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The role of catastrophic floods in shaping the morphology of river beds in small mountain catchment areas

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Abstract. Mountain streams are subjected to the continuous reshaping of their river beds during floods, with the greatest changes occurring during extreme floods caused by sudden and heavy rainfall. River bed transformations during these flash floods are more severe in forested areas, where wooden logs carried by swollen streams are more likely to be deposited on the ground, which in turn leads to the greater accumulation of other transported material and debris.

The study was conducted in the Rybny Potok catchment area (Babia Góra National Park). An extreme flash flood occurred on 15–16 May 2014 because of heavy rainfall, which, on 15 May amounted to 138 mm. The total amount of precipitation in the catchment area was 216.5 mm in three days. This resulted in sudden and full streams in spate, contributing to significant geomorphological transformations reaching all the way to the bottom of the river beds. During the flash flood, already established river beds and streams increased in size and many new river courses were formed.

Keywords: extreme events, flash flood, geomorphological transformations, Carpathians, forest

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1. Introduction

The streams of the Beskidy region are characterised by large fluctuations of flow during the year and, therefore, are subject to continuous modelling by the processes of erosion and accumulation. However, the greatest changes that occur within their channels and flood zones during violent floods are caused by torrential rainfall. Flash floods, however, are local phenomena (Bryndal 2008), affecting small areas, and thus have not been given much attention in the literature. But locally, they can result in a very high risk of flooding (Bryndal 2008 and 2011, Pociask-Karteczka, Żychowski 2014), which, especially in mountainous areas, can take on catastrophic proportions.

Flash floods occur in small catchment areas experiencing short-term (lasting up to several hours) but very intense rainfall (Parczewski 1960), whose range usually does not exceed 100 km^2. Additionally, the area affected in half of such cases does not even reach 25 km^2 (Lenart 1993; Bryndal 2010), thus flash floods occur in one or, at most, several small adjacent catchment areas.

The high water flowing within the catchment area can result in a significant transformation of the river bed and floodplain. In addition, these geomorphological transformations are intensified during floods in heavily forested catchment areas, where the flood zone is overgrown with dense tree stands and large amounts of organic matter can fall into the river channel. The transported large woody debris is deposited within the channel and floodplain terraces, with mineral material increasing its accumulation above these deposits (Gurnell et al. 1995; Gippel 1995; Wyżga et al., 2003, 2012; Wyżga 2007). In turn, channel erosion increases below these debris deposits (Franczak 2014), resulting in modifications to the hydraulic conditions of river (Wyżga et al. 2012).

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The study of flash floods in small mountain catchments and subsequently incurred geomorphological transformations has been undertaken by a small number of authors. These phenomena have been the subject of only individual studies thus far. Study results available in the literature in this field focus mainly on describing the course of the floods, the property damage caused in its wake and also the geomorphological transformations that occurred (Dębski 1969; Ciepielowski 1970; Żurawek 1999; Lach, Lewik 2002; Łach 2003; Gorczyca 2004; Bajgier-Kowalska, Ziętara 2008; Długosz, Gębica 2008; Gorczyca, Krzemień 2008; Gorczyca, Wrońska-Wałach 2008; Krzaklewski 2008; Izmaiłow et al. 2008; Bryndal 2009, 2011; Bucała Budek 2011; Starkel 2011; Bucała 2012; Franczak 2014a; Franczak, Listwan-Franczak 2015).

The aim of this study was to investigate the geomorphological changes caused by catastrophic floods in small mountain catchment areas having densely afforested flood zones. The study was conducted on the example of the flood in May 2014 in the upper catchment of the Skawica River.

