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SPATIAL VARIATIONS OF SUSPENDED SEDIMENT GRAIN SIZE IN SMALL MOUNTAIN CATCHMENT DURING SUMMER FLOODS

Abstract: The grain size of material transported during flood along the longitudinal profile of the small Carpathian stream (the Bystrzanka stream) and its main tributaries was examined. The silt fraction is the dominant material transported during floods. The average content of this fraction varies from 67 to 88%. The highest standard deviation was recorded in relation to the sand fraction, what have been linked with the human impact (especially in the channel). During the rising limb phase the sand fraction showed a higher percentage content than during decreasing limb (at the same water level) and contrary in the case of the finest fraction. There were observed a statistically significant (<0.05) inverse relationship between the sand and silt fraction and the sand and clay fraction. The study showed no statistically significant impact of factors (precipitation, discharge) controlling summer floods on the size of suspended sediment.

Keywords: grain size, suspended sediment, floods, mountain stream, Carpathian Mts., Poland

INTRODUCTION

The information about grain size is the key to a better understanding of the processes occurring in a catchment as well as a river engineering and management. Detailed characteristics of grain size is commonly used in any physically based modelling study (Williams et al 2008; Grangeon 2012). The grain size analysis is also useful in hydraulic, sedimentological and geomorphological research, as well as in the chemical field because sediment absorbed chemicals and pollutants (Walling, Moorehead 1987; Russell et al. 2001; Foster, Charlesworth 1996; Meharg et al. 1999). According to J. Bogen (1992), to predict the circulation of pollutants in a catchment, there is required a detailed knowledge on the temporal and spatial variation of grain size. More information about grain size is also a key to a better understanding and insight in to transport and sedimentation processes. During a flood, the erosion activity of rivers reactivates sediment pollutants and transports it to new areas. The grain size of material transported in rivers to a large extent is related to hydraulic conditions and sediment sources, and is therefore a useful piece of information for analysing the connectivity between hillslopes and river channels (Walling, Webb 1992).

The previous knowledge on the fractional composition of suspended sediments indicates its high time and space complexity (Xu 2000).

Small mountain streams often carry significant amounts of sediment entering larger rivers (Milliman, Syvitski 1992) and often cause silting of water reservoirs, as well as damage to hydroelectric installations by, i.a., the excessive wear of turbines in large power plants. The studies of grain size in small mountain streams are still not well documented (Francke et al. 2008; Lopez-Tarazón et al. 2010; Navratil et al. 2011). Research often focus mainly on monitoring of extreme flows and suspended sediment concentration (SSC). Very few studies of particle size composition in mountainous environments are available (Lenzi, Marchi 2000; Woodward et al. 2002; Petticre 2005; Haritashya et al. 2010) mainly due to technical difficulties during the research (Grangeon et al. 2012).

The main aim of the study was: (1) to determine variability of the grain size of the suspended sediment transported during summer floods along the longitudinal profile of the small Carpathian stream and its main tributaries from the Beskids and Carpathian Foothills, and (2) to assess the variability of particle size in relation to the controlling factors.

STUDY AREA

The study focus on the Bystrzanka catchment (13 km^2), with main stream 7.2 km, located in the border of two major geomorphological units of flysch Carpathians: the Beskid Mountains (Low Beskids) and Carpathian Foothills (Starkel 1972), (Fig. 1). The region of the Beskids covering the north-western part of the catchment is built of sandstone series of Magura layers (Świdziński 1973). Specific lithologic complexes are of different resistance to degradation. In the geological structure of the foothills' ridges, there prevail medium-resistant to erosion-denudation factors shale-sandstone inoceramic layers and little resistant spotted shales of Eocene and, predominantly, shale Krosno layers.

