Earth Surface Processes and Landforms
Earth Surf. Process. Landforms (2007)
Published online in Wiley InterScience
(www.interscience.wiley.com) **DOI:** 10.1002/esp.1568

Downstream variation in bed sediment size along the East Carpathian rivers: evidence of the role of sediment sources

Maria Rădoane,[1] Nicolae Rădoane[1], Dan Dumitriu[2] and Crina Miclăuş[3]*
[1] *University of Suceava, Department of Geography, Suceava, Romania*
[2] *University of Iasi, Department of Geography, Iasi, Romania*
[3] *University of Iasi, Department of Geology, Iasi, Romania*

*Correspondence to: Maria Rădoane, University of Suceava, Department of Geography, Universitatii 13, Suceava 720229, Romania.
E-mail: radoane@usv.ro

Received 23 July 2006;
Revised 4 May 2007;
Accepted 30 May 2007

Abstract

Taking as an example six main rivers that drain the western flank of the Eastern Carpathians, a conceptual model has been developed, according to which fluvial bed sediment bimodality can be explained by the overlapping of two grain size distribution curves of different origins.

Thus, for *Carpathian tributaries* of the Siret, coarse gravel joins an unimodal distribution presenting a right skewness with enhanced downstream fining. The source of the coarse material distributions is *autohtonous* (by abrasion and hydraulic sorting mechanisms). A second distribution with a sandy mode is, in general, skewed to the left. The source of the second distribution is *allohtonous* (the quantity of sand that reaches the river-bed through the erosion of the hillslope basin terrains). The intersection of the two distributions occurs in the area of the 0·5–8 mm fractions, where, in fact, the right skewness (for gravel) and left skewness (for sand) histogram tails meet. This also explains the lack of particles in the 0·5–8 mm interval. For rivers where fine sediment sources are low, the 0·5–8 mm fractions have a higher proportion than the fractions under 1 mm.

For *the Siret River itself*, bed sediment bimodality is greatly enhanced due to the fact that the second mode is more than 25% of the full sample. As opposed to its tributaries, the source of the first mode, of gravel, is *allohtonous* to the Siret river, generated by the massive input of coarse sediment through the Carpathian tributaries, while the second mode, of the sands, is local. In this case we can also observe that the two distributions of particles of different origins overlap in the 0·5–8 mm fraction domain, creating the illusion of 'particle lack' in the fluvial bed sediments. Copyright © 2007 John Wiley & Sons, Ltd.

Keywords: fluvial bed sediment; downstream fining; sediment supply; bimodality; Siret drainage basin; Romania

Introduction

Fluvial bed sediments are some of the first phenomena that scientists have studied and observed amongst other river-bed properties such as morphology, hydraulic characteristics and ability to alter their section in a short distance. This is most probably due to their direct evidence and ease of observation. Gomez *et al.* (2001) conducted a notable study on the evolution of ideas in this field, of which one can conclude that the interest that this domain has raised has been shown for a long period of time; the study also includes the first comments on the causes of the processes of reduction of bed material size, mainly by particle abrasion and hydraulic sorting. The phenomena has been widely investigated considering the numerous complications involved in this mechanism, such as the equal mobility condition (Parker *et al.*, 1982; Wilcock, 1992; Gasparini *et al.*, 2004), the role of the local base level (Ferguson *et al.*, 1996) or the river-bed aggradation (Seal *et al.*, 1997; Gomez *et al.*, 2001), river basin concavity (Gasparini *et al.*, 2004), lateral input of sediments (Knighton, 1999, 1980; Ichim and Rãdoane, 1990; Rice and Church, 1998; Rice, 1999) and human interventions (Surian, 2002).

Although the list of scientific results in this domain is quite large and many questions related to 'downstream fining' have been answered, at this moment there is still a need for wide systematic research in this field related to the acquisition of a comprehensive database in order to better understand the diversity of situations in the field that may involve the process of river-bed material diminution. This opinion is shared by many authors (Sambrook Smith and Ferguson, 1996; Rice, 1998; Gomez *et al.*, 2001) and we also sustain it.

For 10 years we have focused our attention on rivers in the drainage basin of the Siret, an important affluent of the Danube in the Romanian territory. We took as examples the experience of many authors (Brierley and Hickin, 1985; Dawson, 1988; Parker, 1991; Werrity, 1992; Seal and Paola, 1995; Pizzuto, 1995; Ferguson *et al.*, 1996; Rice and Church, 1998; Knighton, 1982, 1999) in their research on downstream variation in grain size on a single river or a river sector; we also thought that a spatial approach of the variability of the river-bed material on many rivers in a river system of over 43 000 km^2 would bring an important understanding in this field. A similar approach has been taken by authors such as Yatsu (1955), Knighton (1980), Ibbeken and Schleyer (1991) and many others. This method proves to be difficult due to the fact that volumetric sampling in river gravel-beds is a significant stumbling block for those that study the phenomena. For instance, in the higher part of the Carpathian rivers that we have sampled, the weight of the sample *in situ* was more than 1000 kg, which implied an extraordinary effort for the team (see Figure 3 below).

In conclusion, our paper intends to approach the phenomena of river-bed material variability inside a network of 1640 km of rivers from the drainage basin of Siret as a link between sediment sources and their sediment delivery. We will particularly focus on the spatial variability of the distribution types of river-bed material and we will try to moot the origin of bimodality of river-bed deposits. Sustaining our research, we have used a series of concepts and theoretical foundations (fluvial system, Schumm, 1977; sediment budget, Dietrich and Dunne, 1978; time of sediment residence, Madej, 1987; Nakamura *et al.*, 1987; sediment delivery, Walling, 1983) to better understand the way that bed materials vary along the rivers. 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) and Sambrook Smith *et al.* (1997) that have helped create a comprehensive image of this phenomenon.

Study Area and Work Method

To sustain our own observations, our research targeted the main rivers that drain in the east side of the East Carpathians and that are direct tributaries of the Siret river. These total 10 rivers, of which only six have been studied using the river-bed material criterion; their action was and still continues to be the cause of the piedmont surface on the outside of the East Carpathians. Table I contains some general informations regarding the studied rivers; Figure 1 displays the geographic position of the studied area.

Table I. Data on the studied rivers

No.	River	Cross section	Drainage basin area A (km^2)	River length L (km)	Mean yearly discharge Q ($m^3 s^{-1}$)	Suspended sediment load Q_s ($kg s^{-1}$)	Sediment yield S_y ($t km^{-2} year^{-1}$)
1	Suceava	Cf. Siret	2 616	172·3	14·1	13·6	180·40
2	Moldova	Tupilati	4 016	169·9	32·8	35·3	277·74
	Moldova	Roman	4 316	205·0		16·1	117·64
3	Bistriţa	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	2·6	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 (Danube)	43 933	725·8	254·0		

DOI: 10.1002/esp

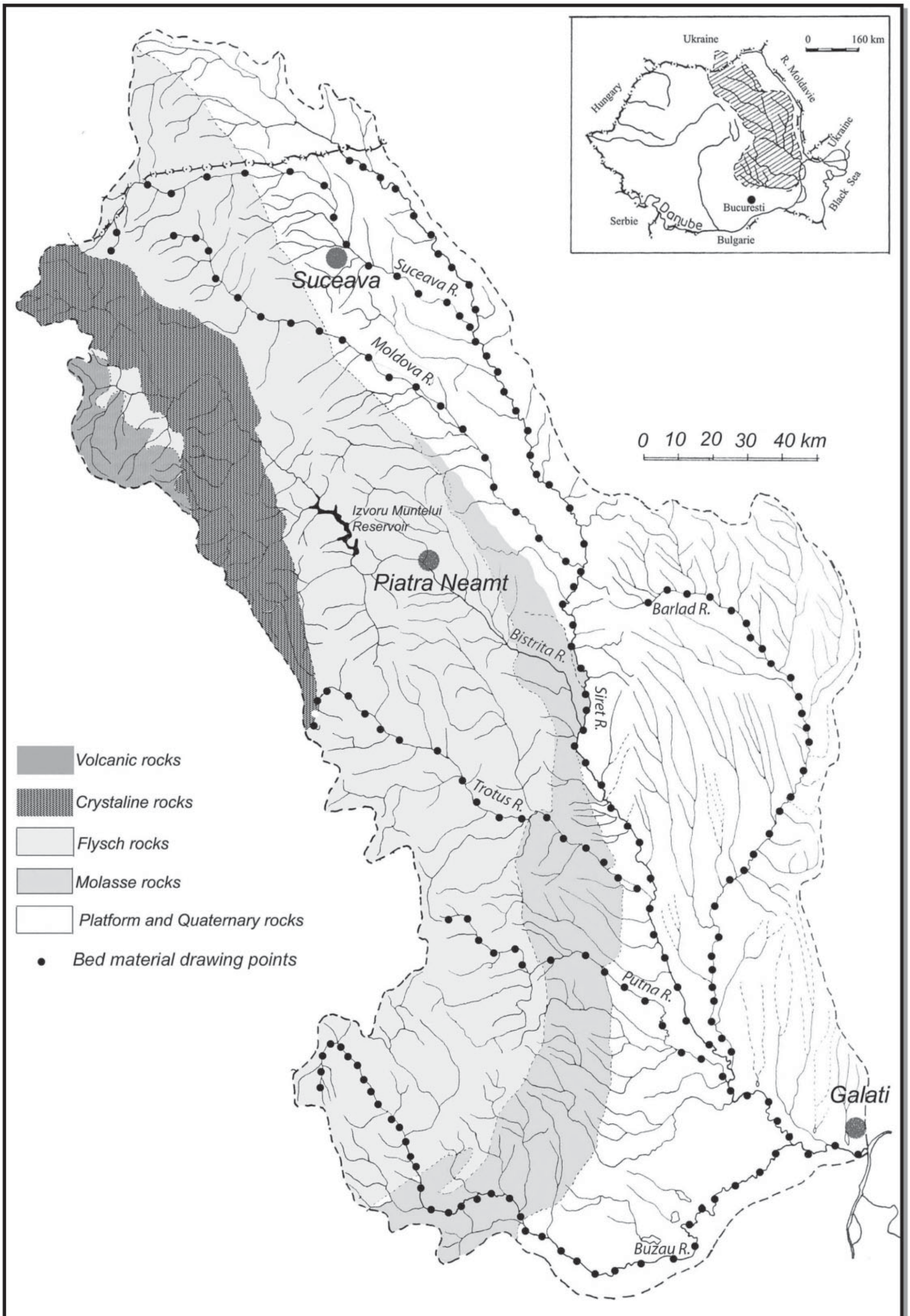

Figure 1. Location of the study area.

