Grain-size variability of river-bed sediments in mountain areas (the Gemenea and Slătioara rivers, Eastern Carpathians)

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ABSTRACT: Rivers in mountain areas have alluvial beds largely consisting of coarse alluvia (blocks, cobble, gravel) mobilized and transported downstream only during exceptional hydrological phenomena. Their distribution influences river-bed stability, sediment transport rates and high-water levels, because alluvial deposits define bed roughness. As a rule, especially in large rivers, the size of alluvia deposited on river-beds gradually decreases downstream (downstream fining), as the river transport capacity is reduced. This tendency can be interrupted by discontinuities, caused by the lateral input of alluvia or by anthropogenic interventions. The aim of this paper is to analyze the spatial distribution of the size of bed material along two small rivers, Gemenea and Slătioara, located in the northeastern part of the Eastern Carpathians, Romania. The phenomena of grain-size fining or coarsening of the material deposited along these river-beds are of low intensity. The high degree of connectivity between river-bed and hillslopes and scarps of meadow terraces has generally resulted in unimodal distributions centered on the coarse fraction (gravel, cobble and blocks, over 60% of the total), whereas the fine fraction (sands) is below 1%. A slight tendency of bimodality begins to emerge towards the lower course of the Gemenea river profile (sand increases to slightly over 5% of the total bed material). This occurs with meadow development and the reduction of the connectivity between river-bed and adjacent hillslopes. Hence the conclusion that lateral input and longitudinal sorting of particles are among the main causes of bed deposits bimodality in our study area.

KEY WORDS: small mountain river; bed sediment; downstream fining; downstream coarsening; bimodality

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1. Introduction

In the mountain areas, river-bed deposits are included in the coarse sediment fraction (> 2 mm), divided into grain-size classes such as blocks (> 181 mm), cobble (181-64 mm) and gravel (64 - 2 mm). Their diameter reflects the transport competence of a river, induced by the energy and power of the current, characteristics that vary according to bed slope and river flow rate. Generally, the spatial distribution of bed deposits is in accordance with Sternberg's law (1875), which states that bed sediment grain-size is fining downstream proportional to the mechanical work performed as a result of particle friction along the bed. The studies carried out for the East Carpathian rivers in Romania indicate this sediment behavior throughout the entire length of the Suceava and Moldova rivers (Ichim et al., 1996, Rădoane et al., 2002, 2003, 2007, 2008). Downstream fining of sediments is a rule that does not apply to all river-beds and not to their entire length. For example, in some sections of the rivers Trotuş (mountain sector), Putna (Subcarpathian sector), Buzău (outer Carpathian sector) and Siret (piedmont sector) (Rădoane et al., 2007, 2008; Dumitriu et al., 2011), an increase in the size of bed deposits has been observed, a tendency also observed for the Prut river (the sector downstream of Stânca-Costeşti lake, between km 438 and km 946) (Rădoane et al., 2007); this increase was favored by: the occurrence of discontinuities in the slope of the longitudinal profile; disturbances caused by the input of alluvia from the tributaries; the presence of high-energy bed sectors, downstream of an important source of alluvia a.s.o. (Rădoane et al., 2002).

Another issue, observed in the gravel-bed East-Carpathian rivers, tributaries of the Siret river (Moldova, Suceava, Trotus, Putna, Buzau) is the bimodality highlighted by the granulometric distribution histogram, and characterized by the presence of two modes separated by the lack of sediments in the gravel class, i.e., with sizes 1-8 mm (Sambrook Smith, 1996 quoted by Rădoane et al., 2007). The explanation given in this situation, where a 'grain-size jump' marks the transition from gravel to sand, characterized by the intersection of the two modes on the small gravel fraction, is related to the different sources of bed sediment. That is, the first mode with right asymmetric distribution is connected to allochthonous sources and overlaps the blocks, gravel and cobble fractions that reduce their size along river-beds through mechanical friction and hydraulic sorting processes, and the second mode, with a left asymmetric distribution, corresponds to the sand fraction fed by hillslope basin erosion (Rădoane et al., 2007).

In the present study we performed grain-size analyses of bed deposits in different sections along two small rivers in the Eastern Carpathians, in order to identify whether the deposits of these rivers are subject to the same laws observed in the spatial distribution of bed sediments of the large, Eastern-Carpathian rivers. More precisely, we aim to: i) identify the tendency in the spatial distribution of median grain diameter in the Gemenea and Slătioara river-beds; ii) understand this dynamics for reduced-length beds; iii) understand the presence or absence of bimodality in the distribution of grain-size classes and their significance in erosion, transport and deposition of alluvia.

1.1. The study area

The hydrographic systems of the Gemenea and Slătioara rivers form the Gemenea catchment (Figure 1). With an area of 77.76 km^2, this catchment is part of the small catchments category, and is located in the northeastern part of the Eastern Carpathians.

