S T U D I A G E O M O R P H O L O G I C A C A R P A T H O - B A L C A N I C A

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IMPACT OF DOWNPOURS ON FLUVIAL PROCESSES IN THE POLISH CARPATHIANS AS EXEMPLIFIED BY THE BYSTRZANKA STREAM

Abstract. This paper present the results of the geomorphological mapping of transformations in the Bystrzanka channel after the rainfall in May and June 2010. Mapping data from June 2010 were compared to observations from April 2010. Total rainfall in the 20-day period from 15 May to 3 June was 320.4 mm, which constituted the highest two-decade value in the last 40 years. Research of concentration of suspended sediments showed that sediments concentration in the main tributary (Gerucha) during the flood on June was up to 4.5 times higher than the concentration in the Bystrzanka. High discharge (57.7 $m^3 \cdot s^{-1}$) have caused significant transformations of the Bystrzanka channel (main stream 7,1 km, area 13 km^2). Numerous cut banks occurred at an irregular fashion along the whole length of the stream. Cut banks of the channel most often reached the height of 2 m. Point bars and central bars of varied size and shape, depending on channel morphology, were observed along the whole length of the study channel and consisted mainly of sand, gravel, and boulders both abraded (in varying degrees) and non-abraded. Also observed was the activation of rotational landslides at the stream banks, the fronts of which almost entirely blocked the bottom of the stream. High discharge during the flood caused damage to the road, resulting in the riverbank receding by about 10 m.

Key words: downpours, fluvial processes, Bystrzanka stream, Polish Carpathians

INTRODUCTION

Precipitation is the main factor in land forming. The intensity of denudation, erosion, and accumulation on slopes and in the bottoms of valleys depends on volume, duration, and local scope of rainfall (Kaszowski, Kotarba 1970; Starkel 1976, Welc 1988, Kostrzewski et al. 1992, Kotarba 2002). Intense rainstorms often coincide with continuous rainfall over large areas that last for several days, resulting in a rapid water level rises and significant transformations of river channels. River channels in the Carpathian Mountains are characterized by a high runoff diversity stemming from, e.g., rainfall and low retention of the catchment (Soja 2002). L. Starkel (1976) distinguished three types of land forming rainfall in the Carpathians. The divisions are made according to the rainfall's volume, duration, and rate: short-duration, small-area rainfall of a rate of 2–4 mm · min^{-1} and a daily total of 100–150 mm that cause intensive soil and rocky slope wash and local flooding in small catchments; rainfall lasting for several days at a rate of up to 10 mm · h^{-1} and a total of 200–500 mm over larger catchments that cause landslides and suffosion; and low-rate rainfall that lasts for several weeks or sometimes several months for a total of 100–200 mm per month that cause oversaturation of water in the soil, deep landslides, and bank erosion.

In recent years, the problem of extreme hydrometeorological phenomena has gained particular significance (Goudie 2006, Guzzeti et al. 2007, Alcántara-Ayala 2010, Frandorfer, Lehotsky 2011; Starkel 2011). Land forming processes are several orders of magnitude more intense during extreme hydrometeorological phenomena than during average conditions (Gil, Starkel 1979; Rodzik et al. 1998, Ziętara 2002, Krzemień, Gorczyca 2010). Such phenomena involve both bedload transport and the transformation of river channels and floodplains. The morphological role of flood in the Polish Carpathians continues to be the subject of numerous publications. T. Ziętara (1968) analyzed extreme rainfall in the catchment of the Soła River from 1958 to 1960. W. Froehlich (1972) analyzed fluvial transport in the catchment of the Kamienica Nawojowska River, while M. Niemirowski (1972) analyzed it in the catchment of the Jaszcze and Jamne streams, which is where A. Bucała (2009) also maintains her research, seeking, for instance, to demonstrate the role of heavy rains that cause greater transformations of stream channels than of slopes in the Gorce Mountain range (Western Carpathians). Similar research that has been conducted in the Łososina catchment in the Island Beskids (Gorczyca 2004) showed a morphological influence of freshet waves mainly related to erosion and bedload transport. E. Cebulak et al. (2008) conducted research in 2005 in the upper catchment of the San River after heavy rains of up to 80 mm per day, and observed intense lowering of the river channel, bank erosion, and accumulation of material in the form of point bars and central bars. M. Długosz (2011) analyzed the role of precipitation in the Gubałowskie Foothills and observed that the greatest transformations occurred in the middle parts of river channels, where smaller side valleys converge. A. Welc (1988) analyzed the impact of volume and spatial diversity of rainfall in the channel of the Bystrzanka on sediment transport. Maximum sediment concentrations were observed mainly during heavy rainfalls over the middle and upper parts of the asymmetrical catchment.

The aim of this article is to evaluate the role of downpours in shaping stream channel in a small Carpathian catchment. The research was conducted in the Bystrzanka catchment after heavy rains that occurred in May and June 2010. A clustering of flood that occurred over a short time resulted in significant transformations of the stream channel. Research conducted in small catchments, such as the Bystrzanka catchment, is of key importance in understanding the role of rainfall in shaping the morphodynamic processes of the Polish Carpathians.

