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BIMODALITY ORIGIN OF FLUVIAL BED SEDIMENTS. STUDY CASE: EAST CARPATHIANS RIVERS

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Abstract. Taking as an example main great rivers that drain the western flank of the Eastern Carpathians, a study regarding the current fluvial bed sediment has been carried out, in order to tackle, among others, such controversial problems as “downstream fining” and “downstream coarsening”, of river bed deposits’ bimodality, of the effect of the sediment sources in the basin. One of the study’s conclusions is that the river bed deposits’ bimodality can be explained, in the cases we studied, by the superimposing of two grain size distributions, of different origin.

For the East Carpathian Rivers (without the Siret River), the coarse particles are part of a unimodal distribution with a right skewness and a strong “downstream fining”. The source of these materials is autochthone (through the abrasion and hydraulic sorting of the bed material). For the same rivers there has been observed a second distribution with a 0.5-0.25 mm class mode and which generally has a left skewness. The source of the second distribution is allochthone (the quantity of sand that reaches the river bed through the erosion of the hillslope basin fields). The intersection of the two distributions occurs in the area of the 1-8 mm fractions where, in fact, the right skewness (for gravel) and left skewness (for sand) histograms tails meet. The idea that the 1-8 mm fractions would be in penury in the bed deposits, is false because for the rivers that have low sources of fine sediments in the basin the 1-8 mm fractions have a higher proportion that the fractions under 1 mm.

For the Siret River, the bed sediment bimodality is highest because the second mode, that of the sands, represents 25 % of the full sample. Unlike the tributaries, the source of the first mode, that of the gravel, is foreign to the Siret (the massive input of coarse sediment through the Carpathian tributaries), while the second mode, of the sands, is local.

Key words: bed sediment, downstream fining, downstream coarsening, sediment supply, bimodality

1. INTRODUCTION

Along with other features of the river beds like morphology, hydraulic characteristics, the capacity to modify their section in a very short time, etc., river bed deposits have been, without a doubt, one of the first phenomenon observed and studied by the scientists, perhaps also for the fact that their evidence is so direct and so easily noticeable. It is said that Leonardo Da Vinci had published the first ever commentary regarding the progressive downstream reduction in the size of the fluvial sediments in “Codex Hammer” (1504-1506) (Richter et al., 1939, quoted by Gomez et al., 2001). At the same time with this observation there also appeared explanations on the possible causes for the phenomenon. If most of the authors mention Sternberg (1875) as being the one to discover “the weight reduction law of the fluvial sediments’ particles”, Gomez et al. (2001) have carried out a more thorough investigation in the history of the matter and so we found out that ever since the 17th century there had been released the hypothesis that *the bed materials’ abrasion* during transport is the main cause for progressive reduction in the size of the sediments (Guglielmini, 1697, chap. V, sentence VI), and, some time later, Frisi (1762, chap. II, all quoted by Gomez et al. (2001) had invoked the second process as well, *hydraulic sorting* that, along with abrasion, are the basis of explaining the phenomenon. After these important reference points there have followed numerous qualitative and quantitative observations based on systematic field studies that have culminated with Sternberg’s (1875) and which are at the basis of the classical weight reduction law: $W = W_0 e^{-aX}$, where W_0 is the initial weight of the sediment particle in the river bed, W is the weight of the particle at the distance X along the river and a is a coefficient that describes the particular conditions of a river.

Starting from these observations there have developed two directions of the research and experiments, in accordance with which the scientists have also polarized; on one hand, there were the ones that sustained the chief role of particle abrasion in reducing and shaping the river bed material along the river and that abrasion is, in fact, a number of fragmentizing processes of the rocks that depend on litology (e.g. Kuenen, 1956; Shaw and Kellerhals, 1982; Kodama, 1992); and on the other hand, others that supported hydraulic sorting as the main mechanism of differentiating the shapes and sizes of fluvial sediments’ particles (Russell, 1939; Einstein, 1950). The phenomenon has been thoroughly studied under the aspect of the numerous complications that occur in this mechanism, like: the condition of equal mobility (Parker et al., 1982; Wilcock, 1992; Gasparini et al., 2004), the role of the local base level (Ferguson et al., 1996) or of the river bed’s aggradation (Seal et al., 1997; Gomez et al., 2001), river basin concavity (Gasparini et al., 2004), the role of lateral sediment input (Knighton, 1980; 1982; 1999; Ichim and Rãdoane, 1990; Rice and Church, 1998; Rice, 1999) or of human intervention (Surian, 2002; Rădoane et al., 2005). Numerical models replicate these field and laboratory observations and also provided a perspective on the development of downstream fining processes (Paola et al., 1992; Seal et al., 1997; Hoey and Ferguson, 1994; Pizzuto, 1995, Toro-Escobar et al., 2000; Lewin and Brewer, 2002, etc)

Although the list of scientific results in this field is wide and numerous questions have been answered regarding the "downstream fining" phenomenon, there still is, up to this day, a necessity for systematic field research of greater scale, for compiling a comprehensive data base in order to better understand the diversity of field situations regarding the river bed material reduction phenomenon. It's an opinion sustained by many authors (Pizzuto, 1995; Sambrock Smith and Ferguson, 1996; Rice, 1998; Gomez et al., 2001) to which, through this study, we also relate.

Following the specialized literature for our research field, we were pleased to find that a case study from our investigations (the "downstream coarsening" phenomenon along the Siret River (Ichim and Rãdoane, 1990) had been widely exemplified in order to explain some of the situations that deviate from the Sternberg's law. This has been another reason for us to continue our research and to extend them onto other rivers of the same drainage system. For ten years we've focused our attention on the rivers of the Siret basin, one of the major tributaries of the Danube on Romania's territory. Being supported by the experience of numerous authors in studies of great elegance regarding *downstream variation in grain size* on a single river or river sector (Brierley and Hickin, 1985; Dawson, 1988; Ferguson and Ashworth, 1991; Werrity, 1992; Seal and Paola, 1995; Ferguson et al., 1996; Gomez et al., 2001, Surian, 2002 and many others), we've also thought if a spatial approach on the variability of bed material on a number of rivers within a fluvial system of over 43,000 km^2 could bring new reference points in the knowledge of this phenomenon. A similar manner of approach had also been in the attention of other authors such as: Yatsu (1955), Knighton (1980), Shaw and Kellerhals, 1982; Ibbeken and Schleyer, 1991; Kodama, 1994; Moussavi-Harami et al., 2004) and many others. It is a difficult method because volumetric sampling in the rivers with gravel beds is a real challenge for those engaged in studying the phenomenon (for example, in the superior part of the sampled Carpathian Rivers, the weight of the sample sieved in situ always exceeded 1000 kg, which has been an extraordinary effort for the team). But we've enthusiastically engaged in this research because nothing can be compared with the intellectual satisfaction given by the knowledge of such a wonderfully assembled system like the fluvial one, where "*streams are the gutters down which flow the ruins of the continents*" (Leopold, et al. 1964, p. 97).

The necessity to have a close knowledge of the variability of river bed materials has also a well out-lined practical side, even if we only refer to the case studied by us. The rivers of the Siret drainage system, alike other rivers from our continent, have, for a long time and nonsensically, been under human intervention, either through the exploit of construction materials or by using their hydropower potential, to name the most important. The powerful and irreversible impact of arrangements and using the rivers and terrains of the drainage basin, have caused Romania great unbalances and economic shortcomings, some consequences being hard to estimate. And all this only referred to the level of the entire sediment system, from terrain erosion, to sediment delivery rate, dam-lake clogging, the indirect effect over the Black Sea's shore, to the reserves of mineral aggregates for constructions (Ichim and Rădoane, 1986). In this context we shall mention a few aspects that we find especially alarming (Ichim et al., 1998):

i) Of the almost 13 billion m^3 of man-made lakes arranged on Romania's rivers, approximately 3 billion m^3 are already clogged and the small reservoirs (under 10 million m^3) are clogged in a proportion of over 50 %;

ii) The rate of terrain erosion is high on almost 700,000 hectares of terrain and, in the conditions of applying the landed property law, it has been accelerated. This has led to great disturbances in the regime of slope stability and terrain erosion, which is obviously reflected in the rivers' sediment system and network arrangement works;

iii) The prominent discontinuities in the sediment transit on account of the arrangements in the Danube basin, have also heavily influenced the condition of the Black Sea's littoral, having been observed a growth in the sea's aggressiveness (presently, the rate of shore retreat is, in average, of 2-2.5 m/year and in some areas of 25-30 m/year);

iv) The industry of construction materials and hydro-technical arrangement are currently consuming a volume of aggregates (gravel, cobbler and sands) from the river's bed of over two times the possibility of suspended sediment load transport and of over 20 times the rate of bed load transport, which would ensure the regeneration of these aggregates. We also add the disturbances regarding the stability of the river bed and adjacent works (bridges, dams).

