorting (So) is the measure of standard deviation - width of the grain size distribution (**Equation 3**). It shows efficiency of the transporting media (river water) to separate various grain sizes.

$$So = \frac{\Phi_{84}-\Phi_{16}}{4} + \frac{\Phi_{95}-\Phi_{5}}{6.6} \quad (3)$$

Where are:

So –sorting coefficient,
Φn – grain size at the n^{th} percentile.

(5) The asymmetry coefficient – Skewness (Sk) shows prevailing fractions in the sample (larger or smaller grains than the median value). It changes the cumulative granulometric curve toward the larger grains (Sk < 1) or toward the smaller grains (Sk > 1). It is calculated from **Equation 4**.

$$Sk = \frac{\Phi_{16}+\Phi_{84}-2\Phi_{50}}{2(\Phi_{84}-\Phi_{16})} + \frac{\Phi_{5}+\Phi_{95}-2\Phi_{50}}{2(\Phi_{95}-\Phi_{5})} \quad (4)$$

Where are:

Sk – coefficient of asymmetry,
Φn – grain size at the nth percentile.

3. Results

Pebble shapes (disc, sphere, blade or rod) were quantitatively defined for all main lithotypes in each sample by comparing their measured axes (according to **Table 1**). The results are presented in the Zingg diagrams with the Wadell sphericity values curves and in histograms (see **Figures 2** and **3**), from the west downstream to the east. Measured diameters and calculated flatness ratios, depend also on different lithologies and hydrodynamic conditions during the transport of the pebbles, and these attributions are further critically evaluated.

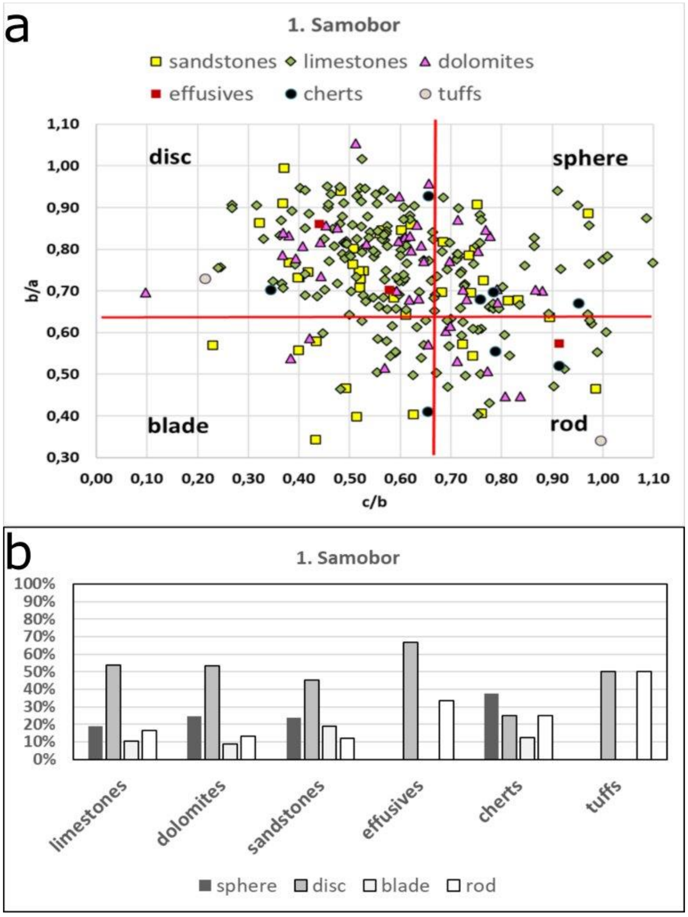

Figure 2: Pebble shapes of main lithotypes plotted in Zingg diagram with the overlapping curves for the same Wadell sphericity values (a) and presented in histograms (b). The far west sampling site (red dot) in **Figure 1**. Adapted after **Barudžija et al., 2020**.