THE AREA AND METHOD OF RESEARCH

The catchment of the Bystrzanka (Fig. 1) has a surface area of 13 km^2 and is located on the border of two geographical units of the Carpathians: the Carpathian Foothills and the Low Beskids (Starkel 1972). The northeastern part of the catchment is located in the Magura layered-sandstone Beskid region (Kozikowski 1956) up to 753 m a.s.l. high (Maślana Mountain). The north-east-facing Beskid slopes (15–35° gradient) (Dauksza et al. 1970) are covered with forest. The remaining part of the catchment is comprised of wide, flat-topped hummocks up to 500 m a.s.l. and predominantly 8–15° in gradient that are composed of shale-sandstone Cretaceous layers. The majority of the Carpathian Foothills area is covered with grasslands and, to a lesser extent, farmlands. Bystrzanka is a 7.1-km-long left tributary of the Ropa River with a mean gradient of 26‰. Its springs are located at 560 m a.s.l. In its upper part, the Bystrzanka is a typical V-shaped valley with a narrow bottom and steep slopes up to 15 m high; in its middle part, the valley is a few dozen meters wide. The stream chan-

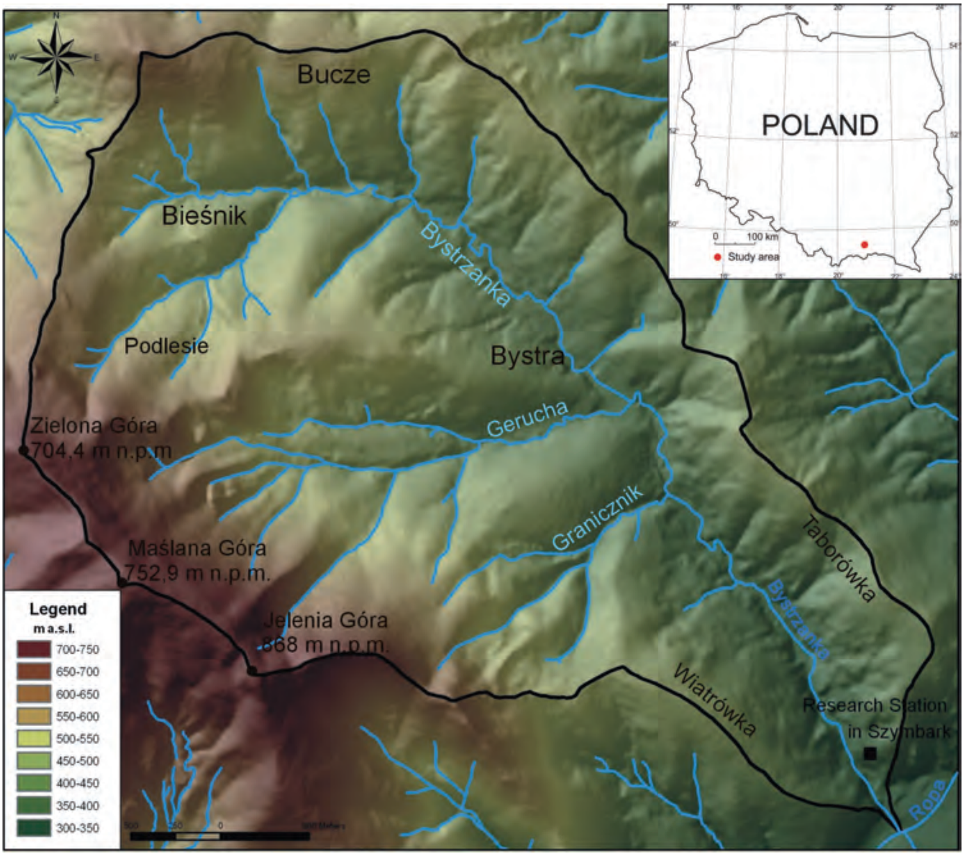


Fig. 1. Area of research (Source: self-reported data on the basis of topographic map 1 : 10,000)

nel widens systematically with distance: from 3–4 m at its middle part to about 13 m at its mouth. Drainage density of permanent streams in the catchment is 1.5 km · km^{-2} and drainage density of periodic streams is 1.1 km · km^{-2} (D a u k s z a et al. 1970). The Gerucha Stream (Fig. 1), which is Bystrzanka's longest tributary, is 3.1 km long, is located in a deep V-shaped valley, and carries water coming from the forest-covered slopes of Maślana Mountain. Tributaries of main stream have an important role in the shaping of the freshet wave, both in delaying or hurrying the culmination wave (W e l c 1988).

The most common soil in the Bystrzanka catchment is cambisols, classified as medium and heavy clays (A d a m c z y k et al. 1973), with a relatively low water capacity. The weathered cover, with a large content of stone fraction on the slopes, reaches several meters in thickness.

Average total annual rainfall for the 1968–2010 period is 832.2 mm and the average annual temperature is 7.9°C. Discharge values observed for the Bystrzanka are diverse. Increased surface runoff from the Bystrzanka catchment can be observed mainly from February to April, and in the summer (from May to October) (K i j o w s k a 2011a). Ordinary flood due to rainfall are the most common type of flood in the catchment. These rises are relatively rare (only 7% of the water year), short (3.2 days), and with one, usually single, culmination wave. Winter rises are longer, which is connected to the way the stream channel receives water from the (usually slowly) thawing snow layer and different parts of the asymmetrical catchment. The average discharge in the Bystrzanka is 0.18 m^{3} · s^{-1} (1994–2010). Discharge values recorded in the Bystrzanka are typical for the eastern macroregion, with the majority of discharge taking place from November to April (54%) (Z i e m o ń s k a 1973, K i j o w s k a 2011a).