In conclusion, our study is planned to deal with the phenomenon of river bed material variability along a network of 1640 km river length in the Siret drainage basin as a segment of correlation between their sediment sources and sediment delivery. In a very special way we shall focus on the spatial variability of the river bed materials distribution types and we will try to discuss upon the origin of the fluvial deposits' bimodality. As a support for our assignment we dispose of a series of concepts and theoretical fundaments as advantages in favor of our knowledge (the fluvial system, Schumm, 1977; the sediment budget, Dietrich and Dunne, 1978; the time of sediment residence, Madej, 1987; Nakamura, 1987; the sediment delivery, Walling, 1983; patterns of sediment yield, Walling and Webb, 1983) and which we shall use in order to better understand the way in which the variation of bed material characteristics takes place along a river. These are joined by the excellent research studies and synthesis from around the world regarding the gravel – sand transition in river beds carried out by Sambrook Smith and Ferguson, 1995, Sambrook Smith, 1996, Sambrook Smith et al., 1997) or the bed particle size variation in subaerial aqueous flows carried out by Morris and Williams (1999a, b), that have helped create a comprehensive image of this phenomenon.

2. THE STUDY AREA AND WORK METHOD

In order to argument our own observations, our research has focused on the major rivers that drain the eastern flank of the Eastern Carpathians and are direct tributaries of the Siret River. There are a total of 10 rivers (of which only six have been monitored under the aspect of river bed deposits) and their action has been and, as we shall see, continues to

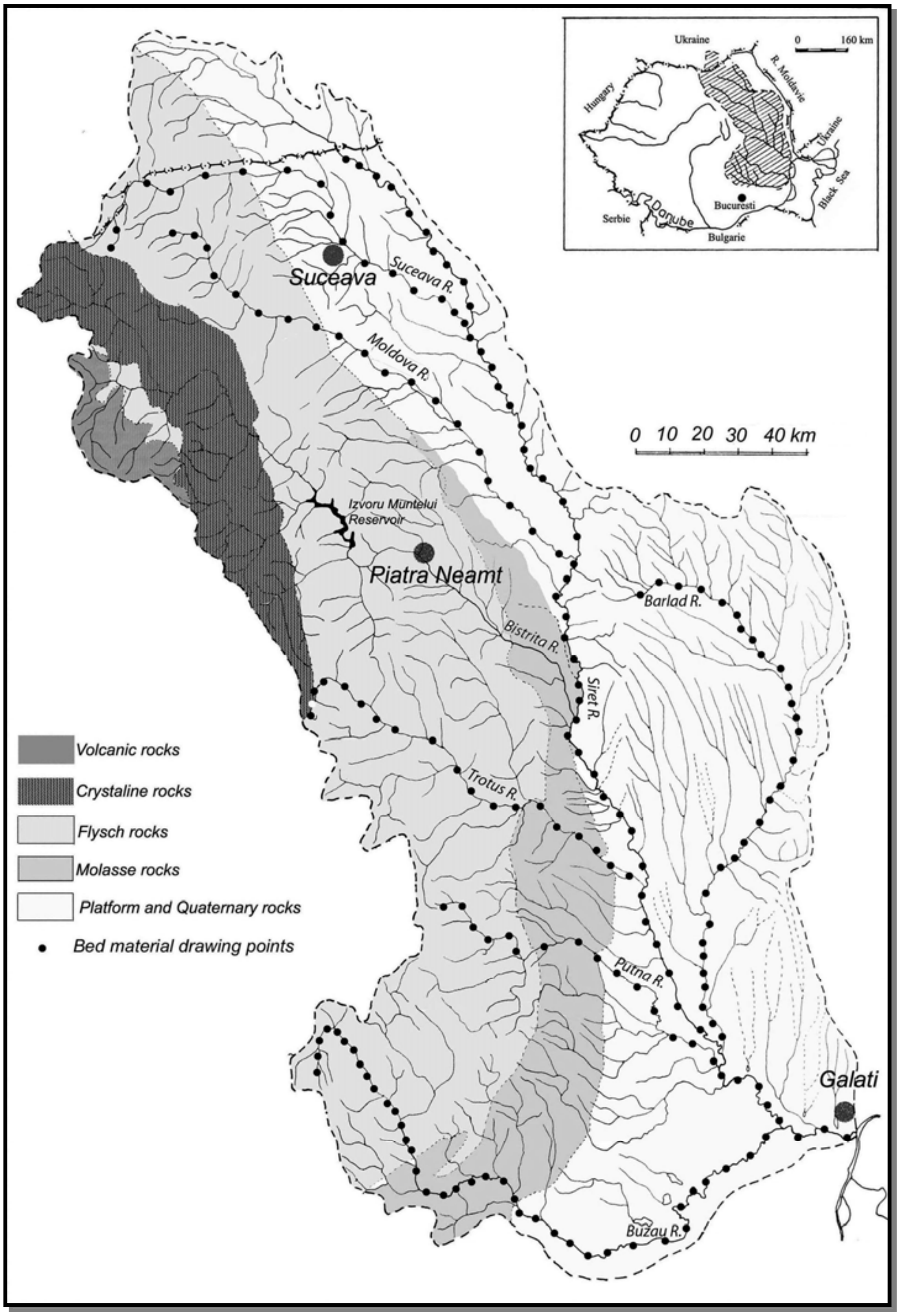

Fig. 1. Location of the study area.

be at the origin of piedmont area development on the exterior Eastern Carpathians. A few general data about them are shown in Table 1 and the geographical position of the study area is depicted in fig. 1.

Table 1. General data on the studied rivers

Nr. crt.	River	Cross section	Drainage basin area A (km²)	River length L (km)	Mean yearly discharge Q ($m^3 s^{-1}$)	Suspended sediment load Qs ($kg s^{-1}$)	Sediment yield Sy ($t km^{-2} year^{-1}$)
1	Suceava	Cf. Siret	2,616	172.3	14.1	13.6	180.4
2	Moldova	Tupilati	4,016	169.9	32.8	35.3	277.74
	Moldova	Roman	4,316	205.0		16.1	117.64
3	Bistrița	Frunzeni	6,974	239.8	52.0	8.30	37.53
	Bistrita (reconstituted)	“	5,695	278.8	62.8	20.2	98.15
4	Trotuş	Cf. Siret	4,456	149.2	33.0	38.4	394.00
5	Putna	“	2,518	146.5	13.4	91.8	1400.00
6	Milcov	Cf. Putna	395	73.5	1.1	16.9	1349.00
7	Ramna	“	334	63.0	0.6	36.0	3399.00
8	Rm. Sarat	Cf. Siret	935	139.5	2.65	32.2	1086.00
9	Buzau	Racovita	5,264	293.0	25.7	80.3	811.00
10	Siret	Siret	1,647	140.0	14.2	8.6	165.40
		Hutani	2,164	207.9	16.9	13.5	196.70
		Lespezi	5,945	306.8	37.2	52.9	280.60
		Dragesti	11,899	446.1	78.8	62.1	164.60
		Racatau	19,639	516.2	170.0	114.0	183.00
		Lungoci	36,123	651.8	211.0	261.0	227.90
		Cf. Dunare	43,933	725.8	254.0		

The main river, the Siret, has its origin in the Paleocene flysch area of the Forested Carpathians (on the Ukrainian territory), at an altitude of 1238 m. Even from its source it generates a transversal valley, typically mountainous, then a wide valley, a real channel with a typically sub-mountainous course until the confluence with the Danube. The tributaries of Siret, with the exception of Bârlad River, adapted to the hill region (and which is not the object of the present study), are mostly formed in the area of the Carpathian flysch and only two of them – Moldova and Bistrița – reach, through their springs, the inner crystalline area of the Eastern Carpathians.

These rivers (fig. 2) have been studied upon for many years by our team; therefore we have a consistent data base regarding the sediment transit, the river bed changes, the river deposits, etc. They are characteristic cases for the morphodynamic conditions of this region, as referenced to natural conditions but also to human impact, mainly, the presence of dams (Bistrița River has the most intense employment of hydro-power potential through the 13 reservoirs in usage) and ballast exploitations (over 150 counterweights along the main rivers).