DOI: 10.1002/esp

Figure 2. River channel near the source (Trotuş River – upper left). Putna River channel downstream of 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). This figure is available in colour online at www.interscience.wiley.com/journal/espl

The main river, the Siret, has its origin in the Paleocene flysch area of the Woody Carpathians (in the Ukrainian territory), at an altitude of 1238 m. As it springs out, it generates a typical mountain valley, followed by a large valley with a typical out-mountainous course to its delivery to the Danube. All of the Siret's tributaries, except the Barlad, which is adapted to the hill region (which is not the subject of this article), form mostly inside the Carpathian flysch area, and only two of them – Moldova and Bistrita – spring out from the inner crystalline area of the East Carpathians (Figure 1).

These rivers (Figure 2) have been studied for many years by our team; therefore, we have a consistent database regarding the sediment transit, the river-bed changes, the fluvial sediments etc. They are characteristic cases for the morphodynamic conditions of this region, as referenced by natural conditions, but also by human impact, mainly by the presence of dams (Bistriţa 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 in the form of their longitudinal profile, with a series of mathematical models having been applied in order to deduce the form of the equilibrium profile (Rãdoane *et al.*, 2003); research has been performed on the tendencies of current changes of the river-beds (Ichim *et al.*, 1995, 1998), using data from over 60 cross-sections in the area of the hydrometric stations. However, 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 fluvial bed materials of the Trotuş River have been comprehensively researched and documented within a PhD thesis (Dumitriu, 2003).

The bed sections from which the sediments have been sampled are situated along each of the rivers at a distance of 8–10 km from each other and are depicted in Figure 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 of the important tributaries of the rivers. In total, over 190 river channel cross sections have been investigated, for which measurements of the river slope have also been recorded.

The samples were collected on a surface of one square meter from the centre of the active bar. Distinct samples have been taken 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 was no differentiation between surface and subsurface layers and a global sample was taken. The fractions bigger than 6 mm were separated through sieving directly in the field, and those over 64 mm were individually measured with sliding calipers. The biggest clast weighed in the field was 130 kg and had a diameter of 540 mm. The fractions under 8 mm were separated in the laboratory.

DOI: 10.1002/esp

Figure 3. Illustration of the bed material sampling methods. (A) A sampling perimeter of one square meter; hand picking of surface material. (B) Surface material is collected on a plastic sheet. Each clast is measured using a gravel meter. (C) Use of hand sieving to separate the subsurface particles. (D) Vertical section in the Bistrita river-bed material. This figure is available in colour online at www.interscience.wiley.com/journal/espl

Once the sampling perimeter was identified (Figure 3(A)), the pavement layer was collected and the material placed on a plastic sheet to avoid contamination with material from the subsurface layer. The thickness of the pavement layer was considered equal to the thickness of the biggest clast on the corresponding surface (Church *et al.*, 1987). Thus, on the sheet we had coarse material of over 3 kg. To measure the dimensions of the clasts, we used an aluminum FIPS gravel meter featuring 14 holes varying from −1 *phi* to 7·5 *phi* (2–180 mm) (Figure 3(B)), but we also performed sieving directly in the field using a set of sieves with holes having diameters according to the Wentworth scale. We used four sieves (the maximum number of sieves we could handle efficiently) featuring the following hole diameters: 64 mm (–6 *phi*), 32 mm (–5 *phi*), 16 mm (–4 *phi*) and 8 mm (–3 *phi*) (Figure 3(C)).

To measure the sediment from the subsurface layer, we used a volumetric method described by Mosley and Tindale (1985) and Church *et al.* (1987). According to this method, the total sample weight is a function of the biggest clast in the sampling perimeter. The biggest clast was 5% of the total mass of the sample. Some of the samples weighed over 1000 kg and they were sieved at the sampling site (Figure 3(C)).

Each sample between 128 and 256 mm was weighed and measured at the site using a special caliper. Particles greater than 256 mm were difficult to handle and weigh at the site. Due to this fact, we used a scale for conversion from diameter to weight, built on the basis of the river clasts we investigated by evaluating the weight of the biggest clasts on the basis of the *B* axis (according to Church *et al.*, 1987).

Fractions lower than 8 mm were taken into the laboratory for the continuation of sieving after having been dried at 90 °C in the oven. We brought samples weighing up to 5 kg into the laboratory. The sieve diameters were 4 mm (−3 *phi*), 2 mm (−2 *phi*), 1 mm (0), 0·5 mm (+1 *phi*), 0·250 mm (+2 *phi*), 0·125 mm (+3 *phi*) and 0·063 mm (+4 *phi*). This last fraction was generally less than 1% of the total of the samples.

Finally, we obtained information regarding grain distribution in the pavement layer and the subsurface layer (Figure 3(D)). By summing the two sample categories, we obtained a global sample representing a sampling point. In the situation where the grains smaller than 2 mm in diameter made up more than 50% of the bar's surface, a difference was not noted between the surface and subsurface and, hence, a global sample of 5 kg was taken. Differentiating sampling was applied to all investigated rivers, except for the Siret river, where samples were taken directly as mixed samples.

DOI: 10.1002/esp

The data was put into tables from which histograms of the frequency distributions were built and cumulative curves of the frequency distributions were drawn. In addition, a series of distribution parameters such as median diameter, sorting, skewness and kurtosis was computed. Particular attention was given to computation of the bimodality indices. Wilcock (1993) has proposed a B parameter to describe the bimodality degree. The parameter is based on the distance between the two modes and on the sediment quantity contained in the modes. We used computation methods described in other reports (Bunte and Abt, 2001). The formula that Wilcock proposed is

$$B = \left(\frac{D_{cm}}{D_{fm}}\right)^{0\cdot5}(P_{cm}P_{fm})$$

where D_{cm} is the dimension of the particles in the coarse mode expressed in mm, D_{fm} is the dimension of the particles in the fine mode expressed in mm, P_{cm} is the fraction of sediment in the coarse mode and P_{fm} is the fraction of sediment in the fine mode. Another bimodality index has been proposed by Sambrook Smith *et al.* (1997), but in this case we used Wilcock's model.

The East-Carpathian Rivers' Sediment Source and their Transfer Rate

The source of the deposits in the Carpathian river-beds is located in the areas featuring cohesive lithology from the western half of the hydrographic basin. The distribution of these lithological units features bands oriented from north to south and succeeding from west to east (Figure 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), and 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 such as andesites with amphiboles and pyroxenes, diorites and micro-diorites, gabbros, piroclastic rocks and 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), which is represented by filites, sericitous, cloritous or grafitous schists, quartz, gneiss, limestone, crystalline dolomites and others. In some places, over the crystalline shield, 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 by a wide variety of sedimentary rocks: conglomerates, sandstone, marls, disodilic schists, menilites and limestone, which are arranged in close pleated 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 to 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.

The landscape developed on this substratum is presented in steps from west to east and is fragmented by a drainage network asymmetrically disposed over the main river, the Siret. Along this network, there are 140 hydrometric stations used to measure the discharges, of which 92 are equipped for measurement of the suspended load. None of these stations perform measurements of the bed load. The development of a very well shaped piedmont at the eastern edge of the Carpathians and Subcarpathians (the shaded area in Figure 5) is a relevant clue to the existence, at some point in time, of an important transfer of coarse sediments. This area is well known to Romanian geomorphologists as the Moldavian Piedmont, which started developing since the Sarmatian (Martiniuc, 1948). At the present moment, this area is partially eroded, mostly on the northern side of the region. The piedmontan activity is still present, shown by the river-bed's behavior at its output from the mountain area (i.e. the braiding and even avulsion phenomena, the deformation of the longitudinal profile of the Siret river – Ichim and Rădoane, 1990).

Although we acquired only indirect information regarding the coarse sediment transport, we obtained direct information on the transport of suspended sediments from over 92 measurement sections over a time interval from 1950 to 2003 (their position is shown in Figure 4). This data has been used in the evaluation of the sources of suspended sediments using the methods described by Walling (1983) and Walling and Webb (1983). The source for the suspended sediments is mostly erosion of the soils from the hillside basin. Once these sediments get into the river-beds they play an important role in the control of grain size distribution of the bed material. This is why we intend to show the arial distribution of the sources of fine sediment in the analysis area (Figure 4); on the other hand, it explains the distinct role of the amount of suspended sediment flux along the main rivers (Figure 5). We have chosen this particular

DOI: 10.1002/esp

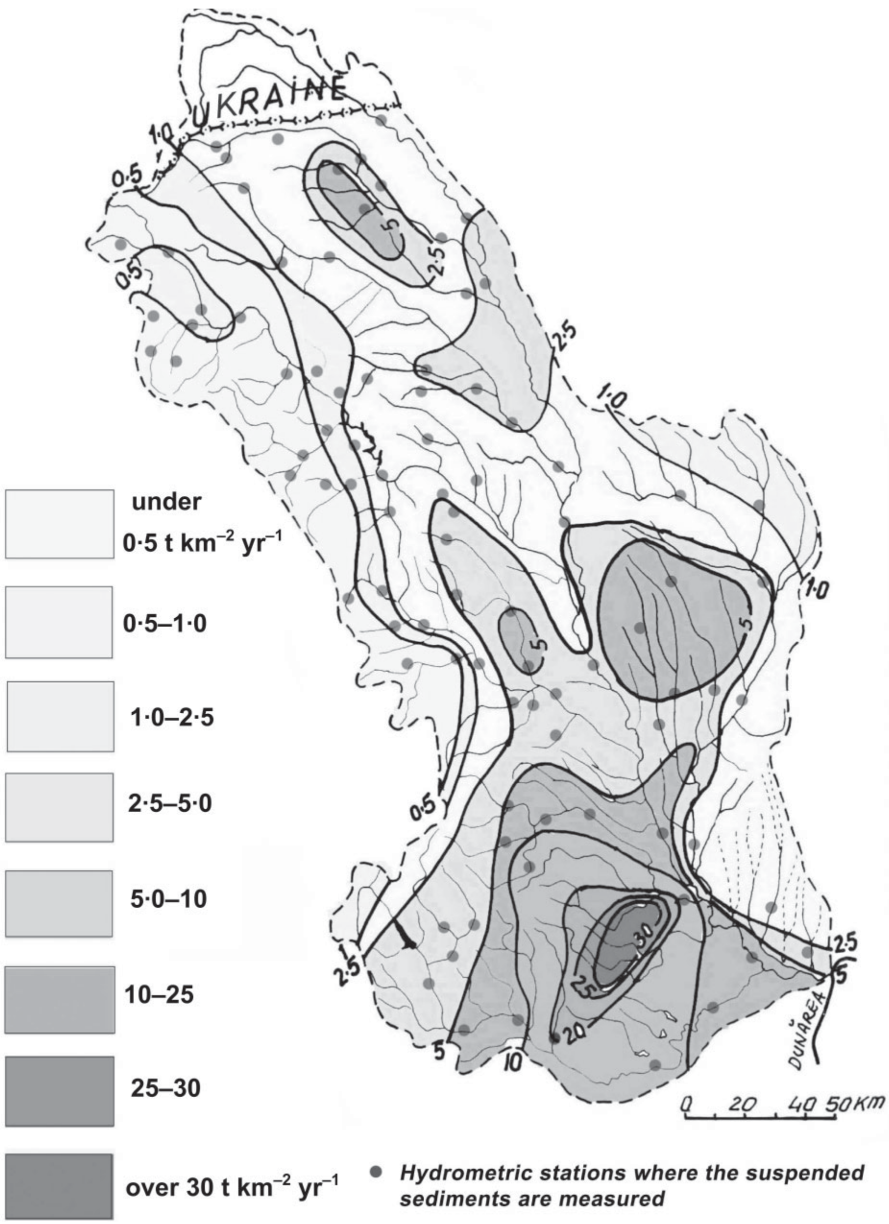

Figure 4. Map of sediment sources in the Siret drainage basin, based on the suspended sediment measurements for 92 hydrometric stations.

approach to argue for the role of fine sediments in determining the shape of grain size distributions in the bed materials.