The Bystrzanka stream is a left tributary of the Ropa River. In the upper part, the Bystrzanka is V-shaped valley with narrow bottom and steep slopes of up to 15 meters high, while in the middle course, it expands to several tens of meters. The width of the river is growing steadily from 3–4 m in the middle section to about 10 m in the estuarial section. The catchment is asymmetrical in relation to the course of the main stream, with a majority (70%) of the western part (of the Beskids). In the catchment, there dominate forest zones, which represent 40% of the area, grasslands cover 30% and arable land – 14% (Kijowska-Strugała 2015).

The Bystrzanka catchment has a warm, humid continental climate (Dfb), (Köppen 1931). Mean annual precipitations ranges from 530 to 1171 mm.

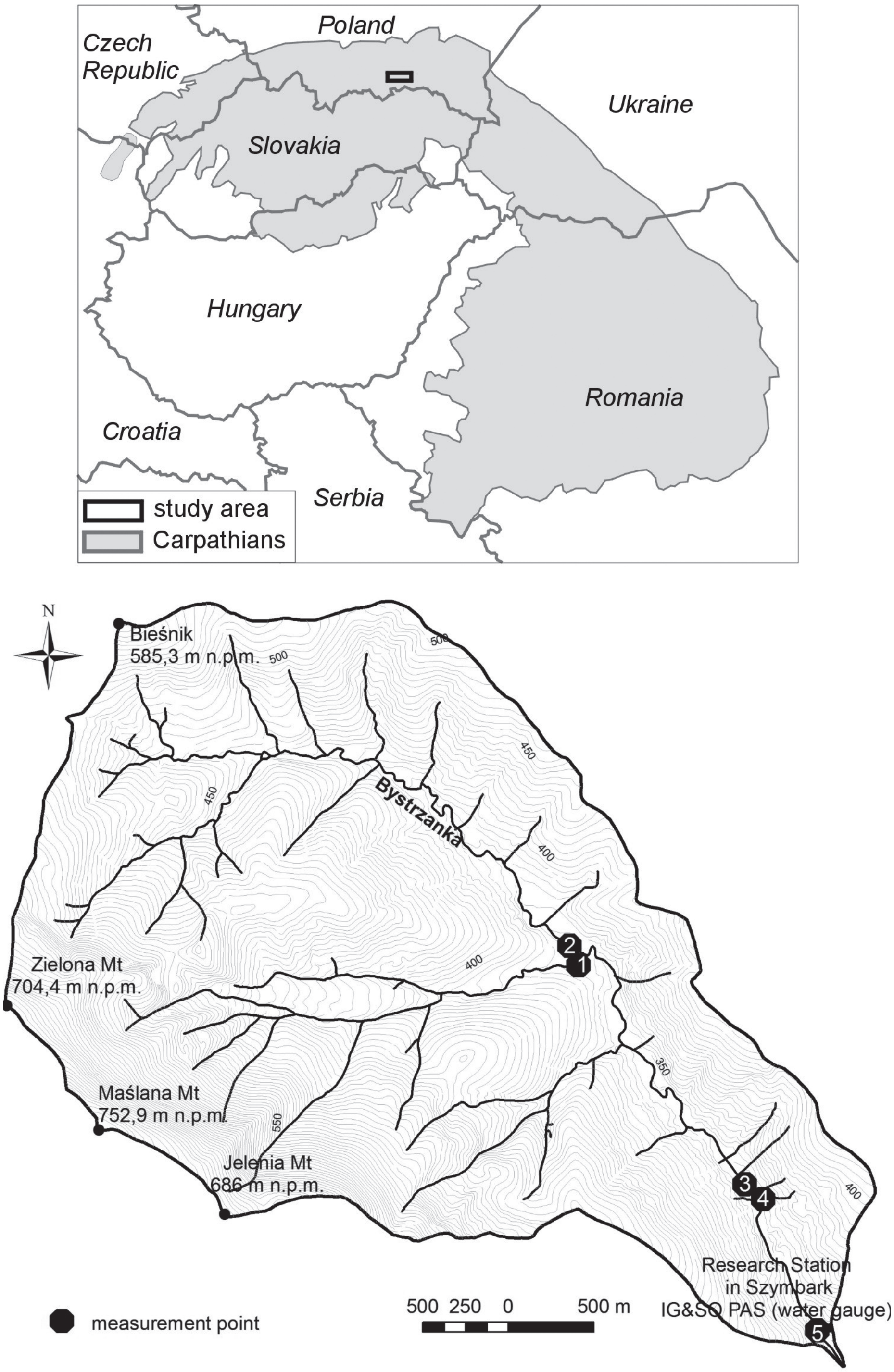

Fig. 1. Location of the Bystrzanka catchment and the measurements points

RESEARCH METHODS

The samples of water of a capacity of 1 dm^3 were taken during the nine summer floods in 2010 and 2011 using a bottle bathometer along the longitudinal profile of the main Bystrzanka stream and its tributaries. In the Bystrzanka stream samples were collected at the stream gauge (estuarial section of the stream) and also at 990 m and 2700 m distance from the stream gauge in the direction the stream source. In addition, there was analysed the fractional composition for one tributary from the Beskids and Carpathian Foothills. The water samples were always collected in the same part of the stream channel, in the current of the stream, at the same depth below the water surface. The frequency of water sampling during floods was dependent on rapidity of the water level changes.

The water samples were filtered, oven dried (105°C), and weighed to determine the concentration of suspended sediment (SSC). The fractional composition of the suspended material in 47 samples was determined by laser diffraction using a Fritsch Analysette 22 diffractometer. Sedimentological indicators: the mean grain diameter in the phi scale (Mz) and standard deviation (σ1) were calculated using the Folk and Ward (1957) method. There was adopted the following classification of grain sizes: medium sand (0.5–0.25 mm); fine sand (0.25–0.1 mm); very fine sand (0.1–0.05 mm); coarse silt (0.05–0.02 mm); fine silt (0.02–0.002 mm); clay (<0.002 mm) (Polish Society... 2008).