The rivers have been investigated on the form of their longitudinal profile, having been applied a series of mathematical models in order to deduce the form of the equilibrium profile (Rãdoane et al., 2003); there has been research done on the tendencies

Fig.2. River channel at the near source (Trotuş River – upper left). Putna River channel downstream the submountain area (upper right). Moldova river channel in the out-Carpathian area (lower left). Suceava river channel upstream of the Siret confluence (lower right).

in current changes of the river beds (Rãdoane and Ichim, 1991; Ichim et al., 1995), using data from over 60 cross sections in the area of the hydrometric stations. But the most important and laborious investigation has been made regarding the bed deposits of the Siret basin rivers, on which we shall especially focus on in this study. The bed deposits of the Trotuş River have been comprehensively researched within a PhD thesis (Dumitriu, 2003).

The bed sections that the deposits have been sampled from are situated along each of the rivers at a distance of 8-10 km of each other and are depicted in fig. 1. The sampling has been carried out so that the effect of the tributaries would stand out, meaning that the samples were taken upstream and downstream from each important tributary of the rivers. In total, there have been investigated over 190 river channel cross sections, for which there have been taken measurements of the river slope as well. The samples were collected on a surface of one square meter from the centre of the active bar. The bulk sampling method has been used, described by Mosley and Tindale (1985), Church et al. (1987), the total weight of the taken sample being in correspondence with the weight of the largest clast found in the analyzed section. The largest clast has represented 5 % of the total weight of the sample. There have been taken distinct samples from the surface and subsurface layers. Where the grains with a diameter under 2 mm had a percentage of over 50 % of the bar's surface, there hasn't been a differentiation between surface and subsurface layers and a global sample has been taken. The fractions bigger than 6 mm have been separated through sieving directly in the field, and the ones over 64 mm have been individually measured with the sliding calipers. The biggest clast weighted in the field has had 130 kg and a diameter of 540 mm. The fractions under 8 mm were separated in the laboratory.

The analysis of river channel deposits has been carried out through sampling the bed material in three options: as *surface sample* (being represented only the hydraulic surface layer that has a thickness equal to the diameter of the largest clast); as *subsurface sample* (the material under the hydraulic surface layer being represented) and as *global sample* (by summing up the two previous categories). By sieving the material from the samples thus collected we have obtained 14 grain size classes separated at intervals of 1 phi. These classes have been grouped in five levels of dimensions (according to the Wentworth grain size scale), described in the following terms: silt (under 4 phi or 0.063 mm); sand (between 4 phi or 0.063 mm and -1 phi or 2 mm); gravel (between -1 phi or 2 mm and -6 phi or 64 mm); cobbler (between -6 phi or 64 mm and -8 phi or 256 mm); blocks (over -8 phi or 256 mm). The gravel from the grain size classes of 16-32 mm and 32-64 mm has been chosen to have their petrography and particle shape identified, but the results of these investigations are not the focus of the present study.

3. THE EAST-CARPATHIAN RIVERS' SOURCE OF SEDIMENT AND THEIR TRANSFER RATE

The gravel source of the Carpathian river beds lies in areas with a different litology from the drainage basins. The distribution of the litological units of the Siret drainage basin shows an arrangement of stripes with north-south orientation and that proceed from west to east (Fig. 1). From a geological point of view, these belong to the Neocene and volcano-sedimentary volcanism of the Eastern Carpathians (in the north-western extremity), to the crystalline-Mesozoic area, to the cretaceous-Paleocene area (in the middle part), to the Neocene molasses and Moldavian Platform in the eastern side of the basin. A short characterization of each of these units is next.

The volcanic region only represents 1.33 % of the Siret River basin and is comprised of eruptive rocks like andesites with amphiboles and pyroxenes, diorites and micro-diorites, gabbros, piroclastic rocks, the volcanogenic-sedimentary formation (agglomerates, piroclastic breccias, micro-conglomerates and tuffs). East of this region *the crystalline-Mesozoic area* follows (6.79 % of the basin's surface) represented by filites, sericitous, cloritous or grafitous schists, quartz, gneiss, limestone, crystalline dolomites and others. In some places, over the crystalline socle, Mesozoic sedimentary rocks are superposed, made up of limestone, sandstone, conglomerates and heavily pleated marls.

East of the crystalline-Mesozoic area there lies *the flysch zone* (33.29 % of the basin surface) represented through a wide variety of sedimentary rocks: conglomerates, sand stone, marls, disodilic schists, menilites, limestone that are arranged in close folded layers, until the overthrusting.

The next area towards the east belongs to the *Neocene molasses*, made up of marls, clay, sand and limestone in interpolations with volcanic tuffs (10.12 %); they are pleated but in smaller degrees than the flysch area. The largest part of the basin (47.94 %) belongs to the *Moldavian platform* made up of marls, sands, sandstones, gravel, oolitic limestone, etc. The layers are slowly inclined south-east and at the contact with the molasses they are easily wavy.

An aspect that comes to demonstrate the accentuated morphodynamics in the border zone of the Eastern Carpathians and Sub-Carpathians is the one regarding the sediment yield and transport in the Siret River basin. This phenomenon reflects the morphodynamics conditions of the present-day development period of the relief, respectively, the latest decades since we have systematic observations on the suspended sediment transport of the rivers. Based on them we have sketched the sediment transport flux along the main rivers of the Siret basin, as it currently is in our reference area. The short analysis of these cartographic materials (Fig. 3) has resulted in the following observations:

- on the considered investigation space (A = 43,933 km^2) there is a development of the entire pletora of specific sediment productions that on Romania's territory range from the smallest, of under 0.5 t/ha/y, to the highest values, of over 25 t/ha/y.

- *the litological composition of the sub-layer* which generates sediments and *the size of the drainage basins* are major factors that ensure a selection of the sediment quantities transported from the source area to the delivery (Walling, 1983; Rãdoane and Rãdoane, 2005). Thus, the small basins of the Eastern Carpathians' crystalline area supply the smallest quantity of sediment for the transport within the river network, under 0.5 t/ha/y. The basins situated on flysch rocks (sandstone, marls, limestone, conglomerates covered by the hillslope deposits which frequently exceeds 10 m in thickness), especially north of Trotuş, but also the ones situated on sandy rocks of Sarmatic origin, on the superior part of Bârlad, have a sediment production of around 1 t/ha/y. The contribution to the suspended sediment quantity released in the transport circuit easily increases in the lower sectors of Suceava, Moldova, Trotuş with all its tributaries, but most of all Bârlad, to over 2.5 t/ha/y. The highest values of the suspended sediment transport from the source area to the drainage system are recorded in the basins of the Putna and Buzău rivers, situated in the southern part of the region we've studied (over 30 t/ha/y). These basins, together with the basin of Râmnicul Sărat, are the areas with the highest erosion rate on the surface level in Romania, but also the largest sediment transport in the drainage system. The high susceptibility of terrains to erode is mainly because of the spread of friable rocks, of high landform fragmentation, of a raised erosion potential.

