DYNAMICS OF SUSPENDED MATERIAL CARRIED OUT FROM THE FLYSCH BYSTRZANKA CATCHMENT DURING SELECTED RAINFALL EVENTS IN THE PERIOD OF 1997–2008

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Abstract. Hydrometeorological conditions in Research Station in Szymbark were analysed, and then the influence of these conditions on the water level. The investigations were carried out during the selected high stage in the period 1997–2008. Relations between the precipitation totals, discharge and changes of the amount of material carried away were analysed. Percentage of the suspended matter in complete denudation from the catchment area of the Bystrzanka was also assayed. The results showed that more than 95% of suspended material can be carry out in a single flood. Parameters regarding to the transport of suspended matter in the period 1997–2008 were referenced to the same parameters estimated in the period 1971–1979, and the load of suspended material in the review period was higher by 26%.

Keywords: rainfall events, transport of suspended matter, Bystrzanka catchment, Low Beskid

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Introduction

River erosion, fluvial transportation and downwash of materials from slopes as well as sediment supply to river channels are the processes which play a significant role in relief modelling (*i.e.* Gregory & Walling 1973, Froehlich 1975, 1982, 1995, Kostrzewski & Zwoliński 1990, 1992, Philips 1991, Biernat, Ciupa 1992, Fryirs & Brierley 2001, Sammori 2004). Dynamics of morphogenetic processes, which transform river channels, depends mainly on peak discharges occurring during high water stages and on a type of channel material (Froehlich 1972, 1975). Transport of a river load during a year varies and is limited only to periods of high discharges when stream competence exceeds thresholds of river down cutting and sets off sediment transport. A fundamental element of water circulation in a catchment is precipitation which total, frequency, duration and intensity are decisive for relief transformation (Starkel 1976, 1996, Kostrzewski *et al.* 1992, Kotarba 2002). Short-term catastrophic processes induced by heavy downpours or persistent rainfalls are the most important for river channel transformation. During a single flood event up to 95% of annual sediment yield, originating from bank erosion and channel bed deepening as well as washed from cart roads, can be carried away (Welc 1972, 1988).

Many authors in their work focuses on identifying the mechanism of delivery of material from the slope to the channel and determine the degree of interaction between these two subsystems in the drainage of material from the catchment (Froehlich 1975, 1982, Walling 1983, 1990, Harvey 1991, Fryirs & Brierley 1999, 2001). Material transported as suspended load comprises sediment delivered by tributaries, material derived from bank scarps, washed bedrock, channel alluvia and over bank deposits (Krzemień & Sobiecki 1998, Święchowicz 2002, Calvin Rose 2004, Ciupa 2005). Cart roads play also an important role in a supply of weathered material to river channels (Figuła 1966, Słupik 1973, Froehlich 1975, Słupik & Froehlich 1986, 1992, Soja & Prokop 1996). A network of dry tiny valleys, contacting directly a channel or a flood terrace, is often a route of material delivery from arable land prone to erosion. The material "pre-processed" by moles and musk-rats, living in riverside areas and digging systems of passages and pushed-up hills, is usually an underrated source of clastic material ready for transportation (Biernat & Ciupa 1992).

Purpose and methods of study

This paper aims to present variability in concentration of suspended load as well as dynamics of suspended load transportation in a river channel in a gauging section that closes the Bystrzanka catchment during floods induced by precipitation of variable intensity and totals, occurring in summer seasons in 1997–2008. The results are analyzed in comparison to those obtained by Welc (1988) in 1971–1979 when the discussed area was under different landuse, i.a. when arable fields predominated.

Concentration of suspended material was determined by filtrating method 1 litre samples, drying at 105°C and weighing dry residue (Brański 1968b). Water samples were collected from the bank. The frequency of sampling depended of the discharge size. The samples were taken usually every 0.5–1 hour and in the final phase of flooding the frequency was decrease. Suspended load was calculated as a product of suspended material concentration and water discharge. Detailed characteristics of precipitation conditions and discharges are based on pluviographs and water level records collected at Research Station of the Institute of Geography and Spatial Organization, Polish Academy of Sciences (IGSO PAS) in Szymbark.

Study area

The Bystrzanka catchment, 13,59 km^2 in area and with 7.1 km long main stream, is asymmetric (Fig. 1). The catchment location makes two relief types to interweave. These are the relief of the Carpathian foothills and of the Beskidy Mts., controlled by geologic structures and tectonics (Kotarba *et al.* 1970, Starkel 1973).

