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CHANNEL SEDIMENT VARIABILITY ALONG A RIVER: A CASE STUDY OF THE SIRET RIVER (ROMANIA)

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ABSTRACT

The Siret River has the largest drainage basin (42 274 km^2) in Romania. It gathers all the rivers from the eastern part of the Eastern Carpathians, a fact that causes marked asymmetry of the basin. This study is principally concerned with changes in the form of the longitudinal profile and the grain size variability introduced by the Carpathian tributaries. Channel sediment analyses considered the petrography, granulometry, and morphometry of the pebbles, relating these to the river bed and floodplain geometry and to some properties of the drainage basin.

The following conclusions arise. The Siret River undergoes an intense regrading of its longitudinal profile, with marked aggradation between transects 24 and 26 (see Figures 1 and 2). This reflects selective accumulation of coarse material due to the massive contribution of the Carpathian tributaries. This phenomenon has been continuous throughout the Holocene, resulting in the gravel sheet formation of the Pericarpathian piedmont.

KEY WORDS Channel sediments Particle size, petrography, and morphometry Long profile form Piedmont rivers

INTRODUCTION

In this paper we discuss some aspects of variability in longitudinal stream profile and channel deposit characteristics along the largest river in Romania, the Siret River. The study has as its starting point the 'geomorphic paradox' of this river, namely that for 85 per cent of its length, the river flows through a hill region, but the channel deposits, river bed dynamics, and other features are typically Carpathian.

It is known that the longitudinal profile form and slope are imposed, on the one hand, by the geological (lithology, structure, and neotectonics) and morphoclimatic conditions, and on the other hand, by conditions imposed both from upstream and by the downstream base level. These represent a very general level of explanation, and the major dynamic variables controlling the form and the slope are the discharge, sediment load, and downstream change of material calibre.

An intrinsic relation between the grain size distribution of the river bed sediment and the longitudinal profile form of a river has been demonstrated by several researchers since Sternberg (1875), who enunciated the 'abrasion law' for grain size reduction (Shulits, 1941; Yatsu, 1955; Hack, 1957; Miller, 1958; Knighton, 1980; Richards, 1982; Shaw and Kellerhals, 1982; Williams and Wolman, 1984; Chien, 1985; Ichim and Radoane, 1986; Snow and Slingerland, 1986; Dietrich *et al.*, 1987; Chang, 1988; Ichim *et al.*, 1989). In particular, the identification of discontinuities of grain size variation along rivers, rather than simple exponential trends, includes consideration of the effects of:

1. Longitudinal slope discontinuities and discontinuous reduction of grain size from 2 to 4 mm (Yatsu, 1955);
2. Sediment supply from tributaries (Miller, 1958; Knighton, 1980; Dawson, 1988);
3. Varying abrasion rates of gravel depending on lithology (Shaw and Kellerhals, 1982; Dawson, 1988), and
4. Man-made impact (Williams and Wolman, 1984; Chien, 1985; Ichim and Radoane, 1986).

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In this study of the Siret River, the largest tributary of the Danube in Romania, particular attention is given to the changing longitudinal profile form and grain size variability induced by Carpathian tributaries which supply coarse bed material. Channel sediment analyses relate to petrography, grain size, morphometry of pebbles, channel and floodplain geometry, some drainage basin properties, and lithology.

STUDY AREA, DATA COLLECTION, AND METHODS

The Siret River (Figure 1) has its source in the North Carpathians in the Soviet Union. Of its total length of 657 km, 544 km is in Romania: its total drainage basin area is 42 274 km^2 The most important tributaries are those from the Eastern Carpathians listed in Table I. From the Moldova Tableland, the most important tributary is the Birlad River (area = 7,354 km^2, mean annual flows = 6·38 m^3 s^{-1}).

Ninety-six per cent of the drainage basin area of the Siret River is within Romania, and 98 per cent of the mean annual runoff is generated, together with about 98 per cent of the mean annual suspended sediment load. From its entry into Romania to its junction with the Danube the specific runoff of the Siret River is very low, being between 5·95 l s^{-1} km^{-2} and 7·2 l s^{-1} km^{-2} (Gâstescu *et al.*, 1983). Mean discharge ($\bar{Q}$) increases from 13·6 m^3 s^{-1} at Siret Town gauging station to 254 m^3 s^{-1} at the confluence with the Danube. The maximum registered discharge is 3186 m^3 s^{-1}, while the discharge with a return period of 100 years is

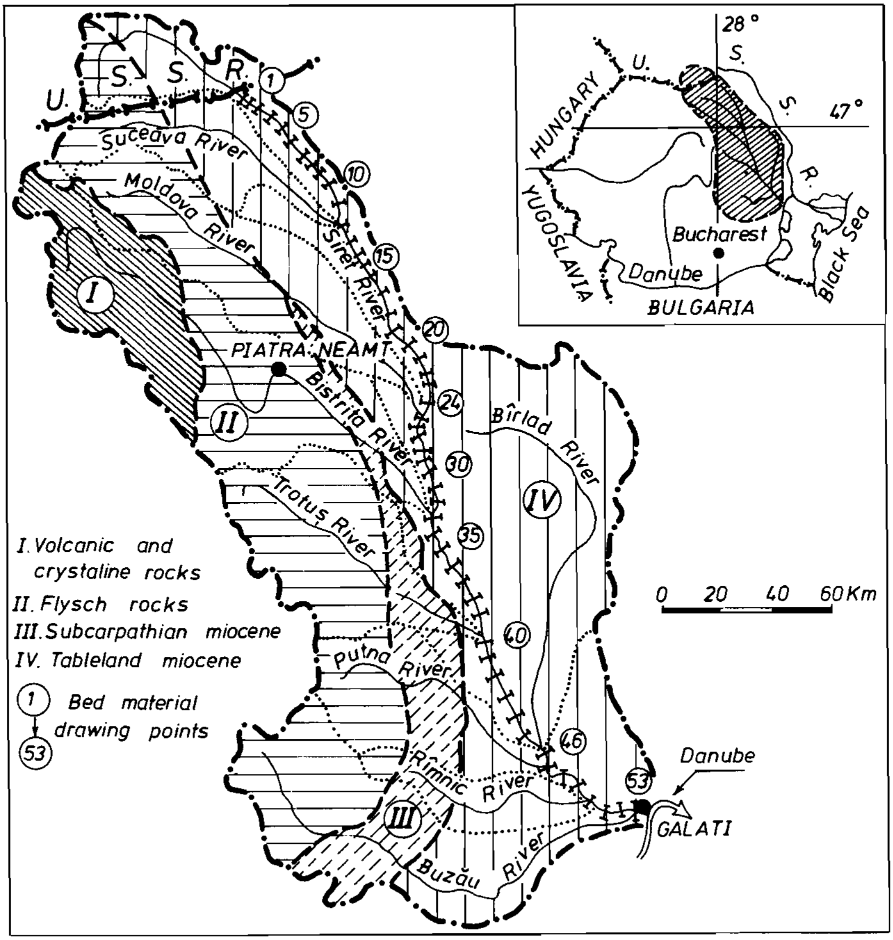

Figure 1. The Siret basin with major tributaries, sediment sample point, and bedrock geology. Inset map shows location of basin in Romania