An analysis of these cartographic materials leads to the following observations.

(i) The investigation area we considered in our study ($A = 43\,933$ km^2) presents the entire range of sediment production in Romania's territory, from the smallest values of under 0·5 t/ha/year to the greatest values of over 25 t/ha/year.

(ii) The lithological composition of the sub-layer generating the sediments and the size of the drainage basins are the major factors that provide a volumetric selection of the sediments *in transit* from its source to the delivery point (Walling, 1983; Rădoane and Rădoane, 2005). Thus, the small basins of the Eastern Carpathians' crystalline area supply the smallest quantity of sediment for transport within the river network, under 0·5 t/ha/y.

DOI: 10.1002/esp

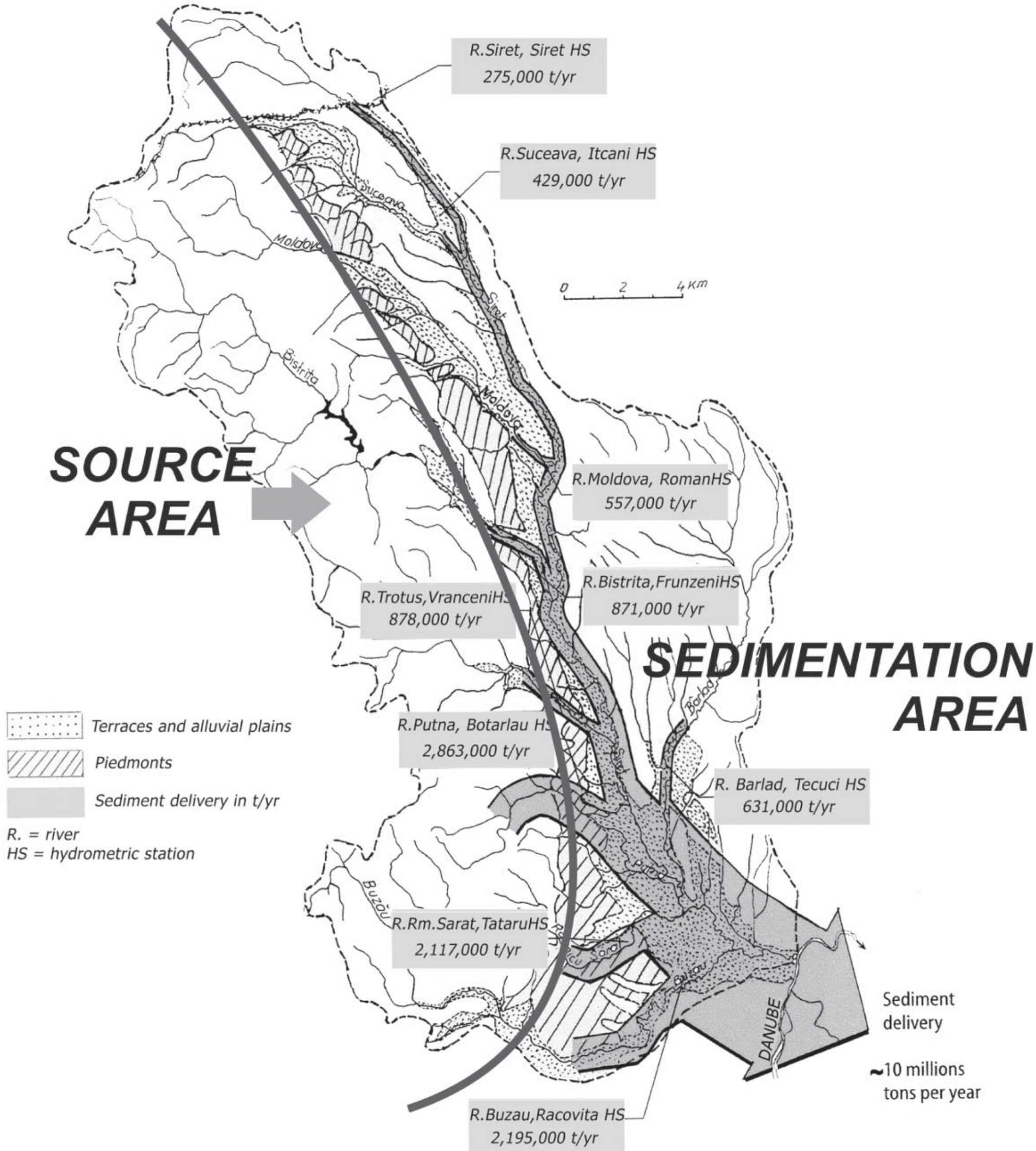

Figure 5. Map of suspended sediment transport in the Siret drainage basin. The transport of fine sediment represented by arrows is superimposed on the coarse sediment transport, identified by the extension of piedmonts and alluvial terraces. The central line divides the two main areas of the sediment system: source area and sedimentation area.

The basins situated on flysch rocks (sandstone, marls, limestone, conglomerates covered by the hillslope deposits, which frequently exceed 10 m in thickness), especially north of the Trotuş, but also the ones situated on sandy rocks of Sarmatic origin, on the superior part of the 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 the Suceava, Moldova and Trotuş with all its tributaries, but most of all with the Bârlad, to over 2·5 t/ha/y. The highest values of 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 that we 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,

DOI: 10.1002/esp

but they also have the largest sediment transport in the drainage system. The high susceptibility of terrains to erosion is mainly due to the spread of friable rocks, high landform fragmentation and a raised erosion potential.

(iii) The flux of suspended sediment transport, as suggested by the measurements on the national network in the past decades (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 subtract the effect of the man-made lakes built along this river) and Trotuş have increasing values of sediment entry, from 275 000 t/y when the Siret enters the country to over 800 000 t/y at the entry of the Trotuş into the Siret.
(iv) Almost all of the east-Carpathian rivers show an increase in sediment production as they draw closer to confluence with the Siret; the only one that shows a decrease is the Bârlad, because it manifests a heavy sediment storage in its middle and inferior parts. In another study, we 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).
(v) Immediately south of the Trotuş confluence, the sediment transport flux of the east-Carpathian rivers becomes very large, with each of the three major rivers pouring into the Siret over 2 million t/y, which causes the Siret to release a quantity of 10 million tons of sediment per year.
(vi) Due to the lack of direct measurements of the coarse sediment transportation, we used indirect evaluation of the amount of this type of transportation. Beyond the piedmont area that is shaded in Figure 5, we used a point representation of the surfaces of fluvial terraces and flood plains, which mostly contain coarse sediments of Carpathian origin. Based on this representation, we concluded that the flow of suspended sediments (presented in absolute data) overlaps with the transportation of coarse sediments of at least the same importance (without having absolute data).

In conclusion, inside the movement environment of sediments from source to delivery that we described previously, the river-beds will present a specific response at the bed material level, shown by their distribution and their arrangement along the river. We will focus on this response in the next sections of this paper, mostly attending to the variation of *bed material sizes* and *the shape of grain size distributions*.

Grain Size Distributions of Bed Material

Variation of river-bed material size along the rivers

In our investigation of river-bed material variability in rivers from the Siret drainage basin, we focused mostly on verifying the exponential model of size decreasing along the river, according to Sternberg's law, which proves that bed particles decrease in size in proportion to the mechanical work necessary to inflict friction along the river. Figure 6 shows this variation for six main rivers from the Siret drainage basin, which vary in length from 150 to 725 km. Depending on the length of the river, the median diameter, D_{50}, exponentially decreases overall, although the exponential variation is highly disturbed along important lengths of these rivers. The Trotus and Siret rivers even show an increase in material size over great distances of their lengths. Table II presents the river segments with exponentially increasing or decreasing material size, the determination coefficient of the model and the fining and the grain-size increase coeffients of the river-bed material. The only rivers that appropriately apply the exponential model along their entire lengths are the Suceava and Moldova.

The Sternberg model is not verified for the other four rivers, mostly due to the tributary contributions, which provide a massive entrance of sediment that outruns a river's processing power. Rivers in the northern part of the studied region, the Suceava and Moldova, have drainage basins with lower sediment production compared with the southern part of the region and, consequently, neither of their tributary rivers releases more coarse material into the main collector. In this manner, the collecting rivers establish an exponential decrease of bed material with similar values for the fining coefficients of the two rivers ($-0{\cdot}0143$ km^{-1} and $-0{\cdot}0102$ km^{-1}, respectively).

On the other hand, rivers situated in the southern part of the studied region (Trotus, Putna, Buzau), with drainage basins overlapping areas that produce a high amount of sediment, present an increasing size of river-bed materials. A representative case is that of the Trotus river in the mountain reach, where the tributaries' aggressiveness over the main river is so great that the phenomenon of increase of the bed material occurs for a length of over 100 km. Similar effects are presented by the Putna river over a shorter segment, and the Buzau river into its gorge reach. Yet, the most evident example is the river Siret itself, which presents a material size increasing process along a segment of over 566 km, which is over 80% of its length. This is due exclusively to the enhanced activity of its Carpathian tributaries, given the fact that Siret itself does not go through a mountainous area at all.