Lithologically, the western part of the catchment corresponds to the eastern extremity of the Rarău marginal syncline and the crystalline-Mesozoic area, whereas the eastern part belongs to the Carpathian flysch belt, Ceahlău, Teleajen and Audia nappes respectively. These two lithologies are distinctive through higher altitudes and slope gradients in the western half of the catchment and gentler landforms in the eastern half. From the morphometric point of view, the catchment extends between 1628 m a.s.l. (Colţii Rarăului) and 580 m a.s.l. (confluence with Suha Bucovineană), with an average elevation of 1104 m. The geomorphology of the Gemenea catchment is characterized by the presence of the Slătioara - Gemenea valley system, by selective erosion forms and river terraces (Livarciuc, Patriche, 2016).

Major vegetation types, i.e. forests and meadows, are represented in the general landscape by dense, sometimes old-growth spruce, fir and beech forests, interspersed with meadows of complex floristic composition. The general forest cover coefficient is rather high for almost the entire catchment area, with 76% for Gemenea and 86% for Slătioara.

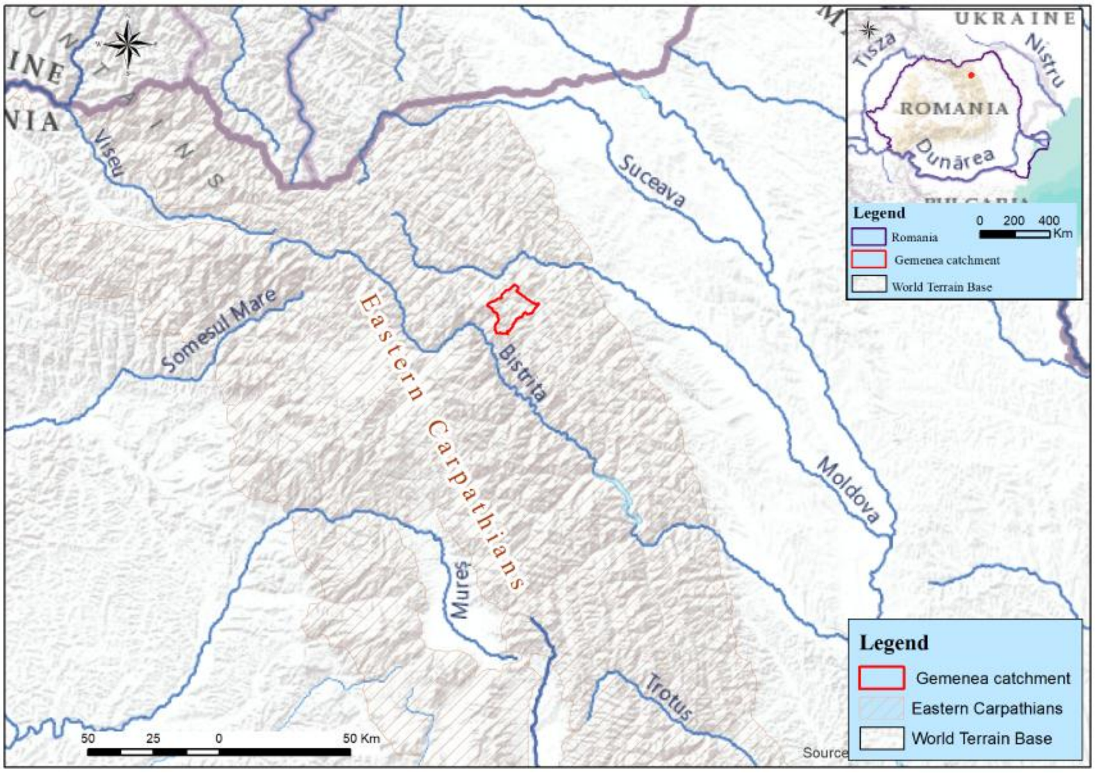

Figure 1. Location of the studied catchment. This figure is available in colour online at www.georeview.ro