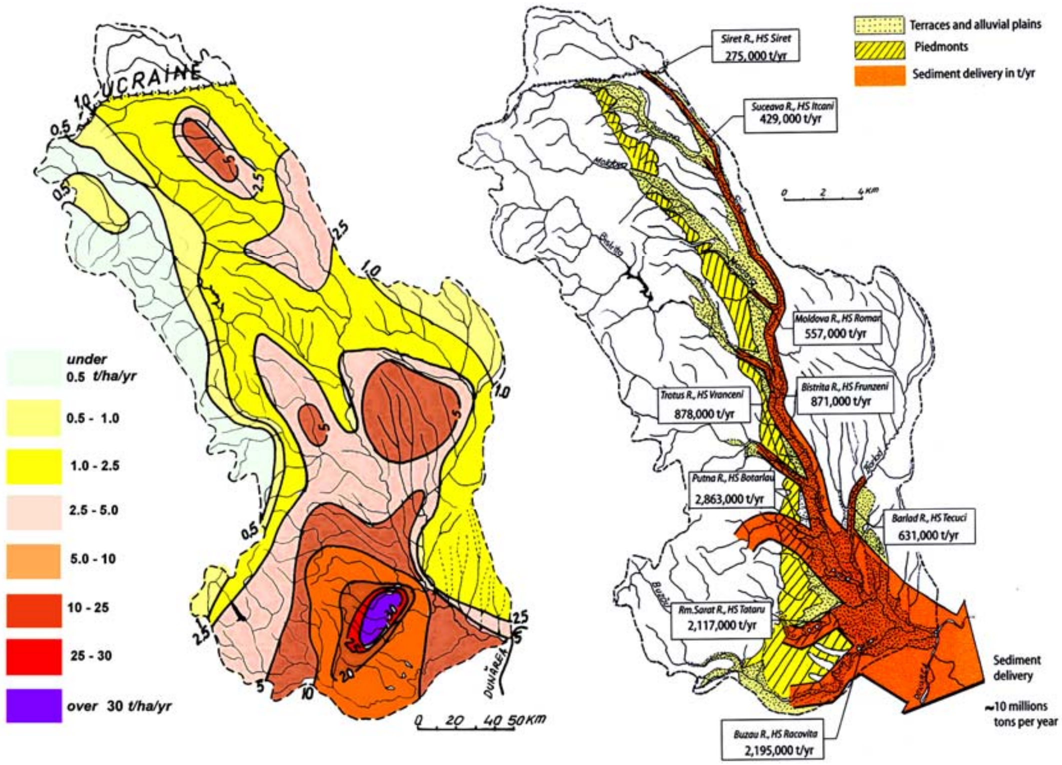

Fig. 3. Maps of sediment sources and sediment transport in the Siret drainage basin.

- the flux of suspended sediment transport, as it looks after the measurements in the past decades made on the national network (the reference period being 1950 - 2002), very clearly indicates the contribution of each major tributary of the Siret. From north to south, the Siret itself, then the Suceava, Moldova, Bistriţa (modified values in order to remove the effect of the man-made lakes built along this river) and the Trotuş have increasing values of sediment entry, from 275 000 t/y, when Siret enters the country, to over 800 000 t/y at the entry of Trotuş into the Siret.

- all the east-Carpathian rivers show an increase in the sediment production as the draw closer to the confluence with the Siret, the only one that shows a decrease is the Bârlad because it manifests a heavy sediment storage in the middle and inferior parts. In another study we've observed that the Bârlad only releases 4 % of the sediment quantity set in motion in the source areas of the basin (Rãdoane and Rãdoane, 2001).

- Immediately south of the Trotuş confluence, the sediment transport flux of the east-Carpathian rivers becomes very large, each of the three major rivers pouring into the Siret over 2 million t/y, which causes the Siret to consequently release a quantity of 10 million tons of sediment per year.

- If we were to superpose the graphic dimension of this sediment transport over the area occupied by the alluvial terraces and lowlands of the Siret and its tributaries, we would notice a rather close match, which leads us to observe that the current tendencies noticed in sediment transport have been kept unchanged, at least during the Holocene.

- we need to specify that in the transport's flux only the volume of sediment transported in suspension is presented; if the bed load is added, the one that actually contributes to the formation of bed materials, the image of this sediment dynamics would truly be whole and the real meaning of Carpathian source area contribution to the development, also in the present, of the east-Carpathian piedmont area would be represented.

In conclusion, the current tendencies observed in the sediment transport dynamics from the source area to the storage and delivery areas of the Siret fluvial system are the heritage of a long evolution that, for the area upstream of the Trotuş, dates back from the Sarmatian. The difference lies in the rate of the process' development, faster or slower, but never interrupted from its trend. If the east-Carpathian Rivers haven't forgotten this heritage, we have all the right to consider that the functionality of the east-Carpathian piedmont had never been definitely interrupted; it only had its natural phases of growth and decrease.

Next, we intend on doing and analysis of the sediment size and grain size distribution shapes, from source to delivery, in the area of over 43,000 km^2 of the Siret river basin. And, as the agents responsible with the movement of millions of tons of sediment are the rivers with their working and transport forces, the bed deposits store a lot of information about the processes and mechanisms responsible for all these actions. For now, our attention is focused on one of the parameters that describe the sediment quality – grain size. Other parameters like morphometry and petrography of the sedimentary particles will be the object of a separate study.

4. THE GRAIN SIZE OF BED DEPOSITS

4.1. The variation of bed material dimension along the rivers

Our investigation on the bed material variability of the Siret Basin Rivers were mainly focused on verifying the exponential model of reduction in the sediment size along the river, according to the so-called "Sternberg's law" which shows that the river bed particles reduce their dimension proportionally with the mechanic work made against friction along the river. Figure 4 presents this variation for six large rivers of the Siret basin, that have lengths between 150 km and 725 km. Depending on the length of the river, the median diameter, D50, is exponentially reduced, upon a whole, but on important lengths of the rivers the exponential decrease is acutely disturbed. The Trotuş and Siret rivers even show an increase in the material's dimension on most of their length. There are identified, in Table 2, the river lengths on which there are manifested the exponential increasing or decreasing of the bed material size, the model determining coefficient and the "fining" or "coarsening" coefficients of the bed material. The only rivers that nearly relate to the exponential model on their entire length are the Suceava and the Moldova.

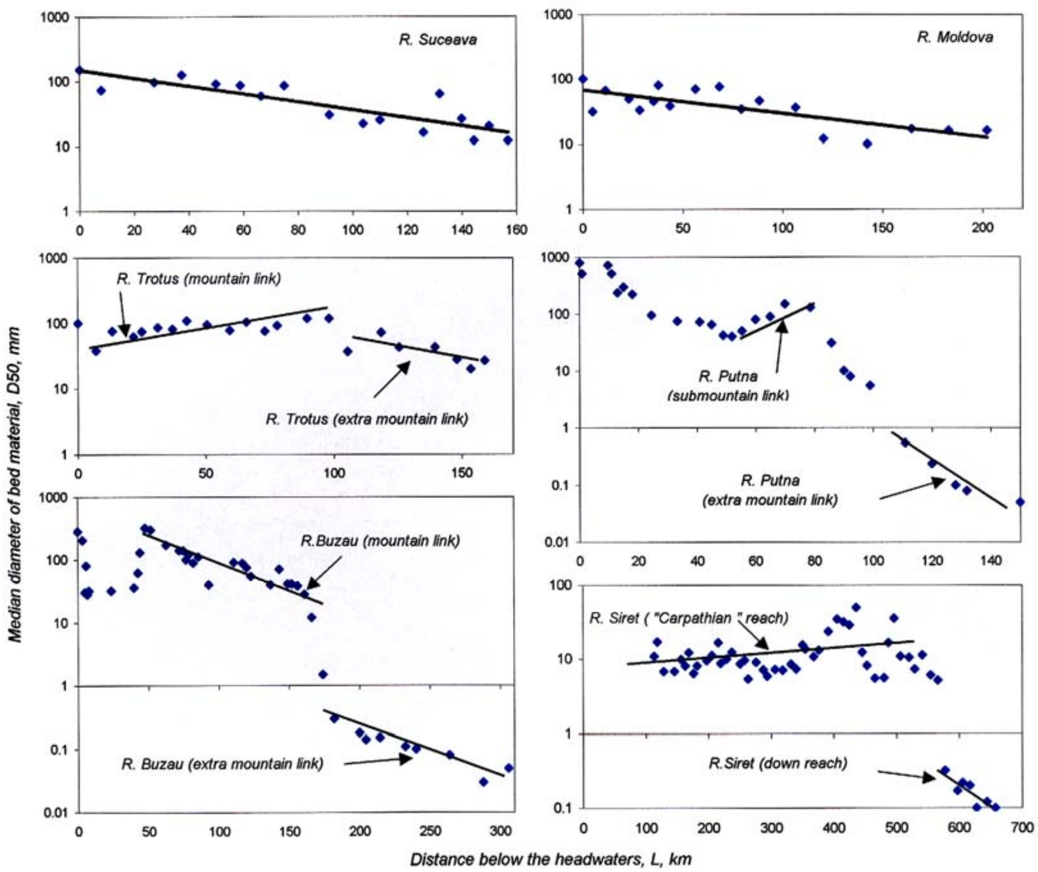

Fig. 4. Downstream variation in bed material grain size along the main rivers from the Siret drainage basin.

