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THE RATE OF GRAVEL ABRASION IN THE CARPATHIAN RIVERS

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The paper presents the rate of gravel abrasion during fluvial transport. It is manifest in pebble alterations, including the change in their size. The study was done in alluvia of the Soła and Skawa rivers in the West Carpathians (Poland) and of the Prut and Cheremosh rivers in the East Carpathians (Ukraine). The largest clasts in modern channel bars were studied. The reduction index determined using the Sternberg formula was compared with similar indices calculated for other rivers. An attempt was also made to explain the difference in these indices between the East and West Carpathian rivers.

Key words: fluvial processes, gravels, Soła, Skawa, Prut, Cheremosh

INTRODUCTION

The Carpathian rivers are gravel-bed rivers. Pebble size in these river varies depending on the local characteristics of the basement. The initial size of rock fragments in the flysch Carpathians is related to the thickness of sandstone and conglomerate layers, as these rocks are the natural source of gravels in these areas. Transport of the coarsest fractions present in the channel takes place during high-water stages and floods. It is then when transported material is subject to abrasion, impacting and crushing (Marshall 1927). Kuenen (1956) lists seven mechanisms of particle wear in fluvial environments: breaking, grinding, split-

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ting, fracturing, mutual polishing of pebbles, weathering and polishing of pebbles by sand. These processes, conventionally called abrasion, result in size reduction of the pebbles, but also in changes in the rounding, shapes and petrographical composition of the gravels. In mountain areas, tributaries, bank undercutting and bottom erosion supply fresh rock material to the channel. After the rivers leave the Carpathians, the supply of flysch material from bedrock ceases and the rivers modify the alluvium derived from the mountains. Pebble size decreases downstream in foreland areas and the relation between the pebble size and the distance travelled is logarithmic (Sternberg 1875). This was confirmed by many other authors (Unrug 1957, Mikoš 1993 and Kodama 1994).

The coarse clastic material in the bottoms of the Carpathian valleys is transported only during the highest water stages. These are caused by two types of extreme rainfall: heavy short-lasting and prolonged, less intense, rainfalls (Starkel 1976). Disregarding human activity, alluvium in flood channels remains stable even for decades. During a short-lasting high-water stage, even of a few hours in some cases, the mobilized pebbles and boulders change their position, size, nature of surface, and, by breaking, even shapes. Boulders originally lying on a bar surface, near the main stream, are in some cases deeply buried after the water-level rise, far from the channel. Floods in the Carpathians can move 90 % of the annual load of suspension and bedload (Froehlich 1975). The changes in gravel characteristics depend on the duration of the interflood periods. The pebbles remain immobile during this time and are subject to weathering and abrasion by material carried in suspension. This in turn, influences the later rate of change during flood transport.

Rivers whose drainage basins include the highest parts of the flysch West and East Carpathians and whose low reaches are situated in the foreland were selected for the study of the rate of flysch pebble (sandstones and conglomerates) abrasion. These conditions are met by the Soła and Skawa, which have sources in the Beskid Żywiecki, the highest mountain group of the West Outer Carpathians, and the Prut and Cheremosh, whose sources lie in the Chernohora, the highest mountain group of the East Carpathians. The lower parts of the drainage basins of the four selected rivers lie in the Carpathian foreland where Neogene deposits in the bedrock do not supply gravel-size sediments to the river channels. The channels of these rivers fall into Schumm's (1963) group I (bedload channels), in which the proportion of silt and clay material does not exceed 5 %, and coarse clastics prevail. These channels also belong to the channels cut into loose material, according to the classification by Knighton (1984). Gravel-bed reaches, of "threshold" type prevail in these rivers, where coarse-grained bedload entrainment occurs only during high-water stages and floods. Gravel alluvia predominate also in the lower courses of these rivers. It is so in the foreland of both, the West Carpathians (Soła and Skawa) and the East Carpathians (Prut and Cheremosh). Some of the highest situated mountain reaches of both rivers may be included in the boulder type (cf. Knighton 1984), transitional to the bedrock channels. Straight sections of channels are seldom present. These rivers display a tendency to meandering within the alluvial channel in both the Carpathians and the foreland.