RESULT AND DISCUSSION

SPATIAL VARIABILITY OF SUSPENDED SEDIMENT GRAIN SIZE

In order to determine the dominant type of graining of the suspended sediment, there was calculated the percentage of the basic fractions. In the estuarial section of Bystrzanka stream, in water samples collected during the floods, there dominated the silt fraction (0.05–0.002 mm), representing 80% of the material transported in suspension, with the highest percentage of fine silt (0.02–0.002), which accounted for 62%. The clay fraction accounted for 8.6% of the material. Such fractional composition is typical for rivers in the Beskids (Froehlich 1982). Based on the values of the variation rate, it can be noted that the fine sand fraction, along the longitudinal profile of Bystrzanka stream, underwent the greatest changes (Cv = 76%), while the smallest changes occurred in the case of the fine silt (Cv = 9%) (Table 1). The grain size distribution did not vary much and the d_{50} ranged from 0.015 (during the rising limb) to 0.014 mm (during the falling limb).

The spatial variation of percentage of the fine silt fraction was the highest in samples taken from the tributary from the Carpathian Foothills part of the catchment (68%) and the lowest – in the samples taken from the middle section

Table 1
The average content [%] of each fraction of suspended sediment in samples taken in the estuary section of Bystrzanka stream (water gauge near Research Station in Szymbark: measurement point number 5)

Fraction	Fine sand	Very fine sand	Coarse silt	Fine silt	Clay
[mm]	0.25–0.1	0.1–0.05	0.05–0.02	0.02–0.002	<0.002
The average contain (%)	3.0	5.3	20.9	62.2	8.6
Standard deviation (SD)	2.3	2.9	2.7	5.4	1.5
Coefficient of variation (CV) [%]	75.9	53.7	12.9	8.7	17.7

Table 2
The average content [%] of each fraction of suspended sediment in samples taken in the Bystrzanka catchment