2. Study site

The catchment area of the upper Skawica River, an area of 48.6 km^2, is located on the northern slopes of the Babia Góra Massif (Fig. 1). Towering over the Skawica valley, the Babia Góra Massif was thrust above the neighbouring mountain ridges by the isostatic uplifting of an element of a hanging wing during normal faulting activity. As a result, the northern slopes formed an edge zone (Jankowski, Margielewski 2014), rising approximately 500 m above the adjacent mountain ranges. The northern slopes of the massif form a cuesta, with a slope of 20° to more than 45° (Ziętara 2004). The upper parts of the catchment area (above approximately 1,000 m a.s.l.) are made up of resilient thick-bedded Magura sandstones, in turn, its lower fragment is made up of a thin-bedded hieroglyphic layer. A softer cover of Quaternary sediments is found at the foot of Babia Góra, within its valleys, forming Pleistocene and Holocene terraces and alluvial fans (Książkiewicz 1983). The predominant type of soil in the catchment area is poorly permeable acidic brown soils (Miechówka et al. 2004), on which evolved a classic layered plant system on the slopes: lower montane zone, upper montane zone, subalpine zone and alpine zone (Voloshin et al. 2000; Pasierbek et al. 2009).

The layout of the river network on the north side of the Babia Góra ridge is fan-like and convergent (Lajcak 1998, 2004), consisting of the Jaworzyna and Czatożanka streams and their main tributaries: Urwisko, Marków Potok, Rybny Potok, Dejaków Potok and Norczak. The largest of the studied catchments – Rybny Potok – has an area of 9.19 km^2. The Rybny Potok catchment area, located in the central part of the massif, has the largest catchment length (5.11 km) and watershed (19.77 km). The greatest average width of the catchment is located in the western and eastern part of the Czatożanki (1.56 km) and Jaworzyna (1.55 km) massif basins. Amongst the studied catchment areas, Rybny Potok is located at the highest altitude and has the greatest denivelation (1,041 m). The studied catchment areas were dominated by slopes between 10° and 30°. The largest share of slopes with a gradient exceeding 40° was in the Rybny Potok catchment area – 3.9% (Franczak et al. 2015). Inclines in the sections of streams' sources significantly exceeded 250‰. The incline of the streams decreases along their course. Marków Potok has the highest average incline (170‰), whilst Jaworzyna has the lowest (75‰).

Forests are a key element of the natural environment of Babia Góra. In the area of the Babiogórski National Park (BgPN), they comprise an area of 2,868 ha, which together with the area occupied by mountain pine (327 ha) means that forest and shrub communities cover 95% of the massif located within the national park (Holeksa et al. 2004). Sixteen species of trees grow in these forests. However, the species composition and structure of the forest stands are heterogeneous. Their differentiation is caused by local conditions in the landscape, such as

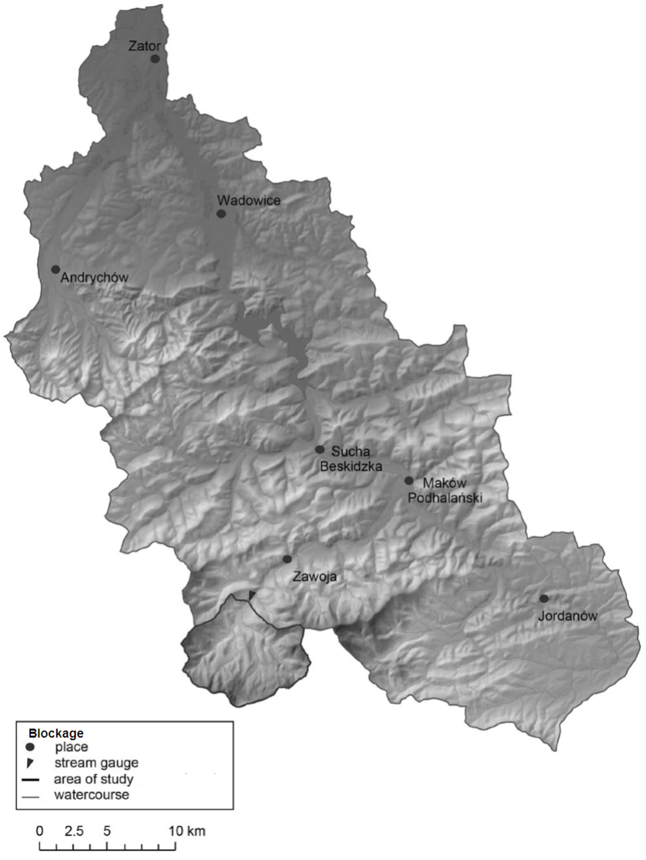

Figure 1. Location of the research area

Source: Author's own work

differences in altitude above sea level and exposure. Human activity also plays an important role, to greater or lesser intensity over the centuries (from intensive forest management to gradually introduced protection). The forests growing on the northern slopes of Babia Góra in the study area extend in a vertical scale from about 700 m a.s.l. in the lower section of the Rybny Potok, extending to an average altitude of 1,370 m a.s.l. in its upper limit (Czaja, Kaczka 2014).