Several days after heavy rainfall in June, geomorphological research was conducted to investigate transformations in the morphology of the bottom of the Bystrzanka valley that involved recording the effects of flood in terms of erosion and accumulation of material over the length of about 5.5 km in the lower and middle parts of the stream. During the research, geomorphological mapping of transformations in the stream channel was performed. Measurements were taken of the height and depth of cut banks, sediment thickness, size of pot-holes, size of point bars and central bars, diameter of bedload fraction on the surface of the bars, and torrential fans at the mouths of side valleys. Mapping data from June 2010 were compared to observations from April 2010. In addition, cross- sections were created at selected points of the stream channel. The concentration of transported sediments during the flood was measured using the drying and weighting method. Samples measuring 1.0 L were taken from the main stream and its tributaries. The number of samples taken was adjusted to the rate of water level changes. Local variation of total rainfall in the Bystrzanka catchment was determined using a Hellman rain gauge in the lower and middle parts of the catchment, and rainfall rate was determined using a remote rain gauge, located at the Research Station of the Institute of Geography and Spatial Organization

Polish Academy of Science (IG&SO PAS) in Szymbark. Discharge values in the Bystrzanka channel were obtained from hydrographic water level records at the mouth of the stream.

RAINFALL IN MAY AND JUNE 2010

In May 2010, extraordinarily intense rainfall was observed in southern Poland, especially in the marginal and western parts of the Carpathians. The deciding factors affecting the rate and volume of the rainfall were very humid air lingering over Poland and a corresponding high thickness of stratus clouds and a strong, northerly wind in the lower troposphere. Total monthly rainfall in May and June 2010 in Poland was strongly diversified between different areas. The range of monthly values was very wide, stretching from below 100 mm in the western part of the country to over 500 mm in southern Poland.

Rainfall at the Research Station in Szymbark in May and June amounted to 210.2 mm and 222.5 mm, respectively, and in Bystra amounted to 237.3 mm and 200.9 mm (Fig. 2). Total rainfall in May was the highest recorded value for that month at the station in Szymbark since the beginning of the station's operation (1968) and constituted 224% of the long-term average total monthly rainfall for May, and 25% of the average total annual rainfall (Fig. 3). During that month, the rain lasted 27 days (13 days without stopping). Total rainfall in June was almost twice as high as the monthly norm (124.7 mm) and constituted 27% of the average long-term total rainfall. The highest total daily rainfall of 107 mm was recorded on 3 June, with the maximum intensity of 0.85 mm · min^{-1}. The

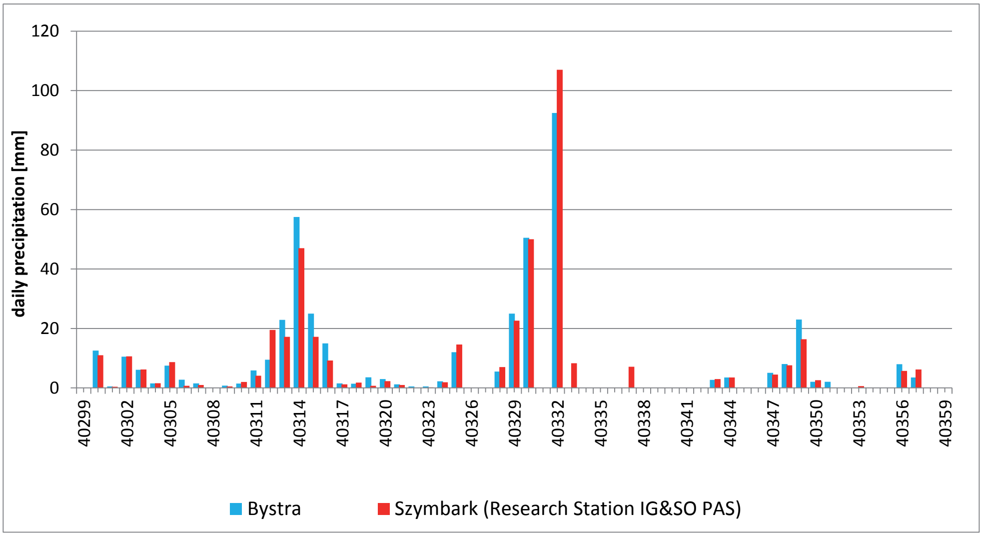


Fig. 2. Total daily rainfall recorded in May and June 2010 in Bystra and Szymbark (Research Station IG&SO PAS) (Source: self-reported data)