The main channel has a length of 15.9 km and an average slope of 4.38%. At a distance of 11.7 km from the headwaters, the Gemenea river meets the Slătioara river which has a length of 9.8 km and a slope of 5.75%. If we refer to Gemenea rive-bed only to the confluence point, we observe that its slope is 5.4%, almost similar to Slătioara. These two rivers have a low mean annual flow rate of 0.909 m^3/s, however, the discharge peak during the warm season can be one hundred times higher than the mean annual flow rate. For example, in 2016 the flow rate reached the historical value of 86.7 m^3 / s on the Gemenea river and 95.3 m^3 / s on the Slătioara river in 2008 (Livarciuc et al., 2015). The hydrological regime of these rivers follows a general increasing trend, but this is not limited to a confined area, but is observable on a larger scale. The meteorological records of climatic elements over a period of 50 years (1961-2010) from the northeastern part of Romania showed an increase in the frequency and magnitude of the climatic and hydrological phenomena caused by the global warming (Piticar, 2013). Increasing magnitude and frequency of exceptional hydrological phenomena is accompanied by accelerated landform dynamics and an intensification of the transport of alluvia, especially on rivers with torrential flow regime, which feed the main river-bed with coarser material than that existing at the confluence point. At the same time, the input of eroded material from the hillslope base is intensified, depending on the degree of connectivity with the bed. For the analyzed sectors, the direct connection of the river-bed with the hillslopes is reduced because the bed is framed by meadow terraces for much of its length. The high connectivity with the hillslopes is characteristic of rivers pertaining to the I and II orders according to Strahler classification system; such slopes have a higher density in the upper course of Gemenea compared to the upper course of Slătioara, a situation which is reflected in the grain-size composition of bed sediments and in the spatial dynamics of median grain diameter.

2. Methods

The volumetric method was used in the analysis of bed deposits (Mosley and Tindale, 1985; Church et al., 1987 cited by Rădoane, 1992), which implies taking into account the following issue during sampling procedures: the total weight of the sample taken is a function of the weight of the largest clast in the analyzed section. The largest clast should represent 5% of the total weight of the sample. The volumetric method consists of undergoing a fieldwork stage and a laboratory stage. During the fieldwork stage, large clasts (180-64 mm) are measured in the field and samples (< 64 mm) are taken to continue measurement during the laboratory stage. A set of 13 sampling sections were established for fieldwork, of which 9 sections on the Gemenea bed (sections 1-9) and 4 sections on the Slătioara bed (sections 10-13), represented in Figure 2.

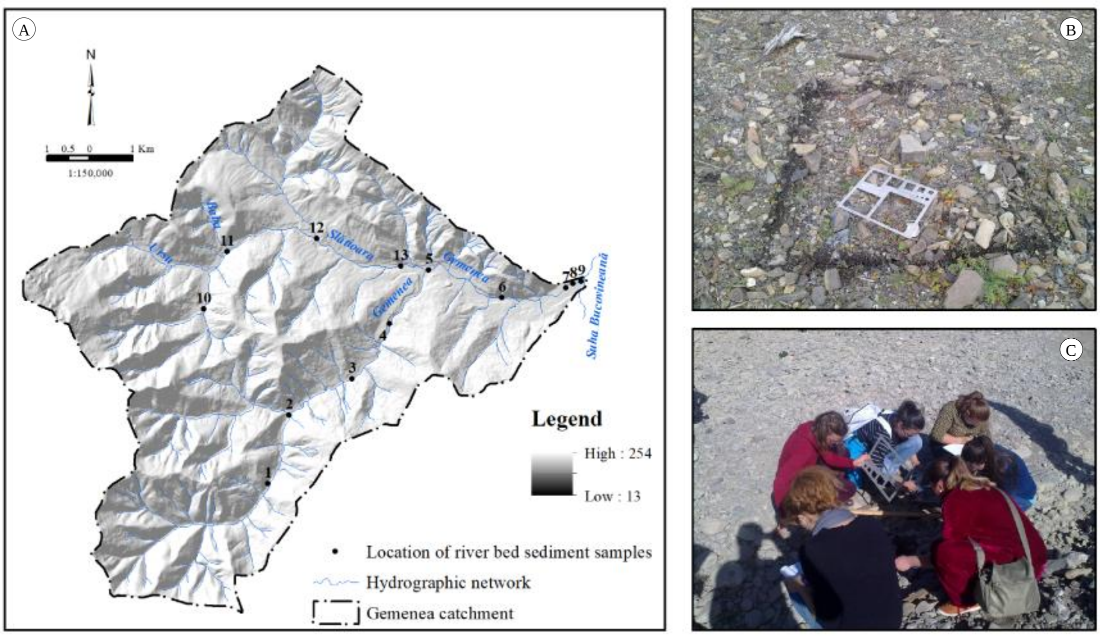

Figure 2. A) Location of the measuring and sampling sections of bed deposits, B) and C) Measuring clasts in the field. This figure is available in color online at www.georeview.com

In each section, a representative area of 1 m^2 was chosen from which every clast was measured. The fractions > 64 mm (cobble, 180-64mm) on this area were measured in the field using a template (Wolman Method, 1954), (Photo. 2.1. B) and for the determination of their weight the conversion scale diameter-weight proposed by Ichim et al., (1992) was used, developed based on measurements and literature data. The authors show that the b-axis is the best estimator of the nominal diameter [Dn = (abc) 1/3] of an ellipsoid and propose the following formula for calculating the weight of the clasts that cannot be weighed in the field: $G = 0.0011D^{3.001}$ (Dumitriu, 2007). For fractions < 64 mm samples were taken and analyzed for grain-size in the laboratory.