In the far west location predominant limestone and dolomite pebbles have mainly disc to mildly sphere shapes (see **Figure 2**). Subordinate lithotypes show more scattered distributions of pebble shapes, with sandstones being the most diverse.

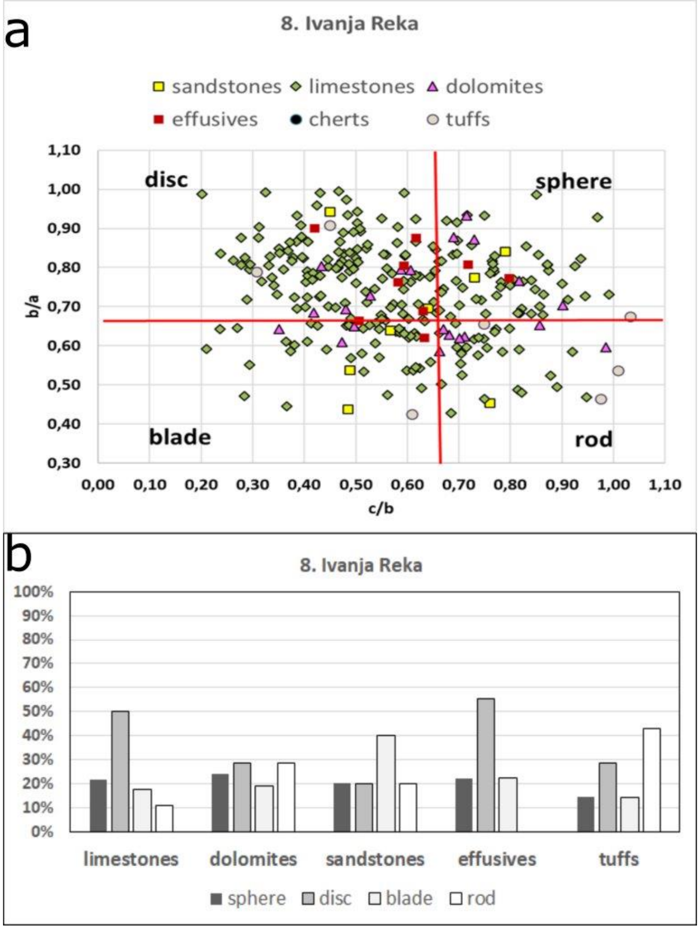

Figure 3: Pebble shapes of main lithotypes plotted in Zingg diagram with the overlapping curves for the same Wadell sphericity values (a) and presented in histograms (b). The far east sampling site (red dot) in **Figure 1**. Adapted after **Barudžija et al., 2020**.

In the far east site, all major lithotypes are significantly present (see **Figure 3**). Limestones slightly increase, having mainly disc to sphere pebble shapes. Sandstone pebbles with mainly blade shapes prevail.

The results of granulometric analysis are presented downstream the Sava River by a histograms of grain size distribution, cumulative frequency curves of grain size and a cumulative granulometric curves (see examples in **Figures 4** and **5**).