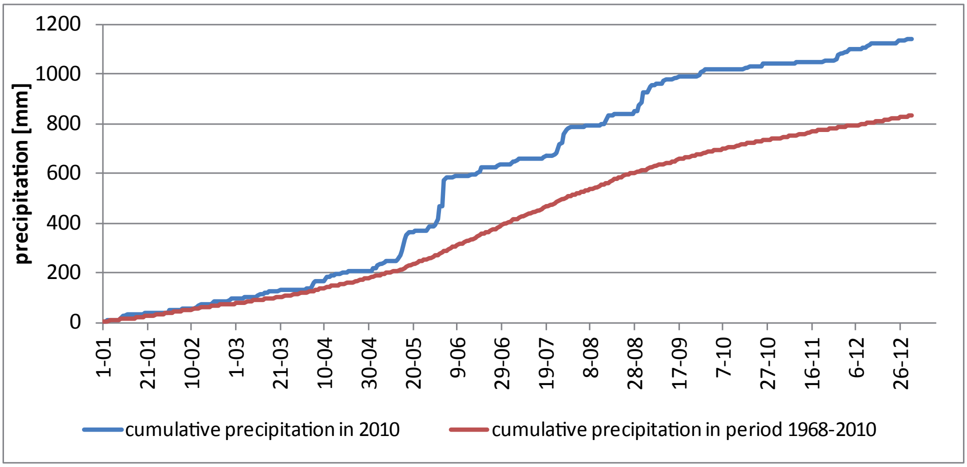


Fig. 3. Cumulative total daily rainfall in 2010 with marked periods of intense rain in May and June, with average total rainfall in the 1968–2010 period. (Source: Research Station in Szymbark)

probability of such heavy daily rainfall occurring is 3.9% (less than once per 25 years). The highest total hourly rainfall was 28.0 mm and occurred between 4:00 a.m. and 5:00 a.m. on 4 June. Calculated according to the precipitation efficiency classification developed by K. Chomicz (1951), and based on total rainfall and duration of rainfall, the precipitation efficiency coefficient α was 3.61, thus classifying the rainfall as "III degree downpours." Total rainfall in the 20-day period from 15 May to 3 June was 320.4 mm, which constituted the highest two-decade value in the last 40 years. The probability of such total rainfall occurring is 4.7% (less than once per 20 years).

IMPACT OF DOWNPOURS ON FLUVIAL PROCESSES

DISCHARGE VALUES

The co-occurrence of different types of rainstorms and continuous rainfall in the Bystrzanka catchment in 2010 caused rapid water level rises, accompanied by high discharge that resulted in the transformations of the stream channel and slope destabilization.

Discharge values in the Bystrzanka catchment during the flood in June were significantly higher than the values from May. The downpours of 107.0 mm (3 June 2010) that occurred towards the end of the rain period in May, especially after the rainfalls of 80 mm from 29 May to 1 June, had a significant impact on the effect and intensity of landforming processes. The rains caused such a quick water level rise in the stream channel because of the complete saturation of soil with water. A record discharge of 57.7 $m^3 \cdot s^{-1}$ (Fig. 4) (40.3 $m^3 \cdot s^{-1}$ higher than the instantaneous discharge on 17–18 May) was observed in the Bystrzanka stream

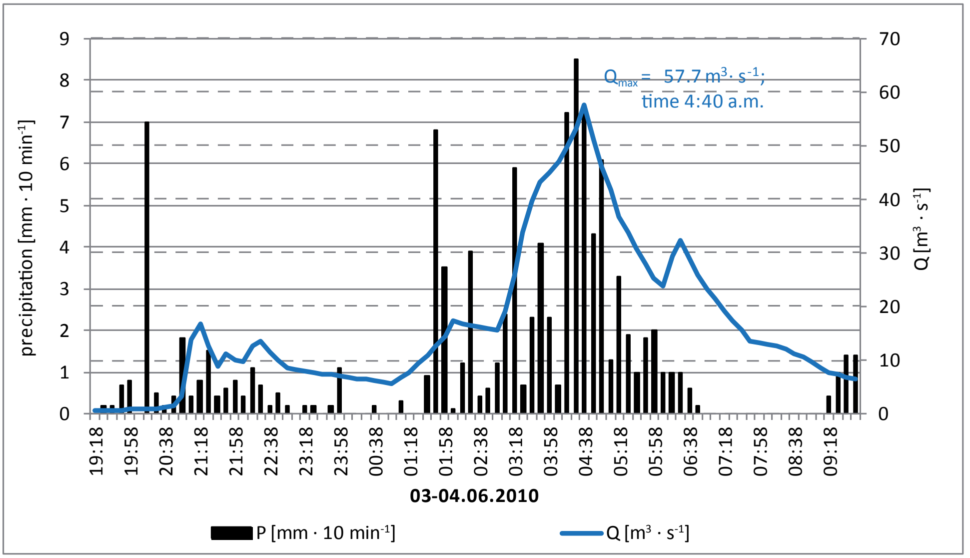


Fig. 4. Rainfall and discharge in Bystrzanka at June 3–4, 2010.
(Source: Research Station in Szymbark)

at 4:40 a.m. on June 4, 2010, caused by intense rainfall that lasted without stopping for over 3 hours and reached the total of 60 mm before the culmination of flood. Average daily discharge then was 11.67 $m^3 \cdot s^{-1}$, which is 60 times higher than the average discharge for the long-term period of 1994–2010.