The main cause for which the Sternberg model doesn't verify for the other four rivers lies in the contribution of the tributaries with a massive sediment input in the rivers in question, a lot greater than their ability to modify. We can better understand the phenomenon if we superpose the rivers in question on the sediment production and sediment transport maps (Fig. 3). We can notice a close relation between the rate of sediment generation in the secondary basins and the river reaches with an increasing the bed material's size ("downstream coarsening"). The rivers from the north of the studied region, the Suceava and the Moldova, have basins in which the sediment production is smaller when compared to the southern part of the region (Fig. 3) and, consequently, their tributaries do not transport a great deal of suspended material either. Thus, the collecting rivers manage an exponential decreasing of the bed material, the "fining" coefficients being close in value for the two rivers (-0.0143 km^1 and, respectively, -0.0102 km^{-1}).

Table 2. Fining and coarsening coefficients of the bed sediment from the Siret drainage basin

Rivers	Length of sedimentary link (km)	Determination coefficient of the exponential equations *D*50 = f(*L*) (R^2)	Fining coefficient	Coarsening coefficient
Suceava R.	157	0.753	-0.0143	
Moldova R.	202	0.739	-0.0102	
Trotuş R. (all river)	159	0.349	-0.0061	
Trotus R. (mountain reach)	98	0.480		0.0056
Trotus R.(sub- and out-Carpathians reach)	61	0.590	-0.0147	
Putna R. (all river)	150	0.793	-0.0565	
Putna R. (mountain reach)	99	0.736	-0.0381	
Putna R. (sub-Carpathian reach)	27			0.0371
Putna R. (out-Carpathian reach)	51	0.882	-0.0615	
Buzău R. (all river)	306	0.908	-0.0288	
Buzău R. (mountain reach)	166	0.800	-0.0185	
Buzău R. (out-Carpathian reach)	140	0.887	-0.0155	
« Carpathian » Siret R.	566	0.028		0.0007
Siret R. (out-Carpathian reach)	159	0.778	-0.0141	

In turn, for the rivers of the southern part of the studied region (Trotuş, Putna and Buzău) that have their basins superposed on areas with large sediment production, the variability of bed material size increases. A representative case is the Trotuş in the mountain reach, where the tributaries' aggressively over the main river is so great that the phenomenon of exponential increase of the bed material occurs in a length of over 100 km. Likewise, the Putna River, on a shorter reach, and the Buzău River, in the gorge reach. But the river to stir many references in the specialty literature (Pizzuto, 1995; Sambrook Smith and Ferguson, 1995,1996; Rice, 1998; Surian, 2002; Gasparini et al., 2004, etc) is the Siret, where the phenomenon of bed material dimension increase (a reversal of the classic exponential negative model) is manifested on 566 km, meaning 80 % of its length and this without it running through a mountain area just as long. Only the extremely dynamic geomorphologic activity of the Carpathian tributaries has managed such a performance.

The field observations and numerical simulations of the "downstream fining" (Parker, 1991; Hoey and Ferguson, 1994) have brought attention onto the fact that a strong concavity of the longitudinal profile can cause a faster decrease of the bed material, which has been confirmed in our case as well (Rădoane et al., 2003).

The passing from the "coarsening" reach to the "fining" reach is made through a threshold or "grain size jump" which varies between 7 km at the Trotuş, 10 km at the Siret and 22 km at the Buzău and, respectively, 30 km at the Putna. The distance on which this passage is realized is very short, as it has also been noted in other situations reported in literature (Ashworth, Ferguson, 1989; Sambrook Smith and Ferguson, 1995; Ferguson et al., 1996), and the scientists' interest in order to explain this passage has been great (Yatsu, 1955; Ibbeken, 1983; Sambrook Smith and Ferguson, 1995; Sambrook Smith, 1996; Rice, 1998; Constantine et al., 2003; Gasparini et al., 2004) although without reaching a firm conclusion. The research called attention on another feature of the bed deposits which is the bimodal character of their grain size distributions. Our observations on bed deposits bimodality have led us to a possible answer for the cause of this phenomenon, including the cause for "grain size jump".

4.1. On the bimodality of fluvial bed sediments

The bed deposits of the rivers with gravel bed (Fig. 5) have a distinct characteristic to other types of deposits which is bimodality, defined as the existence of two modes (peaks) in the grain size distribution, separated by a penury of material in the category of small gravel, respectively, the 1-8 mm fraction (Sambrook Smith, 1996).

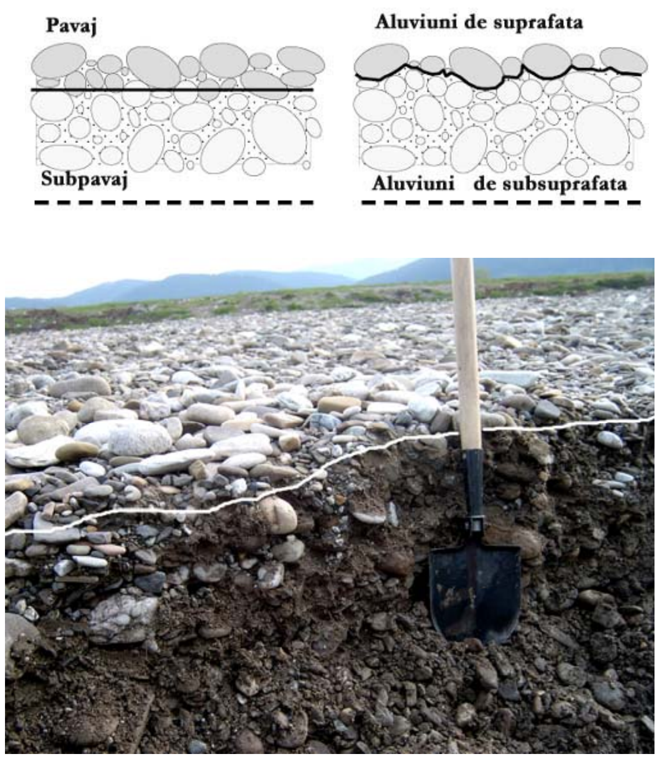

Fig. 5. The illustration of the arrangement mode of the bed deposits, the minor channel of the Bistrița River at Roznov. (Photo: N. Rãdoane).

There still is a wide dispute regarding this phenomenon, synthesized by Sambrook Smith and Ferguson (1995) and Sambrook Smith (1996) from which we figure out that it hasn't yet come down to a single unanimous explanation concerning the phenomenon upon the whole. The authors synthesize three possible causes, demonstrated in significant studies: (I) the effect of the base level (that seems to have the greatest chances of being encountered on a greater and more variable number of rivers), (II) the lateral input of fine sediment (that requires important sediment sources) and (III) the bed material abrasion (especially justifiable for the large rivers)

Our research have shown that the lateral input of fine sediment (the second cause in the synthesis of the authors mentioned above) is the main cause for the bimodality of the grain size distributions of the rivers with gravel bed from the Siret basin. In this view, we concentrated on answering the following questions:

How big does the sand quantity of the bed needs to be for the bimodality phenomenon to appear?

Which is the sand source of the second mode? It is mostly from the river bed (resulting from the abrasion of the larger particles) or the hillslope basin (through the process of erosion and transport)?

Why does a penury of material between 1-8 mm appear? Isn't it that this penury exists as long as the second mode, of the sand, is foreign to the river channel?

As we said above, we disposed of an impressive data base, so that we were able to evaluate the types of grain size distribution separately, for the surface layer, the subsurface layer (Fig. 6) and the full sample (the latter one as a mix between the surface and subsurface samples), all of them considered in the longitudinal profile of the rivers. The diagrams for the studied rivers focus on the difference between the distribution types of the surface material compared to the subsurface (Fig. 6). Having a large number of samples to analyze (n = 190) for six large rivers, we tried to observe if a series of general or particular tendencies stands out for the whole length of the rivers or in certain reaches, if there are any differences present between the Carpathian tributaries or between the tributaries and the main river, the Siret, under their strong control. These are the observations:

1. As it was expected, the surface samples show a mode strongly located on the gravel and cobbler classes and the sand class is almost inexistent. The sediment layer that the river channel reveals is usually washed by fine material of under 2 mm, the sand, what is left being in overwhelming proportion (90-95 %) gravel, cobbler and blocks. In this situation the distributions are unimodal, except for the transition reaches from gravel to sand where, on short distances of 10-15 km, the bimodality is manifested in the case of surface samples as well. In the layer beneath, the sand becomes very evident, even forcing a distinct mode.