During the laboratory stage, samples taken in the field were dried at 105°C, followed by continuation of measurements initiated during fieldwork. For grain-size fractions from the gravel category (<64 mm) a set of sieves were used corresponding to the grain size classes of: 64-32 mm; 32 - 16 mm; 16 - 8 mm and 8 - 4 mm, whereas for the sand fraction (2 - 0.063 mm), an Endecotts Minor sieving machine with vertical and horizontal vibrations was used. This machine is equipped with a set of 5 superimposed sieves with mesh sizes of: 2 - 1 mm; 1 - 0.5 mm; 0.5 - 0.25 mm; 0.25 - 0.125 mm; 0.125 - 0.063 mm. For each analyzed sample a table sheet was created, where grain-size classes and their weight were recorded. From the total weight of the sample, the simple frequency and the cumulative frequency of the grain-size classes required to draw the granulometric curve were calculated. The granulometric curve was used to extract the median diameter (D_{50}) and other percentiles required to obtain the statistical parameters. For the classification and size-based representation of bed deposits, the Wentworth granulometric scale was employed (Church et al., 1987).

3. Results and discussion

3.1. Variation of median diameter along the river beds

The laboratory results allowed us to graphically represent the grain-size curves for each sampling section. These, as we can see in Figure 3. A. and B, retain their characteristics along the two river-beds, except for sections 8 and 9 located at the mouth of the Gemenea river. The similarity of the grain-size curves among the sampling sections is given by the grain-size composition of bed deposits that does not record large variations along the river; however, the most effective indicator in describing this dynamics is the median particle diameter (D50), which can easily be extracted from the granulometric curve.

From upstream to downstream, the median diameter of each section of the Gemenea bed is reduced from 120 mm to 49 mm, whilst in the case of Slătioara bed, the median diameter increases from 90 mm to 105 mm (Figure 3. C.). We note, therefore, that the two beds exhibit a different behavior of the spatial grain-size distribution, which in the case of Gemenea valley follows a fining trend, according to Stenberg's law (1875), whereas for the Slătioara valley the trend is of grain-size coarsening, contrary to the aforementioned law.

In order to perform a fair comparison between the two river-beds, we first consider the bed sectors upstream of their confluence. Within these limits, Gemenea bed has a length of 11.7 km and a width that varies successively along the river, from 3 m to a maximum of 70 m. The bed is mostly enclosed in meadow terraces overlaid by the forest road that follows the river on its entire length. Therefore, the direct connectivity of the river with the hillslopes between the sampling points occurs only over a short length of 1.9 km, where hillslopes are visibly affected by the lateral erosion of the river. Occasionally, there can be observed a reduced thickness of the weathered horizon, washed away from the bedrock during high waters. The alluvial input of the tributaries into the main bed is visible through the alluvial cones they form at the confluence points; the sampling sections were chosen downstream of the confluences, at too large a distance from these cones and did not capture changes in the spatial granulometric distribution. Therefore, in the aforementioned Gemenea bed sector, the median diameter is fining from 120 mm upstream to 100 mm downstream as a result of hydraulic sorting and sediment friction, which is also allowed by the greater bed length, of 11.7 km. Moreover, along the river there are successive short segments where the bed suddenly narrows to a width of 4-6 m, behind which, at maximum flow rates, lateral circular currents are formed which determine the sorting and deposition of alluvia, especially coarse-grained. In this sector, which includes Gemenea bed to the confluence with Slătioara, the average median grain diameter is 110 mm.