METHODS OF STUDY

Pebbles decrease in size during fluvial transport by abrasion, breaking and weathering. While studying the alluvium of the Weser River, Seifert (1939) found that the mean grain diameter of siliceous slates decreased from 5 to 0.75 mm after the transport distance of 400 km, sandstone grains with mean diameter of 15 mm were abraded to fine sand over the distance of 100 km, and limestones disappear from the gravel composition already after 15 km. This process was described quantitatively already in the 19th century by Sternberg (1875):

$$S = S_0 e^{-KX}$$

where S is the pebble diameter after the transport distance X, S_0 is initial diameter, e is the base of the natural logarithm and K is coefficient of reduction, constant for a given rock type. A modified version of this formula is presented by Knighton (1982):

$$D = D_0 e^{-(K_1+K_2)L}$$

The coefficient K_1 concerns the reduction of the rock fragments by abrasion, and K_2 by natural selection caused by decrease in vertical gradient and flow velocity. D is the diameter or weight of a pebble after the transport distance L, D_0 is initial diameter or weight. The coefficient K differs markedly depending on the rock resistance to abrasion, kind of accompanying material and transport rate. Krumbein (1941) has shown by field studies and experiments in rotating drums that pebble size decreases during transport at a decreasing rate, initially fast and then slower and slower. Laboratory investigations were also used to determine the weight reduction of rolling pebbles. The reduction coefficient (K) is here much lower than indicated by field observations (Mikoš 1993 and Kodama 1994a).

This process was studied by many authors (Darcel 1857 quoted in Mikoš 1993, Schoklitsch 1933, Unrug 1957, Bradley 1970, Knighton 1982 and Mikoš 1993) and the results differ (Tab. 1). This is due to both the various lengths of the studied reaches, variable petrographical composition and, hence, variable resistance to abrasion, as well as to differences in methods of measurement (arithmetical mean, median, largest pebbles).

Knowing the values of the coefficient K one may estimate the distance after which the gravel-size fraction will disappear from the channel and the largest grains in alluvium will have diameters below 2 mm.

FIELD SETTING

The study was done in the valleys of the Soła and Skawa in the West Carpathians and of the Prut and Cheremosh in the Ukrainian East Carpathians. The Soła and Skawa are two large Carpathians tributaries of the Vistula. Their adjacent drainage basins are similar in size (Tab. 2) and have similar geological structure (Fig. 1). In their mountain reaches the rivers dissect the flysch members of the Magura, Silesian and Subsilesian nappe. The foreland reaches situated in the Oświęcim Basin dissect Miocene strata developed mainly as clays and sands. The Soła is a river with three dams and its water levels are artificially controlled. The Skawa is the last of the large Carpathian tributaries of the Vistula and its drainage basin is still free of dams. The water stages are controlled here by natural processes. Three large floods occurred in both rivers during the last decade (1996, 1997 and 2001). The material presented here comes from the studies made immediately after the 1997 flood.