2. In the subsurface samples, where the fine material is more abundant (between 5 – 26 %), the distributions tend to contain the second mode, with the peak on the sand grain size. A penury of particles in the 1-8 mm interval is in fact visible between the two modes (Fig. 6). Considering the bulk sampling of the bed material which we have completed for

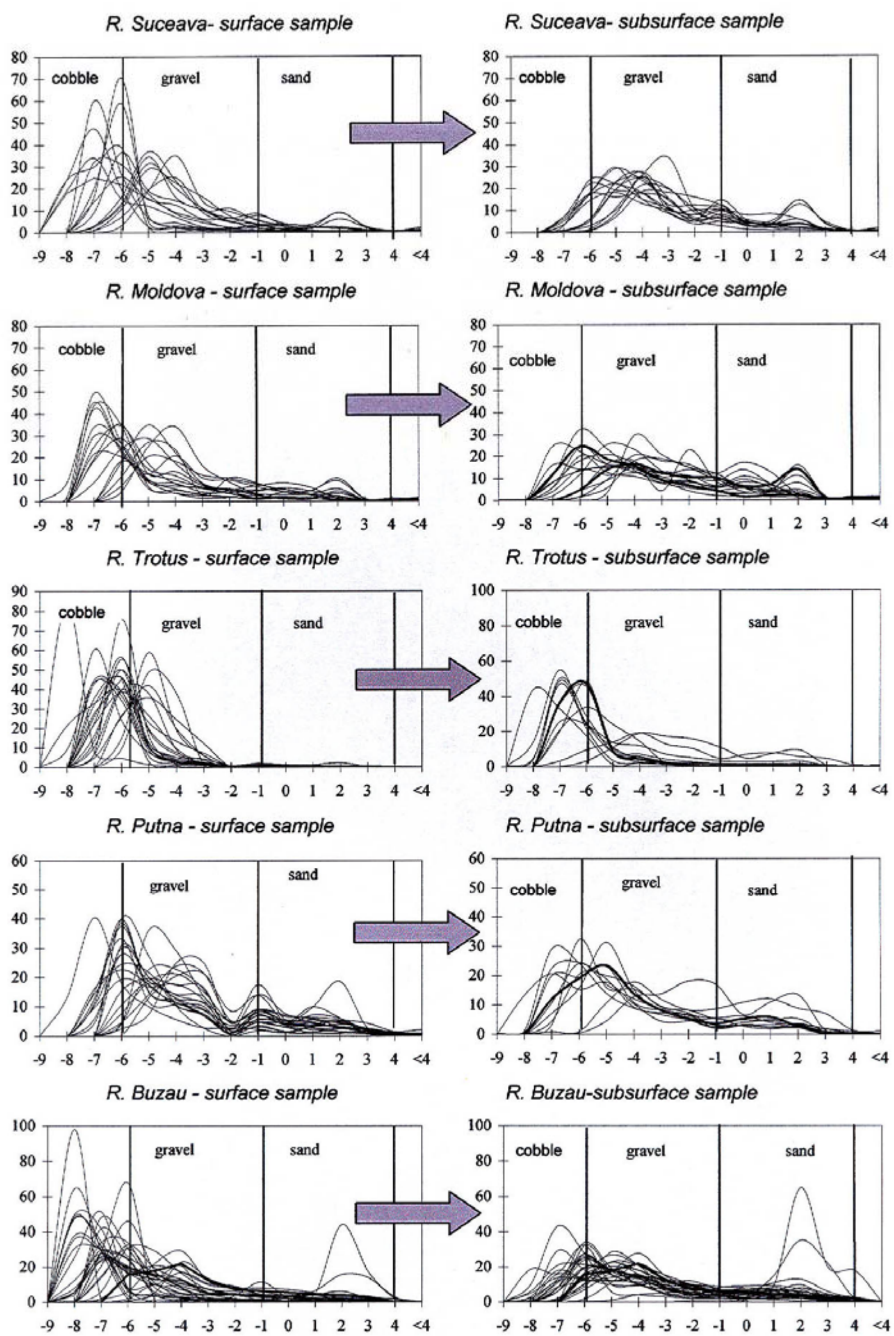

Fig. 6. Grain size distributions of bed material along main East-Carpathians Rivers. The comparison between surface samples to subsurface samples.

all the studied sections (and which have required dimensions of the hundred-kilogram samples), the possibility of not identifying the interval because of the sampling methods is excluded.

3. The bimodality is limited in the Carpathian rivers, belonging to the Siret basin, compared with the Siret itself where bimodality is cvasi-generally spared (Table 3 and Fig. 7). For these rivers, with lengths between 150-300 km, we would have expected an obvious tendency of bimodality increase along them as it had been observed on rivers from various physiographic environments, like the ones in Italy (Ibbeken and Schleyer, 1991), Japan (Kodama, 1991, 1994), Canada (Shaw and Kellerhals, 1982) or Scotland (Sambrook Smith, 1996). Instead, as the statistic of the total of 190 full samples indicates (Table 3), the unimodal distributions are dominant for all Carpathian rivers of the Siret basin. The bimodality is observable on the last 40 km of the Suceava and the Moldova, on the Trotuş River in only one section. Only on the Putna and the Buzău bimodality is recorded on river lengths below 100 km in the middle-lower part of them.

Table 3. Synthesis of the grain size distribution types of the Siret River basin waters, of the parental material proportion in the source basin, of the 1-8 mm fractions and under 1 mm fractions in the bed material (average values for the entire river).

River	All cross section sampled (bulk samples)	Unimodal distributions	Bimodal distributions	Parental material (molasse rocks and quaternary rocks) (%)	Weight of 1 – 8 mm fractions in the bed material (%)	Sand weight (under 1 mm) in the bed material (%)
Suceava	17	14	3	62.2	14.00	9.34
Moldova	18	7	5	20.2	17.40	9.38
Trotus	21	20	1	24.6	6.35	5.43
Putna	16	7	9	38.9	10.24	14.27
Buzau	41	31	10	21.6	10.96	13.84
Siret	**53**	**6**	**47**	**58.2**	**23.24**	**26.51**

4. The bimodality of bed deposits is correlated with the quality of the parental material which represents the source of the bed sand and the source of the second mode, respectively. In order to demonstrate this we employed the sediment source map (Fig. 3) which indicates the areas with a greater or smaller potential of sediment release (in t/ha/y) in the basins of all rivers studied.

For example, the Suceava River basin exposes on 62.2 % a parental material susceptible to release fine sediment, but the rate of soil erosion in this area is relatively small, under 2 t/ha/y. As a consequence, in the bed deposits there will be relatively few sand (9.34 %) which means a small bimodality of the bed material (only in three sections of the lower part of the river). In the case of the Moldova River basin, the parental material, as well as the rate of sediment erosion and transfer, is relatively low, and the river bed's sand proportion is also small (9.38 %). Consequently, the bimodality is very low manifested. For the Trotuş we have recorded the smallest quantity of sand in the analyzed samples (an average of 5.43 %), thus bimodality is present in only one bed cross section.