DOI: 10.1002/esp

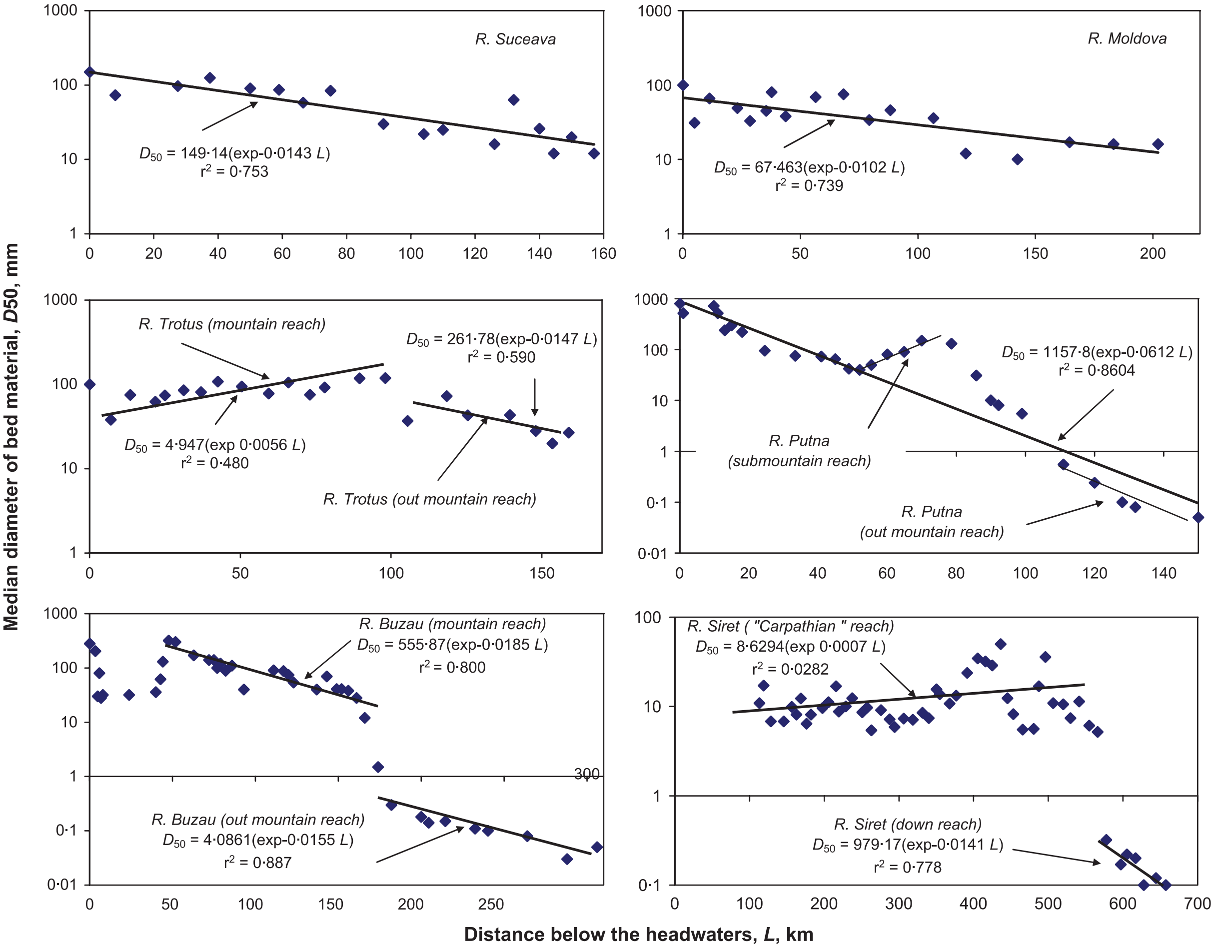

Figure 6. Downstream variation in bed material grain size along the main rivers from the Siret drainage basin. This figure is available in colour online at www.interscience.wiley.com/journal/espl

Table II. Fining and of grain-size increase coefficients of the bed sediment from the Siret drainage basin for the relationships presented in Figure 6

Rivers	Length of river reach (km)	Determination coefficient of the exponential equations $D_{50} = f(L)$ (R^2)	Fining coefficient	Coefficient of grain-size increase downstream
Suceava R.	157	0·753	−0·0143	
Moldova R.	202	0·739	−0·0102	
Trotuş R. (whole river)	159	0·349	−0·0061	
Trotus R. (montain reach)	98	0·480		0·0056
Trotus R. (sub- and out-Carpathian reach)	61	0·590	−0·0147	
Putna R. (whole river)	150	0·793	−0·0565	
Putna R. (montain 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. (whole river)	306	0·908	−0·0288	
Buzău R. (montain 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	

DOI: 10.1002/esp

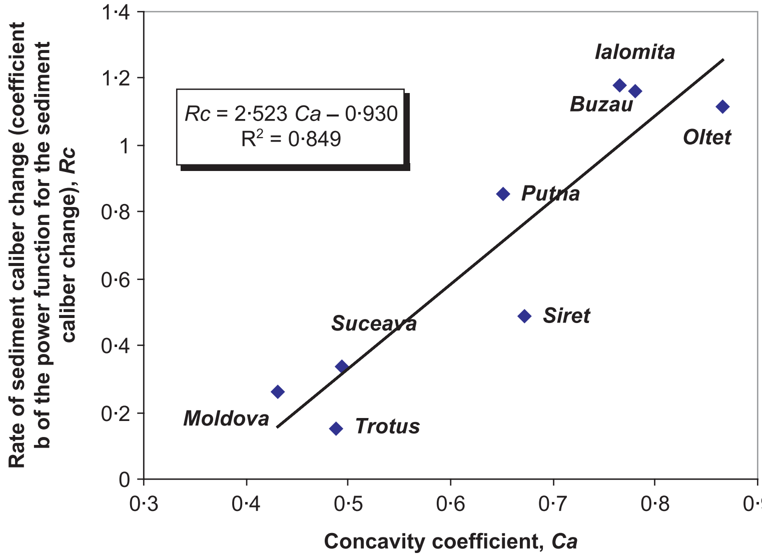

Figure 7. The concavity coefficient, C_a, in relation to the rate of sediment calibre change of bed material, R_c. The streams with a low concavity coefficient (Suceava, Moldova, Trotus) are characterized by a low rate of sediment calibre change; on the other hand, streams with high concavity (Ialomita, Oltet) have a high rate of bed material diminution (Rădoane *et al.*, 2003). This figure is available in colour online at www.interscience.wiley.com/journal/espl

Field observations and numerical simulations of downstream fining (Parker, 1991; Hoey and Ferguson, 1994) confirmed the fact that a pronounced concavity of the longitudinal profile could force a more rapid decrease in deposited material, which has also been confirmed in our case (Figure 7). Thus, the rivers with a longitudinal profile of enhanced concavity (which we measured using a formula suggested by Snow and Slingerland, 1987), such as the Buzau and Putna rivers, also present a higher rate of size reduction to river-bed material from blocks, cobble and gravel to fine material such as sand and even silt. Rivers from north of the region, such as the Suceava, Moldova and Trotus, present longitudinal profiles with reduced concavity and lower rates of decrease in bed material size.

The gravel–sand transition occurs by a threshold or a grain size jump that varies between 7 km for the Trotus, 10 km for the Siret, 22 km for the Buzau and 30 km for the Putna. The distance for which this jump appears is very short, as has been reported in the literature (Ashworth and Ferguson, 1989; Ferguson and Ashworth, 1991; Sambrook Smith and Ferguson, 1995; Ferguson *et al.*, 1996); explanation of this phenomenon has garnered great interest from the scientific community (Yatsu, 1955; Ibbeken, 1983; Sambrook Smith and Ferguson, 1995; Sambrook Smith, 1996; Rice, 1998; Constantine *et al.*, 2003; Gasparini *et al.*, 2004), but they have not reported a firm conclusion. Research in the field has brought other features of the deposited materials into focus, such as the bimodal character of grain size distributions. Our observations on the bimodality of river-bed deposits have enabled us to develop a conceptual model that may contribute to reaching a possible answer to this open question.

The bimodality of river-bed sediments

Bed sediments for rivers with gravel beds present a distinctive characteristic of bimodality, defined by the presence of two modes (peaks) in the grain size distribution separated by a lack of material of the small gravel type, the 1–8 mm fraction. At the present moment there is still a large debate over the phenomena, which are mostly synthesized by Sambrook Smith and Ferguson (1995) and Sambrook Smith (1996), and of which we conclude that there is no unanimously accepted explanation of the phenomena. The authors suggest three main possible causes that have been proven in pertinent studies: (i) the effect of the base level (which seems to have the greatest chance to be developed by a greater number of rivers); (ii) lateral inputs of fine sediments (which require important sources of sediments) and (iii) abrasion of bed material (mostly for large rivers).

Our research has shown that lateral input of fine sediments (which is the second cause suggested by the previously quoted authors) provides the main explanation of the bimodal distributions of grain sizes in the rivers with gravel beds from the Siret's basin. We tried to answer the following questions. What is the necessary amount of sand in river-bed sediment that is needed for bimodality to appear? What is the source of the sand in the second mode? Does it originate mostly from the river-bed sediments by abrasion of larger particles or is it from the hillside basin (by soil erosion and transportation)? Why is it that we could not identify a modal class of the coarse sand type or small gravel type (0·5–8 mm) in any of the samples? Is it indeed a lack of material or is it more likely a unimodal grain size distribution which overlaps with another unimodal grain size distribution whose source is foreign to the proper river channel?

We will try to answer these questions using our database that describes the six rivers we studied; thus, we were interested in obtaining a series of general or particular conclusions for either whole river lengths or certain river segments, and learning of any differences that may appear between the Carpathian tributaries or the tributaries and the main river, the Siret, which is strongly controlled by its Carpathian tributaries. Table III provides a synthesis of our observations of the grain size distributions; Figure 8 displays histograms of grain size distributions for the global samples. The shaded area marks the concavity area inside the diagrams. Figure 9 completes the whole picture by displaying how the bimodality indices vary along the rivers. Wilcock (1993) found a threshold value of $B = 1{\cdot}7$ for the bimodality index, which separates a modal sediment ($B \leq 1.7$) from another modal sediment ($B \geq 1{\cdot}7$). In our study, we found a threshold value of $B = 2{\cdot}0$, which is very close to the one determined by Wilcock.

Results and Discussion

Detailed analysis of the results has led us to the following observations.