A widening right side of the Bystrzanka catchment rises westward to the height of 735 m a.s.l. It has Beskidian relief with forested, steep slopes (up to 35°). It is almost completely built of the Magura sandstones (Świdiński 1973). Streams draining this catchment part are the longest tributaries to the Bystrzanka. During heavy downpours or long-lasting rainy periods the density of the stream network doubles (Niemirowska 1970). The left part of the catchment rises to 400–450 m a.s.l. Here, relief is of a foothill type. This catchment part is built of shale-sandstone series of the Inoceramian beds. Arable fields and grassland

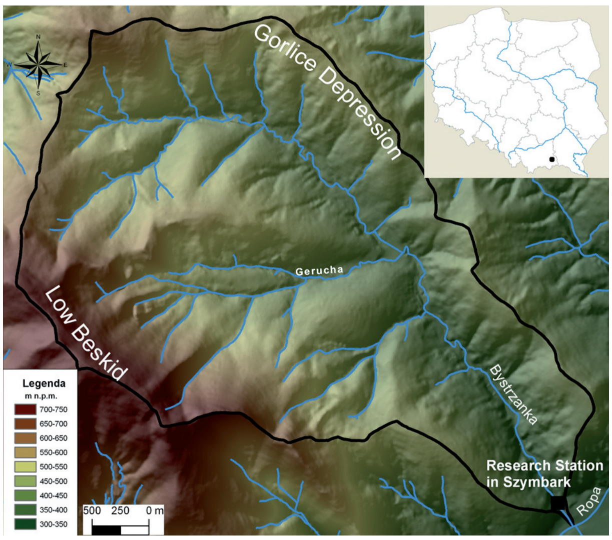

Fig.1. Study area

predominate in the landuse (Kotarba *el al*. 1970). Streams draining foothill slopes are short (250–700 m), thus water quickly reaches the Bystrzanka channel.

Meteorological and hydrological conditions in the study period

Mean annul precipitation in 1997–2008 was 851.9 mm and varied form 611.3 mm (in 2003) to 1000.5 mm (in 2001). According to precipitation classification of Kaczorowska (1962) the year of 2003 was very dry while 2001 – was moist. At average, 8 years in the studied period (1997, 1999, 2000, 2002, 2004, 2005, 2006, and 2008) were within a normal precipitation range (Fig. 2A). Mean precipitation in summer seasons was 561.3 mm and varied from 381.4 mm in 2003 to 711.5 mm in 2001 (Fig. 2B).

When considering precipitation, not only are their totals important, but also their variability in time. According to the studies performed by Wit-Jóźwik (1977) in the discussed area, mean frequency of precipitation decreases as precipitation totals increase. In 1997–2008 a number of days with precipitation amounted to 206 in a year at average and days with a very small (0.1–1.0 mm) and small (1.1–5.0 mm) precipitation predominated. They summed up to 75.5% of all days with precipitation while days with precipitation exceeding 20.0 mm amounted to 3.3%. The highest daily totals of precipitation in the discussed period were as follows: 68.3mm on 15.08.2002; 65.1 mm on 3.06.2006 and 62.3 mm on 28.07.2004.

Mean discharge at the gauging section in 1997–2008 was 174.2 $dm^3\ s^{-1}$,while daily means varied from 1,2 $dm^3\ s^{-1}$ to 8197,6 $dm^3\ s^{-1}$. The highest values of mean annual discharges were recorded in 1998 (222.3 $dm^3\ s^{-1}$) and in 2001 (221.3 $dm^3\ s^{-1}$) (Fig. 3). Mean specific runoff in the same period was 13,4 $dm^3\ s^{-1}\ km^{-2}$.

Mean annual runoff index in the Bystrzanka catchment was 421.6 mm. In summer seasons of the analyzed period, the highest monthly runoff index was in July 2001 (189.8 mm) when monthly precipitation was 251.8 mm and the lowest index was in July 2007 (1.0 mm) during a soil drought. Mean runoff coefficient was 54.6% in the discussed period. The highest monthly values in summer seasons were reached in July 2006 (133,3%), while the lowest values were, alike in the case of runoff index, in July 2007 (1.5%).