Place of sampling / Grain size [mm]	Tributary from the Carpathian Foothills (point 4)	Beskids' tributary (point 1)	Bystrzanka stream before Beskids tributary (point 2)	Bystrzanka stream after Beskids tributary (point 3)	Bystrzanka stream water gauge (point 5)
Medium sand (0.5–0.25)	0.0	0.0	0.0	0.0	0.1
Fine sand (0.25–0.)	0.8	2.0	3.2	2.9	3.0
Very fine sand (0.1–0.0)	3.6	4.6	6.4	5.7	5.3
Coarse silt (0.05–0.002)	18.0	20.6	22.9	21.7	20.9
Fine silt (0.02–0.002)	67.7	63.4	59.8	60.9	62.3
Clay (<0.002)	9.9	9.4	7.7	8.8	8.4
Sum	100.0	100.0	100.0	100.0	100.0

of Bystrzanka stream (Table 2). The coarse silt, in Bystrzanka stream before the mouth of the Beskids' tributary (measurement point number 2) accounted for 23% and was the highest average percentage in comparison to all other sampling points. The lowest very fine silt percentage, just as the sand percentage, was noted in the tributary from the Carpathian Foothills' part of the catchment. The clay fraction percentage in this part of the catchment was the highest. It was also observed a dependence of a percentage decline of the sand fraction and an increase in the content of the fine silt with increasing catchment area (Table 2). Similar patterns were observed in the Beskid Sądecki (Froehlich 1982). This should be associated with reduced course slope of and water velocity. By sorting, finer grains are involved in the transport much faster and at a greater distance than coarse grains (Allen 1965). According to Kostrzewski et al. (1994) the percentage increase in the amount of finer grains in the longitudinal profile was as