1. As expected, the surface samples share a mode that is well centered upon the cobble and gravel class, whereas the sand class hardly exists. The sediment layer exposed by the river-bed is usually washed of fine material of less than 2 mm size, namely sands, and what remains is mainly gravel (90–95%), cobble and blocks. Thus, distributions are unimodal ($B < 0{\cdot}7$), showing a strong asymmetry to the right, except for a few sectors of short distances of less than 10 km, where bimodality appears for other pavement samples (B ranges from 2·0 to 9·05). The median values of the sand fractions for all of the sampled rivers are less than 7%, which is 2–3% lower than the fractions of the 0·5–4 mm class (see Table III), and thus explains the strong unimodal characteristic of the pavement.
2. The subsurface sample population, where the fine material is more abundant (11–17%), presents grain size distributions that tend to include the second mode with a peak in the grain size class of sand. In between the two modes there is a lack of particles with sizes in the 0·5–8 mm range, respectively between 1 *phi* and –3 *phi*. Considering the bulk sampling we performed, which implied sample weights of several hundred kilograms, we excluded the misidentification of the interval due to sampling methods. The bimodality index varies between 2·0 and 10·8 and characterizes most of the sampling points along the studied rivers. The fractions between 0·5 and 4 mm began to be lacking in the subsurface samples mostly for the Putna and Buzau rivers, situated in the southern part of the studied region. For rivers in the northern area, the median values of these fractions are nearly equal to those of sand fractions, which explain the lower bimodality of these rivers.
3. Figure 8 displays histograms of the distributions of mixed surface–subsurface samples. We marked on each diagram the areas that belong to the main grain size classes: cobble, gravel and sand. Particles with a diameter of less than 0·063 mm (4 *phi*) are silt and clay, but these materials are scarcely represented in the river-bed deposits. Also, we used a grey color frame to mark the area of absence of particle fractions that vary between 4 mm (–2 *phi*) and 0·5 mm (1 *phi*) for the Suceava, Moldova and Putna rivers, particles between 8 mm (–3 *phi*) and 0·5 mm (1 *phi*) for the Buzau river and particles between 2 mm (–1 *phi*) and 0·5 mm (1 *phi*) for the Siret river. From the diagrams we can see that bimodality is best distinguished for the Siret's river-bed material, where the 4 mm (–2 *phi*) to 0·5 mm (1 *phi*) fraction is less than 4% of the global sample. In this case, the sand fraction is 26·9% on average (but there are sampling points where the sand fraction can be up to 45–55%). Carpathian rivers affluent to the Siret river feature a less pronounced bimodality, which is spread over a larger spectrum of diameters. Actually, the sand fraction percentage in the global samples is 10% on average for northern rivers and up to 20% for the southern rivers in the studied area. For the northern rivers, the difference between the sand fractions and the fraction class separating the modes is very small (which implies a less evident bimodality), whereas for the rivers in the southern part of the studied area this difference increases, which leads to more pronounced bimodality of the river-bed material (Table III).
4. From the previous discussions we can draw the conclusion that *the bimodality appears to be limited to the Carpathian rivers and the tributary to the Siret, and very pronounced for the Siret river itself.* For the first rivers with lengths between 150 and 300 km, we were expecting an increasing bimodality along their course, as occurs with other rivers in various geographic environments, such as those in Italy (Ibbeken and Schleyer, 1991), Japonia (Kodama, 1992, 1994), Canada (Shaw and Kellerhals, 1982) and Scotland (Sambrook Smith, 1996). However, statistics on a total of 190 global samples (Table III) demonstrate that unimodal distributions prevail for all Carpathian rivers that are tributary to the Siret. Bimodality is present on river segments shorter than those that

DOI: 10.1002/esp

Table III. A synthesis of the bimodality degrees of the fluvial bed sediments, together with average data on the proportion of parent material and on the proportions of 0·5–4 mm, 1–8 mm and under 1 mm fractions in the fluvial bed material

River	Sampled points along the river (~L, km)	Unimodal distributions ($B < 2·0$)		Bimodal distributions ($B > 2·0$)		Parental material (molasse rocks and quaternary rocks)	Weight of 0.5–4 mm fractions in the bed material	Weight of 1–8 mm fractions in the bed material	Sand weight (under 1 mm) in the bed material
		N	$\bar{B}$	N	$\bar{B}$ ($B_{min} \div B_{max}$)	(%)			
						Surface samples			
Suceava	16 (172 km)	14 (~152 km)	0·553	2 (~20 km)	6·14 (B: 4·43 ÷ 7·84)	64·6	6·21	9·04	4·89
Moldova	18 (205 km)	13 (~150 km)	0·446	5 (~55 km)	4·888 (B: 3·48 ÷ 6·47)	21·2	9·86	12·54	6·96
Trotus	21 (149 km)	20 (~140 km)	0·703	1 (~7 km)	8·00	24·6	1·41	1·59	1·26
Putna	11 (95 km)	8 (~68 km)	0·614	3 (~27 km)	4·27 (B: 2·63 ÷ 6·60)	36·6	6·19	5·57	4·62
Buzau	33 (214 km)	26 (~164 km)	0·539	7 (~50 km)	5·31 (B: 2·04 ÷ 9·05)	21·6	6·27	7·43	7·23
						Subsurface samples			
Suceava	16 (172 km)	4 (~40 km)	0·469	12 (~132 km)	4·22 (B: 2·01 ÷ 6·36)	64·6	12·61	20·66	11·61
Moldova	18 (205 km)	3 (~35 km)	0·283	15 (~170 km)	3·53 (B: 2·16 ÷ 5·06)	21·2	13·89	24·74	13·10
Trotus	21 (149 km)	4 (~28 km)	0·740	17 (~121 km)	3·63 (B: 2·01 ÷ 5·31)	24·6	11·58	14·22	11·74
Putna	11 (95 km)	2 (~16 km)	0·866	9 (~79 km)	4·80 (B: 2·33 ÷ 10·80)	36·6	9·81	17·44	12·10
Buzau	33 (214 km)	10 (~70 km)	0·470	23 (~144 km)	5·22 (B: 2·31 ÷ 8·32)	21·6	9·24	15·39	17·12
						Global samples			
Suceava	16 (172 km)	13 (~112 km)	0·479	3 (~60 km)	4·77 (B: 3·0 ÷ 5·84)	64·6	7·59	13·10	7·39
Moldova	18 (205 km)	9 (~90 km)	0·471	9 (~90 km)	4·13 (B: 3·50 ÷ 4·68)	21·2	10·83	17·62	9·38
Trotus	21 (149 km)	17 (~121 km)	0·564	4 (~28 km)	4·89 (B: 3·31 ÷ 7·17)	24·6	5·56	6·84	5·44
Putna	17 (146 km)	6 (~52 km)	0·610	11 (~94 km)	5·44 (B: 2·38 ÷ 11·90)	36·6	7·27	12·66	16·58
Buzau	41 (293 km)	20 (~143 km)	0·459	21 (~150 km)	6·47 (B: 2·04 ÷ 19·0)	21·6	6·54	10·96	13·84
Siret	53 (725 km)	6 (~80 km)	0·636	47 (~645 km)	7·11 (B: 3·04 ÷ 9·40)		3·81	21·94	26·94

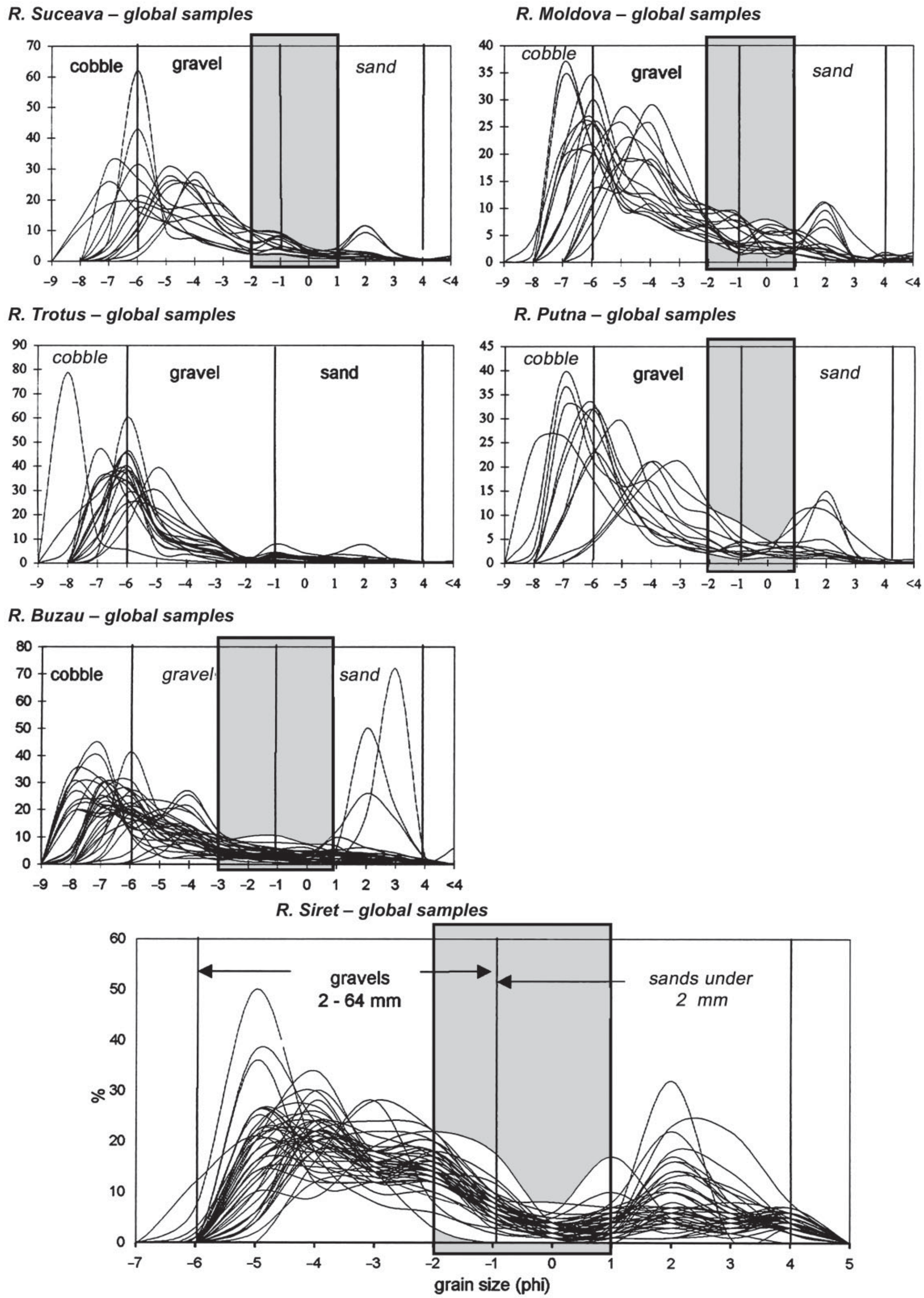

Figure 8. Histograms representing the grain size distributions for the global samples taken at certain points along the rivers. The gray area shows the 1–8 mm interval or the 0·5–4 mm interval.