A flood (risen water level), following the definition of Ozga-Zielińska & Brzezinski (1994), is a period when discharges are equal to or higher than the threshold value (Q ≥ Qgr), calculated according to the formula ½(NWQ+WSQ) where NWQ is the lowest of the yearly maximum discharges and WSQ is the highest of the yearly mean discharges. In the discussed multi-year period the threshold discharge of Bystrzanka was 768 $dm^3\ s^{-1}$. In 1997–2008, discharge rises were small in 32 cases ($Q_{śr}$ was in a range from Q_{gr} to NWQ, *i.e.* 768 to 1320 $dm^3\ s^{-1}$), and in 34 cases discharge rises were normal ($Q_{śr}$ was in a range from NWQ to SWQ, *i.e.* 1320 do 4704 $dm^3\ s^{-1}$) but 7 were very large ($Q_{śr}$ above SWQ, *i.e.* 4704 $dm^3\ s^{-1}$). Large discharge rises predominated in summer seasons (6 cases). In 2001 two such discharge rises were recorded: on 23 and 27 July. They were

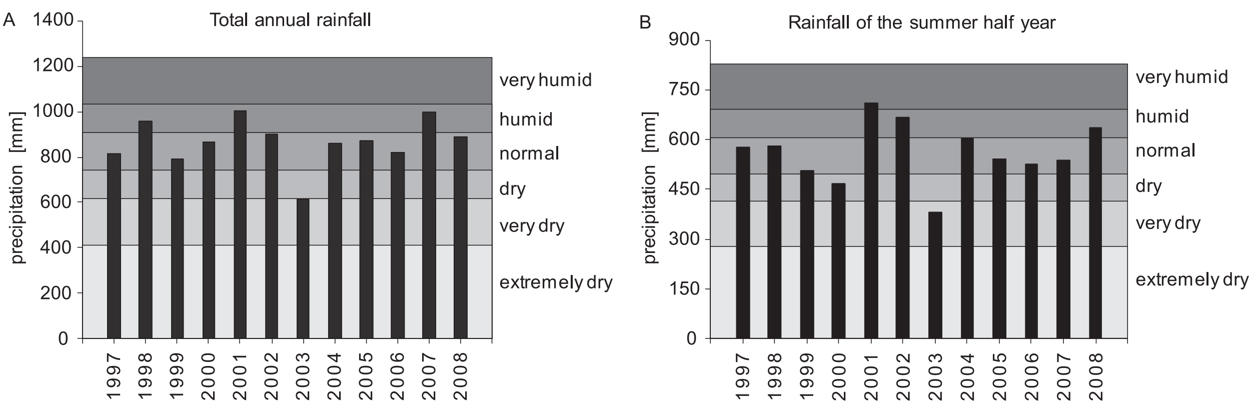

Fig. 2. Annual precipitation totals (A) and summer season precipitation in Szymbark in 1997–2008 against a background of precipitation classification after Kaczorowska (1962)

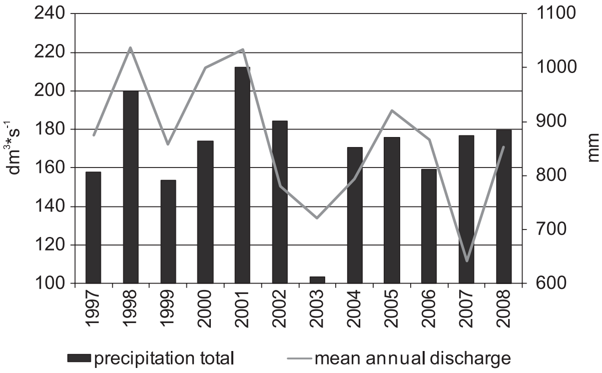

Fig. 3. Mean annual discharge compared with precipitation totals in the Bystrzanka catchment in 1997–2008

related to intensive diurnal rain storms reaching 46.5 mm and 42.3 mm, respectively. In summer season of 2001, normal discharge rises were the most common and they reached from 1320 to 4704 dm^3 s^{-1} (Table 1).