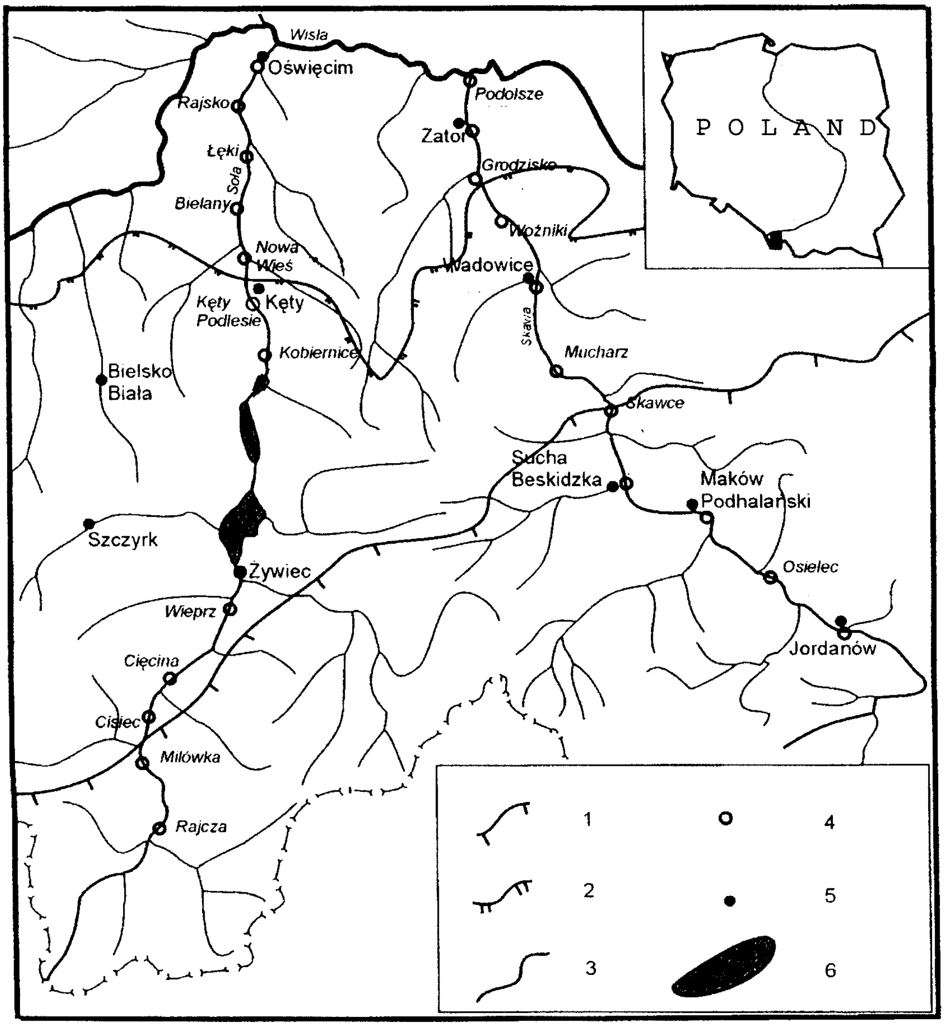

Fig.1. Schematic map of the Soła river and Skawa river

1 – Magura nappe nord border, 2 – Silesian and Subsilesian nappe nord border, 3 – rivers, 4 – studied sites, 5 – towns, 6 – dam lakes

The Prut is one of the largest left tributaries of the Danube. It is 953 km long and the area of its drainage basin equals 27,000 km^2 (Tab. 2). The Prut sources lie on the east slopes of the Hoverla, the highest peak of the East Carpathians

(2060 m a.s.l.). The river flows initially to the north across the lithostratigraphical units belonging to the Charnohora Nappe, Krosno Zone, Skole Nappe and the Skiba Folds. The Prut leaves the Carpathians near the village of Delatyn, below Yaremcha, and Neogene, mainly Sarmatian, deposits appear in the bedrock. The Cheremosh originates by confluence of the Byelyy and Chernyy Cheremosh. Both rivers have their sources in the Charnohora range and they dissect similar flysch units as the Prut. The Cheremosh is the biggest Carpathian tributary of the Prut. Both, the Prut and the Cheremosh still have no dams and the water stages are naturally controlled. The biggest floods in the 20th century were noted in these rivers in 1927 and 1968.

Tab. 1. Coefficient of rock fragment size reduction in natural conditions after various authors

Author	River (length of study reach in km)	Value of coefficient *K*	Base of analysis
Darcel (1857)	Seine (236)	0,0032	Mean grain diameter
Sternberg (1875)	Rhine (260,9)	0,0029	Mean grain diameter
Kreuter (1913)	Danube (32)	0,0106	Largest pebbles
Keller (1916)	Rhine (35) Rhine (63) Rhine (55)	0,0146 0,0139 0,0176	Largest pebbles
Schoklitsch (1933)	Rhine (75,3) Danube (272,7)	0,0100-0,0462 0,0077	Largest pebbles
Krumbein (1942)	Arroyo Seco (17)	0,1226	Largest pebbles
Unrug (1957 after Matakiewicz 1936)	Dunajec (247)	0,0040	Largest pebbles
Bradley (1970)	Colorado (257,6)	0,0028	Largest pebbles
Knighton (1982)	Noe (20)	0,016-0,042	Mean grain diameter
Mikoš (1993)	Alpine Rhine (65,2)	0,0012-0,0030	Largest pebbles
Kodama (1994b)	Watarase (23,4)	0,089	Median

