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RELATION BETWEEN DISSOLVED AND SUSPENDED MATTER CONTENT EXPORTED FROM THE DRAINAGE BASINS IN THE CARPATHIAN FOOTHILL REGION, SOUTHERN POLAND

INTRODUCTION

Suspended and dissolved waste loads carried in riverbeds reflect complex geomorphological processes throughout each catchment area and riverbed. The amount of dissolved and suspended solids indicate the level of geomorphological activity of the given area. This paper focuses primarily on this aspect of the circulation of matter in foothill watersheds in the area of the Jagiellonian University Institute of Geography's Research Station in Łazy near Bochnia.

Research done heretofore in the foothill watersheds in the region of the edge zone of the Carpathian Foothills focused primarily in the differentiation and changing concentrations of dissolved and suspended solids. Corresponding data have been published by Chełmicki et al. (1992) and Krzemień and Święchowicz (1992). To date, run-off mechanical denudation has been calculated in literature only on the basis of the suspended sediment yield of transit rivers (Łajczak 1989, 1992).

The objective of this paper is to present the study of the differentiation and seasonal changes of the outflow of dissolved and suspended waste from various size foothill river catchment areas and the relationships between the types of the transported material. This paper is the result of three years (1993 through 1995) of stationary field site research, performed under the research agenda of the Jagiellonian University Institute of Geography's Research Station in Łazy near Bochnia. Study tests were made in the watersheds of the Stara Rzeka (Old River) and Dworski Potok (Manor Stream) rivers. The study was funded by the Science Research Committee (Komitet Badań Naukowych, KBN), under research project PB 0389/P2/93/04.

STUDY METHOD

The subject Stara Rzeka and Dworski Potok watersheds were closed with measuring stations (Fig. 1) where water levels were recorded and one liter samples were taken in order to measure electrical conductivity and dissolved solids and suspended sediment concentrations. Conductivity was tested daily, while dissolved and suspended concentrations were tested every three days. Test frequencies were appropriately increased during peak flows. Conductivity was measured with a CC–315 microprocessor controlled conductivity meter at the fiducial temperature of 25°C. Dissolved solids concentrations were determined through evaporation of water from the sample and drying at 180°C. Daily dissolved solids conductivities were determined on the basis of its relationship to electrical conductivity. Concentrations of the suspended sediment were measured primarily by separation in a MPW–6 type centrifuge, followed by the evaporation of the remnants of water at 105°C. All test were made at the hydrochemical laboratory of the Jagiellonian University Institute of Geography's Research Station in Łazy.

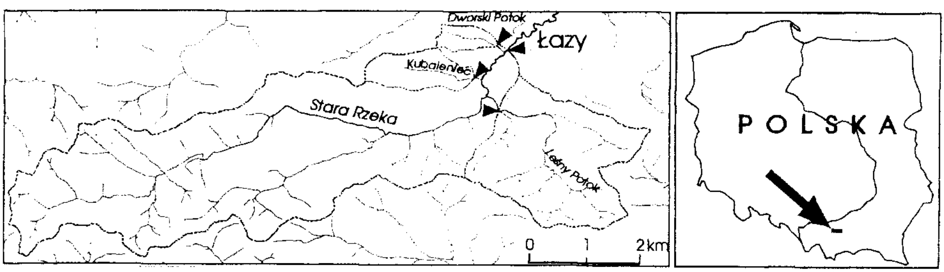

Fig. 1. Location of the study area

Ryc. 1. Położenie obszaru badań

Dissolved loads were calculated as the product of the material concentration and waterflow volume for individual days, months, and years. Suspended loads were calculated separately for peak and off-peak flow periods as the product of the concentration of the suspended sediment and the volume of water flow and time interval between tests.

STUDY AREA

The 22.4 km^2 Stara Rzeka watershed lies in the outer part of the Wiśnicz Foothills, in the Bochnia area. The study area consists of Silesian and Subsilesian rock units flysch and Miocene sandstones and clays. Slopes and hilltops are covered with thicker loess-like strata and valley floors — with proluvial fan silts. Wide, even rises of this area reach 260–360 m a.s.l. The principal valley floor is flat, some 100 to 250 m in width. A 20 to 30 m wide, winding channel cuts the valley floor three to five meters deep. A four meter wide riverbed occupies the bottom of the channel. Riverbed and erosion channel slopes have been undercut and washed out over considerable distances. Wooded areas occupy 41.3%, grassland — 13.3%, and arable land — 38.7% of the Stara Rzeka catchment area.