Transport of clastic weathered material in the Bystrzanka channel

The detailed analysis comprised 7 floods (risen discharges) for which precipitation totals and intensities, maximum discharges and suspended load concentrations differed (Table 2). Precipitation is a major cause of water level rises and transportation of suspended sediment. Based on examination of continuous records of precipitation (pluviographs), maximum intensities were identified and precipitation categories according to Chomicz's (1951) scheme were assigned to them. The analyzed floods were induced by: heavy rainfalls (A_0) (29–30.07.2000), 1-st grade downpours (A_1) (02–03.08.1997; 21–25.06.1999; 26–31.07.2004; 23–26.07.2008) and 3-rd grade downpours (A_3) (23–24.07.2001; 04.07.2002). The maximum discharge 37,023.0 dm^3 s^{-1} and the maximum concentration of suspended sediment 33,4 g dm^{-3} were recorded during the flood of 4 July 2002 and were preceded by precipitation that reached maximum intensity of 24 mm h^{-1} (Table 2). Significant turbidity of water resulted from: a rapid rise in discharge and a large amount of loose weathered material which formed due to over-drying of a top layer of ground and accumulated in long antecedent period. Percentage of suspended sediment load, carried away from the Bystrzanka catchment, varied from 3,8% (29–30.07.2000) to 96,0% (26–31.07.2004). The largest loads of suspended sediment are carried away during persistent rainfalls due to duration of a flood wave (Tab. 2).

A hysteresis is a graphic expression of a relationship between water discharge and concentration of suspended load. Each flood has a different shape of the hysteresis (Walling 1974, Froehlich 1975) that depends on many factors, among which the variability in precipitation conditions is assumed to be the most important. Precipitation conditions, duration of an antecedent flood,

Table 1. Number of flood flows above threshold discharge established on the basis of a hydrological criterion* in the Bystrzanka in hydrological years of 1997–2008

Year	Winter half year			Summer half year		
	Small flood	Ordinary flood	Enormous flood	Small flood	Ordinary flood	Enormous flood
1997	3	0	0	3	2	0
1998	1	3	0	1	2	0
1999	2	1	0	0	1	0
2000	3	3	0	0	2	0
2001	1	2	0	2	3	2
2002	1	1	0	4	2	0
2003	0	3	0	1	1	0
2004	1	1	0	1	0	1
2005	1	1	0	1	2	1
2006	1	0	1	1	2	1
2007	1	0	0	2	0	0
2008	0	0	0	1	2	1
1997–2008	15	15	1	17	19	6

* According to Ozga-Zielińska & Brzeziński (1994).

Table 2. Hydrometeorological data and transportation of suspended sediment during selected rainfall induced floods in the Bystrzanka catchment in 1997–2008

Date	Precipitation categories according to Chomicz's (1951) scheme	P (mm)	Pi ($mm*h^{-1}$)	Q max (dm^3*s^{-1})	Cs max ($g*dm^{-3}$)	Runoff (%)	Load of suspended sediment (t)	Percentage of suspended sediment load (%)
02–03.08.1997	1-st grade downpours (A_1)	33,4	12,1	9155,0	9,0	5,1	528,0	8,7
21–25.06.1999	1-st grade downpours (A_1)	82,3	11,2	5651,0	11,1	11,61	1110,0	56,0
29–30.07.2000	Heavy rainfall (A_0)	50,4	4,0	4674,0	1,28	3,5	127,0	3,8
23–24.07.2001	3-rd grade downpours (A_3)	36,2	27,4	33654,0	21,0	7,7	9933,0	81,7
04.07.2002	3-rd grade downpours (A_3)	27,0	24,0	37023,0	33,4	5,0	3034,0	80,2
26–31.07.2004	1-st grade downpours (A_1)	164,0	10,4	19591,0	7,8	44,9	12672,0	96,0
23–26.07.2008	1-st grade downpours (A_1)	72,0	10,4	17404,0	8,3	15,7	3724,0	85,8

moisture of substratum (water storage of a catchment), type and pattern of a vegetation cover (Kostrzewski *et al.* 1994) exert a major influence over delivery of clastic weathered materials to be transported by a river. In the analyzed period, normal (clockwise) and inverse (counter-clockwise) hysteresis are observed. The clockwise hystereses are related to situations when a maximum concentration of suspended sediment precedes a peak discharge (Froehlich 1975, 1982, Krzemień & Święchowicz 1992, Święchowicz 2002). Such hystereses were observed in the Bystrzanka catchment during the floods of 02–03.08.1997, 04.07.2002 and 23–26.07.2008 (Fig. 4). A small width of the hysteresis can be an evidence of small differences in delivery of suspended sediment during rising and falling phases of flood waves (Froehlich 1982).