The field studies were done in 1997 (Soła and Skawa) and 2000 (Cheremosh and Prut). Their results, separately for the individual rivers, were presented in the author's earlier papers (Malarz 2001, 2002 and 2003). At selected sites, whose number is shown in Tab. 2 and locations in Figs. 1 and 2, twenty largest clasts were investigated by determination of their petrographical composition, roundness and the length of three axes: length (*a*), width (*b*) and thickness (*c*). Gravel bars directly adjacent to the channel, lacking any traces of exploitation or other forms of human impact were studied. The arithmetic mean was calculated for the studied clast populations (Tab. 3). On the basis of the obtained results indices of pebble size reduction were calculated for the mountain and foreland reaches of the studied rivers.

Pebble sizes decrease downstream. This is especially apparent in the lower courses of the rivers, in the foreland (Fig. 3), but it is not so clear in the mountainous parts of the river courses. There, the greatest boulders are not always found in the farthest upstream sites. The largest clasts in the Prut valley are present in the second farthest upstream site (Tatarów) and in the Skawa valley only in the third one (Maków Podhalański). These greatest pebbles originated by abrasion of sandstones and conglomerates of various grain size.

Tab. 2. Characteristics of the Soła, Skawa, Prut and Cheremosh drainage basins

Characteristics of the drainage basin	Soła	Skawa	Prut	Cheremosh
Area (in km^2)	1390,6	1160,1	27000	2600
Length of the studied reach (in km)	73,0	71,5	167,5	70,5
Length of its foreland part (in km)	25,0	21	85,0	33,0
Sources at altitude (in m a.s.l.)	755	701	1750	1620*
Mouth (in m a.s.l.)	230	217	115	191
Highest point (in m a.s.l.)	1557 (Pilsko)	1725 (Babia Góra)	2060 (Hoverla)	2035 (Charnohora)
Number of study sites	12	11	9	6
Number of foreland sites	7	5	6	3

* Chernyy Cheremosh

Tab. 3. Dimensions of the greatest clasts in the gravel bars of the Soła, Skawa, Prut and Cheremosh (mean of 20 largest specimens in mm)

Soła Site	1997	Skawa Site	1997	Prut Site	2000	Cheremosh Site	2000
Oświęcim	210	Podolsze	161	Worokhta	573	Ustieryki	845
Rajsko	238	Zator	213	Tatarov	1465	Stebniv	920
Łęki	280	Grodzisko	226	Yaremcha	1261	Roztoki	664
Bielany	380	Woźniki	243	Lanchyn	445	Wyzhnitsa	301
Nowa Wieś	348	Wadowice	375	Kolomyya	298	Banyliv	228
Podlesie	372	Mucharz	420	Zabolotov	184	Chartoryya	230
Kobiernice	380	Skawce	465	Snyatyn	130		
Wieprz	534	Sucha	369	Dubovtsi	159		
Cięcina	660	Maków P.	764	Chernovtsi	121		
Cisiec	520	Osielec	709				
Milówka	643	Jordanów	385				
Rajcza	990						

The measurements of the greatest pebbles provided a base for calculation of the reduction coefficient K for the Soła, Skawa, Prut and Cheremosh. The study was done in the foreland sections: of the Soła between Kobiernice and Oświęcim (24 km), the Skawa at the section Wadowice – Podolsze (19 km), the Prut between Lanchin and Dubovtsi (85 km) and the Cheremosh between Wyzhnitsa and Chartoryya (33 km). The reduction coefficients K were calculated from the formula:

$$K = \frac{\ln S/S_0}{-X}$$

where S is mean pebble size (axis a, b, c) after transport (at the final site), S_0 is pebble size at the beginning of transport (at the initial site), X is distance between the initial and final sites in km. Calculated values of the coefficient K are shown in Tab. 4.