The 0.29 m^2 Dworski Potok watershed lies in a lower part of the Stara Rzeka catchment area (Fig. 1). Dworski Potok valley floor is flat, formed by accretion, and 30 to 100 m wide. The riverbed has cut into a 0.5 to 1.5 m deep channel. The Dworski Potok riverbed is substantially overgrown with hydrophillic vegetation. Wooded areas occupy 1.6%, grassland — 59.8%, and arable land — 33.2% of the Dworski Potok catchment area.

Annual rainfalls during the test period varied from 540.4 mm in 1993 to 722.0 mm in 1994. Compared with the 1987–1995 nine year average of 607.0 mm, 1993 was a "drier" year, while 1995 closely approximated the average rainfall, and 1994 was a clearly more "rainy" year (Chełmicki *et al.* 1995).

Average annual Stara Rzeka flows varied from 0.072 m^3/s to 0.116 m^3/s. Compared with the 1987–1995 nine year average of 0.127 m^3/s, average Stara Rzeka flows were lower over the test period (Chełmicki *et al.* 1995). Average, annual Dworski Potok flows varied from 1.16 l/s to 1.45 l/s. Compared with the 1987–1995 nine year average of 1.22 l/s, average annual Dworski Potok flows were lower in 1993 and close to the average in 1994 and somewhat higher 1995.

DISSOLVED SOLIDS OUTFLOW FROM THE CATCHMENT AREAS

River waters tested in the Stara Rzeka watershed show a considerable range of dissolved solids concentration, from 103 to 759 mg/l; these concentrations are a function of sample origin, date, and the path traveled (Chełmicki *et al.* 1992). At 335 mg/l, Stara Rzeka waters contain less dissolved mineral matter than those of Dworski Potok, at up to 759 mg/l. This situation results from the geology of the two watersheds. The upper part of the Stara Rzeka river, along with the Leśny Potok (Forest Stream) river, drains primarily the flysch edge zone. Over this area, the rivers are fed with relatively mineral-free water. But the lower part of Stara Rzeka is fed with the waters of Dworski Potok and Brzeźnicki Potok tributaries, which drain an area consisting primarily of Miocene sandstones and clays. Loess-like cover is also thicker in this area. The relationship of dissolved solids concentrations and electrical conductivity is fairly close in the study catchments (Chełmicki *et al.* 1992).

Over the study period, Stara Rzeka and Dworski Potok watershed dissolved loads reflect closely the stream transport regime features (Fig. 2). Dissolved solids flows are highest in the winter six months; they are associated with the snowmelt and rain peak river flows (Table 1). Between 69.8 and 92.5% of the

Table 1 — Tabela 1

Share of winter and summer six month periods in the dissolved load carried out of the Stara Rzeka and Dworski Potok drainage basins from 1993 through 1995

Udział półroczy: zimowego i letniego w wynoszeniu materiału rozpuszczonego ze zlewni Starej Rzeki i Dworskiego Potoku w latach 1993–1995

Drainage basin Zlewnia	Hydrologic year Rok hydrologiczny	Annual load in tons Ładunek roczny (w tonach)	Percent share of the winter six months Udział ładunku półrocza zimowego w %	Percent share of the summer six months Udział ładunku półrocza letniego w %
Stara Rzeka	1993	758.693	92.5	7.5
	1994	873.315	71.9	28.1
	1995	657.880	69.8	30.2
Dworski Potok	1993	14.348	87.6	12.4
	1994	17.162	72.8	27.2
	1995	14.193	73.4	26.6

annual dissolved load was carried out in the Stara Rzeka watershed in the winter six months; this number for Dworski Potok was from 72.8 to 87.6% (Table 1). The largest monthly loads usually occurred in both watersheds in April; the only exception was March 1995 that proved to be the peak month for Dworski Potok for that season. The dissolved loads were usually lowest in both catchment areas during the August low flows (Fig. 2).

Over the three year (1993 through 1995) study period, the annual dissolved loads carried out of the Stara Rzeka watershed ranged from 657.880 t to 873.315 t (Table 1). The material removed from the Dworski Potok watershed during the same period averaged annually from 14.193 to 17.162 t.