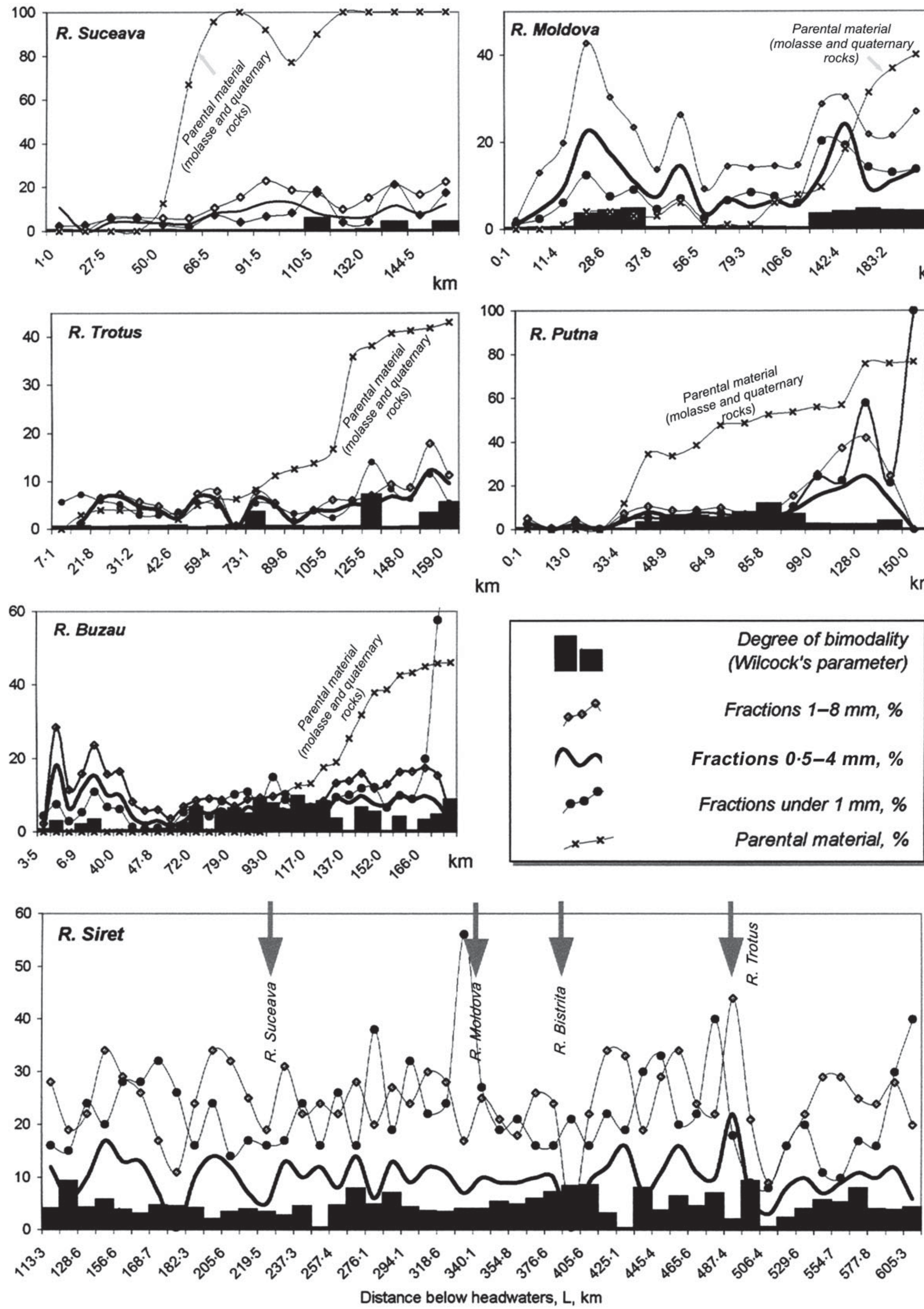

Figure 9. Variability of some parameters controlling the bimodality degrees of the studied fluvial bed sediments.

feature unimodality (Table III also displays the length of the river segment for which river-bed material is unimodal or bimodal); on the last 40 km of the Suceava, Moldova and Trotus bimodality appears at only four sampling points. Only the Putna and Buzau rivers present bimodality along river lengths of less than 100 km in the medium–inferior part of the rivers. In contrast, for the Siret river-bed, material bimodality is quasi-general. In this case, the river-bed material presents a low bimodality or it is unimodal for very short river segments that are immediately downstream of the confluence spot.

5. *The bimodality of river-bed materials is related to the quality of the parent material*, which is also the source of the river-bed sand and the source of the second mode. To demonstrate this, we approached the relationship between the bimodality parameter and the fraction of parent material in the drainage basin (Figure 10). Although these relations show a reduced sensitivity, they also indicate a certain dependence of the bimodality parameter on the parent material – mainly friable rocks – weight coefficient, and the delivery potential for fine materials in river-beds. The bold line on the diagrams shows the threshold for unimodal and bimodal distributions. The highest transfer rates

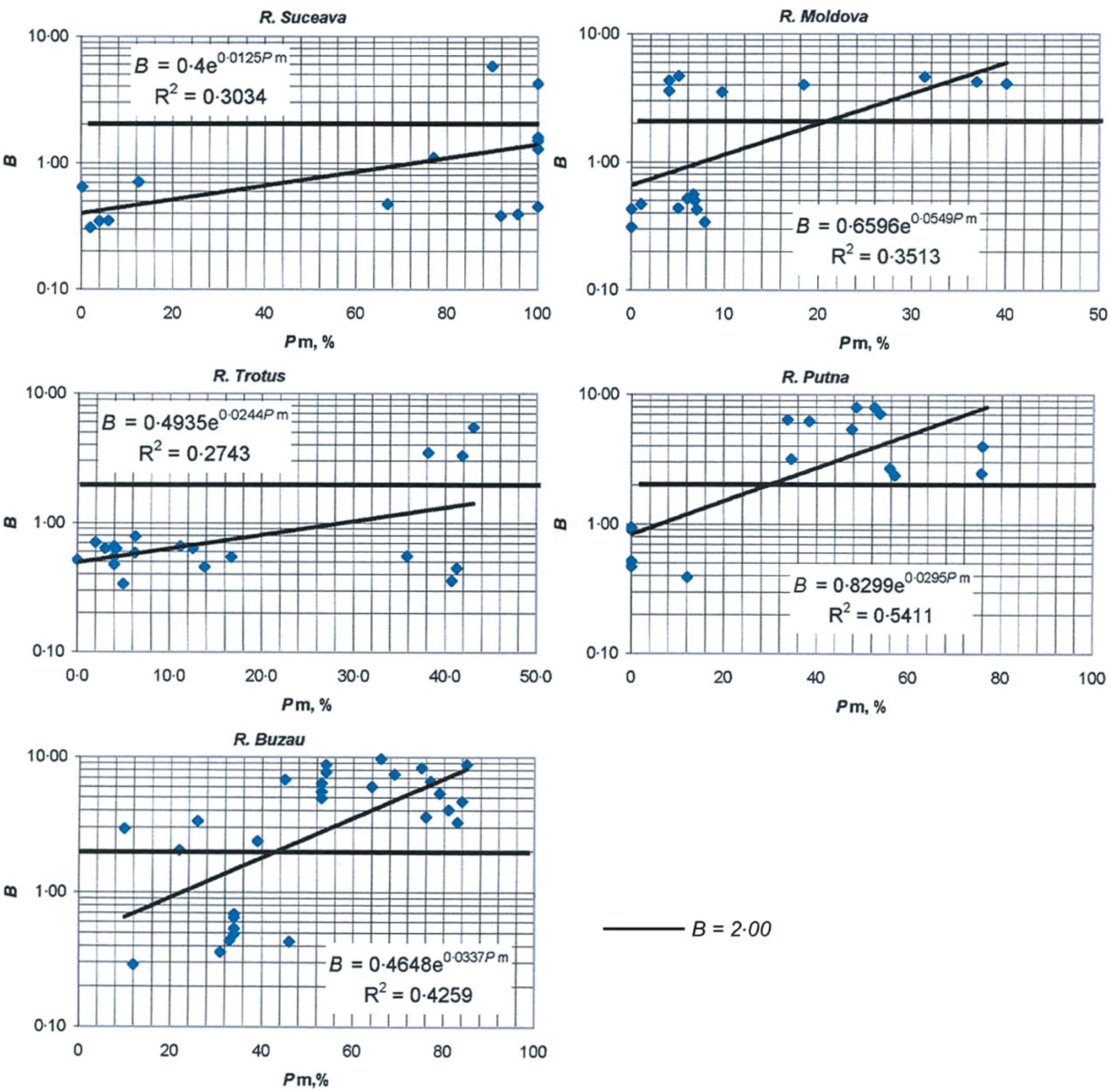

Figure 10. Relationships between the bimodality parameter (*B*) and the proportion of the parent material (mainly molasses and quaternary rocks) in the drainage basin (P_m, %). This figure is available in colour online at www.interscience.wiley.com/journal/espl

DOI: 10.1002/esp

for fine sediments from the hillside area into the main collecting river-beds were registered into the drainage basins of the Putna and Buzau rivers, with values higher than 20 t/ha/year. These sandy and silty sediments, by their high volume, simply overwhelm the bed coarse materials that are well sorted and distributed according to the Sternberg law. This develops into an overlap of a new grain size distribution that points towards the sand fraction over an already existing grain size fraction that is pointing towards gravel. Figure 11 demonstrates this idea by displaying distinct distributions of gravel and sand for two different rivers, the Suceava from the northern part and the Buzau from the southern part of the studied area.