Table I. Tributaries of the Siret River draining from the Eastern Carpathians

Tributary	Basin area (km^2)	Mean annual flows (m^3 s^{-1})
Suceava River	2600·0	13·0
Moldova River	4326·0	26·2
Bistrita River	7042·0	59·0
Trotus River	4349·0	25·0
Putna River	2742·0	13·4
Rimnicu Sarat River	943·0	2·7
Buzau River	4763·0	25·4

3970 m^3 s^{-1}. Between its entry into Romania and the Danube junction, the slope decreases from 1·475 m km^{-1} to 0·06 m km^{-1}; the channel width increases from 35 m to 250 m, the active channel belt increases from 300 m to 2600 m and the floodplain width from 1,500 m to 12 000 m; the sinuosity index and braiding index increase from 1·2–3·48 and 1·0–3·84, respectively.

For our investigation, we collected samples of sediment from the banks and bed at 53 cross-sections spaced on average at 8–10 km apart (Figure 1). We also took into account the main confluences when selecting sampling sites. Bed samples were obtained after a long drought, when the river lowered considerably and a large surface of the river bed was exposed. In each cross-section, a volumetric sample has been taken from a homogeneous body of sediment. We have collected bulk samples of a quantity such that the largest particle accounts for less than about 5 per cent of the total sample volume (*cf.* Mosley and Tindale, 1985). Sampling generally conforms with ISO–4364–1977 (*cf.* Mosley and Tindale, 1985; Church *et al.*, 1987). From each cross-section we collected between 30–50 kg per sample in conditions in which the largest clast is 95 mm in diameter (observed at the Trotus River confluence). Bulk samples of bed material were collected as close as possible to the channel thalweg. The river bed is armoured and therefore these samples contained both a mixture of surface and subsurface material. For gravel bed deposits we determined the morphometry of 100 grains from each sample exceeding 16·5 mm diameter Cailleux's (1947) method. Petrographical analyses were performed on about 100 pebbles per sample from 24 cross-sections considered to be representative for this river.

Bank sediment samples were collected with reference to the broad stratigraphy, morphology and elevation of the bank, and generally, 4–5 kg of material were obtained per river cross-section. The silt–clay percentage in the bank sediment was obtained from wet-sieve analysis of a bulk sample of up to several kilograms of sediment.

We also determined for every cross-section the values of certain variables relating to the basin or stream channel: the drainage basin area upstream of each cross-section; the river length from its source; the floodplain width bounded by obstacles to river migration, such as terraces or fault scarps; the width of the active channel belt defined by Bridge and Leeder (1979) as the zone in which the river is free to migrate laterally. For single curved channels this is approximately equal to the maximum amplitude of river bends and includes abandoned as well as active channel curves. For multiple channel (braided) streams, the active channel belt is the maximum width confined at bankfull stage.

From topographic maps of scale 1:50 000, the long profile slope, the braiding index (total length of bankfull channel cut into the floodplain surface divided by distance along the main channel), and the stream bed sinuosity index were measured, between the surveyed cross-sections. The length of reach over which measurements were taken varied between five and ten meander wavelengths about 8–10 km.

Mean annual discharges ($\bar{Q}$) were obtained from eight gauging stations with measurements for 35–40 years surveyed by the National Water Council (cross-sections: 1, 4, 8, 16, 28, 35, 47, 52). For the other cross-sections, data were obtained from an empirical relation between $\bar{Q}$ and drainage basin area ($r = 0{\cdot}986$; $r^2 = 0{\cdot}973$) based on the data for the eight gauging stations. Variables used in study are listed in Table II. We also determined a series of bivariate relations which describe the trends in some variables as functions of river length (Table IV).

Table II. Variables used in study

Variable name	Symbol	Units	Range
Stream length	L	km	113·3–657·3
Drainage basin area	A	km^2	1651·0–43910·0
Floodplain width	Fw	m	1550·0–22000·0
Active channel belt width	Aw	m	600·0–8000·0
Channel width	w	m	36·0–240·0
Slope	S	m/1000 m	0·036–1·475
Sinuosity index	SI	—	1·191–1·571
Braiding index	BI	—	1·0–4·336
Mean annual discharge	$\bar{Q}$	$m^3 s^{-1}$	13·11–254·31
Median diameter of bed sediment	d_{50}	mm	0·075–35·0
Mean diameter of bed sediment	$\bar{d}$	mm	0·17–36·7
Representative diameter of bed sediment	d_{84}	mm	0·15–68·0
Folk–Ward Sorting*	σ	—	8·6–32·5
Folk–Ward Kurtosis*	K	—	0·63–1·55
Folk–Ward Skewness*	Sk	—	−0·55–1·0
Roundness index of pebbles*	U_t	—	180·0–395·5
Flatness index of pebbles*	FI	—	1·99–3·47
Asymmetry index of pebbles*	AS	—	0·64–0·72
Median diameter of bank sediment	DB_{50}	mm	0·030–0·48
Silt–clay percentage, bank sediment	M	%	1·0–94·0

* Calculated only for $d_{50} > 5$ mm.

CHANNEL SEDIMENT PETROGRAPHY

Petrographical analysis was undertaken for pebbles and cobbles, with the help of thin sections. About 2400 pebbles with diameters between 16·5 mm and 30 mm were analysed (Table III). Several conclusions can be drawn from these analyses.