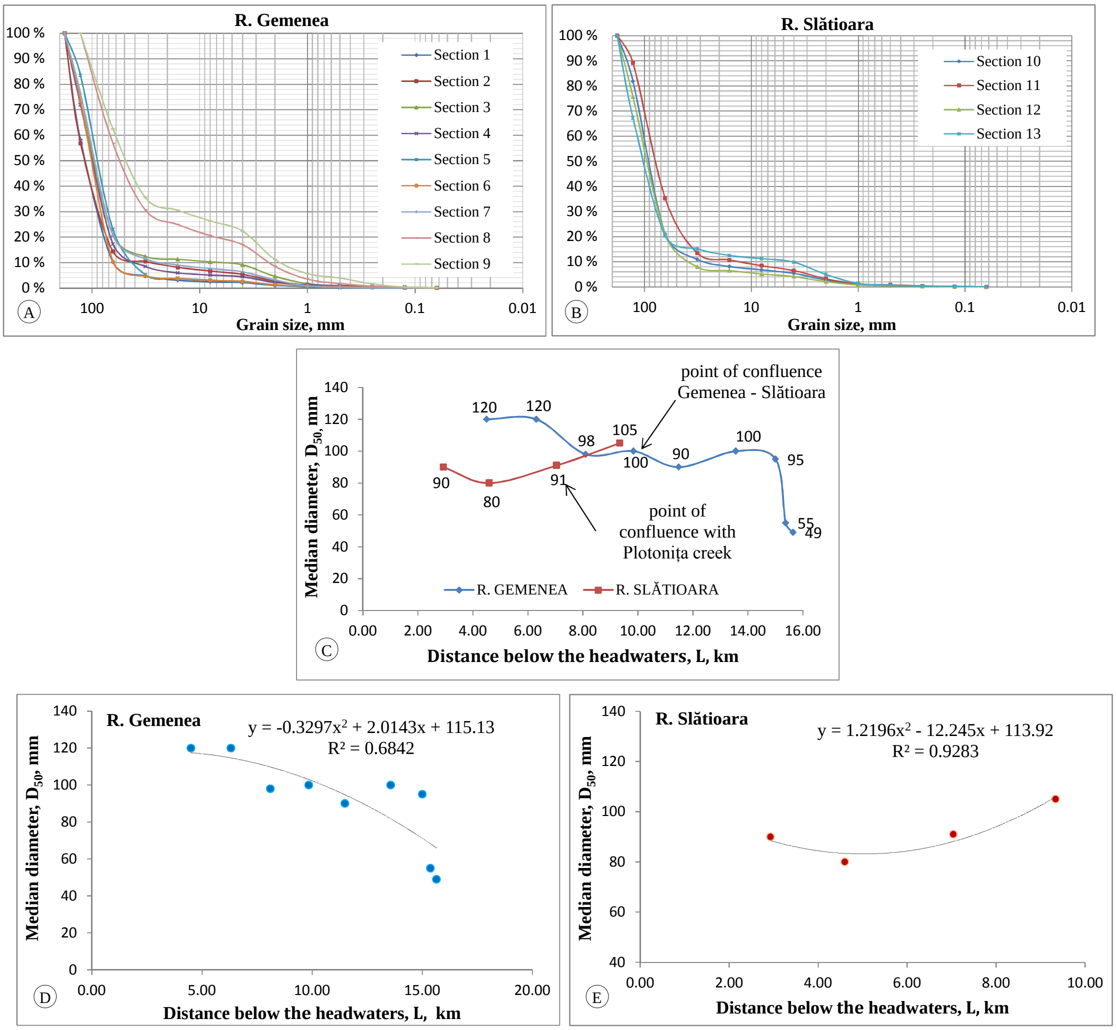

Figure 3. A) and B) Grain-size curves resulting from the analysis of bed deposits; C) Variation of the median diameter along the Gemenea and Slătioara beds; D) and E) Polynomial function describing the median diameter variation.

The characteristics of the Slătioara bed are similar to those of the Gemenea bed in the upstream sector, i.e., both rivers are largely framed by meadow terraces overlaid by the access road in the area and the connectivity of the riverbed directly with the hillslopes is observed on a slightly longer distance in the case of Slătioara compared to Gemenea, 2.3 km respectively. We can refer to a direct connectivity with the meadow terraces scarps that are a friable source of sediments. For this bed, we observed a slight increase in the median diameter (coarsening) downstream, from 90 mm to 105 mm. However, the average D50 is 92 mm, which shows that the Slătioara river bed sediments have a smaller grain-size compared to the bed sediments of the Gemenea river. The variations in the median diameter are not particularly high; its increase can be observed for section 12 (kilometer 7), where the Plotonița stream meets Slătioara and where distinct samples were taken from each bed. The median diameter obtained following sample processing was 91 mm for the Plotonița bed and 95 mm for the Slătioarea bed. This suggests that the Plotonița stream is not the only source of coarse alluvia for Slătioara bed, but there are other sources upstream of the confluence, which contribute to the increase in the median diameter along Slătioara bed.

The closest source to the confluence (at a distance of 0.5 km) is a bed segment carved in bedrock (flysch, Ceahlău nappe), the upstream Baba brook and a 200 m hillslope segment with the base eroded by the river. The fall of the weathered horizon along the high steep hillslopes (> 45 °) and the rolling over of rocks detached from bedrock outcrops, constantly feed the river-bed. Another aspect to be considered is that the roads parallel to the Gemenea and Slătioare rivers are made of river alluvia, which can have a grain-size different from that of the bed deposits. Certain sectors of these roads are rapidly eroded during flash floods. Rebuilding these road segments generally involves using the alluvia from the adjacent river-beds, but using alluvia brought from other river-beds is also common. The Slătioara river is less regularized than the Gemenea river, and between sections 11 and 12 the road is often eroded during high waters. Altogether, this suggests that eroded roads can also influence the granulometric composition of bed sediments.