Along its length of 150 km, the river-bed of the Suceava presented only three sections with a bimodal distribution near its confluence with the Siret; otherwise, its sediments have a unimodal distribution with a peak in the cobble

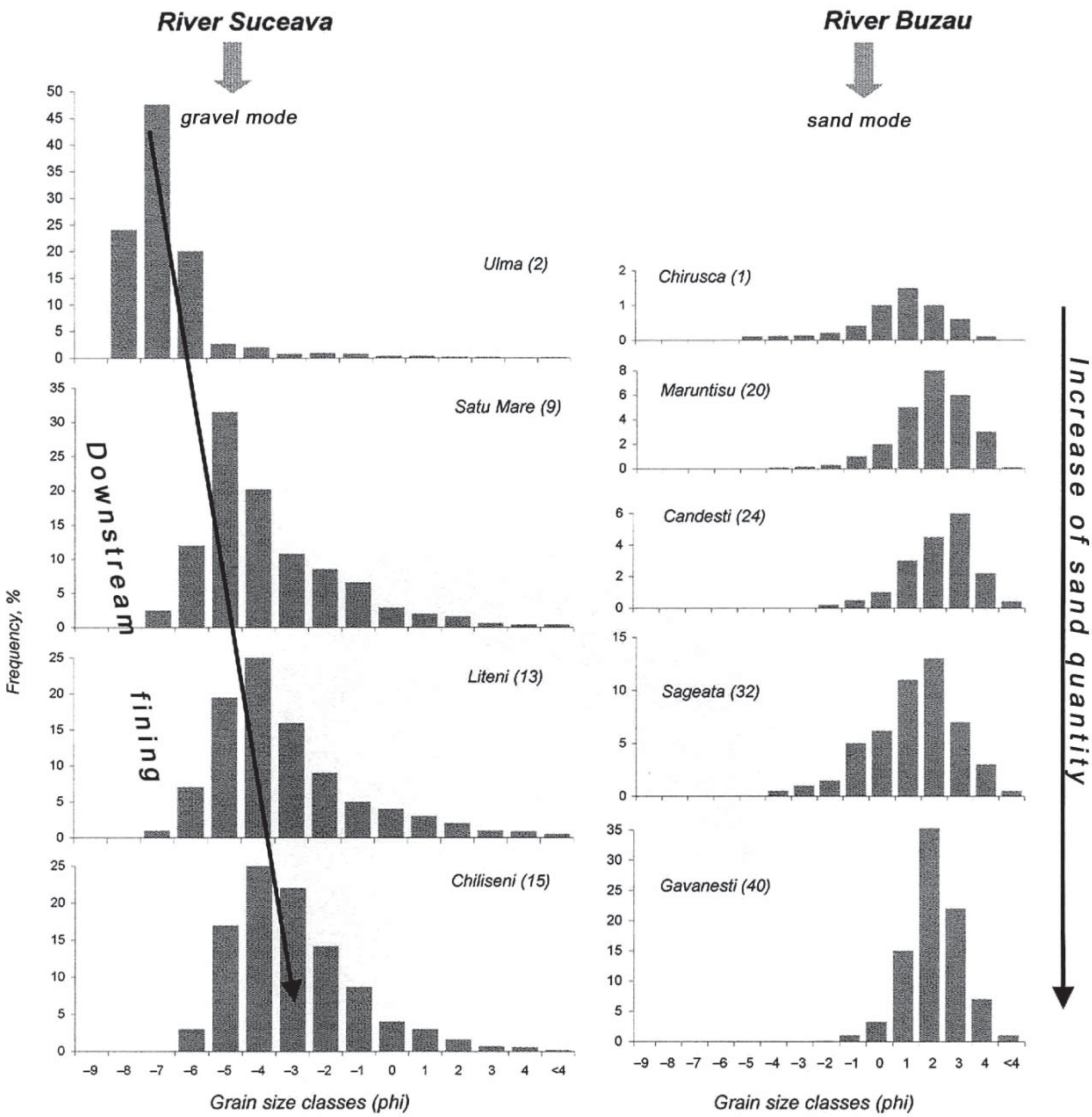

Figure 11. Grain size distributions of the gravel along the Suceava river (left). Grain size distributions of the sand along the Buzau river (right). Numbers indicate the position of sampling points below headwaters.

DOI: 10.1002/esp

and gravel class. In its drainage basin, the source of fine materials is very rich (over 60% of the basin contains friable rocks), but these sediments do not get into the river-bed due to a reduced rate of erosion and of transfer to the river-bed. Thus, grain size distributions in the river-bed are not disturbed by a high input of sediments, leading to a downstream fining according to exponential laws. This does not mean that the river-bed does not contain sand fractions at all, but rather that they have such a weight coefficient that they do not disturb the unimodal distribution of the river-bed material. A similar situation occurs for the Moldova and Trotus rivers.

In contrast, for the Putna and Buzau rivers, whose drainage basins are placed in areas with the highest rate of erosion and transfer of fine alluvia to the river-beds, the amount of sand increases along the river such that much of it outruns the river's ability to compensate for it. Thus, the sand fractions are stored and their presence is shown by a distinct distribution with a peak at 1–3 *phi* and slight left asymmetry (Figure 11).

6. The bimodal distributions of the river-bed sediments appear as the overlap of unimodal distributions of sand from the drainage basin area over the unimodal distributions of gravel processed by the river through abrasion and hydraulic sorting. Figure 12 exemplifies various sampling points along the Buzau river. In this figure, we marked the two distributions distinctively to suggest the different sources of their content. The grey color marks the coarse material and the white color marks the distribution of fine material. The two distributions intersect in the 0·5–8 mm fraction segment, falsely suggesting a lack of these fractions in the river-bed material. Actually, the amount of these fractions would be higher than that of sands if parent material did not provide fine sediments to the river-bed.
7. In this conceptual model we have drawn for the Carpathian tributaries, the case of the Siret river appears somewhat reversed. We have shown earlier (Table III and Figure 8) that the river-bed material is characterized by a strong bimodality along most of its length. The difference is that the gravel mode has an allohtonous source whereas the sand mode is owned by the river itself. If, for the Carpathian tributaries, the gravel mode is affected by a downstream fining, which clearly indicates the autohtonous source of their processing and sorting, the Siret would be mostly fit for transportation of fine particles, but it needs to face an 'avalanche' of gravel with increasing sizes along the river from its lateral inputs. Simply put, an alien coarse grain size distribution overlaps over a relatively fine river-bed grain size distribution of the Siret itself. Evidently, a very strong penury of the diameters within the 0.5–4 mm range appears between the two distributions. This is due, in our conceptual model, to the fact that the tails of the gravel mode and the sands mode overlap in this sector.

Sediment links (according to Rice, 1998, 1999) not only affect the downstream fining process, but they also affect the action of the bimodality. Along the Siret river, between the two Carpathian confluences, the bimodality of the river-bed material reaches a peak upstream of the confluence, but it is hardly noticeable immediately downstream of the Carpathian confluence. Figure 9 demonstrates this fact by the variation of the bimodality parameter upstream of the confluences (strongly bimodal) and downstream of the confluence (with a tendency of unimodality over the gravel class). Massive input of gravel causes unimodality immediately downstream of the confluence, which reduces rapidly due to a high amount of autohtonous sand (20–30% on average).

Conclusions

The main conclusion of this paper is that the bimodality of river-bed materials is explained in the cases we studied by overlapping of two grain size distributions with different sources.

For east-Carpathian rivers that are tributaries to the Siret river (Moldova, Suceava, Trotus, Putna, Buzau), blocks, cobble and gravel present a unimodal distribution skewed to the right with an exponential decrease along the river. The mechanism of processing and disposal along the river is strongly controlled by the river itself through mechanic abrasion and hydraulic sorting.

For these rivers, a secondary unimodal distribution appears that peaks in the sand class; this is less evident for the Suceava, Moldova and Trotus rivers and is well pronounced for the Putna and Buzau rivers. The source of the second distribution is mostly the amount of sand that entered the river-bed by terrain erosion in the hillside basin. For the other rivers, where disposal of fine material from the drainage basin is reduced, the riverbed contains enough sand to mark a second mode. The relationship between the amount of parent material and the bimodality parameter clearly suggests this tendency.

The intersection of the two modes is placed in the area of fractions from the 0·5–8 mm range, whereas the tails of histograms skewed to the right (for the gravel) and skewed to the left (for the sands) actually intersect. We envision that a river with a bed of gravel that flows through a river-bed that does not provide fine sediments would present a unimodal distribution in the class of gravel with a increasing skewness on the right side. In this tail, the fractions

DOI: 10.1002/esp

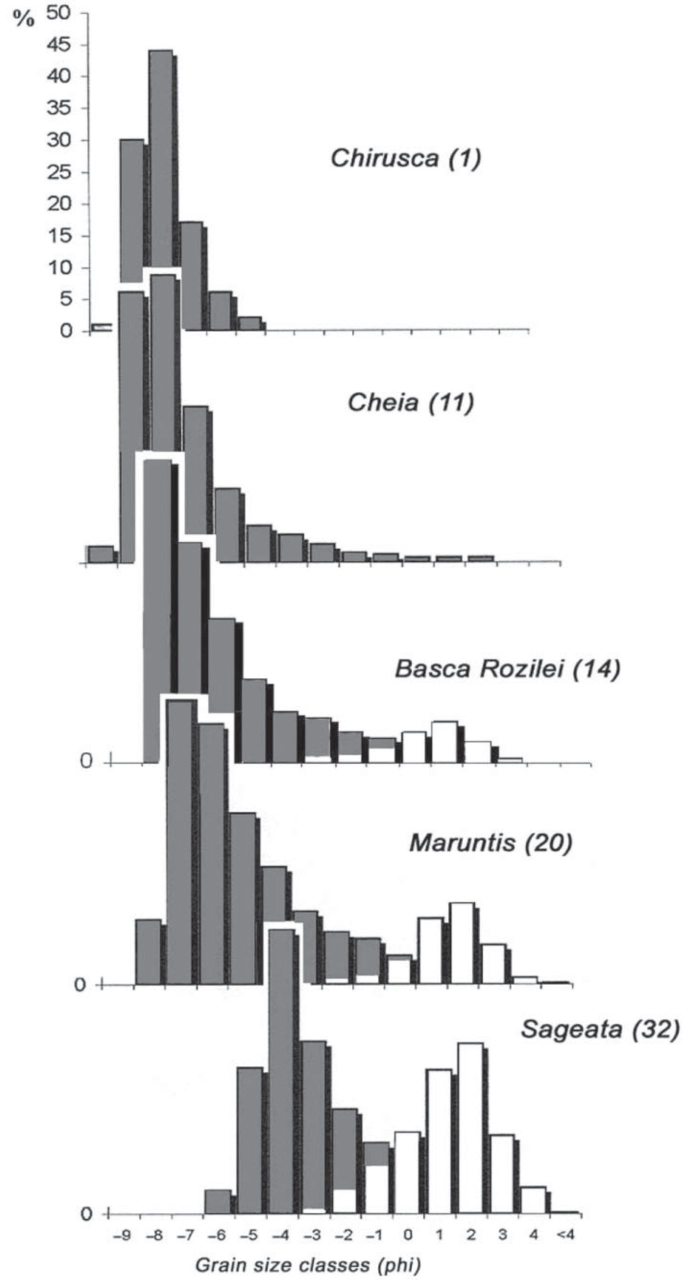

Figure 12. The development of bimodality through the intersection of the two distributions. The Buzău river-bed serves as an example. The numbers of the sections indicate the positions of the sampling points from the origin to the river mouth.

within the 0·5–8 mm range would be greater than the 1 mm fractions, such as is the case of Suceava and Moldova rivers where sand, but not gravel, is missing.

The strong bimodality of the river-bed material of the Siret is also explained by the difference in origin of the two intersecting distributions, except that the source of the first mode, that of gravel, is allohtonous and that of the sand material is from the river itself. This distribution with a unimodal tendency over the gravel class appears mostly downstream of the Carpathian rivers following the entrance of coarse material. If it were not for these Carpathian tributaries, the Siret would be a river that transports fine sediments.