First, from the map of lithological outcrops within the Siret drainage basin (Figure 1) we can observe that sedimentary rocks occupy the largest area, although in the mountain regions, flysch rocks occur together with metamorphic and volcanic rocks. Thus at the Bistrita River confluence with the Siret River, metamorphic and volcanic rocks cover 15·6 per cent of the Siret drainage area; at the Trotus River confluence the proportion is 12 per cent; and at the Putna River confluence it is about 8 per cent. The percentage distribution of mountain regime in the total drainage area of the Siret River upstream of each confluence can be defined (Figure 2A). There is an increasing proportion of mountain area from 30 per cent at the entrance into Romania, to 61 per cent at the confluence with Trotus River, following which it decreases to 49 per cent at the confluence with Buzau River.

Second, 80 per cent of the gravel of the Siret River bed is composed of sedimentary rocks. The reach between the confluences with the Bistrita and Trotus Rivers is an exception, as the sedimentary proportion is here about 50 per cent (Figure 2C). Among the sedimentary rocks the largest proportion is of sandstone, which represents 80–90 per cent in the section upstream from the confluence with the Moldova, decreasing to 40 per cent downstream from the confluence with the Trotus.

Third, mineralogically, the sandstones are made up of quartz (70–90 per cent) in subrounded and well-cemented granules. There is also chlorite, muscovite, and feldspars. In all the samples analysed the presence of iron oxides is obvious, in either the form of a thin coating on the quartz granules, of pigments in quartz cement, or of fillings in the voids between altered minerals (Catana *et al.*, 1985). This may indicate an effect of storage and delay in sediment transfer caused by imbricated deposition in the bed sediments, which are then taken again into effective transport after long periods of weathering. Finally, a small percentage of the sedimentary rock is composed of limestone, sandstone–limestone, and marl.

Fourth, pebbles of metamorphic rock generally contribute relatively less to the bedload, from a maximum in excess of 50 per cent at the confluence with the Bistrita, but decreasing sharply downstream from the

Table III. Petrographical nature of pebbles from Siret River channel

	Sedimentary rocks						Metamorphic rocks				
Cross section	Sand-stones	Limestones and sandstones	Lime-stones	Silico-lites	Siltites	Percent-ages	Quartz	Schistes quartz	Gneiss	Rhyolit meta-tuffs	Percent-tages
1	90	0	2	0	2	94	6	0	0	0	6
2 I	88	2	0	2	0	92	6	0	0	2	8
2 II	84	2	4	2	2	94	5	0	0	1	6
4	91	1	3	1	1	97	3	0	0	0	3
5	83	0	3	5	2	93	5	0	0	2	7
6 I	84	2	6	4	2	98	2	0	0	0	2
6 II	92	0	0	2	1	95	0	0	0	5	5
7	90	0	1	3	2	96	3	0	0	1	4
9	90	0	0	2	0	92	7	0	0	1	8
10	91	0	0	2	1	94	6	0	0	0	6
11	88	0	0	4	2	94	5	0	0	1	6
12	85	1	1	1	1	89	10	1	0	0	11
Confluence with Suceava River											
13	87	2	2	3	2	97	3	1	0	0	4
14	95	1	1	2	0	99	1	0	0	0	1
24	92	1	0	5	2	100	0	0	0	0	0
Confluence with Moldova River											
25	81	2	4	3	1	91	5	1	2	1	9
26	47	3	7	3	2	72	17	6	1	4	28
28	56	3	10	7	2	78	11	6	1	4	22
29	32	11	15	8	1	67	19	2	3	9	33
Confluence with Bistrita River											
30	15	14	17	2	1	49	30	8	9	4	51
31	21	18	14	3	2	58	33	2	4	3	42
38	23	11	12	3	1	50	31	6	11	2	50
Confluence with Trotus River											
39	43	18	15	1	2	79	17	1	2	1	21
Confluence with Putna River											
48	48	17	11	5	2	83	12	1	3	1	17

confluence with the Trotus River. Quartz pebbles dominate (33 per cent), while gneisses contribute a maximum of 11 per cent.

Fifth, the effect of confluences on the general pattern of lithological dominance is marked (Figure 2C). Differentiation of the following petrographical sectors along the Siret River can be suggested: *calcareous*, between the Moldova River and the Bistrita River; *quartzose* downstream from the confluence with the Bistrita River; and *sandstone–calcareous* downstream from the confluence with the Trotus River.

Finally, downstream from the Bistrita River inflow, the gravel petrography reflects competition between grains with different abrasion rates. The input of the resistant metamorphic and volcanic rocks from the Bistrita River represents the main explanation for this. As shown in Figure 1, these rocks cover only 15·6 per cent of the Siret drainage area and in river bed gravels the percentage decreases from above 50 per cent to 8 per cent at 100 km below the Bistrita inflow. Evidently, lithological differences of mineral size and hardness seem to cause the discontinuous collapse of the gravel petrographic distribution (Figures 1 and 2C). It is necessary to note here that the petrographic analysis has been performed only on grain sizes exceeding 16·5 mm diameter.