The rate of chemical run-off denudation in the Stara Rzeka basin ranged from 29.36 t/km^2/year in 1995 to 38.99 t/km^2/year in 1994. The same numbers for the Dworski Potok watershed ranged from 48.94 t/km^2/year in 1995 to 59.18 t/km^2/year in 1994.

SUSPENDED SEDIMENT OUTFLOW FROM THE CATCHMENT AREAS

Suspended sediment concentrations recorded to date do not substantially differ from those recorded in other foothill river basins and fall towards the bottom of the peak values quoted in literature (Krzemień and Święcho-

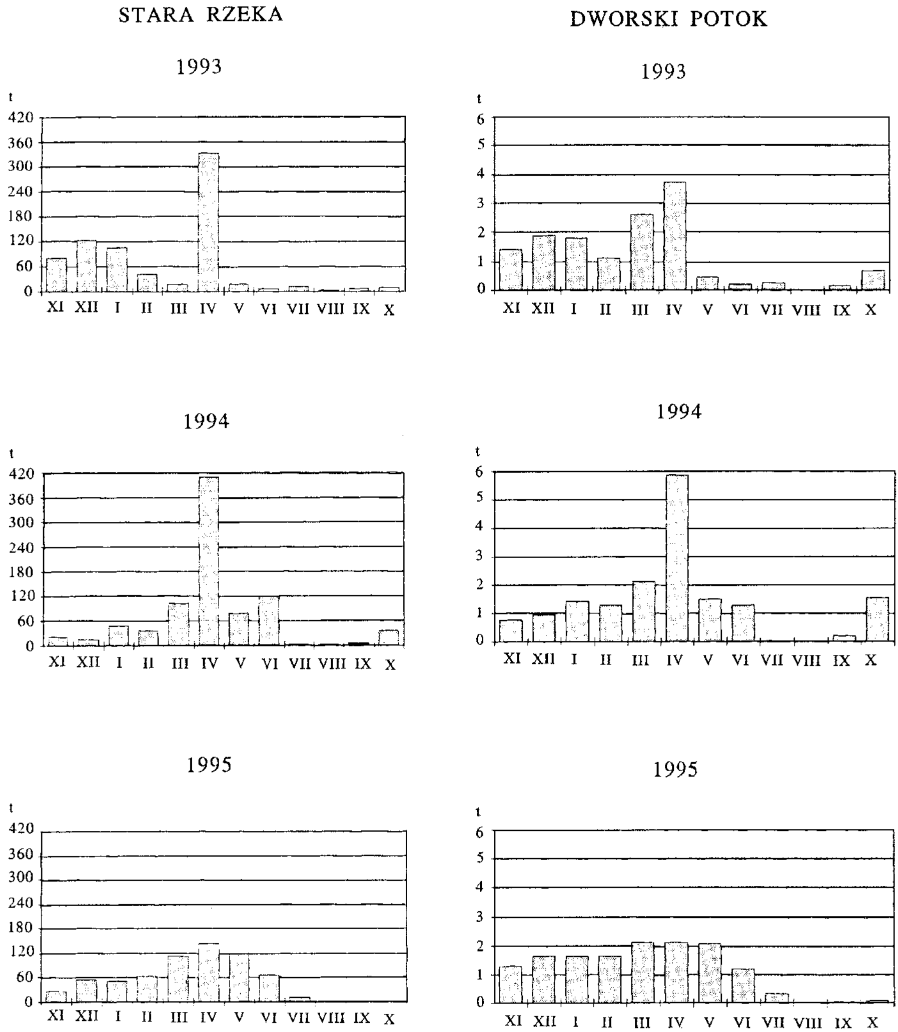

Fig. 2. Monthly loads, in tons, of the dissolved material transported from the Stara Rzeka and Dworski Potok watersheds from 1993 through 1995

Ryc. 2. Miesięczne ładunki (w tonach) wyniesionego materiału rozpuszczonego ze zlewni Starej Rzeki i Dworskiego Potoku w latach 1993–1995

wicz 1992). Peak foothill watershed suspended concentration values quoted in literature to date range from 1,000 to 7,040 mg/l. These values are considerably lower than those recorded in Pieninian or Beskidian catchment areas (Figuła 1966 and Froehlich 1982).