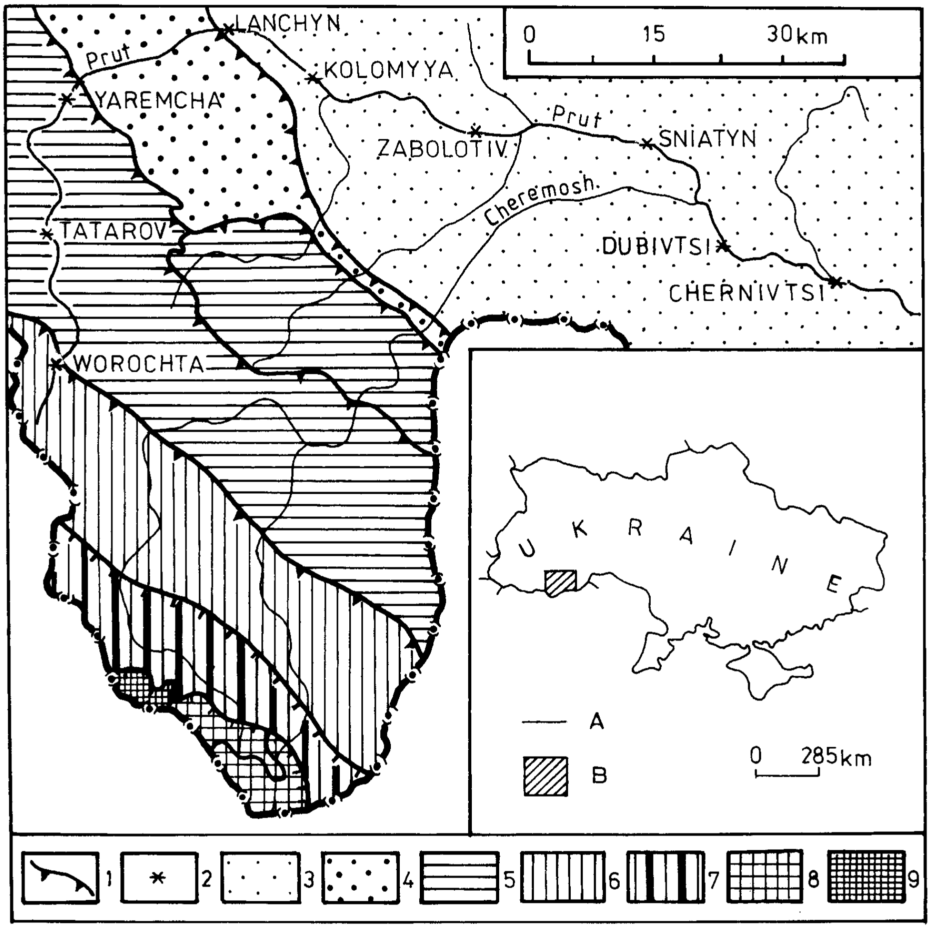

Fig. 2. Schematic geological map of the upper Prut river basin

1 – major overthrusts, 2 – studied sites, 3 – Neogene, 4 – Skole nappe, 5 – Krosno zone, 6 – Chernogora nappe, 7 – Suchow zone, 8 – Marmarosz zone, 9 – Rachow zone

The reduction coefficients K vary between 0,0081 (for axis a) in the Cheremosh to 0,0402 (for axis a) in the Skawa. These values do not depart markedly from those quoted in literature (Tab. 1). The data in the table allow us to determine the following trends. Pebble widths (b axis) are reduced fastest. Pebble thickness (c axis) changes at the lowest rate. This is probably due to the mode of pebble rolling during a high water stage. The a and b axes are most exposed to collisions and hence abrasion. This rule may also be discerned by the analysis of the percentage reduction in length, width and thickness. Thickness is reduced at the lowest rate and length and width at the highest.