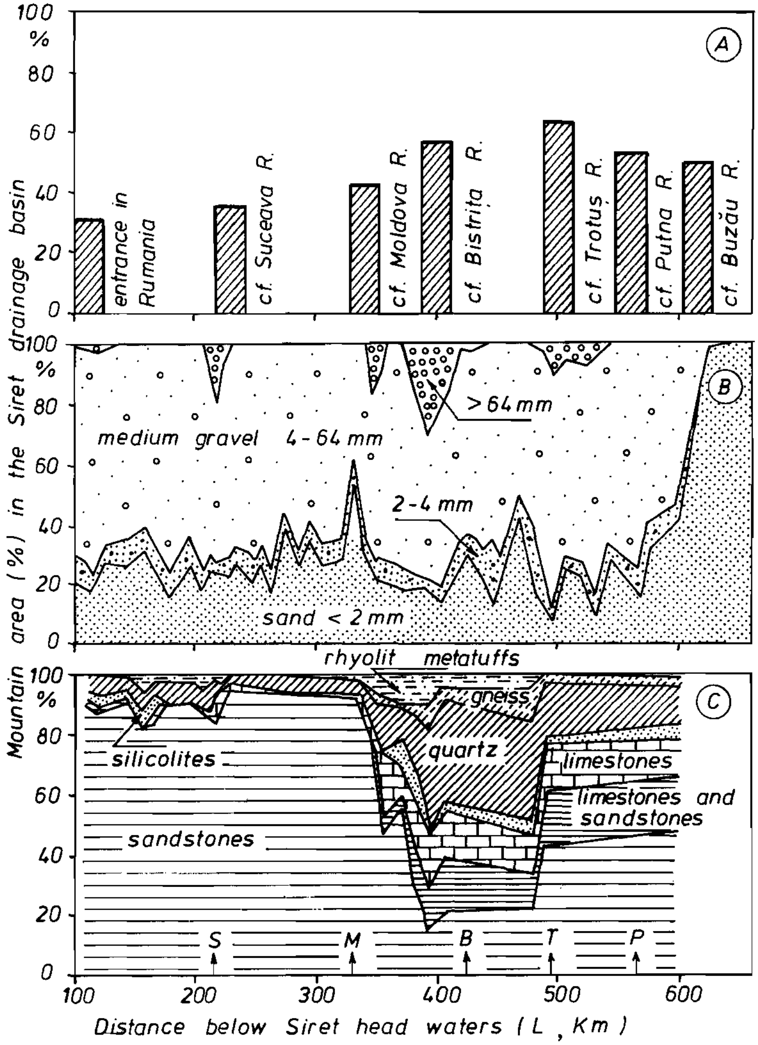

Figure 2. (A) Percentage of mountain area in the Siret drainage basin; (B) Downstream variation in the grain size distribution (Wentworth scale); (C) Changes in the petrographic distribution of channel sediments

THE RIVER BANK SEDIMENTS

River bank sediments (sampled from each cross-section at the level of the geomorphological complex of the floodplain, normally in the height range of 2–6 m above the bed), have d_{50} of 0·125–0·135 mm throughout the upper Siret, but are about 0·014 mm in the lower reach. Pebbles appear only sporadically in the form of lenses, marking the beds of palaeochannels. In the downstream direction, confluences and local facies (such as abandoned silted meanders) disturb the trend of decreasing particle size (Figure 3B). The strongest influences occur at the confluences of the Suceava, Moldova, and Bistrita rivers. The channel banks of the Siret River are generally sandy (Figure 3A). Downstream of the Bistrita River confluence the effect of tributaries is less clear. This may be because the Siret River is further from the mountain region. The variability of d_{50} decreases, while the bank composition is predominantly fine (silt/clay content is more than 50 per cent). The general conclusion is that over the whole river length, the banks formed in the floodplain sediments are predominantly of fine sediments, although at the base there are gravels as far downstream as sections 44–45.

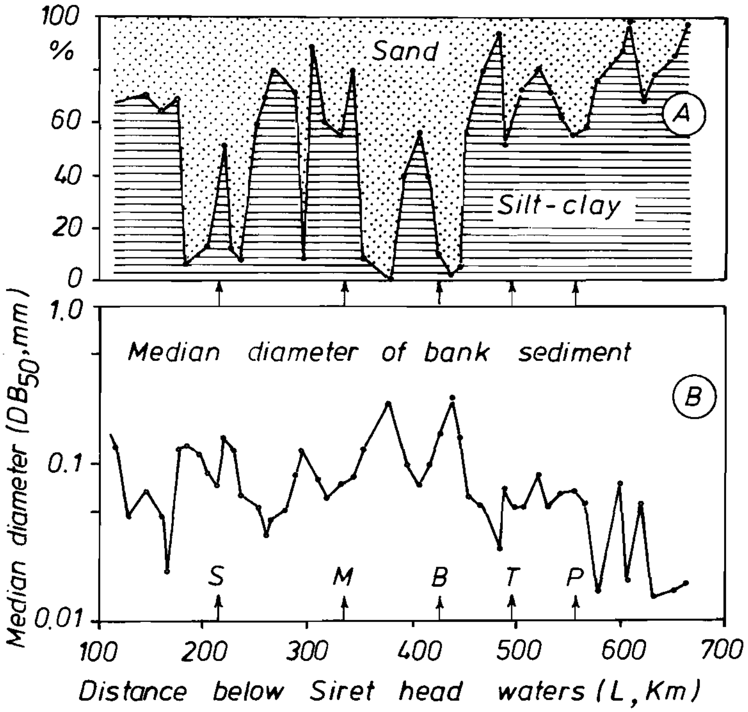

Figure 3. Downstream variation in the bank sediments

THE RIVER BED SEDIMENT

Analysis of stream bed material granulometry and pebble morphometry (Figures 2B, and 4) results in the following conclusions concerning downstream variation.

Medium sized pebbles (defined by the Wentworth classification as between 4–64 mm in diameter) dominate over almost 82 per cent of the river length (up to section 46) (Figure 2B). Between sections 1 and 46, over a distance of 460 km, average d_{50} is more or less constant at a value of about 10 mm. The variability introduced by Carpathian tributaries is evident. The most important influences occur below the confluence of the Bistrita River ($d_{50} \sim 29$ mm) and Trotus River ($d_{50} \sim 35$ mm) (Figure 4C). Between cross-sections 46 and 47, at 566 km and 578 km from the source respectively, there is a sudden transition from gravel facies to sandy facies (d_{50} reduces from 5 mm to 0·3 mm), after which there is a rapid size diminution of the coarse sands to fine ones (Figure 4C). Some examples of grain size distribution curves of channel deposits are illustrated in Figure 5. The observed granulometric discontinuities have also been identified on other rivers regarded as exhibiting a graded condition. Yatsu (1955) explained an absence of 2–4 mm diameter particles by the discontinuous breakdown of debris from gravel to sand. Debris of 2–4 mm seems to be produced rarely since the pebble has a tendency to be crushed into individual minerals. Naturally, differences between rocks, such as in mineral size and hardness, seem to cause the discontinuity of size to vary to some degree. For the river bed deposits of the Siret channel the lack of particles of 2–4 mm diameter is also evident, but only where the river is not at 'grade', where the massive contribution of bed load from the Carpathian tributaries greatly influences the d_{50} distribution along the river. Nevertheless, particle collapse takes place about 20 km below the Putna River confluence (the last Carpathian influence with coarse material).