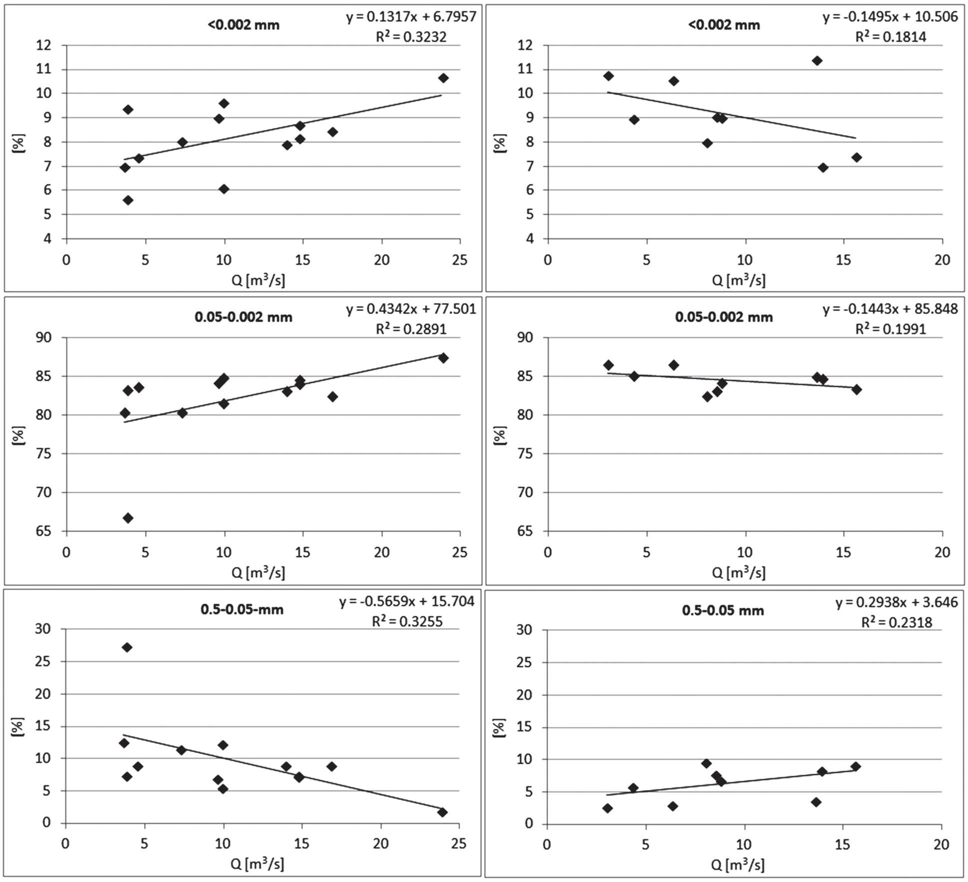

Fig. 2. The percentage of selected fractions of the suspended sediment at a certain discharge in the rising and falling limb in Bystrzanka stream

a result of the sorting process and processes of mechanical grain disintegration. In the Bystrzanka stream, the percentage of each fraction in flooding is closer to the fractional composition recorded in the Beskidy Mountains of Carpathians. This indicates a greater impact of the Beskids' tributaries than of the tributaries of Carpathian Foothills on the development of floods in the Bystrzanka stream and delivery of the material.

In the phi scale, there was also determined the standard deviation (δ_1) according to R.L. Folk and W.C. Ward (1957). The material collected during the floods in 2010 and 2011 was marked by poor sorting (on average: 1.66), except for one sample in Bystrzanka stream during the September flood in 2010, when the material was very poorly sorted and the sand fraction was then up to 28%, which may indicate an anthropogenic origin of the material from the areas covered by stabilization works in the channel after a large flood which was recorded in June 2010 (Kijowska-Strugała 2012). The mean grain diameter (Mz) in the water gauge profile of Bystrzanka stream was 6.39, while in the tributary part of the Beskids and Carpathian Foothills it was 6.50.

There was also carried out an analysis of the grain size of samples taken during rising and decreasing limb of the flood in the estuarial part of the stream (near water gauge). The studies have shown that in the rising limb phase, with increasing discharge rate the sand percentage decreases and the finer fraction percentage, of silt and clay, increases. A strong turbulence in the initial rising limb phase facilitates maintaining the sand fraction in suspension. During the decreasing limb, this relationship is reversed (Fig. 2). Similar patterns have been observed in a small catchment in the UK (Slattery, Burt 1997). The higher sand content in the initial rising limb phase may result in redeposition of the material in the channel. At the same time, in Bystrzanka stream, it has been found that for the same discharge, the sand fraction content in the rising limb phase has a higher percentage than in the falling limb vice versa in the case of the finest fraction. This is due to falling of larger grains at the time of reducing the discharge. An example is the flood of June 2010, when, during the increasing discharge, there was recorded a higher percentage of sand fraction (8%) than in the decreasing phase (4%), unlike the finest clay fraction. High SSC values recorded during the flood, increased the viscosity of water which, together with considerable turbulence, helped to maintain sand and silt particles in suspension. The final flood phases were marked by little SSC, despite the intense grey-brown colour indicating a relatively large amount of the colloidal fraction. During the flood of 31.08–1.09.2010 r., in the rising limb phase, there was recorded the highest sand fraction, 28%. The maximum discharge was 5.1 m^3s^{-1}, and the maximum daily rainfall was 42 mm. W. Froehlich (1982) noted a similar sand fraction percentage (35%) in the mountain stream during floods caused by torrential downpours. The high sand fraction in the stream during this flood indicates an allochthonous origin of the material. The material could be the result of engineering works aimed at strengthening selected, significantly transformed sections of the Bystrzanka course, damaged during the floods in May and June 2010. In addition, the high sand content can indicate that the material derives from cleared roadside ditches.

The studies in other small catchments show a temporal variation of fractional composition during the individual floods (Slattery, Burt 1997). Such variability has been attributed to temporal variations in the nature and efficiency of the sediment delivery processes operating during storms, the importance of particular sediment sources, and the operation of in-stream processes.