SUSPENDED SEDIMENTS CONCENTRATION

During the floods in 2010, water samples were taken at five locations to determine the concentration of sediments: along the Bystrzanka riverbank, in the main right tributary (Gerucha), and in a tributary in the foothills part of catchment. A total of five monitoring points were chosen in the catchment (Fig. 5). Research showed that suspended sediments concentration in the Gerucha during the flood on 4 June was up to 4.5 times higher than the concentration in the Bystrzanka at point 2, which is related to intense rainfall in the forest-covered part of the catchment and to the increased erosion in the V-valley channel, i.e., the deepening of the channel and erosion of slopes, and to the soft unmetalled roads in the forest. Even though no actual measurements of rainfall intensity in the Beskid region were taken (the data were obtained using a Hellman's rain gauge), the scope of sediment transport and erosion in the stream channel allows for the conclusion that the rainfall intensity was higher than the rainfall intensity at the mouth of the Bystrzanka.

Research done by A. W e l c (1988) in the 1970's has shown that sediment concentration in the Bystrzanka is related to, among other factors, total rainfall

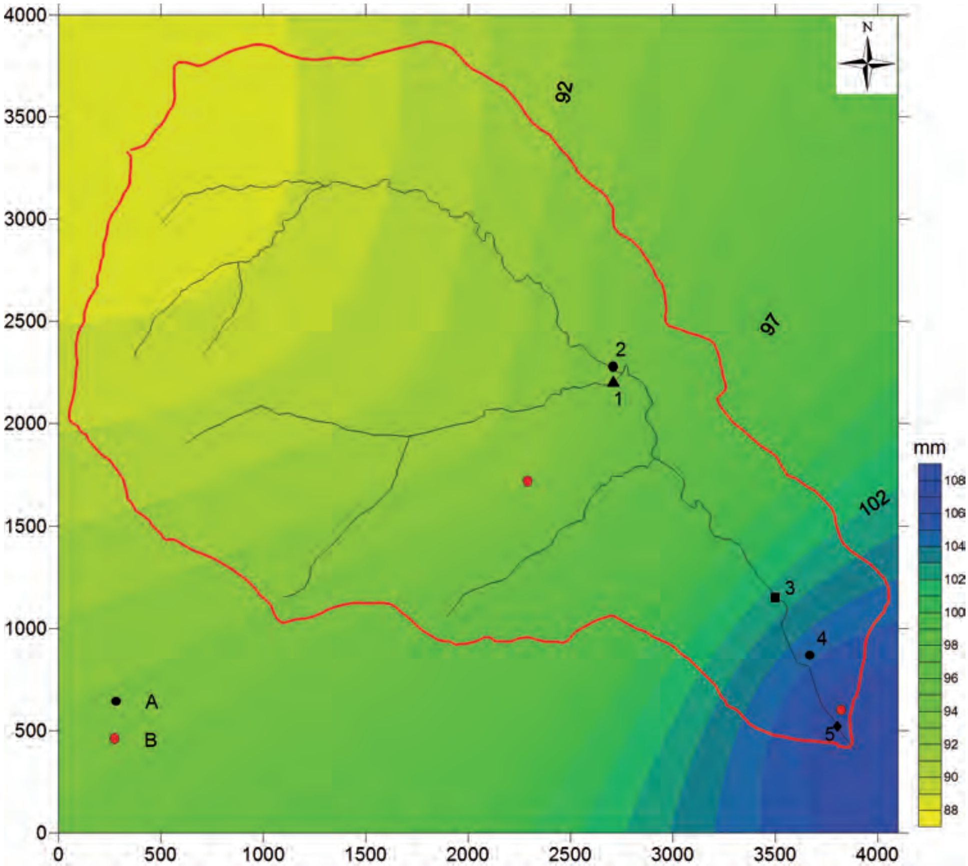


Fig. 5. Total daily rainfall at June 4, 2010, in the Bystrzanka catchment.
A — water sampling points, B — rain gauge x and y axis — distance in meters
(Source: self-reported data)

and rainfall intensity values in the catchment. He concluded that sediment transport is several times more intense during water level rises caused by extreme rains in the upper part of the catchment than for similar rains at the mouth of the catchment. Such diversity is mainly due to the shape of the catchment, land use, and an increasing surface to stream length ratio in the middle and upper part of the catchment compared to its mouth area. Sediment concentration along the Bystrzanka channel during the flood in June increased with the increase of the surface of the catchment, which is characteristic for mountain rivers (Froehlich 1975, Krzemień 1991). Maximum suspended sediment concentration measured in the mouth of Bystrzanka (where it flows into the Ropa) showed significant diversity, with the highest measured value of 45 $g \cdot dm^{-3}$ (Fig. 6). Maximum sediment concentration occurred about 30 minutes before the culmination of flood. Equally high values of suspended sediment (33.4 $g \cdot dm^{-3}$)