Carpathian influence is also clear in the sorting index of Folk and Ward (Figure 4B) which generally increases in the downstream direction. The deviations from the general trend (represented by the regression line, Table IV) coincide in this case too with the reaches into which the tributaries introduce sediments. In the 'graded' rivers the sorting index tend to decrease exponentially but this is locally reversed by tributary

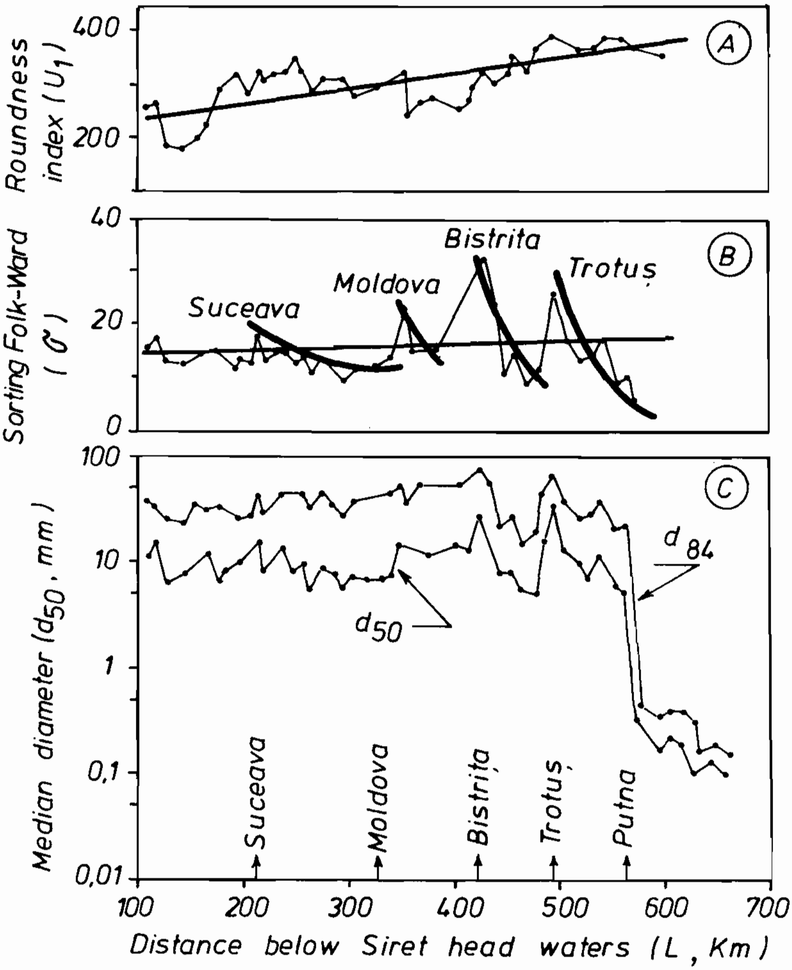

Figure 4. Downstream variation of the roundness (A), sorting (B), and d_{50} (C) of bed material

influences. In the Siret River the general trend is a slight increase in the sorting index on which is superimposed a periodic behaviour with a wavelength of 30–50 km. Between each confluence there is a sharp reduction of the sorting coefficient. This is a typical example of the progressive downstream sorting of sediment supplied at a point, as suggested by Knighton (1980) (Figure 4B). However, as far as the pebble roundness (*cf.* Caillieux, 1947) is concerned, the mountain tributaries do not succeed in disrupting the general downstream trend of increasing roundness, although there is an oscillating variation between the values 200 and 300 (Figure 4A). The tributary effects on the attrition is not significant. Before reaching the Siret, the gravels are transported through high energy reaches and develop a roundness comparable to that found in the collecting river.

A similar conclusion derives from consideration of the pebble asymmetry index, which is defined as the ratio of intermediate to long axis lengths (Caillieux, 1945). This tends to become smaller and smaller along the Siret River. Although the scatter around the regression line is relatively large, the decreasing tendency of the asymmetry index is indicative of the effects of lengthy transport in the fluvial domain (Figure 6A).

Finally, the pebble flatness registers a broadly parabolic trend; with its maximum between the Suceava and Moldova confluence (sections 12 and 24). It is highly probable that the explanation for this pattern lies in the enhanced presence in this reach of pebbles originating from the flysch rocks (Figure 6B).

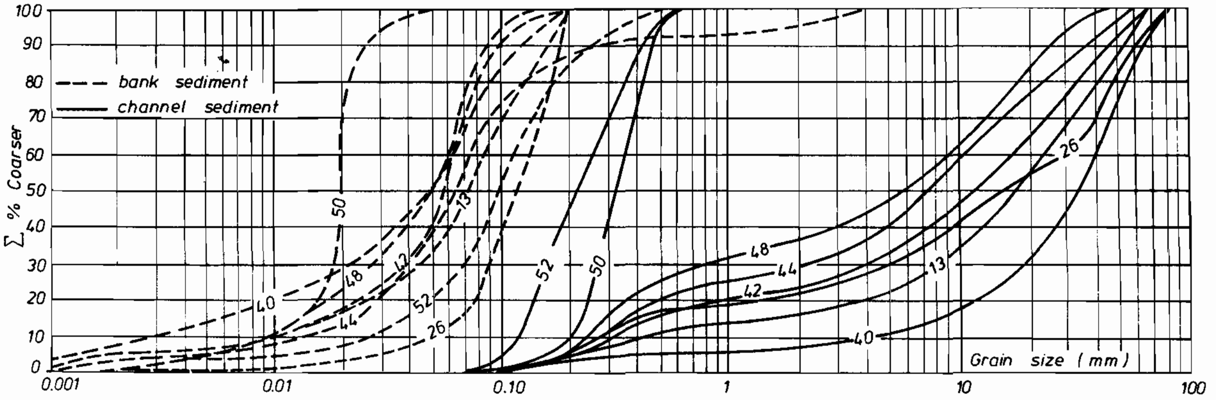

Figure 5. Some examples of grain size curves of bed material

Table IV. Empirical relations obtained for this study

Independent variable	Dependent variable	Relation	Number of obs. (n)	Correlation coeff. (r)	Determination coeff. ($r^2 \times 100$)
River length (L km)	Roundness index (U_1)	$U_1 = 210{\cdot}17 + 0{\cdot}295\,L$	46	0·713	50·9
River length (L km)	Sorting (σ)	$\sigma = 13{\cdot}75 + 0{\cdot}006\,L$	46	0·158	2·5
River length (L km)	Asymmetry index (AS)	$AS = 0{\cdot}707 - 9{\cdot}22 \times 10^{-5}\,L$	46	−0·505	25·5
River length (L km)	Flatness index (FI)	$FI = 1{\cdot}81 + 0{\cdot}0063\,L - 1{\cdot}05 \times 10^{-5}\,L^2$	46	0·628	39·4
River length (L km)	Slope (S)	$S = 627{\cdot}19\,L^{-1{\cdot}227}$	39	−0·833	69·4
River length (L km)	Floodplain width (FW)	$\log FW = 3{\cdot}6005 - 0{\cdot}00119\,L - 2{\cdot}94 \times 10^{-6}\,L^2$	53	0·764	58·4
River length (L km)	Active channel belt width (AW)	$\log AW = 2{\cdot}966 - 0{\cdot}0013\,L + 3{\cdot}64 \times 10^{-6}\,L^2$	53	0·858	73·7
River length (L km)	Channel width (W)	$\log W = 1{\cdot}287 + 0{\cdot}0025\,L - 1{\cdot}5 \times 10^{-6}\,L^2$	53	0·935	87·3