The counter-clockwise hysteresis provide evidences of an increase in suspended sediment concentrations as a flood passes. Processes of suspended sediment supply are differentiated in time – maximum concentrations of suspended sediment occur after peak discharges. It might be attributed to differentiated intensity of rainfalls in particular parts of asymmetric catchment and to delayed geomorphic processes. Such hysteresis were observed during the flood of 23–24.07.2001.

The hysteresis might be even more complicated during floods with several peaks. An example is here the hysteresis related to the flood of June 1999 (Fig. 5) when two successive peaks revealed exhaustion of suspended material. The decrease in suspended sediment concentration took place because the wash load was carried away mainly during an earlier phase of the flood wave and reduced by increased soil moisture which made soil aggregates to hold together. This demonstrates the rapid depletion of material resources available to fluvial transport (Święchowicz & Żelazny 2005). Although the water discharges during both flood peaks were alike, the suspended load concentration during the first culmination was twice as large as during the second culmination. The flood of July 2006 (Fig. 6) was also characterized by a complex hysteresis. A rainfall event of a relatively high total yet of a small intensity resulted in a flood with two peaks. In this case, during the first culmination, the maximum concentration of suspended sediment slightly preceded the maximum water discharge (normal hysteresis) while during the second peak with the higher discharge, the suspended sediment concentration occurred after the maximum water discharge passed (inverse hysteresis). This indicates a complicated mechanism of suspended material delivery (Krzemień & Święchowicz 1992).

The calculated mean load of suspended sediment in 1997–2008 was 5 times that of the dissolved load (Tab. 3). Only in 2005 and 2007, the dissolved load exceeded suspended load, 2 and 3.5 times, respectively.

We compared our results with those obtained in the studies carried out by Welc (1988) in 1971–1979 (Tab. 4). Although the landuse changed and the area of arable grounds decreased (from 45% in 1969 to 19% in 2002), the mean load of suspended sediment in the period that we have examined was higher by 26% than the suspended sediment yield carried away in 1971–1979. That

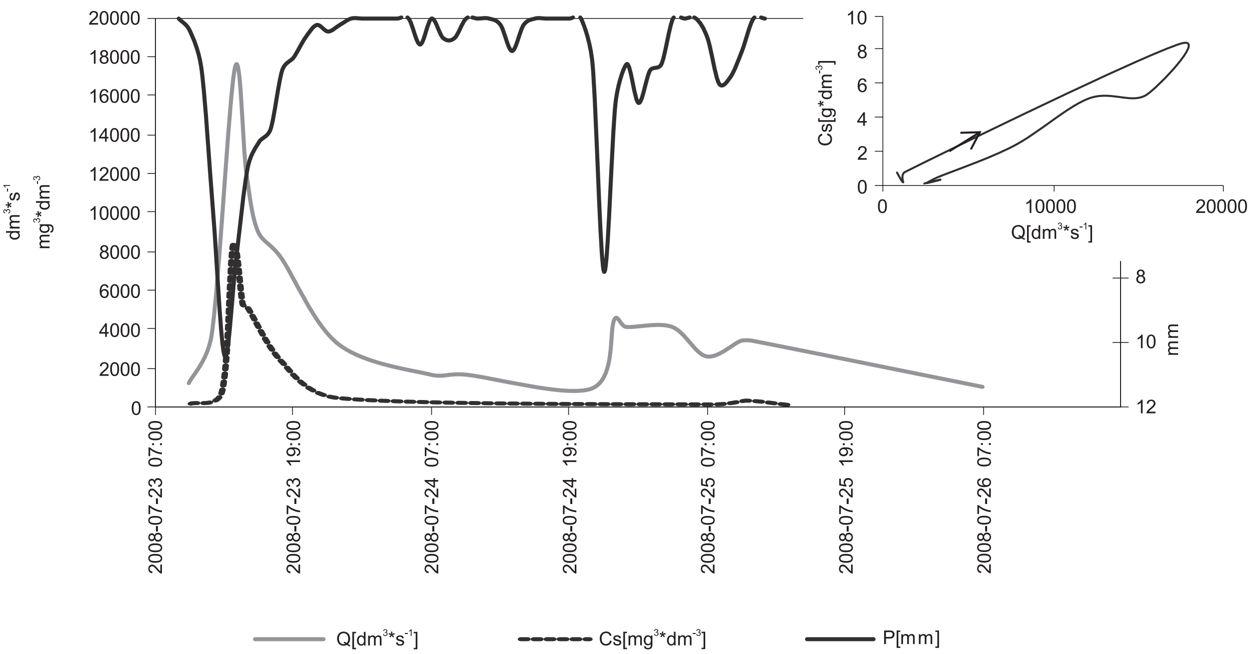

Fig. 4. Changes in suspended sediment concentration (Cs) and discharge (Q) during the flood induced by persistent rainfalls of 23–26 July 2008 in Bystrzanka catchment and relationships between water flow and suspended sediment concentration