The lower course begins downstream of the confluence of the two major rivers in the catchment and extends to the mouth of the Gemenea River. In this sector, with a length of 4.3 km, the bed strongly widens (maximum width, 150 m) and the channel frequently swings during the warm season, when the flow rate is maximum. The direct connectivity between the river and hillslopes is observed on a 2.2 km length and only on the left side of the river, where several perimeters are sporadically characterized by rock falling and rolling processes activated by lateral erosion. These processes feed the river-bed with material of various sizes, but their intensity is reduced because the hillslopes are forested and thus more stable. The median diameter of bed deposits follows a similar fining trend, observed for the middle and upper courses of Gemenea, with small positive variations which are of little significance. Specifically, in section 5 located downstream of the confluence of the two rivers, the median diameter is 90 mm and subsequently increases to 100 mm in section 6. From this section downstream, no positive deviations from the fining trend of the median diameter are noted; the median diameter progressively reduces to 95 mm in section 7, to 55 mm in section 8 and to 49 mm in the last sampling section. The average median diameter for this bed sector is 77.8 mm.

Overall, in the Gemenea bed the decrease in the median grain diameter does not occur linearly but shows slight fluctuations, which are of low importance in the upper and middle course and more pronounced in the lower course of the river. The results of the bed sediment gran-size analysis show that both the Gemenea and Slătioara beds have on average the same median grain diameter of 92 mm. However, the values change for sectors taken separately. The Gemenea bed sediments have an average diameter of 110 mm upstream of the confluence with Slătioara and 77.8 mm in the bed sector downstream of the confluence and to the Gemenea river mouth. We therefore note a slight decrease in the median diameter along the Gemenea river-bed, which can be attributed to hydraulic sorting, particle friction phenomena and river competence. The general tendency of the median diameter is represented by the second-order polynomial function (Figure 3. D. and E.).

3.2. Grain-size spectrum of bed deposits

On average, the petrographic spectrum of bed deposits for the Gemenea and Slătioara rivers is composed of 70% cobble (181-64 mm), 25% gravel (64-2 mm), 4.6% sand (2-0.063 mm) and 0.4% silt (<0.063 mm). This granulometric composition changes along the river beds, either by a decrease in the proportion of cobble or conversely, by an increase in the proportion of this grain-size fraction depending on the bed sector we refer to.

For the upper and middle course of the Gemenea river, i.e., upstream of the confluence with Slătioara, cobble is the only grain-size class that follows the same trend as the median diameter, namely a decrease in proportion downstream (Figure 4. A.). No similar dynamics was found for the gravel fraction, which has a contrasting behavior. These grain-size classes show mirror-like dynamics, i.e., the proportion of gravel progressively increases downstream, parallel to the reduction in the proportion of cobble; the lines describing these trends are intersected further downstream, at the mouth of the Gemenea River. The proportion of sand in this sector first shows an increase in its upper part, which is maintained towards the middle part, followed by a decrease in the lower part of the sector.

The petrographic spectrum of Slătioara bed shows, on average, the same proportion of grain-size fractions as in the case of the middle and upper course of Gemenea bed, but with different spatial dynamics (Figure 4. B.). On a short segment, in the first 4.6 km from the headwaters, the percentage of cobble is reduced, followed by its gradual increase as a result of lateral contribution of sediments (the Baba brook, rock falls on the hillslopes directly connected with the bed) and erosion of the pavement layer. Gravels show a behavior opposite to cobble; in the case of Gemenea bed, the lines defining the behavior of gravel and cobble are intersected downstream, whereas in the case of Slătioara bed, the lines move away from each other. In other words, as the proportion of cobble increases downstream, the proportion of gravel is reduced. The proportion of sand varies to some extent along the Slătioara bed and follows an increasing trend towards the confluence with Gemenea, where it reaches approx. 5% compared to 3% upstream.

Downstream of the confluence between Gemenea and Slătioara, the cobbles and gravels follow a dynamics similar to that initiated in the upper and middle course of Gemenea; the lines indicating these trends are intersected 600 m upstream of the Gemenea river mouth, which suggests a balance between the proportion of cobble and gravel in the river bed, and at the same time, by continuing this trend, a reversal of the weight these grain-size fractions had upstream. After the upstream fluctuation in the proportion of sand, the occurrence of sand in bed sediments increases exponentially downstream, in the alluvial cone of Gemenea, where sand reaches a percentage of 11% in sampling section 9.

Grain-size composition of the measured beds is highlighted by the ternary diagram (Figure 4.C.), from which the overall picture of the proportion of each grain-size class can be easily distinguished. Thus, cobbles have the largest share in analyzed bed sections, followed by gravel. A slight deviation characterizes sections 8 and 9, where the proportions of these grain-size classes are reversed. This granulometric composition is specific to rivers in the Carpathian region, also observe for the Eastern Carpathian rivers (Ichim et al., 1996, Dumitriu, 2007, Rădoane et al., 2002).