LONGITUDINAL PROFILE FORM IN RELATION TO RIVER BED SEDIMENT AND OTHER VARIABLES

The Siret River longitudinal profile has a markedly upward concave form, although this is not a smooth curve. There are frequent slope breaks controlled by the lithology in the upper part of the profile; however, the most important discontinuity occurs downstream in the profile, around 430 km and is due to neither tectonic influences nor a lithological contact (Figure 7).

The longitudinal profile form represents a simple function of elevation versus distance. The essential characteristic of every longitudinal profile, from rills on waste dumps to great rivers, is a concavity increasing toward the source (Leopold *et al.*, 1964). There have been proposed a range of different mathematical expressions for the longitudinal profile form (Shulits, 1941; Hack, 1957; Brush, 1961; Tanner, 1971; Knighton, 1975; Richards, 1982; Zavoianu, 1985; Snow and Slingerland, 1986). Thus, the profile form may also be expressed as a relationship between slope (J) and length (L), in the form of the power function (Hack, 1957).

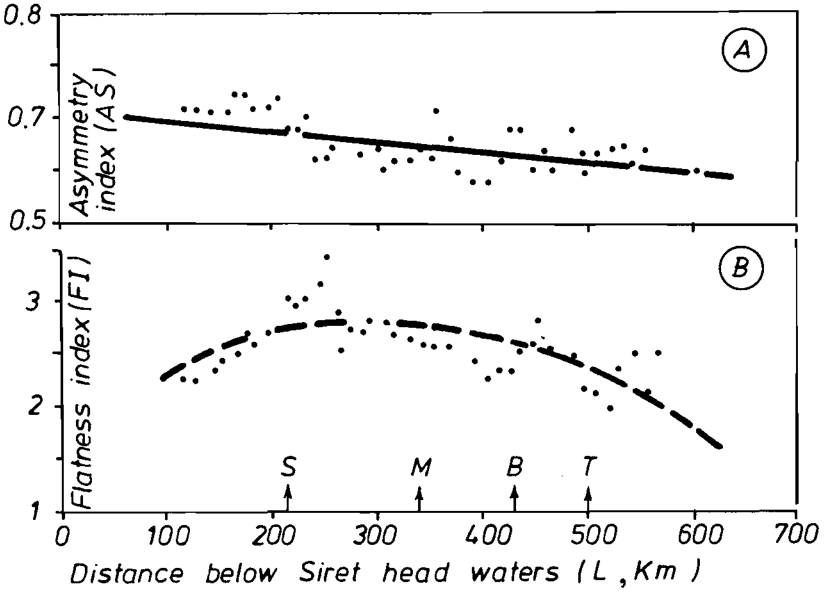

Figure 6. Changes in asymmetry index (A) and flatness index (B) of pebbles

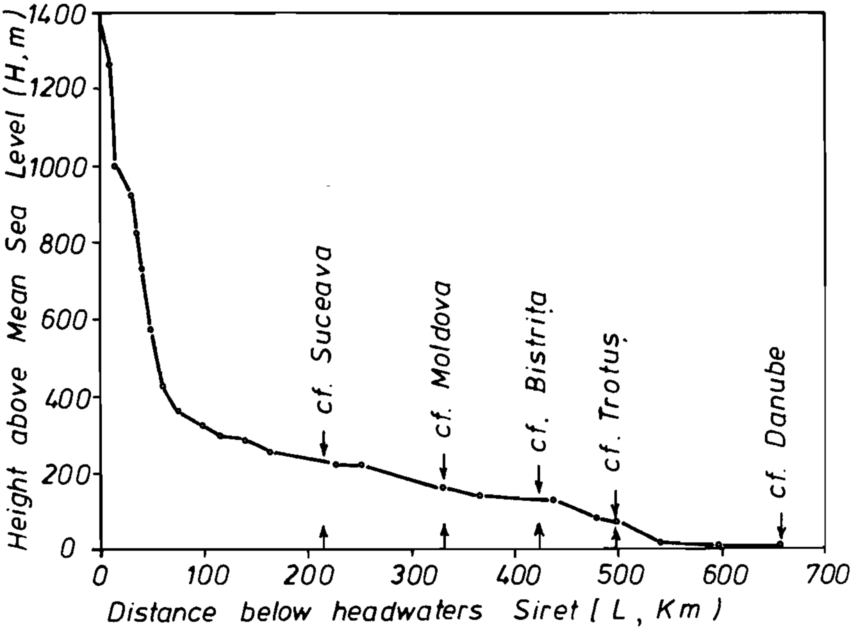

Figure 7. Longitudinal profile of the River Siret

For the Siret River, this relation is illustrated in Figure 8. The coefficients *k* and *n* describe the inclination and concavity of the longitudinal profile (Table IV). The profile of the Siret has a low slope and is highly concave. The profile is broadly comparable to that of a ‘graded’ river, but only from the point of view of the concavity. Marked irregularities registered in the lower–middle course show a departure from the equilibrium form of profile. This may be explained by considering the influences of discharge and bed sediments and the feedback from variations in some geometrical parameters relating to the channel and floodplain.