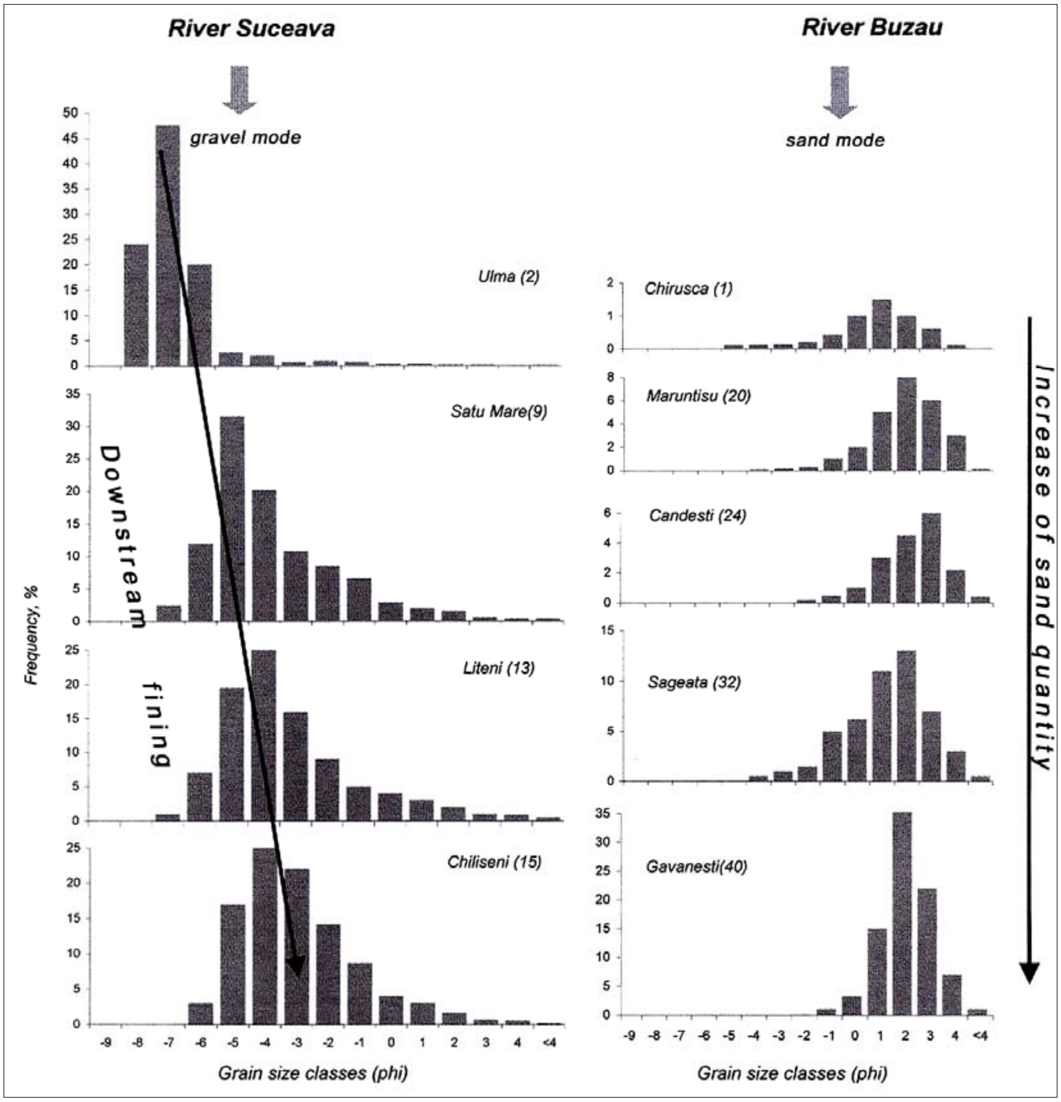

Fig. 7. Grain size distributions of the gravel along the Suceava River (left). Grain size distributions of the sand along the Buzau River (right). Numbers indicate the position of sampling points below head waters.

Nevertheless, in the Putna and Buzău river basins, where the transfer rate of fine sediment from basin to river is very high, of over 20 t/ha/y, the sand proportion has an average of 14 % (in some sections even over 30-35 %), being clearly a part of the second mode. It’s also interesting to follow the proportion of the 1-8 mm fraction as average values on the studied rivers (Table 3), from which we observe that these fractions are in larger quantity than the 1 mm fraction for the Suceava, Moldova and Trotuş rivers and it’s only for the Putna and the Buzău that these ratios are inverted. In other words, for the three large rivers there hasn’t been identified any penury of material from the class of grain size in question, which is intriguing if we consider the cvasi-affirmative deductions on the phenomenon in specialist literature. Hence, summarizing all the above observations, we concluded that.

5. The bimodality can be explained in the transfer rate of fine sediment from the source area to the river bed. These sediments made up of sands and silts, through their large volume, simply overwhelm the normal distributions of the existing bed materials, well sorted and spread according to Sternberg’s law. There’s practically a superimposing of a new normal distribution with the peak on the sand class, the origin of which lies in the tributary basin and reaches the river bed through suspension transport. The demonstration of the idea is made in Fig. 7 through exemplifying the distinct distributions of gravel and sand for two different rivers. The Suceava river bed, in its entire length of 150 km, has only presented three sections with bimodal distribution, near the confluence with the Siret; throughout the rest of it the fluvial deposits are unimodal with the peak on pebble and gravel classes. In the basin, the source of the fine materials is very rich (over 60 % of the basin is occupied by friable rocks), but these sediment do not reach the river bed because the erosion and transfer rate towards the bed is low. Thus the river bed grain size distributions are not disturbed by massive sediment entries, the “downstream fining” proceeds according with the exponential laws. This doesn’t mean that the river bed completely lacks the sand fractions; instead they have a proportion that doesn’t disturb the normal unimodal distribution of the river bed material. The Moldova and the Trotuş are in a similar situation to the one presented for the Suceava.

On the other hand, in the case of the Putna and the Buzău, the basins of which are situated on areas with the biggest rates of soil erosion and fine sediment transfer towards the river beds, the sand quantity increases along the rivers so much that it surpasses the river’s capability to remove it. The sand fractions are stockpiling and their presence has been noticed through a distinct distribution with the peak on 1-2 phi and a light asymmetry towards the left.

6. By superimposing the unimodal distributions of the sands from the basin over the unimodal distributions of the gravel worked by the river, through abrasion and hydraulic sorting, there results the bimodality of the rived bed deposit distributions. The situation is exemplified for a number of cross sections of the Buzău River (Fig. 8). The intersection of the two distributions is made in the 1-8 mm fractions area, giving the impression of a penury of these fractions in the river bed material. In fact, these fractions would be in greater quantity than the sand if the parental material wouldn’t supply the river bed with fine sediment.

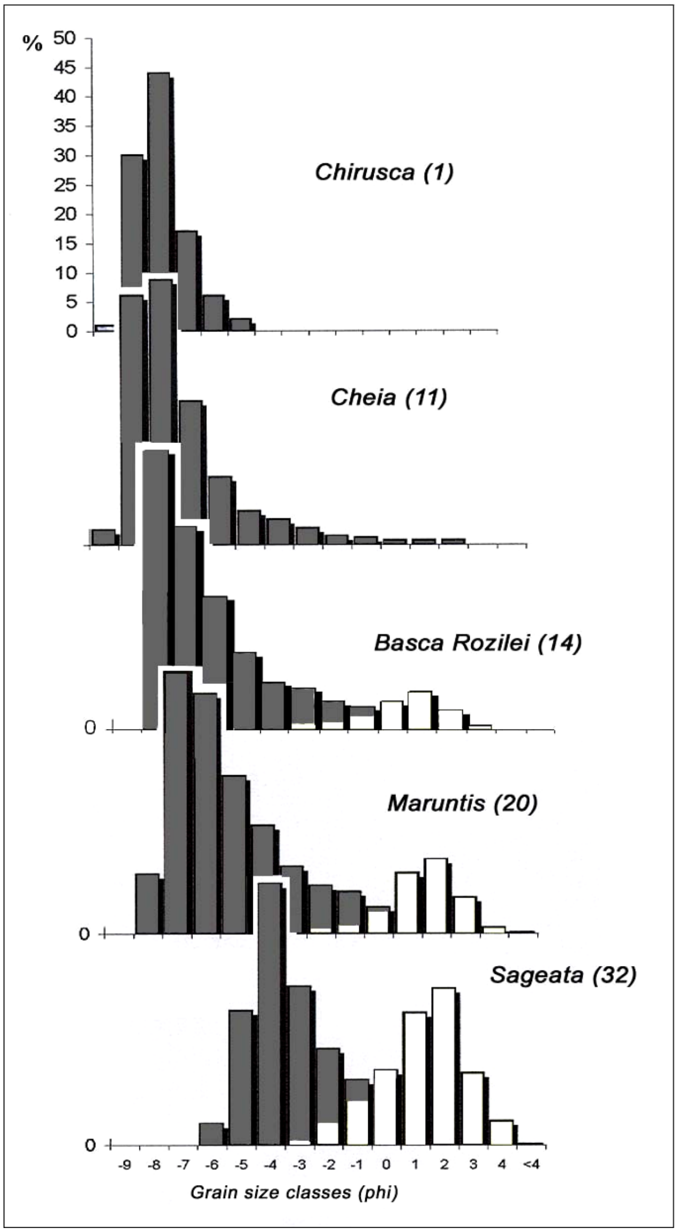

Fig. 8. The emergence of bimodality through the mixture of the two distributions. Exemplifying the Buzău River bed. The numbers of the counting section indicate the position of the sampling points from origin to river mouth.