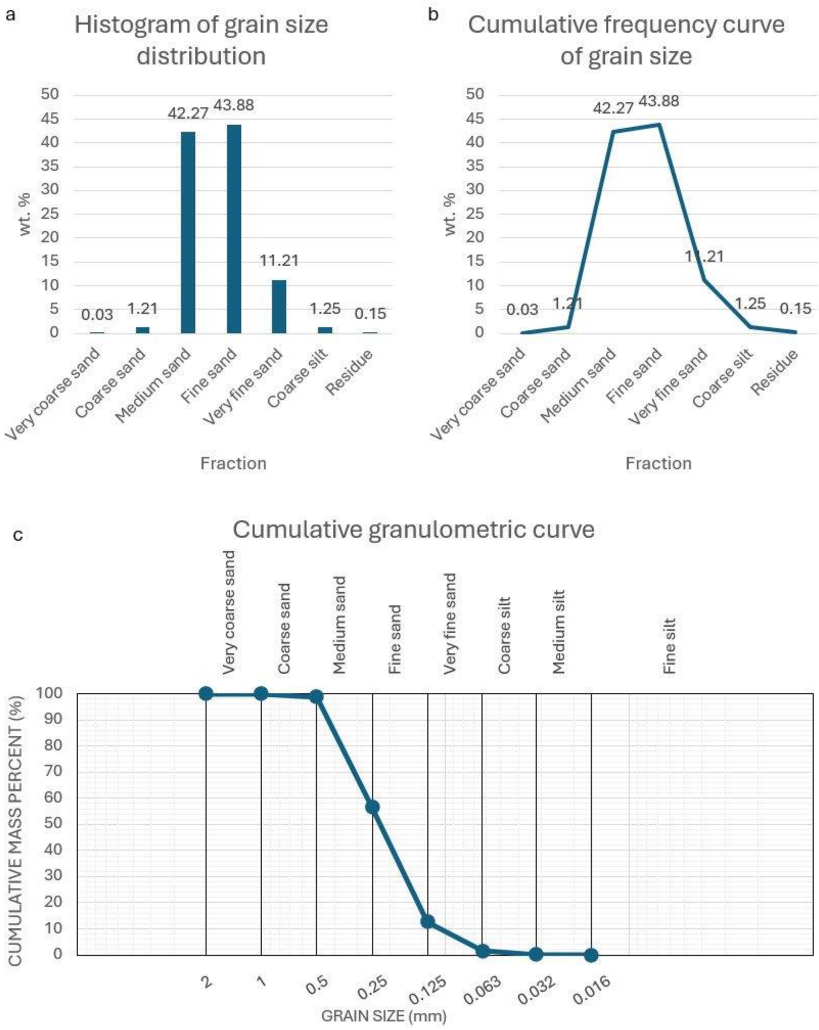

Figure 4: Histograms of grain size distribution, cumulative frequency curve of grain size and a cumulative granulometric curve. The far west sampling site (blue dot in **Figure 1**).