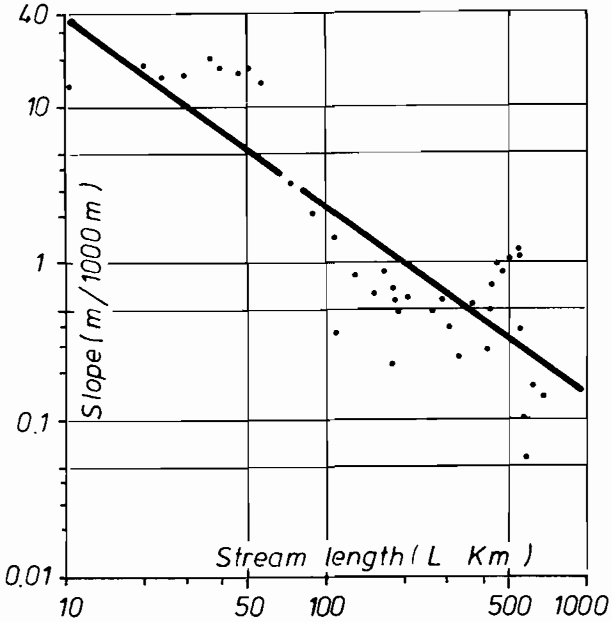

Figure 8. Relation of channel slope to stream length

It is known that the downstream discharge variation is one of the most important factors which controls the longitudinal profile form (Gilbert, 1877). The manner in which the discharge (Q) changes along the river is faithfully reflected in the slope value (J). Langbein and Leopold (1964) showed that $J=aQ^{-z}$ and that the longitudinal profile falls between two limiting conditions: that when $z=-1$, the minimum total work along the stream is performed, and that when $z=-0{\cdot}5$, a uniform distribution of energy expenditure along the stream takes place. These two extremes cannot be attained simultaneously in the case of natural channels, which will therefore tend to an intermediate condition having a maximum probability. Accordingly the condition $z=-0{\cdot}75$ characterizes a situation of quasi-equilibrium in longitudinal profile form and represents the most frequent form in nature. For the Siret River, the slope–discharge relation has the form

$$S=18{\cdot}41\,Q^{-0{\cdot}88}$$

and the exponent is relatively close to $z=-1{\cdot}0$, characteristic of the rivers with pronounced longitudinal profile concavity.

The stream bed material distribution along the river represents a second important control of the profile form, as established by Sternberg in 1875. For graded rivers, without important tributaries, the diameter of the stream bed material diminishes along the river according to an exponential relation (Sternberg's Law), or, due to a power function, as established by Brierley and Hickin (1985).

The median diameter of the bed sediment along the Siret (Figures 4C) does not behave as implied by either of these empirical tendencies. In particular, the confluences cause significant deviations from the average, and the cross-sections in which d_{50} increases correspond closely to the sections where the longitudinal profile tends to become convex (Figure 7). This may be one of the explanations for the anomalies registered in the longitudinal profile form. The tributaries Suceava, Moldova, Bistrita, and Trotus, which together with the upper part of the Siret basin, drain the mountain areas of the basin, furnish considerable quantities of gravel. Because of its reduced slope compared to that of the tributaries, the Siret stream bed cannot transport this large volume of coarse sediment in order to sort and distribute it along the river according to the laws governing this process. The consequence is pebble storage, manifested in an over-heightening of the profile which dominates as long as the Carpathian sediment input exists (up to section 46), downstream of which the d_{50} experiences a sudden decrease, and the profile form returns to the theoretical curve (Figure 7).

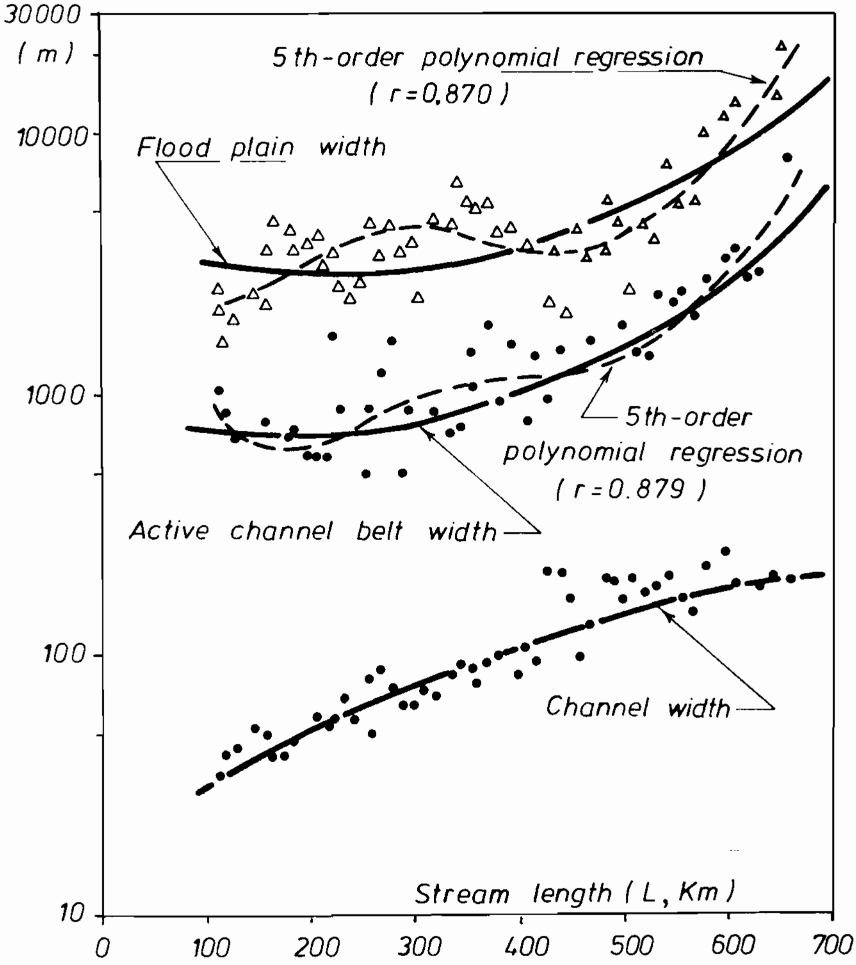

Figure 9. Downstream variation of floodplain width, active channel belt width, and river bed width of the Siret River

The processes responsible for the stream bed material diminishing along the river are those of sorting and abrasion. The way these combine is difficult to establish (Knighton, 1980), and attempts to explain it have produced various results. Generally, it is observed that sorting diminishes and abrasion increases along a river. For the Siret River, this trend is observed in so far as roundness is indicative of abrasion (Figure 4A), but in the case of the sorting index (Figure 4B) the strong Carpathian influence is clearly present.

The marked deviation of the longitudinal profile does not only take place vertically; there is also a similar horizontal tendency of adjustment in the channel and floodplain geometry of the Siret (Figure 9). This is illustrated by considering variations in the floodplain width, that of the active belt of the floodplain, and that of the channel itself.