We have left for last the case of the Siret River which on most of its length has a strong bimodality (Fig. 9). The theory applied on its Carpathian tributaries also extends on the Siret with the mention that the gravel mode has its sources, mostly, from other regions. If for the Carpathian tributaries the gravel mode has a "downstream fining" that clearly indicates the autochthone source of their working and placement, in the case of the Siret we are dealing with a river mostly prepared for the transport of mainly fine particles and which was forced to suffer an "avalanche" of gravel that gradually grows in dimension along the river's length, corresponding with the tributary's point of junction.

In other words, on a relatively fine grain size distribution of the Siret River bed a distribution of coarser grain material, of external origin, has been superimposed. Obviously, between the two distributions a strong decrease of the percentage of diameters between 1-4 mm is apparent, because, in this sector, the gravel mode and the sand mode are in conjunction.

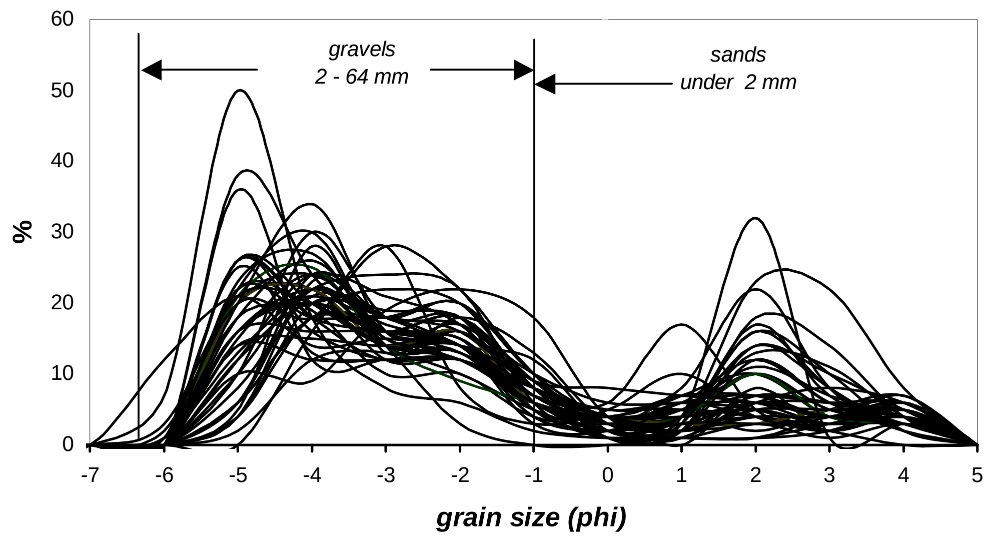

Fig. 9. Bimodality of the Siret bed material.

The "sedimentary links" (cf. Rice, 1998, 1999) are manifested only regarding the "downstream fining", but also in imposing bimodality. Along the Siret River, between two Carpathian confluences the bimodality of the river bed material is highest upstream of the confluence and very little perceptible immediately downstream of the Carpathian confluence.

In Fig. 10 this fact is demonstrated by exemplifying the grain size distributions upstream of the confluences (strongly bimodal) and downstream (with a unimodal tendency of the gravel class). The massive gravel input determines the unimodality immediately downstream of the confluence, but it rapidly diminishes due to a very high local sand quantity (20-30 %) which is especially noticeable upstream of the confluences.

In conclusion, *the bimodality of the fluvial deposits is explained, in the cases studied by us, through the superimposing of two grain size distributions of different origin*.

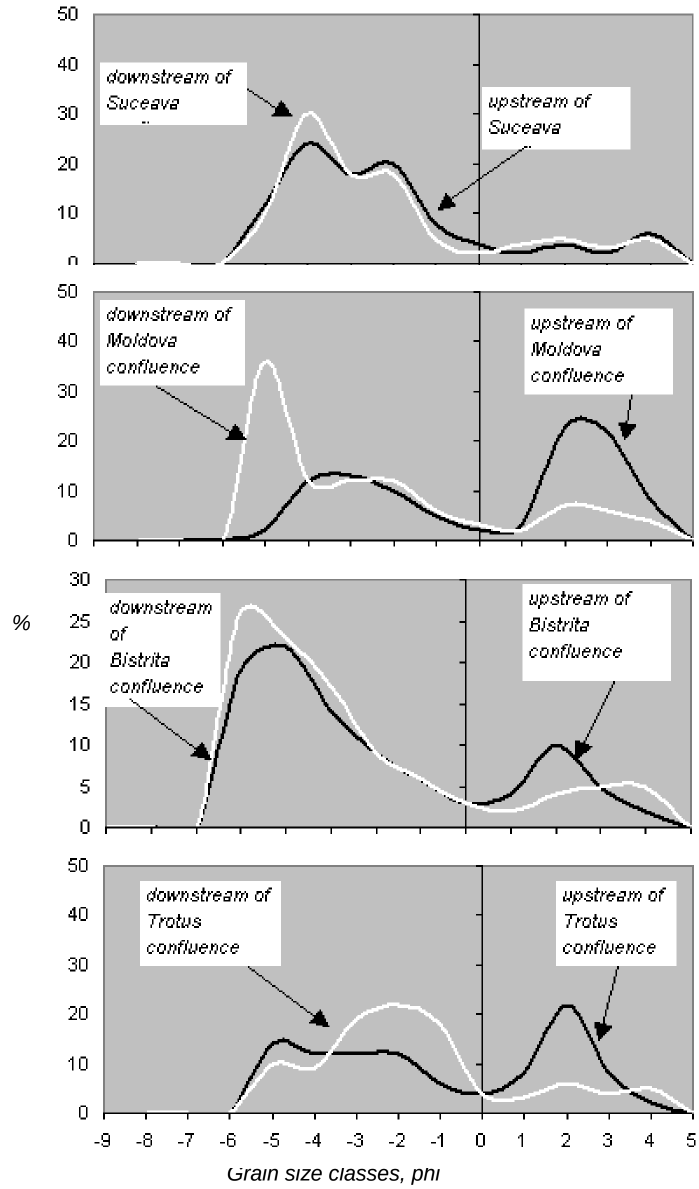

Fig. 10. Types of grain distributions of the Siret River, upstream and downstream of the junctions with the Carpathian tributaries.

For the East-Carpathian Rivers tributary to the Siret (Moldova, Suceava, Trotuş, Putna, Buzău) the boulder, cobbler and gravel have an unimodal distribution with an asymmetry to the right, with an obvious exponential dimensional reduction along the river.

The working and placement mode along the river is heavily controlled by the river itself through the well-known processes of mechanical abrasion and hydraulic sorting

These rivers also poses the second unimodal distribution based of the sand class, very least evident in the Suceava, Moldova and Trotuş rivers and well out-lined in the Putna and Buzău rivers. The source of the second distribution mostly lies in the sand quantity present in the river bed through the soil erosion of the hillslope basin. In the other rivers, where the quantity of fine materials in the basin is small, not even the river bed has enough sand so that a second mode could become noticeable.

The intersection of the two modes happens in the area of the 1-8 mm fractions, where, in fact, the right-asymmetry histogram lines (for gravel) and left-asymmetry lines (for sand) become intersected. Maybe, by using imagination, a river with a gravel bed that would run through a channel with rocky banks and a basin that doesn't provide fine sediment, would have a unimodal distribution on the gravel class and an increasing asymmetry on the right side. In such a histogram line, the 1-8 mm fractions would be in greater amount than the fractions below 1 mm, similar to the situation of the Suceava and Moldova rivers, where the penury has sands and not small gravel. In other words, the idea that the 1-8 mm fractions (after Yatsu (1955) between 2-4 mm, after Ibbeken and Schleyer (1991) between 1-20 mm) would be in the penury of the river bed deposits is false.

The strong bimodality of the Siret River's deposits is also explained through the different origin of the distributions that become intersected, the only difference is that the source of the first mode, the gravel, does not belong to the Siret, and only the sand mode does. This distribution with unimodal tendency on the gravel class becomes visible especially downstream of the Carpathian confluences (Fig. 10), once the more coarse material enters. Without these Carpathian tributaries the Siret would be a river with, mainly, a fine sediment transport.

The transition from gravel to sand in the form of the well-known "grain size jump", which we also identified on the Buzău and Siret rivers, could be similarly explained, through the different sources of grain distributions that, in the river bed's evolution, become superimposed and, at their intersection, the grain size leap mentioned above takes place. Obviously, through abrasion and hydraulic sorting, the river could not supply its bed with fine particles in the quantities we found in the studied rivers unless there would also be another source. And in the present care the source is given by the parental material liable to be eroded and the geomorphological processes responsible for sediment transfer.

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