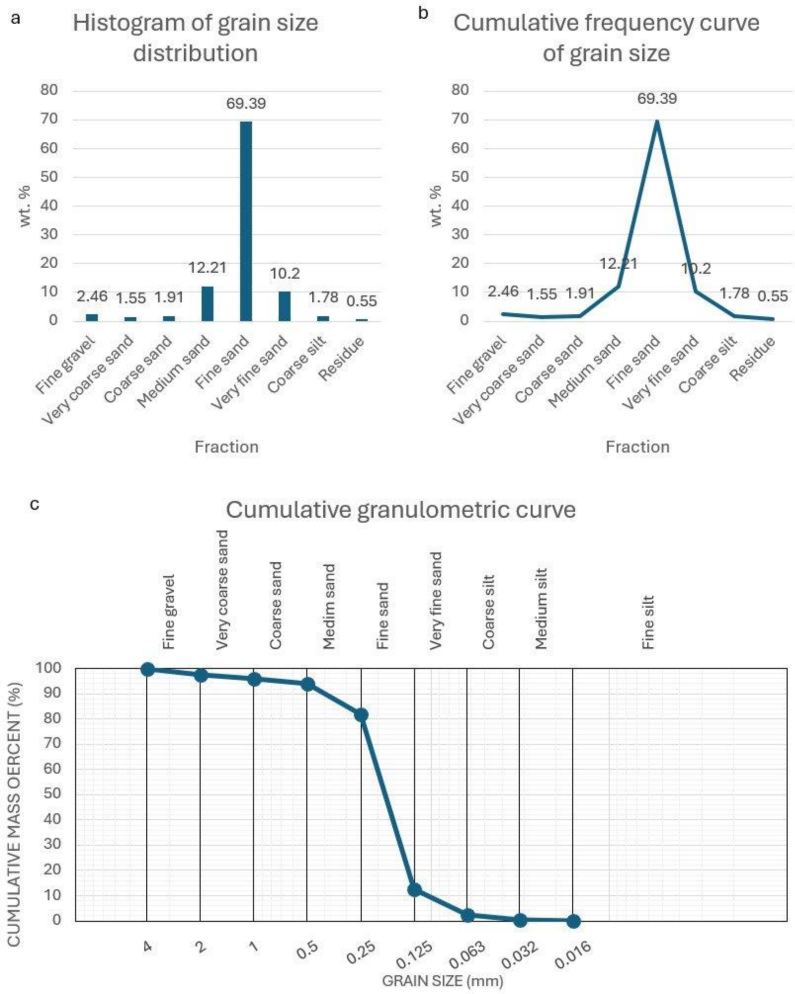

Figure 5: Histograms of grain size distribution, cumulative frequency curve of grain size and a cumulative granulometric curve. The far east sampling site (blue dot in **Figure 1**).

Grain size distribution in all samples is presented on a jointed graph showing cumulative granulometric curves (see **Figure 6**). Shapes of the curves, steepened at fine and medium sand sections, indicate grain size distribution with prevailing medium sand fraction at western sites, as well as the predominance of fine sand at the far east site.

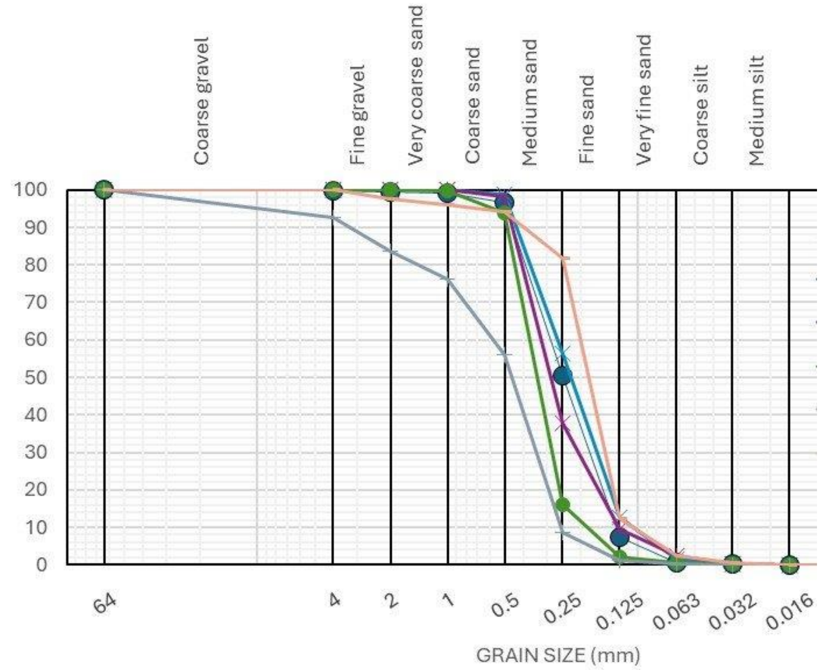

Figure 6: Cumulative granulometric curves for all sampling sites (blue dots in **Figure 1**)

4. Discussion

In the west, significant narrowing of Sava River watercourse is visible: between Medvednica and Samoborska gora, it enters the Zagreb alluvial plain and flows further eastwards as a reduced flow meandering river. This change reflects the distribution of gravel pebbles and its morphometric characteristics, which are mainly related to their lithology. Carbonate pebbles predominantly accumulate at western sites. Incision and deep erosion of the riverbed strongly influenced distribution of other lithotypes downstream.

Pebble shapes in alluvial sediments are primarily influenced by lithology and fabric, and then by hydrodynamic conditions during transport (**Collinson, 1986**). Approaching to ideal sphere pebble shape correlates also well with the increasing hydrodynamic conditions or with relatively long transport. Predominant limestone pebbles at all sites, are of intermediate to moderately high sphericity and have mainly disc to sphere shapes, implying relatively long transport.