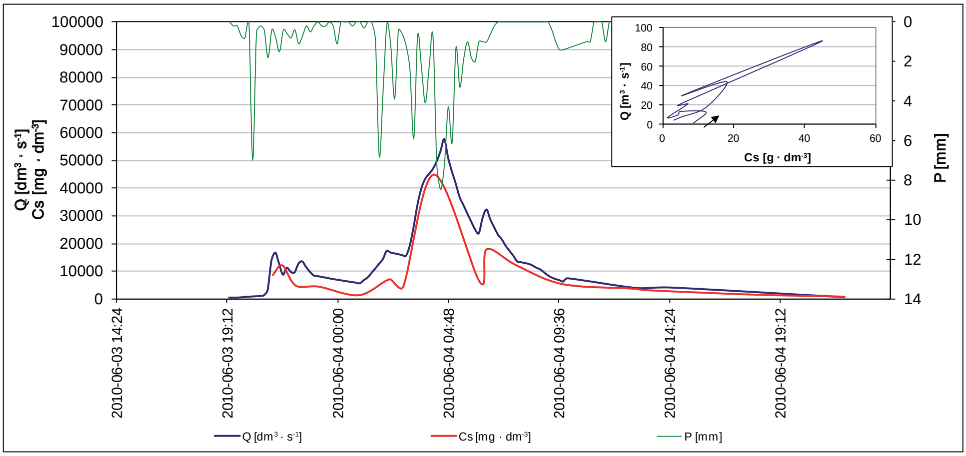


Fig. 6. Sediment concentration during the flood in June 2010 and the hysteresis.
(Source: self-reported data)

recorded in July 2002 and were preceded by precipitation that reached maximum intensity of 24 mm · h^{-1} (Kijowska, Bochenek 2011). The hysteresis has a complicated shape due to several floods, similar to the hysteresis for the water level rise in May. This indicates a complex mechanism of sediment inflow into the stream channel. The shape of the hysteresis also provides information on the stream's transport capacity during different culmination wave, the inflow of sediment, and hydrodynamic conditions in the stream channel (Froehlich 1975). Hysteresis during the flood in May and June were narrow, which was caused by a small difference between sediment inflows during the increase and decrease of wave. Numerous landslides and slope cuts were the primary source of the transported material in the stream, together with the material coming from tributaries and anthropogenic embankments in the Bystrzanka channel erected during regulatory works in 2009. During the June flood was carried out 16843 tones of suspended material.

GEOMORPHOLOGICAL EFFECTS OF FLOOD IN BYSTRZANKA STREAM

High discharge values have caused significant transformations of the Bystrzanka channel. Numerous cut banks occurred at an irregular fashion along the whole length of the stream. Significant bank cuts over 7 m high were connected to the development of bank landslides up to 4 m high that occurred due to the soil being completely saturated with water. The newly formed cut banks along the whole length of the channel most often reached the height of 2 m (about 50%). A definite correlation was observed between water erosion and the concave part of the meanders, where the process was the most intense. The water level rises caused severe erosion of unstable, newly formed banks on the opposite side of the gabions erected in 2009 about 700 m and 1200 m from the mouth of the Bystrzanka, thus removing the weathered material that was brought there during the works in 2009 (Fig. 7). The channel width decreased by 2 m compared to April 2009. The parts of the channel with rock outcrops functioned as passageways for the bedload transport. Potholes up to 1.5 m high formed below rock ledges and in the mouths of the tributaries.

Fig. 7. Erosion of banks in the Bystrzanka during the flood in 2010 (1 — April 2010, 2 — June 2010) (Photo M. Kijowska-Strugała)

Point bars and central bars of varied size and shape, depending on channel morphology, were observed along the whole length of the channel and consisted mainly of sand, gravel, and boulders both abraded (in varying degrees) and non-abraded. The surface area of point bars and central bars reached a maximum of 250 m^2. The combined length of the bars was estimated at about 2450 m, which constituted about 45% of the mapped length of Bystrzanka. Areas of largest bedload deposits were located downstream huge erosive cuts. Slopes adjoining the stream channel were cutted by rills and gullies that transported material from the slopes to the channel, thus forming alluvial fans up to 25 m wide, 5 m long, and about 0.6 m thick. These fans caused the narrowing of the river channel. Their development indicates a significant role of tributaries and gullies in the shaping of the channel. Sediment deposition and a building up of fluvial terraces occurred in areas where the banks were no higher than 1 m. The diameter of the material (sand, gravel, and pebbles) reached about 0.5 m. Also observed was the activation of rotational bank faillures at the stream, the fronts of which almost entirely blocked the bottom of the stream. The landslides carried material composed of clay, rubble and boulders, with the addition of many trees and bushes. Numerous areas strewn with wooden debris, e.g., in front of bridges, blocked the transport of material, as did the damaged gabions. The size of sandstone boulders, more than 1 m in diameter, that were found along the whole length of the stream channel indicates the great amount of energy held by the flowing water. These boulders amassed in several places, filing the whole width of the channel (Fig. 8). Because the outflow from the Bystrzanka was blocked by high water level in the Ropa River, a partial accumulation of

Fig. 8. Accumulated angular boulders in the middle part of the Bystrzanka stream
(Photo M. Kijowska-Strugała)

material occurred in the mouth of the Bystrzanka. The material, carried from the catchment, had a surface area of about 950 m^2 (Fig. 9) and was composed mainly of boulders, gravel, and pebbles.

High discharge during the flood also caused damage to the Szymbark-Szalowa local road in the village of Bystra, resulting in the riverbank receding by about 10 m (Fig. 10). The difference between the cross sections of the channel taken before and after the rise amounted to 8 m^2. At several points along the river, concrete reinforcements of banks were damaged, making it impossible for the local residents to cross the stream. Intense rainfall in 2010 also caused the deterioration of concrete bank reinforcements along the tributaries of Bystrzanka stream. The main role of these reinforcements was to limit the erosion of the stream's bottom and banks that leads to the destabilization of valley slopes and riverbanks.