Top suspended sediment concentrations recorded for snowmelt and summer storm peak flows during the study period ranged from 1,335 to 2,872 mg/l in the Stara Rzeka bed and from 108 to 461 mg/l in the Dworski Potok bed. A clearly defined peak load period for suspended material flowing out monthly from the Stara Rzeka and Dworski Potok basins was found to occur each year in the spring, usually in the month of April. The only exception was found in 1995, when the monthly loads peaked for Stara Rzeka in June, and for Dworski Potok — in May (Fig. 3). In the 1993 and 1994 rainfall years, a considerable majority of the suspended matter outflows from the two river basins during the winter six months, primarily during the snowmelt peak flows. The winter six months in these two years are respon-

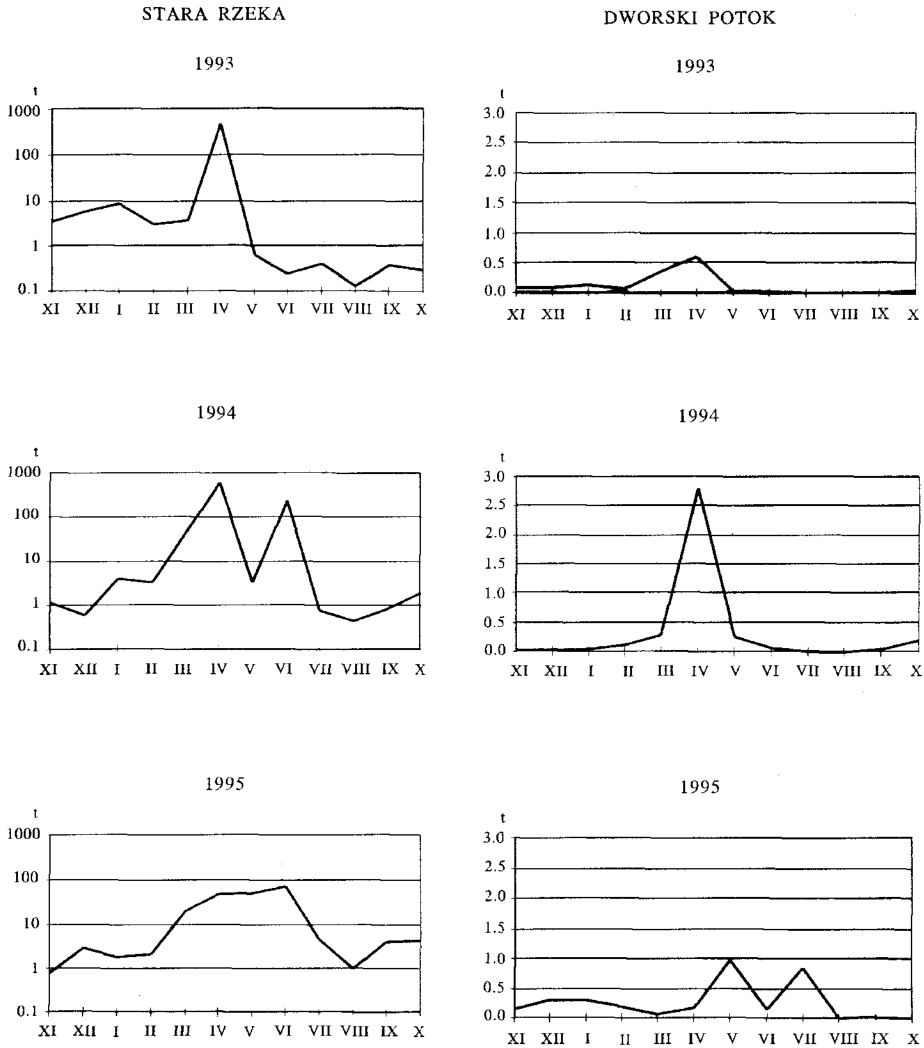

Fig. 3. Monthly loads, in tons, of the suspended sediment transported from the Stara Rzeka and Dworski Potok watersheds from 1993 through 1995

Ryc. 3. Miesięczne ładunki (w tonach) zawiesiny wyniesionej ze zlewni Starej Rzeki i Dworskiego Potoku w latach 1993–1995