In the case of the last variable, there is a relatively clear increase over the first 400–500 km associated with a slight braiding tendency of channel; downstream from this, the rate of width increase lowers as far as the confluence with the Danube, in a sinuous meandering stream. This pattern is not observed in the variables defining the floodplain geometry, which do not only reflect the conditions at the present, but also those experienced throughout the Holocene. There is a general exponential increasing tendency of the floodplain width along the river (Figure 9), but a 5th order polynomial regression defines out a second peak between 200–450 km, where the maximum lateral development occurs of the Siret valley floor. This reflects the braiding processes of the channel and changes of channel alignment throughout the Holocene, phenomena gaining greater amplitude at the tributary confluences. From this point of view, the confluence with the Trotus River is suggestive.

CONCLUSIONS

The Siret River is one of the more important of the Danube's tributaries from Romania. It gathers all the rivers from the eastern part of the Eastern Carpathians. Bed material sampling along 53 transects allowed examination of the long profile form related to the trend in the downstream direction of 22 variables determined for each cross-section.

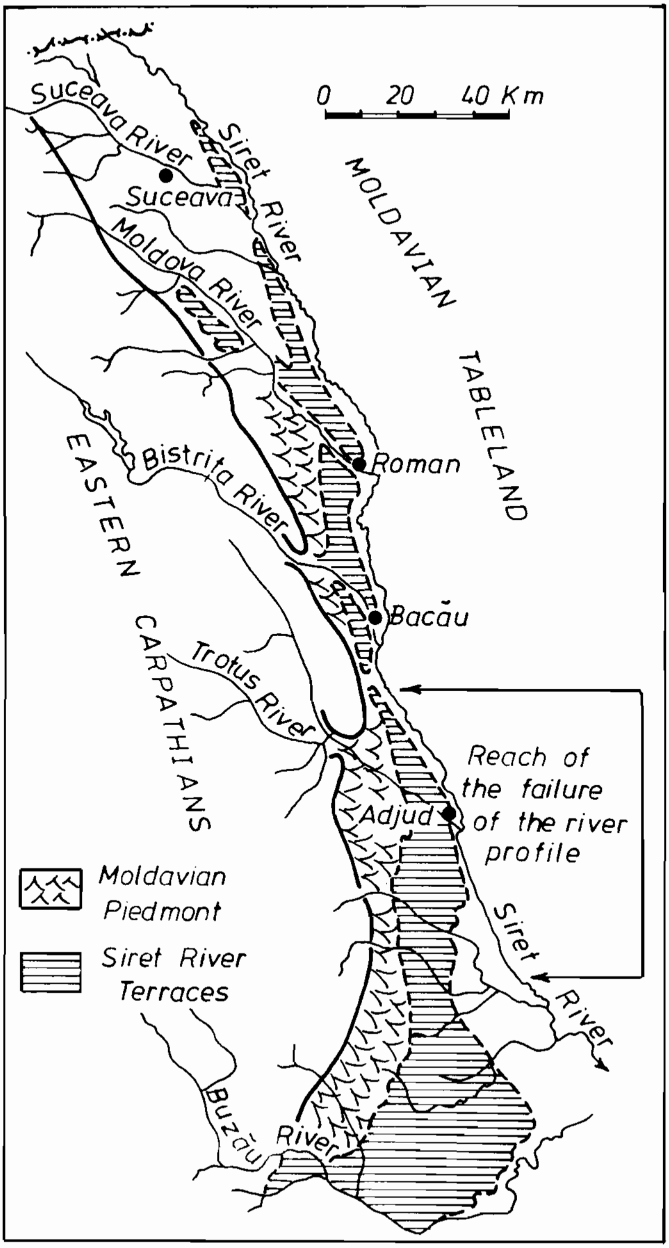

Figure 10. Continuity of development of Pericarpathian Piedmont determined the Siret translation eastward

All findings show that the stream system of the Siret River does not accord with the theoretical form of great rivers in a quasi-graded condition. It is a river that has undergone an intense regradation process (*cf.* Mackin, 1948); aggradation and degradation of different sections of the profile have changed its local slopes, and not the general profile form.

To interpret the longitudinal profile deformation of the Siret River in its middle–lower reach, we suggest the following hypothesis.

The deformation results from the failure of the river to reduce its bed elevation in its middle–lower reach to the theoretical equilibrium profile; thus the river has not attained the state of grade.

This 'deformation' of the longitudinal profile may represent the 'front' of a pebble sheet accumulation which is the limit of present conditions which are continuous with the Moldavian Piedmont formation. This is, in short, an explanation which is of a palaeogeomorphological nature. There is evidence that the main paths of the principal Carpathian tributaries started developing in the Lower and Middle Sarmatien and are more and more recent (Upper Quaternary) in the south. Paradoxically the Siret is 'younger' from the point of view of its Carpathian tributaries. The main rivers, north of the Trotus, formed in the Sarmatien, and flowed into the Sarmatic Sea which covered the present territory of the Moldavian Tableland. The sea retreated to the southeast and the torrential character of the rivers induced the formation of huge fluviodeltaic fans of gravels and sands (Donisa and Harjoaba, 1974). The river that now collects these tributaries formed itself on a surface that had remained immersed. South of the Trotus, the formation of fluviodeltaic fans and later of large alluvial fans continued up to the Quaternary, when the Romanian Plains were covered by a lake that occupied the whole area of the Lower Siret up to the town of Adjud (Figure 10). Consequently, the Siret is younger and younger from north to south and developed itself at the Moldavian Piedmont border. The continuous and marked sediment yield brought by the tributaries imposed an eastward river migration. The best proof of this is the assymetrical extinction of the Siret terraces (Figure 10) and the presence of the Piedmont border. The maximum amplitude of the river translation exceeds 20 km in the reach downstream of Adjud. All these points suggest the continuity of piedmont gravel sheet formation to the present. Thus the limit of the massive presence of gravels in the river bed beyond the mountains may be regarded as the extra-Carpathian limit of the present gravel sheet formation. This morphologically corresponds to the discontinuity of the Siret longitudinal profile (Figure 10).

Taking into consideration all these features, we consider that a natural geomorphological paradox is expressed by the Siret, which is a river situated beyond the Carpathians for the greater part of its length, but from the point of view of its sedimentary facies, its longitudinal profile, and its stream bed dynamics, is a Carpathian river for almost 85 per cent of its total length.

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