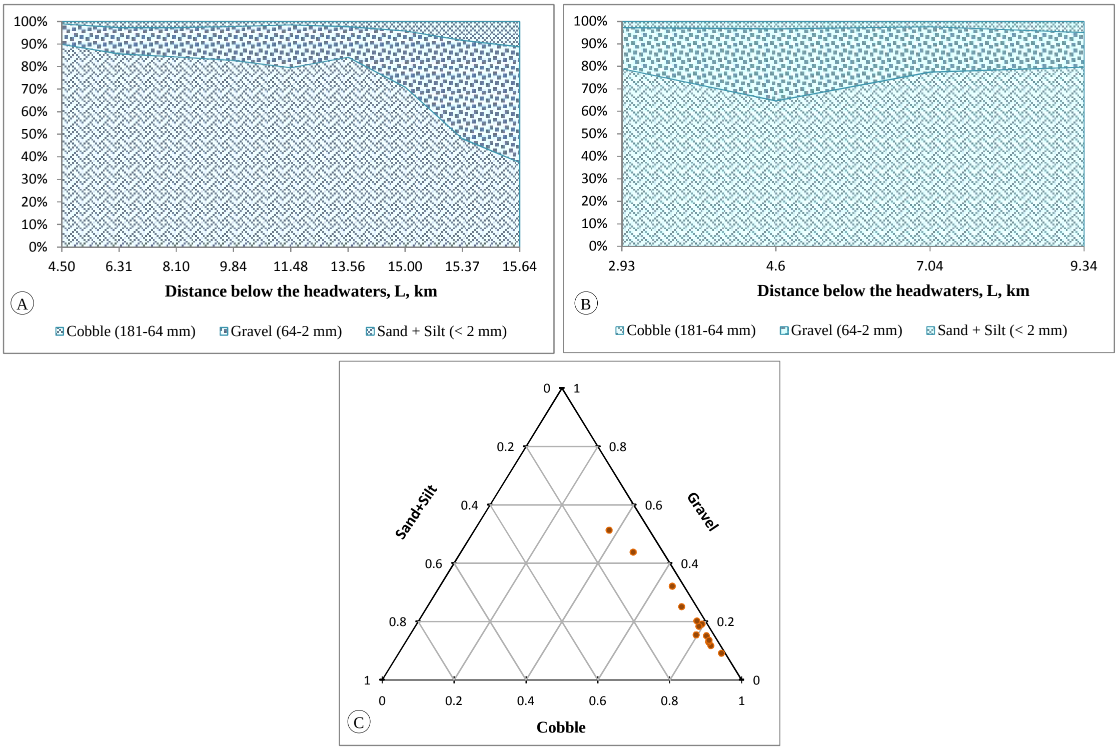

Figure 4. A) Petrographic spectrum of the Gemenea river-bed; B) Petrographic spectrum of the Slătioara river-bed; C) Ternary diagram showing the grain-size composition of the Gemenea and Slătioara river beds

3.3. The unimodal character of grain-size distribution

The graphical representation of grain-size distribution in the form of histograms highlights the unimodal character of grain-size distribution, but also a slight bimodality which is clearer in sections 8 and 9 located at the mouth of the Gemenea river (Figure 5). This type of distribution is characteristic of short rivers or of the upper course of large rivers. The coefficient of asymmetry is negative, indicating both the existence of an excess of coarse clastic material that overlaps the cobble class (-7.5 and -6 phi or 180 - 64 mm) and the grain-size distribution mode, but also a shortage of material in the gravel and sand classes. The second mode appears in the small gravel class with -2 phi (4 mm) grain-size and is more visible in downstream sections, 8 and 9 respectively.

Estimating bed sediment sorting was based on standard deviation values, a method proposed by Folk (1968), which consists in classifying standard deviation into seven classes with different degrees of sorting of river bed alluvia. Alluvial deposits in Gemenea and Slătioara river beds generally have poor sorting (1.3), but there are also sections where sorting is relatively good

(0.60), such as sections 1, 5 and 6 of the Gemenea bed. Therefore, the capacity of the river to separate and deposit grains according to their specific size, shape and weight, varies along the bed depending on local factors.