The transition from gravel to sand is a well known grain size jump that we have also identified for Buzau and Siret rivers. It is also explained by different sources of grain size distributions that overlap during the evolution of

DOI: 10.1002/esp

river-beds; the point where they intersect contains the grain size jump we mentioned earlier. Evidently, by mechanical abrasion and hydraulic sorting, the river cannot feed its river-bed with fine fractions in the amount we found if it were not for another source. In this case, the source is from the parent material, which is susceptible to erosion and geomorphologic processes that are responsible for fine sediment transfer.

Acknowledgements

This research was carried out as part of the research grant funded by the National Education Ministry of Romania (Grant 705/2005) for Suceava University. We thank Iurie Barbu, Raluca Buzdugan and Marina Rusu for their help. In particular, we are very grateful to the anonymous reviewers for their insightful and invaluable comments and suggestions on the original manuscript.

References

Ashworth PJ, Ferguson RI. 1989. Size-selective entrainment of bed-load in gravel bed streams. *Water Resources Research* **25**(4): 627–634.

Brierly GJ, Hickin EJ. 1985. The downstream gradation of particle sizes in the Squamish River, British Columbia. *Earth Surface Processes and Landforms* **10**: 597–606.

Bunte K, Abt SR. 2001. *Sampling Surface and Subsurface Particle-Size Distributions in Wadable Gravel and Cobble Bed Streams for Analyses in Sediment Transport, Hydraulics, and Streambed Monitoring*, USDA, Rocky Mountain Research Station, General Technical Report RMRS-GTR-74; 428pp.

Church MA, McLean DG, Wolcott JF. 1987. River bed gravels: sampling and analysis. In *Sediment Transport in Gravel-Bed Rivers*, Thorne, CR, Bathurst, JC, Hey RD (eds). Wiley: Chichester; 43–79.

Constantine CR, Mount JF, Florsheim JL. 2003. The effects of longitudinal differences in gravel mobility on the downstream fining pattern in the Consumnes River, California. *Journal of Geology* **111**: 233–241.

Dawson M. 1988. Sediment size variation in a braided reach of the Sunwapta River, Alberta, Canada. *Earth Surface Processes and Landforms* **13**: 599–618.

Dietrich WE, Dunne T. 1978. Sediment budget for a small catchment in mountainous terrain. *Zeitschrift für Geomorphologie. N.F., Suppl. Bd.* **29**: 191–126.

Dumitriu D. 2003. *Geomorphology of the Sediment Budget of the Trotus Drainage Basin*, PhD thesis, University of Iassy; 286pp.

Ferguson R, Ashworth PJ. 1991. Slope induced changes in channel character along a gravel bed stream: the Alt Dubhaig, Scotland. *Earth Surface Processes and Landforms* **16**: 65–82.

Ferguson R, Hoey T, Wathen S, Werritty A. 1996. Field evidence for rapid downstream fining of river gravels through selective transport. *Geology* **24**(2): 179–182.

Gasparini NM, Tucker GE, Bras RL. 2004. Network-scale dynamics of grain-size sorting: implications for downstream fining, stream-profile concavity and drainage basin morphology. *Earth Surface Processes and Landforms* **29**: 401–532.

Gomez B, Rosser BJ, Peacock DH, Murray Hicks D. 2001. Downstream fining in a rapidly aggrading gravel bed river. *Water Resources Research* **37**(6): 1813–1823.

Hoey TB, Ferguson R. 1994. Numerical simulation of downstream fining by selective transport in gravel bed rivers: model development and illustration. *Water Resources Research* **30**(7): 2251–2260.

Ibbeken H. 1983. Jointed source rock and fluvial gravel controlled by Rosin's law: a grain-size study in Calabria, South Italy. *Journal of Sedimentology Petrology* **53**(4): 1213–1231.

Ibbeken H, Schleyer R. 1991. *Source and Sediment. A Case Study of Provenance and Mass Balance at an Active Plate Margin (Calabria, Soythern Italy)*. Springer-Verlag: Berlin; 285pp.

Ichim I, Rădoane M. 1990. Channel sediment variability along a river: a case study of the Siret River (Romania). *Earth Surface Processes and Landforms* **15**: 211–225.

Ichim I, Rădoane M, Rădoane N, Grasu C, Miclaus C. 1998. *Sediment Dynamics. Application to the Putna River – Vrancea*. Technical Press: Bucharest; 192pp.

Ichim I, Rădoane M, Rădoane N, Miclaus C. 1995. Carpathian gravel bed rivers in recent time – a regional approach. *Transactions, Japanese Geomorphological Union* **17**(3): 135–157.

Knighton AD. 1980. Longitudinal changes in the size and sorting of stream-bed material in four English rivers. *Bulletin of the Geological Society of America* **91**: 483–502.

Knighton AD. 1982. Longitudinal changes in the size and shape of stream bed material: evidence of variable transport conditions. *Catena* **9**: 25–34.

Knighton AD. 1999. The gravel–sand transition in a disturbed catchment. *Geomorphology* **27**: 325–341.

Kodama Y. 1992. Effect of Abrasion on Downstream Gravel-Size Reduction in the Watarase River, Japan: Field Work and Laboratory Experiments, *Environmental Research Center Papers* **15**: 88pp.

Kodama Y. 1994. Downstream changes in the lithology and grain size of fluvial gravels, the Watarase River, Japan: evidence of the role of abrasion in downstream fining. *Journal of Sedimentary Research* **A64**(1): 68–75.

Madej MA. 1987. Residence times of channel-stored sediment in Redwood Creek, northwestern California. In *Erosion and Sedimentation in the Pacific Rim*, Beschta, RL, Blinn T, Grant GE, Swanson FJ (eds), IAHS Publication 165; 157–164.

DOI: 10.1002/esp

Martiniuc, C. 1948. Contribution à la connaissance du Sarmatien entre Siret et Carpathes. *Analele Stiintifice ale Universitatii din Iasi* (Sci Nat), **XXI**: Iasi.
Mosley NP, Tindale DS. 1985. Sediment variability and bed material sampling in gravel-bed rivers. *Earth Surface Processes and Landforms* **4**: 465–483.
Nakamura F, Araya T, Higashi S. 1987. Influence of river channel morphology and sediment production on residence times and transport distance. In *Erosion and Sedimentation in the Pacific Rim*, Beschta RL, Blinn T, Grant GE, Swanson FJ (eds), IAHS Publication 165; 355–364.
Paola C, Seal R. 1995. Grain size patchiness as a cause of selective deposition and downstream fining. *Water Resources Research* **31**: 1395–1407.
Parker G. 1991. Selective sorting and abrasion of river gravel, II; Applications. *Journal of Hydraulic Engineering* **28**: 529–544.
Parker G, Klingerman PC, McLean DG. 1982. Bedload and size distribution in paved gravel bed streams. *Journal of Hydraulic Engineering Division, American Society of Chemical Engineering* **108**: 544–571.
Pizzuto JE. 1995. Downstream fining in a network of gravel-bedded rivers. *Water Resources Research* **31**(3): 753–759.
Rădoane M, Rădoane N. 2001. Land erosion and sediment transport in the Jijia and Bârlad drainage basins. *Review of Geomorphology, Bucharest* **3**: 73–86.
Rãdoane M, Rãdoane N. 2005. Dams, sediment sources and reservoir silting in Romania. *Geomorphology* **71**: 112–125.
Rãdoane M, Rãdoane N, Dumitriu D. 2003. Geomorphological evolution of longitudinal river profiles in the Carpathians. *Geomorphology* **50**: 293–306.
Rice S. 1998. Which tributaries disrupt downstream fining along gravel-bed rivers? *Geomorphology* **22**: 39–56.
Rice S. 1999. The nature and controls on downstream fining within sedimentary link. *Journal of Sedimentary Research* **69A**: 32–39.
Rice S, Church M. 1998. Grain size along two gravel-bed rivers: statistical variation, spatial patterns and sedimentary links. *Earth Surface Processes and Landforms* **23**: 345–363.
Sambrook Smith GH. 1996. Bimodal fluvial bed sediments: origin, spatial extent and processes. *Progress in Physical Geography* **20**(4): 402–417.
Sambrook Smith GH, Ferguson RI. 1995. The gravel–sand transition along river channels. *Journal of Sedimentary Research* **A65**(2): 423–430.
Sambrook Smith GH, Ferguson RI. 1996. The gravel–sand transition: flume study of channel response to reduced slope. *Geomorphology* **16**: 147–159.
Sambrook Smith GH, Nicholas AP, Ferguson RI. 1997. Measuring and defining bimodal sediments: problems and implications. *Water Resources Research* **33**(5): 1179–1185.
Schumm SA. 1977. *The Fluvial System*. Wiley: New York.
Seal R, Paola C. 1995. Observations of downstream fining on the North Fork Toutle River near Mount St. Helens, Washington. *Water Resources Research* **31**(5): 1409–1419.
Seal R, Paola C, Parker G, Southard JB, Wilcock PR. 1997. Experiments on downstream fining of gravel: I. Narrow-channel runs. *Journal of Hydraulic Engineering Division, American Society of Chemical Engineering* **123**: 874–884.
Shaw J, Kellerhals R. 1982. The composition of recent alluvial gravels in Alberta River beds. *Alberta Research Council Bulletin* **41**.
Snow RS, Slingerland RL. 1987. Mathematical modelling of graded river profiles. *Journal of Geology* **95**: 15–33.
Sternberg H. 1875. Untersuchungen ueber laengen-und querprofil geschiebefuehrende flusse. *Zeitschrift fuer das Bauwesen* **25**: 483–506.
Surian N. 2002. Downstream variation in grain size along an Alpine River, analysis of controls and processes. *Geomorphology* **43**: 137–149.
Walling DE. 1983. The sediment delivery problem. *Journal of Hydrology* **65**: 209–237.
Walling DE, Webb BW. 1983. Patterns of sediment yield. In *Background to Palaeohydrology*, Gregory KJ (ed.). Wiley: Chichester; 69–100.
Werrity A. 1992. Downstream fining in a gravel bed river in Southern Poland: Lithological control and the role of abrasion. In *Dynamics of Gravel Bed Rivers*, Billi P, Hey RD, Thorne CR, Tacconi P (eds). Wiley: Chichester; 333–346.
Wilcock PR. 1992. Experimental investigation of the effects of mixture properties on transport dynamics. In *Dynamics of Gravel Bed Rivers*, Billi P *et al.* (eds). Wiley: New York; 109–131.
Wilcock PR. 1993. Critical shear stress of natural sediments. *Journal of Hydraulic Engineering Division, American Society of Chemical Engineering* **119**(4): 491–505.
Yatsu E. 1955. On the longitudinal profile of the graded river. *Transactions of the American Geophysical Union* **36**: 655–663.

DOI: 10.1002/esp