Downpours in southern Poland in 2010 also caused major transformations in other regions of the Polish Carpathians. In the catchment of the Suszanka Stream (a tributary of the Raba), the flood wave reached about 2 m in height and caused a significant transformation of the channel of the stream that resulted in its deepening. The flood also caused bank undercuts that measured up to 82 m in length, as well as caused the riverbanks to recede in distances of up to 15 m (Bucała, Budek 2011). The heavy and long-lasting rainfall

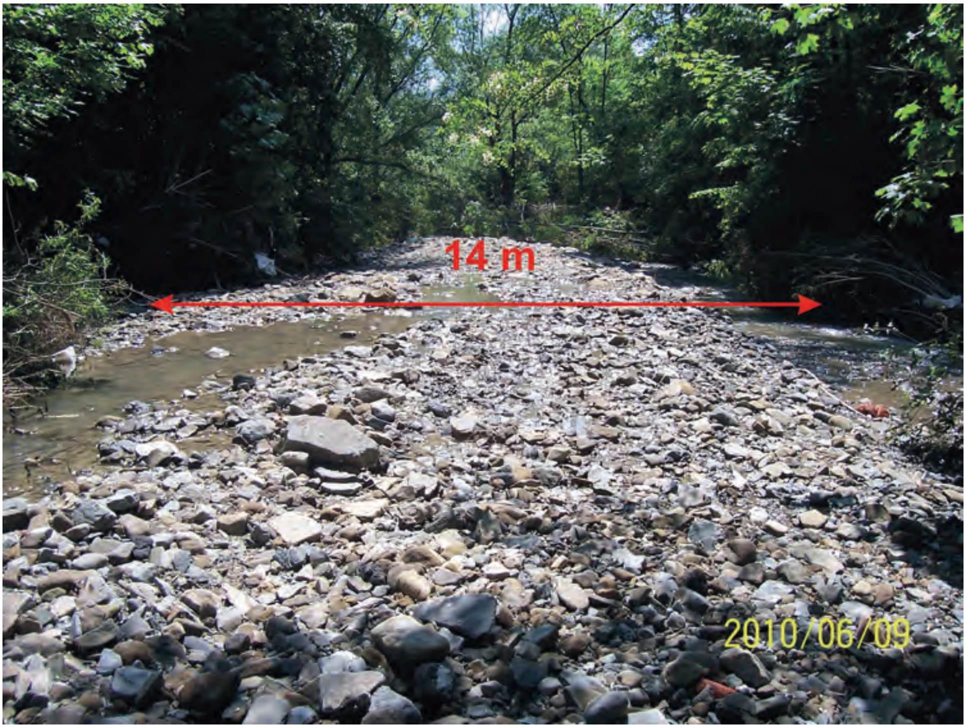
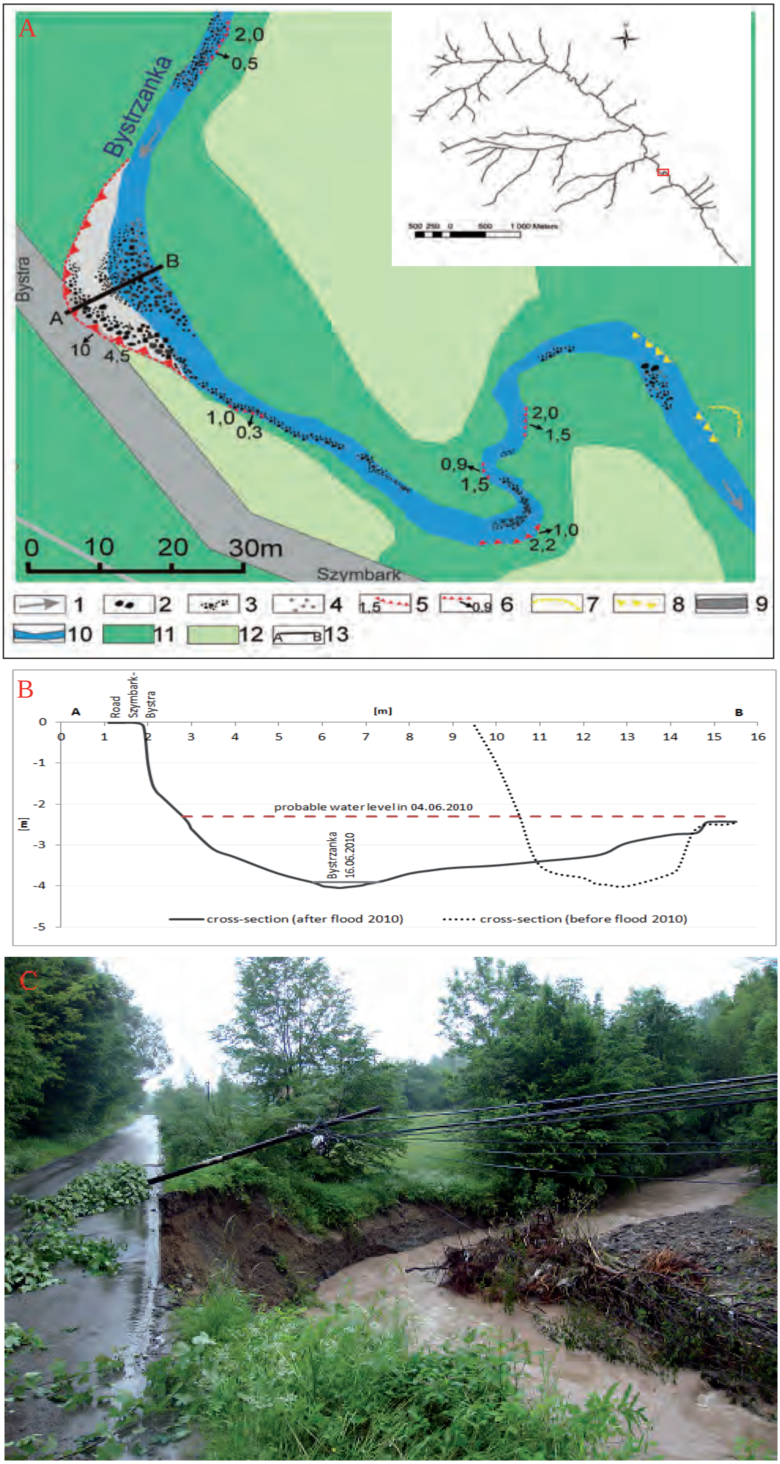