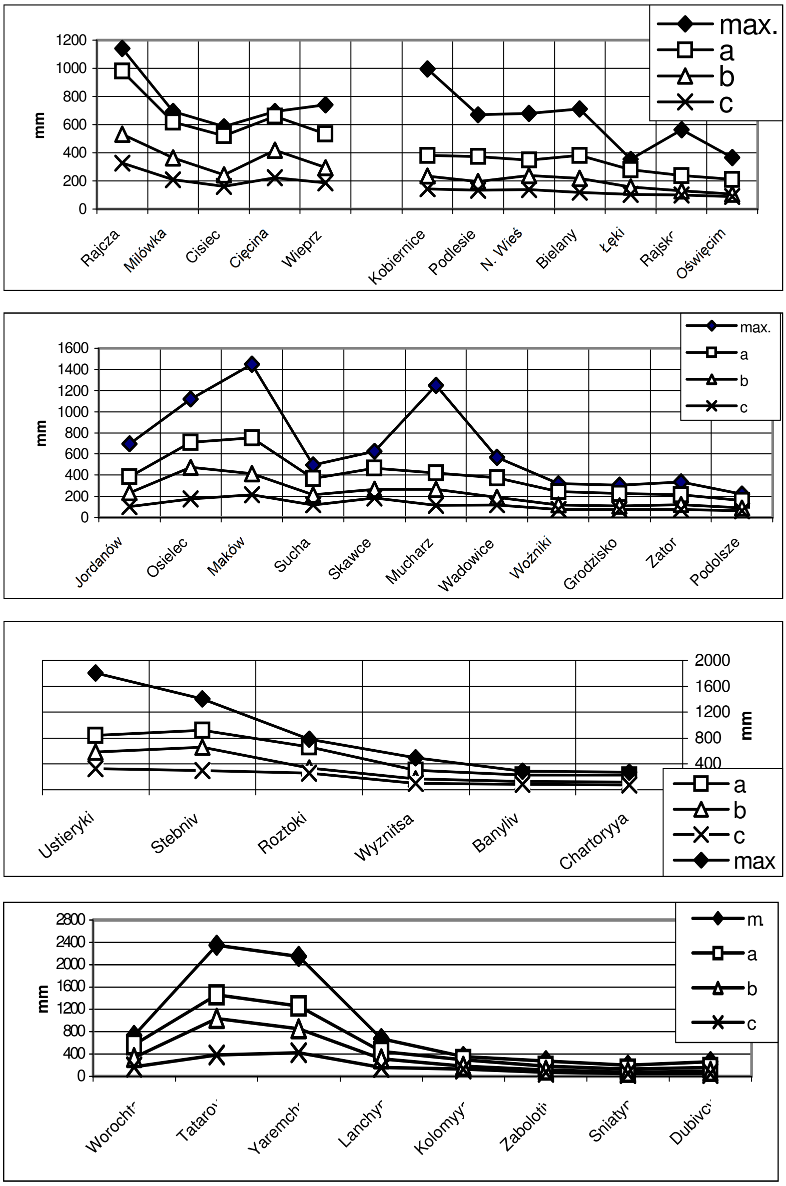

Fig.3. The size of the greatest clasts in the Soła, Skawa. Prut and Cheremosh rivers (in mm)

m (max) – the greatest specimen, a, b, c – mean sizes of 20 greatest specimens

Tab. 4. Coefficient of grain-size reduction (Sternberg coefficient) for the alluvium of the Soła, Skawa, Prut and Cheremosh (foreland reaches)

River and year of study	Reach	Length (in km)	Gradient (‰)	Reduction in axis length		
				a	*b*	*c*
Soła 1997	Kobiernice – Oświęcim	25	2,2	0,0237	0,0322	0,0194
Skawa 1997	Wadowice – Podolsze	21	1,9	0,0402	0,0364	0,0312
Prut 2000	Lanchyn – Dubovtsi	85	2,2	0,0121	0,0147	0,0124
Cheremosh 2000	Vyzhnitsa – Chartoryya	33	3,3	0,0081	0,0100	0,0098

The pebble size reduction coefficient allows us to calculate the distance (l) after which the largest pebbles (S) will be reduced to the dimensions lower than 2 mm. They will thus become the sand fractions and the river will cease to transport gravel. The calculations show that this will happen in the Soła alluvium after 168 km and of the Skawa – after 123 km. Similar calculations for the Prut and Cheremosh give distances of 446 km and 615 km. This shows that the West Carpathian gravels decrease in size much faster than the pebbles in the Prut and Cheremosh. This is related to the abrasion resistance of the largest pebbles in the Soła and Skawa. The pebble-size reduction is much higher in the West Carpathians due to the high proportion of coarse-grained sandstones and conglomerates, the proportion of which is small in the East Carpathian rivers. A high resistance to abrasion is characteristic of fine-grained sandstones. These make up nearly 80 % of the largest clasts in the Prut and Cheremosh at the departure of these rivers from the Carpathians.