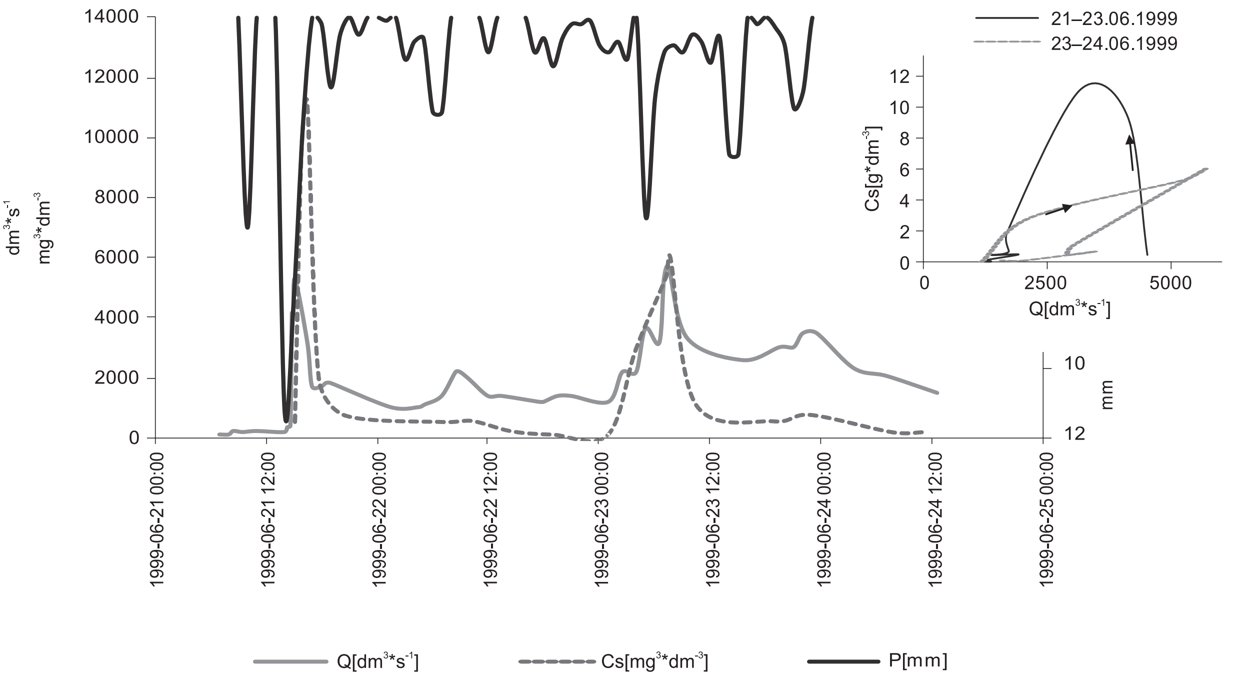

Fig. 5. Changes in suspended sediment concentration (Cs) and discharge (Q) during the flood induced by persistent rainfalls of 21–25 June 1999 in Bystrzanka catchment and relationships between water flow and suspended sediment concentration

likely might be related to an increasing number of road investments.