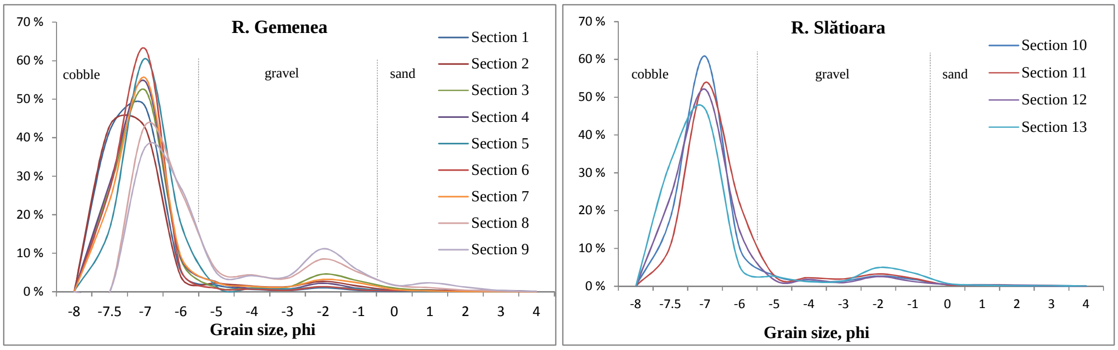

Figure 5. Histograms representing the grain size distributions

In accordance with previous findings, the bimodality of bed sediments is caused by the different contribution of sediment sources on the one hand and the selective transport along the river on the other. The river bed and the hillslope basin are the two sources whose contribution to the sediment budget changes along the river. In the case of the Gemenea river-bed, the low weight of the second mode, very hard to notice in most sampling sections, shows that the major source of sediments in the alluvial beds is the river bed itself (by erosion of the meadow terraces), whilst the input of fine sediments from the hillslope basin is extremely low.

4. Conclusions

From upstream to downstream, alluvia grain-size distribution in the sampling sections indicates slight variations in the median diameter, which generally follow a fining trend for the Gemenea bed, according to Stenberg's law (1875) and a coarsening trend for the Slătioara bed.

The average median diameter for the Gemenea river-bed is 92 mm; it increases to 110 mm in the upper and middle course of the river, i.e., the bed sector from headwaters to the confluence with Slătioara and reduces to 78 mm in the lower course of the river, i.e., downstream of the confluence with Slătioara. The most pronounced variation in the median diameter is observed at the mouth of Gemenea river, where, over a distance of only one kilometer, the median diameter is reduced from 95 mm to 49 mm.

The alluvial deposits in the Slătioara river-bed show a grain-size distribution different from that observed on the Gemenea river, i.e., the median diameter slightly increases towards the confluence with Gemenea. The average river-bed sediment median diameter for Slătioara is 92 mm, slightly lower than in the case of the upper and middle sectors of the Gemenea river (110 mm); this suggests that there is a particle size difference between the two valley sectors crossing the same lithological units. This difference can be caused by the lower number of lower order segments (I and II in the Strahler system) which feed the river with cobbles and gravel, but also by the smaller transport distance of the Slătioara river, which impacts the sorting of bed material.

The median diameter variability in the sampling sections reflects river competence for transport which slightly reduces downstream. The petrographic spectrum of the Gemenea and Slătioara river-bed deposits consists of 70% cobbles (181-64 mm), 25% gravel (64-2 mm), 4.6% sand (2-0.063 mm) and 0.4% silt (< 0.063 mm). This grain-size composition is given by the uptake of material from upstream torrential beds of I and II orders, material that spreads downstream through pulsating movements during maximum river discharge. When these materials exceed the capacity and competence for transport of the river-bed, the alluvia are deposited and form the meadow and terminal accumulations such as proluvia and glacises. In turn, these deposits gradually become alluvial sources through lateral erosion of the river. The grain-size composition of the analyzed alluvial deposits places the Gemenea and Slătioara rivers in the category of river-beds with cobble bed pavement. The characteristic feature of these river-beds is that they have a top pavement layer of coarser alluvia and a subsurface layer of finer alluvia. The difference between these two layers is closely related to the hydrological regime of the river and to the upstream sources of alluvia (Bunte and Abt, 2001).

The bimodality of grain-size distribution observed in the case of large, eastern Carpathian rivers is not necessarily characteristic of river-bed deposits of small rivers; the bimodality of grain-size distribution in the case of small rivers hardly becomes observable in the lower sectors of these rivers (such as the case of the present study). This observation leads to two important deductions concerning the sediment source and transport: i) the share of fine sediment sources in the catchment is relatively small (predominantly skeletal hillslope deposits with sandy matrices in small quantities), and, (ii) the transport distances where mechanical processes of wear and sorting of bed materials can operate are of only several kilometers. As a result, the sediment budget is dominated by the coarse fraction of the rock fragments, and the high energy environment of small mountain rivers rapidly removes the low amount of sandy matrix. Knowing the competition between the two categories of processes (sediment supply from the sources and particle fragmentation during transport) in small catchments (with areas less than 100 km^2) represents an important contribution for understanding the succession of these processes in large rivers (the latter being increasingly studied).

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