Table 2 — Tabela 2

Share of winter and summer six month periods in the suspended sediment carried out of the Stara Rzeka and Dworski Potok drainage basins from 1993 through 1995

Udział półroczy: zimowego i letniego w wynoszeniu zawiesiny ze zlewni Starej Rzeki i Dworskiego Potoku w latach 1993–1995

Drainage basin Zlewnia	Hydrologic year Rok hydrologiczny	Annual load in tons Ładunek roczny (w tonach)	Percent share of the winter six months Udział ładunku półrocza zimowego w %	Percent share of the summer six months Udział ładunku półrocza letniego w %
Stara Rzeka	1993	530.669	99.6	0.4
	1994	908.709	73.8	26.2
	1995	213.758	35.6	64.4
Dworski Potok	1993	1.439	93.2	7.0
	1994	3.816	85.6	14.4
	1995	3.185	37.3	62.7

sible for between 73.8 and 99.6% of suspended sediment carried out from the Stara Rzeka watershed and between 85.6 and 93.0% — from the Dworski Potok watershed (Table 2). However, in 1995 the peak suspended sediment outflow occurred for both river basins in similar proportions during the summer six months. Lowest monthly suspended loads were carried out during the summer and fall low flows, i.e., primarily in August and/or October (Fig. 3). The study has shown so far that a load equal to an entire annual load in a dry year may occur during a single, large snowmelt peak flow. This situation occurred in April 1993 and 1994 in the Stara Rzeka basin, and in April 1994 in Dworski Potok.

The annual suspended load discharge out from the Stara Rzeka catchment area varied from 908.709 t in 1993 to 213.758 t in 1995. The corresponding suspended tonnage for Dworski Potok ranged from 1.439 in 1993 to 3.816 in 1995.

Most of the suspended load carried out of the watersheds originated in riverbeds and the immediate vicinity thereof, as corroborated by the research conducted to date. The suspended sediment concentrations in surface run-off waters on vegetation-free slopes were as high as 264 mg/l, and on grassy slopes — up to 63 mg/l (Krzemień and Święchowicz 1992). Material washed out from arable land slopes accretes on flat, grassy valley floors. This is particularly evident during intense rainfall or snowmelt periods (Wójcik 1994). During peak flows in the Stara Rzeka tributaries, a high of 339 mg/l for suspended concentration was recorded in the bed of Brzeźnicki Potok, and one of 778 mg/l — in that of Dworski Potok (Wójcik 1994; Krzemień and Święchowicz 1992). But the high recorded in the riverbed of Stara Rzeka itself was 3.843 mg/l. The study of the circulation of the clastic material from hilltops through small streams and into larger riverbeds shows a distinct jump between the values found in streamlets and those in larger rivers. At even minutely high water levels, the Stara Rzeka riverbed, cut deeply into the floor of its valley, allows suspended material from the banks of the bed to be freely fed into the river. The delivery of clastic material is much easier as the winding riverbed undercuts its banks in many places. It should also be noted that in the foothills small stream beds are often substantially overgrown with vegetation, and during high flows the supply of transportable clastic material runs out quickly (Krzemień and Święchowicz 1992). Consequently, suspended material carried out of foothill river basins originates from a small proportion of total catchment land area. Calculated mechanical run-off denudation indices are rightly criticized for failing to adequately reflect the process of the removal of material from river basins over the short term. In the literature, however, they are often quoted and relied upon. The run-off mechanical denudation indices in the study area range from 4.95 to 13.16 t/km^2/year in the Dworski Potok basin, and from 9.54 to 40.57 t/km^2/year in the Stara Rzeka basin.

RELATIONSHIPS BETWEEN THE TYPES OF THE TRANSPORTED MATERIAL

The relationships between the types of the transported material provide information on the course and intensity of the geomorphological processes specific to each catchment area and riverbed (Walling and Webb 1981; Kostrzewski *et al.* 1994). The ratio of the dissolved load — Ld, and the suspended load — Ls, transported out of the Stara Rzeka basin over the study period is as follows:

	1993	1994	1995
Ld : Ls [%]	58.8 : 41.2	49.0 : 51.0	75.5 : 24.5

The ratios of these loads transported out of the Dworski Potok basin are somewhat different:

	1993	1994	1995
Ld : Ls [%]	90.9 : 9.1	81.8 : 18.2	81.5 : 18.3

Under the assumption that Ls = 1, the above ratios will assume the following values:

Basin		1993	1994	1995
Stara Rzeka	Ld : Ls	1.43 : 1	0.96 : 1	3.08 : 1
Dworski Potok	Ld : Ls	9.97 : 1	4.50 : 1	4.46 : 1

The above numbers show that chemical denudation dominates the mechanical over the study area. In the basins of larger rivers, such as Stara Rzeka, chemical denudation may surpass mechanical as much as about three times. However, in more rainy years, mechanical denudation may equal, or even surpass, the chemical. In smaller watersheds, chemical denudation surpasses the mechanical 4.5 to 10 times. These data indicate that the chemical denudation in the Carpathian Foothills, or at least on the outer edges thereof, dominates over mechanical denudation. This situation is opposite to that found in the Beskidian part of the Carpathians, where Froehlich (1975) notes that the mechanical denudation is larger than the chemical. Consequently, the view that the size of mechanical denudation is larger than that of the chemical denudation throughout the Carpathians (Figuła 1966, Łajczak 1989) is not true. The idea that the degradation of the Carpathian Foothills through the removal of material carried out by rivers is substantially greater than in the Beskidians (Łajczak 1989, 1992) must also be verified. The numbers calculated on the basis of suspended loads carried by the Foothill transit rivers may not be applied to the region the rivers run through, as these rivers also carry material picked up in other regions and the preponderance of the suspended load originates from the riverbed. The calculated mechanical denudation indices may be greatly overestimated. The values obtained by Łajczak (1989) in the Carpathian Foothills are some 25 to 40 times higher than those found in the Stara Rzeka catchment area. If the Stara Rzeka values were considered against those calculated by A. Łajczak for Beskidian river basins, the mechanical denudation in the latter area would have to be 2 to 18 times greater than in the Wiśnicz Foothills.

CONCLUSIONS

Riverbeds in the Wiśnicz Foothills edge zone dissect the flat floors of wide valleys occupied primarily by grassland. The shape of the valley floors and the type of farming carried out therein results in a relatively small supply of clastic material entering the riverbeds from the slopes. The majority of the suspended material transported by the rivers comes from the riverbeds themselves, consequently leading to substantial transformation of these riverbeds and the immediate vicinity thereof. This process leads to the enlargement of the channels cutting the valley floors.

The chemical denudation over the study area generally dominates over the mechanical. However, it is the mechanical denudation that contributes more directly to the geomorphological transformation of this region.

Research performed to date supports the proposition that chemical denudation dominates in the Carpathian Foothills, while mechanical denudation does so in the Beskidian part of the Carpathians. Mechanical denudation indices obtained recently suggest that the mechanical denudation is more pronounced in the Beskidians than in the Carpathian Foothills.

It should also be noted that run-off denudation indices for individual regions should be calculated on the basis of loads carried by rivers and streams draining exclusively from the given region. Transit rivers may not be considered fully representative of the region they transect.

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STRESZCZENIE

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RELACJE MIĘDZY RODZAJAMI MATERIAŁU ROZPUSZCZONEGO I ZAWIESZONEGO, ODPROWADZANEGO ZE ZLEWNI NA POGÓRZU KARPACKIM, POLSKA POŁUDNIOWA

Celem artykułu jest poznanie zróżnicowania i sezonowej zmienności wynoszenia materiału rozpuszczonego i zawiesiny z różnej wielkości zlewni pogórskich oraz relacji między rodzajami odprowadzanego materiału. Relacje te informują o przebiegu i intensywności procesów morfogenetycznych w danej zlewni i w korycie rzecznym.

W badanym terenie ładunki materiału rozpuszczonego wynoszonego ze zlewni przewyższają ładunki zawiesiny — w zlewniach większych rozmiarów maksymalnie około 3 razy, a w małych nawet do 10 razy. Dotychczasowe badania pozwalają wnosić, że na Pogórzu Karpackim dominuje denudacja chemiczna nad mechaniczną. Jednak o bezpośredniej transformacji geomorfologicznej tego obszaru decyduje w większym stopniu denudacja mechaniczna. Uzyskane wartości wskaźników mechanicznej denudacji odpływowej sugerują, że na Pogórzu Karpackim jest ona mniejsza niż w Beskidach.