In order to find a relationship between discharge, precipitation, timing of flood peaks and concentration of suspended sediment, we calculated Beta coefficient (Statistica v.6.0), which estimates a relative contribution of each independent variable to prediction of dependent variable. Based on the performed analysis it can be concluded, at p=0.04 significance level, that concentration of suspended sediment depends mainly on water discharge for which Beta = 0.73. Figure 7 presents the relationship between water discharge and concentration of suspended mat-

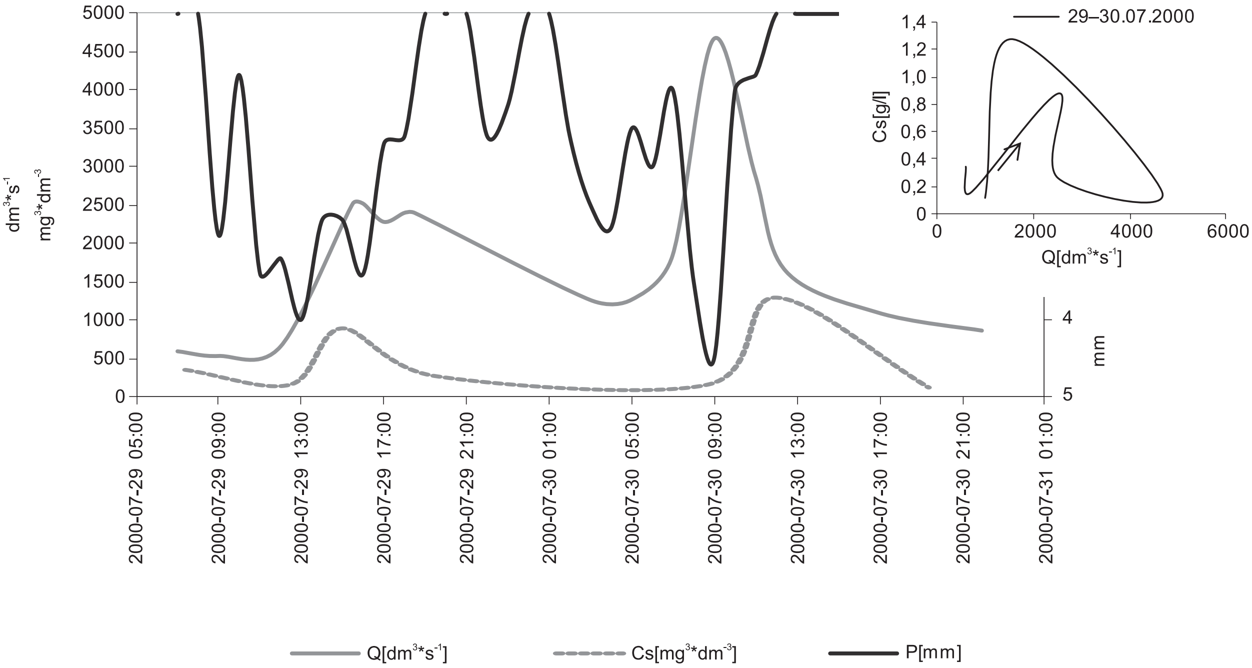

Fig. 6. Changes in suspended sediment concentration (Cs) and discharge (Q) during the flood of 29–30 July 2000 in Bystrzanka catchment and relationships between water flow and suspended sediment concentration

Table 3. Percentage of suspended sediment in total denudation from the Bystrzanka catchment in 1997–2008

Year	Load of suspended material (t)	Load of dissolved material (t)	Participation of the suspended material in complete denudation of the Bystrzanka catchment (%)
1997	6067	836	87,9
1998	6353	1271	83,3
1999	1981	1096	64,4
2000	3333	1277	72,3
2001	12153	1391	89,7
2002	3781	1190	76,1
2003	3152	1066	74,7
2004	12817	913	93,4
2005	706	1379	33,9
2006	14446	1106	92,9
2007	243	846	22,3
2008	4342	1203	78,3

ter with division into samples taken before and after all floods (discharge rises) in 1997–2008. The correlations were high and amounted to 0.77 and 0.73, respectively.

Closing remarks and conclusions

In the examined period, in summer seasons, load of suspended sediment in the Bystrzanka channel varied but generally followed a rhythm of stream outflow from the catchment. Floods were induced mainly by 1-st grade downpours, but also by heavy rains and 3-rd grade downpours. In years when transport of suspended sediment was significant, the load in majority was related to floods induced by persistent rainfalls or downpours. The load during an individual storm event amounted to 95% of a total annual load (flood of 26–31.07.2004).