CONCLUSIONS

Reduction coefficients K are much higher for the West Carpathian rivers – Soła and Skawa – than for the Prut and Cheremosh, representing the East Carpathians.

The cause lies in the petrographical composition of the gravels. In the East Carpathians the coarsest clasts are dominated by specimens of fine-grained sandstones, much more resistant to abrasion than coarse-grained sandstones and conglomerates. The latter appear frequently in the coarsest gravels of the Soła and Skawa.

The b axis is the one which is subject to the fastest reduction, which suggests that the most efficient size reduction occurs by rolling pebbles along the bottom and their rotation around the a axis.

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Roman M a l a r z

INTENZITA ABRÁZIE ŠTRKU V KARPATSKÝCH RIEKACH

Karpatské rieky patria k riekam so štrkovým dnom. Prenos najhrubších frakcií prítomných v koryte sa uskutočňuje počas vysokých stavov vodnej hladiny a počas záplav. Vtedy prenášaný materiál podlieha abrázii, úderom a zomieľaniu. Tieto procesy so spoločným názvom abrázia vedú k zmenšovaniu veľkosti jednotlivých kameňov (od 4 do 64 mm v priemere), ale aj k zmene zaguľatenia, tvaru a petrografického zloženia štrku. V horských oblastiach dodávajú do koryta čerstvý materiál kameňov prítoky, brehová a dnová erózia. Keď rieky opustia Karpaty, dodávka čerstvého flyšového materiálu z podložia sa skončí a rieky menia alúvium odvodené od hôr. Smerom dolu prúdom do podhoria sa veľkosť kameňov zmenšuje a vzťah medzi veľkosťou kameňov a prekonanou vzdialenosťou je logaritmický.

Pre štúdium intenzity abrázie flyšových kameňov (pieskovce a konglomeráty) sme vybrali rieky, ktorých povodia zahŕňajú najvyššie partie flyšových Západných a Východných Karpát a dolné časti ich toku sa nachádzajú v podhorí. Tieto podmienky spĺňali Sola a Skawa, ktoré pramenia v Żywieckych Beskydách, najvyššej horskej skupine vonkajších Západných Karpát, ďalej Prut a Čeremoš, ktorých pramene ležia v Černohore, najvyššej horskej skupine Východných Karpát. Dolné časti povodí týchto štyroch vybraných riek ležia v podhorí Karpát, kde neogénne vrstvy podložia nedodávajú sedimenty veľkosti štrku do riečnych korýt.

Na vybraných miestach sa skúmalo dvadsať najväčších klastov tak, že bolo určené ich petrografické zloženie, zaguľatenosť a dĺžka troch osí: dĺžka (a), šírka (b) a hrúbka (c). Merania najväčších kameňov tvorili základ pre výpočet koeficientu zmenšenia K pre rieky Sola, Skawa, Prut a Čeremoš. Výskum prebiehal v podhorských častiach.

Koeficient zmenšenia K sa pohybuje medzi 0,0081 (na osi a) v prípade Čeremošu a 0,0402 (na osi a) v prípade Skawy. Šírka kameňov (na osi b) sa zmenšuje najrýchlejšie. Hrúbka kameňov (na osi c) sa zmenšuje najpomalšie. Koeficient zmenšovania veľkosti kameňov umožňuje výpočet vzdialenosti (l), po ktorej sa najväčšie kamene (S) zmenšia na rozmery menšie ako 2 mm. Takto sa stávajú frakciami piesku a rieka už štrk neprenáša. Výpočty ukazujú, že k tomuto javu dochádza v alúviu Soly po 168 kilometroch a v prípade Skawy po 123 km. Podobné výpočty pre Prut a Čeremoš priniesli výsledky 446 km a 615 km.

Preložila H. Contrerasová