IMPLICATIONS OF CHANGES IN FRACTIONAL COMPOSITION

The study of correlation between particular fractions, as well as hydro-meteorological parameters in the estuarial section of Bystrzanka stream helped to identify some statistically significant relationships (Table 3). With the increase

Table 3

Pearson correlation coefficient matrix between the following variables in Bystrzanka stream in the water gauge: precipitaion (P); discharge (Q); suspended sediment concentration (SSC); sand (Sd); silt (St); clay (C)

	P	Q	SSC	Sd	St	C
P	1					
Q	**0.77**	1				
SSC	0.27	**0.71**	1			
Sd	–0.31	–0.31	–0.23	1		
St	0.27	0.34	0.26	**–0.98**	1	
C	0.33	0.17	0.10	**–0.82**	**0.67**	1

Numbers in bold are significantly different.

of sand in the water, there declines the silt and clay content, while the increase in the silt and clay content causes a decrease in the sand percentage. There was also noted a positive correlation of the finest fraction content. Based on the analysis of selected samples, there was no statistically significant impact of the amount of SSC and precipitation on the size of transported mineral particles. Studies in the Bystrzanka catchemnt also confirmed that general relation between increasing water discharge and particle size is incompatible with the traditional view of a positive relationship between these variables (Lenzi, Marchi 2000). M.C. Slattery and T.P. Burt (1997) noticed that the influx of silt and clay, predominantly the former, originating on the catchment slopes and brought to the stream by overland flow along vehicle wheelings, roads and tracks; and erosion of fine material from the channel bed and banks is the major cause of reducing the particle size of the suspended material in the river with an increase of the water flow, in the catchment used for agricultural purposes in southern England. They suggest that, while the suspended sediment load generally becomes finer as discharge increases, the sediment also becomes less well aggregated, probably due to increased turbulence and hence greater aggregate breakdown, at higher flow. D.E. Walling and P.W. Moorehead (1987, 1989) and D.E. Walling and B.W. Webb (1992) have made studies on the spatial and temporal variations of grain-size characteristics of suspended sediment in some British rivers. They have found that at local scales, the relationship between suspended sediment and water discharge is complicated and can be generalized as different patterns. The principal reason for this variability in the sediment size/discharge relationship is, of course, that the suspended load is affected not only by the hydraulic conditions within the channel but also by the dynamics of erosion and sediment delivery processes operating throughout the entire catchment (Slattery, Burt 1997).

In the Beskids' tributary to Bystrzanka, unlike to main stream, there was a statistically significant, $p<0.05$, relationship between SSC and clay and sand fractions. A positive correlation was noted for clay, while for sand it was negative.

CONCLUSIONS

The analysis of fractional composition of the suspended material, collected during the summer floods in 2010–2011 (nine floods) along the longitudinal profile of the Bystrzanka stream and its tributaries from the Beskids and Carpathian Foothills showed that:

– the silt fraction is the dominant material transported during floods. The average content of the fraction varies from 67 to 88% along the longitudinal profile of the main stream, from 82 to 86% in the Beskids' tributary and from 80 to 86% in the Carpathian Foothills' tributary;
– the highest standard deviation was recorded in relation to the sand fraction (Bystrzanka stream – the longitudinal profile – 58%, the Beskids' and Carpathian Foothills' tributaries – 42%). The high sand content in the main stream resulted from the human activity (stabilization channel works) within the stream channel;
– in the Beskids' tributary, on average, there was recorded a higher content of the sand fraction and lower content of the silt and clay fraction in comparison to the Carpathian Foothills' tributary;
– along with the course of the main stream, there was no statistically significant changes in the fractional composition of the suspended material;
– in the estuarial section of the main stream, there was observed a statistically significant (<0.05) inverse relationship between the sand and silt fraction and the sand and clay fraction as well as no statistically significant influence of factors controlling summer floods on the size of suspended sediment;
– during the rising limb phase, the sand fraction content showed a higher percentage content (in the same water level), than during the falling limb and contrary in the case of the finest fraction.

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