Dynamics of suspended sediment concentration during floods is typical of the Beskidy and

Table 4. Parameters referring to transportation of suspended sediment in the periods of 1971–1979 and 1997–2008

Parameters regarding to the transport of suspended matter	1971–1979 (Welc 1988)	1997–2008
Mean annual transport of suspended matter (t)	4297,8	5781,2
Mean annual precipitation total (mm)	841,3	852,0
Maximum of annual transport of suspended matter (t)	17236	14446

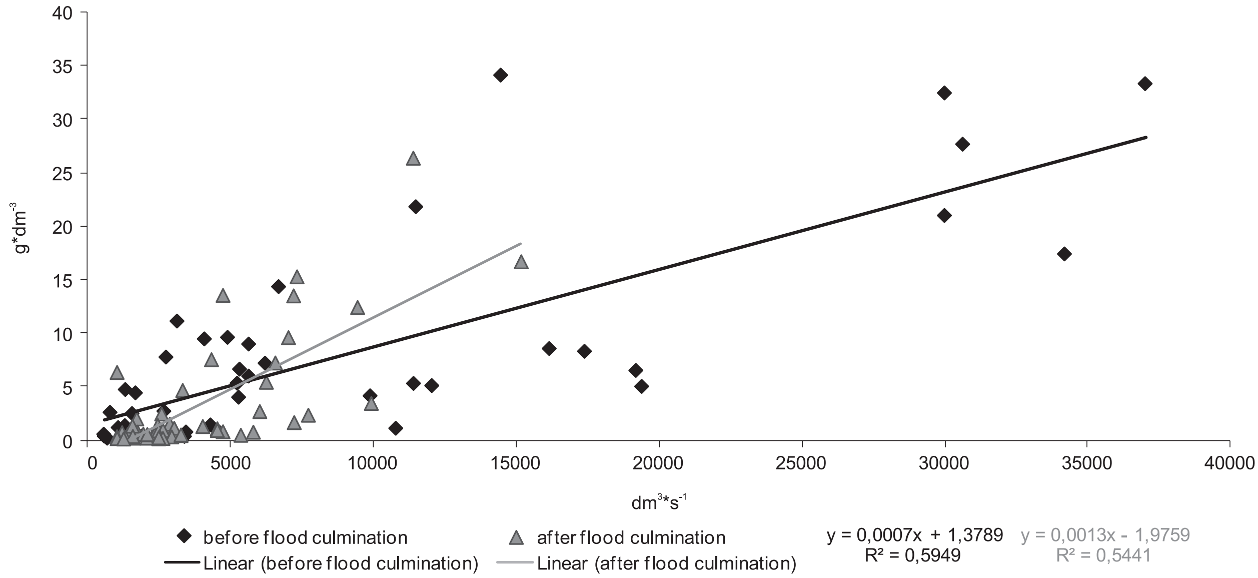

Fig. 7. Functional dependence between discharge and suspended sediment concentration with division of samples into taken before and after flood culmination

Foothills regions. It denotes that maximum concentration of suspended sediment most frequently precedes a peak discharge or coincides with it. That is an evidence of autochthonous origin of sediments transported in suspension. In the analyzed period we recorded also the floods, when maximum concentration of suspended sediment occurred after the peak streamflow. That can be related to local variations in precipitation intensity in particular parts of the asymmetric catchment and to supply of bank-forming material. Very significant changes in concentration of suspended sediment during floods and its considerable reduction during subsequent floods point to a rapid exhaustion of material available for transportation.

Concentrations of suspended sediment did not differ significantly from those reported from other Beskidian catchments (Figuła 1966, Froehlich 1982), yet they were much higher than from the Foothill catchments (*i.e.* from Stara Rzeka catchment – Wiśnicz Foothills) (Krzemień & Święchowicz 1992).

The performed statistical analysis showed that the concentration of suspended sediment depends mainly on water discharge that reflects stream competence for entraining weathered material into suspension.

The mean annual transportation of suspended sediment was by 26% higher in 1997–2008 than in 1971–1979 and showed that a definite relation between slope and channel systems is lacking. The above findings support the results obtained from the studies in other parts of the Carpathians (Łajczak *et al.* 2008). Only a small portion of material transferred on the slopes reaches the Bystrzanka channel as a short duration of rainfalls does not favour transportation over longer distances (Gil 1999). That is evidenced by rates of specific runoff from experimental plots which are by 1/3 higher than in the whole catchment. A growing number of road investments as well as a supply of material originating from unmetalled roads likely affected an increase in concentration of suspended sediment in the examined period.

The obtained results confirm the pattern of suspended sediment dynamics observed in small Carpathian rivers. However, further analyses are needed to explain reasons behind larger loads of suspended sediment carried away from the catchment.

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