Disc and sphere pebble shapes distributions correlate well with main lithologies -limestones and dolomites. Contribution of limestone and dolomite pebbles with predominantly disc and sphere shapes implies similar sources (predominantly distant, with possible local influence) as well as similar transport conditions.

Sandy gravel lake deposits are often recorded in the underlying Middle Pleistocene deposits **(Velić and Durn, 1993; Velić et al, 1999)**, and predominance of the pebbles from such environments indicate redeposition further downstream during the Holocene. However, the potential for reworking of gravel fraction from these older deposits is limited to those parts of the watercourse in which water energy suddenly increase, such as in channelized and embanked parts of the river, like in the urban Zagreb City area.

Predominant carbonate pebbles in the Sava River and their morphometric characteristics can be easily compared with the physical and mechanical properties of local carbonates from the Samoborska gora and Medvednica, described by **(Pavičić et al., 2017; Maričić et al., 2018)**, as well with some world examples, i.e. with one described by **Oluwajana et al., 2021**.

Granulometric research focused on the grain size distribution of Sava River sand in the urban area of the City of Zagreb, as well as downstream. Grain size distribution shows that upstream of the Sava River cumulative medium sand/fine sand fractions are predominant at the western sampling sites, and very fine sand fraction is subordinately present. Hydrodynamic properties of the Sava riverbed in this area allows the deposition of medium and fine sand particles. Further downstream, away from the channelized and embanked riverbed in the urban city area, fine sand fraction increase, due to low hydrodynamic conditions in the low relief area. Granulometric research can be as well compared some world examples, i.e. with one described by **Etobro et al., 2024**.

Prevailing carbonate sands in the western and more siliciclastic content downstream in the eastern part of the investigated area, showed a similar pattern as the distribution of gravel pebbles in the study **(Barudžija et al., 2020)**.

5. Conclusions

- Predominantly disc and sphere shapes of limestone and dolomite pebbles imply similar sources (mainly distant and some local), as well as similar transport conditions.
- Scattered distributions of sandstones pebble shapes indicate possible multiple sources, some of them highly probable as local, from the SW Medvednica and Samoborska gora in the west, and from the SE Medvednica in the east.
- Scattered distributions of pebble shapes for minor lithotypes show no significantly recognized provenance.
- Grain size distribution of the Sava River sands near the city of Zagreb show predominately medium and fine sand deposition with prevailing medium sand downstream, due to a more artificially channelized riverbed.
- Further downstream fine sand deposition significantly prevails, influenced by the lower hydrodynamic conditions.

6. References

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SAŽETAK

Granulometrija i morfometrija riječnih sedimenata – studije pijesaka i šljunaka rijeke Sava (Zagreb, Hrvatska)

Morfometrijom valutica uzorkovanih iz korita rijeke Save na području Zagreba definirana je distribucija oblika na promatranom dijelu vodotoka. Prevladavajuće karbonatne valutice su diskoidalnih i sfernih oblika, što može ukazivati na udaljene izvore materijala. Distribucije oblika valutica u pješčenjacima i ostalim manje zastupljenim litologijama ukazuju na lokalne i udaljene izvore materijala. Granulometrija pijeska uzorkovanih iz korita rijeke Save dobivena suhim sijanjem i laserskom granulometrijskom analizom ukazuje na taloženje prevladavajuće sitnog i srednje krupnog pijeska. Udio srednje krupnog pijeska raste nizvodno, vjerojatno zbog umjetno kanaliziranog riječnog korita u urbanom području. Sitni pijesak prevladava dalje nizvodno u meandrirajućem riječnom području.

Ključne riječi: riječni sedimenti; morfometrija; granulometrija; Sava; Zagreb

Author's contributions

Uroš Barudžija - conceptualisation, methodology, validation, investigation, writing - original draft, writing - review and editing. **Matteo Blatančić** - conceptualisation, methodology, investigation, writing - original draft, visualisation.