Fig. 9. Newly formed fan in the mouth of the Bystrzanka, formed as a result of the flood in May and June 2010 (Photo E.Gil)

that sometimes exceeded 90 mm per day (Institute of Geography and Spatial Management, Jagiellonian University, Research Station in Łazy) resulted in slope wash, surface runoff, and rill wash of the soil, creating a network of rills and very deep gullies transforming into gorges that constituted a passageway for the outflow of soil material onto a corn field. These newly formed gullies measured up to 3 m deep and up to 39 m long. The estimated volume of material eroded from two deep gullies was about 317 m^3. Part of the material traveled through a trench along a road to the stream, while another part accumulated in an area of flat land at the footslope, creating a proluvial – deluvial fan (Kijowska 2011b). Slope shape transformations and huge material loss in southern Poland in 2010 also caused new and renewed landslides (Bajgier-Kowalska 2011). More than 30 landslides having a surface area of several square meters to 20 ha

Fig. 10. Geomorphological and economic effects of flood caused by downpours in the middle part of the Bystrzanka. A. Geomorphological plan of transformations in the channel of the Bystrzanka. 1 – direction of runoff, 2 – non-abraded boulders, 3 – gravel and sand, 4 – boulders, 5 – erosive undercut (height in m), 6 – erosive undercut (depth in m), 7 – area of landslide, 8 – weathered areas (landslides), 9 – local road, 10 – river, 11 – tree-covered area, 12 – meadows and grassland, 13 – cross section. B. Cross section of the river channel. C. Road damages (Source: self-reported data, Photo M. Kijowska-Strugała)


A
Bystrzanka
2,0
0,5
Bystra
B
A
10
4,5
1,0
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0,9
1,5
1,0
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0 10 20 30m
Szymbark
1 2 3 4 5 6 7 8 9
10 11 12 13
B
A
[m]
B
Road Szymbark-Bystra
probable water level in 04.06.2010
Bystrzanka 16.06.2010
[m]
cross-section (after flood 2010)
cross-section (before flood 2010)
C

occurred in the Lanckorona commune over a period of four days (17–20 May), causing significant damage to housing and technical infrastructure. The landslides occurred mainly due to the clay cover and the underlying layer of loam, loose rocks, and interbedded slate with sandstone being saturated with water (Bajgier-Kowalska 2011).

CONCLUSIONS

Rainfall that occurred in May and June 2010 in southern Poland was extreme in nature and caused significant transformations in the Bystrzanka channel. The order in which the morphological changes of the stream channel occurred indicates a prevalence of erosion in narrow initial sections of the Bystrzanka valley and in its tributaries. It also indicated accumulation in the mouth of the stream. The middle part of the Bystrzanka showed a greater diversity of channel transformations and alternating areas of accumulation and erosion, with the prevalence of bank erosion over bottom erosion. This frequently resulted in the renewal of previous cut banks and new ones forming up to 7 m high. Most severe erosion occurred on concave banks, where numerous rotational landslides took place, locally blocking almost the entire river channel with material composed of clay, rubble and boulders, causing flood and, in front of the blockages, the accumulation of material and wooden debris. The damaged gabions, together with the wooden debris, constituted a barrier in the transport of material and at the same time creating potholes up to 1.5 m deep.

The material that eroded from the banks and landslides moved and accumulated mainly throughout the whole length of the river channel, creating point bars and central bars up to 250 m^2 in surface area. The transported material consisted of particles more than 1 m in diameter; also transported were large quantities of sediments primarily from the eroded channel of the Bystrzanka and its tributaries, causing the building up of floodplains in many areas.

The scope of the observed transformations in the channel of the Bystrzanka during the flood in 2010 supports the hypothesis that high-volume, high-intensity rainfall is the main river channel-shaping factor in mountainous regions.

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