The greatest differences in the structure and species composition of the forest in the study area occur in the lower forest. Habitats of fertile mountain beech forests (*Dentario enneaphylli-Fagetum* and *Dentario glandulosae-Fagetum*) close to primary and secondary monocultures of Norway spruce (*Picea abies* (L.) Karst.) are found there. Spruce dominates numerically, with 52% of trees; followed by beech (*Fagus sylvatica* L.) with 34%; and fir (*Abies alba* Mill.) with 7%. However, two areas can be distinguished in the lower montane. A lower area with stands wherein spruce is only slightly more than 40% with a somewhat lesser number of beech, 8% of fir and 1% of sycamore (*Acer pseudoplatanus* L.), grey alder (*Alnus incana* (L.) Moench) and ash (*Fraxinus excelsior* L.). However, in the upper portion of the lower montane zone, spruce makes up a significantly greater share of the stand, exceeding 60%. This diversity stems from the fact that the lowest part of the lower forest was incorporated into the park only in 1997 and had been intensively managed for economic purposes earlier. The density of trees in this part of the forest is 785 individuals/ha (volume of 312 m^3/ha), whilst the upper part of the lower forest is a much higher at 986 individuals/ha (volume of 431 m^3/ha). At the same time, stands of subalpine forests are much more homogeneous in species than the forests of the lower montane zone. Naturally growing spruce dominates there, with a mix of rowan (*Sorbus aucuparia*). The density of trees is much lower than in the lower montane zone, at 414 individuals/ha, but the volume is higher at 431 m^3/ha (Holeksa et al. 2004). This is due to the fact that a natural stand at its optimal stage and in the initial stage of decomposition is located there (Szwagrzyk et al. 1999). In the lower montane zone, the trees are much smaller and stand density is much higher than those in the older stands of the subalpine zone (Holeksa et al. 2004).

In the lower parts of the basin, large areas along the major streams are occupied by riverine grey alder (*Alnetum incanae*) and swamp grey alder (*Caltho-Alnetum*) communities. The former form extensive patches within the low terraces above the riverbeds of the Marków and Jaworzyna streams. They occur to a height of 780 m a.s.l. In turn, the communities of swamp grey alder grow mainly in depressions within the slopes and at the foot of the Marków, Rybny and Jaworzyna stream valleys. They occupy a total area of 34 ha along a range from 650 to 1,005 m a.s.l. (Parusel et al., 2004).

In addition to the diversity of species composition and stand structure, the study area also varies by the amount of residual dead wood present. The largest number of dead trees is found in the strict nature reserves, with an average of 96 trees/ha (with an average volume of 63 m^3/ha). In most of the BgPN, which was brought under protection in 1954, the average amount of dead wood is 74 trees/ha (volume of 39 m^3/ha), whilst in the area annexed to the park in 1997, it is just 41 trees/ha, volume of 4 m^3/ha (Holeksa et al. 2004).

3. Materials and methodology

3.1. Hydrological and meteorological monitoring

The hydrological situation of the upper Skawa River catchment area has been monitored since 1973 by the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB) below the junction where all streams drain from the Babia Góra massif at the water gauge in Zawoja. Detailed studies were made of the catchment areas of four streams: Czatożanki, Marków, Rybny and Jaworzyna. Monitoring was conducted in 2012–2014 at the hydrological stations located on the border of the BgPN (Fig. 2) using a float water level sensor with a Thalimedes OTT recorder. In addition, monitoring was conducted with the use of water gauges at the mouths of Dejakowy and Urwisko streams. Precipitation in the BgPN area was monitored at the Rybny Glade (710 m a.s.l.) using a SEBA RG 50 type rain gauge produced by SEBA Hydrometrie GmbH. Results were supplemented with data obtained from IMGW-PIB for the meteorological stations in Zawoja (697 m a.s.l.).

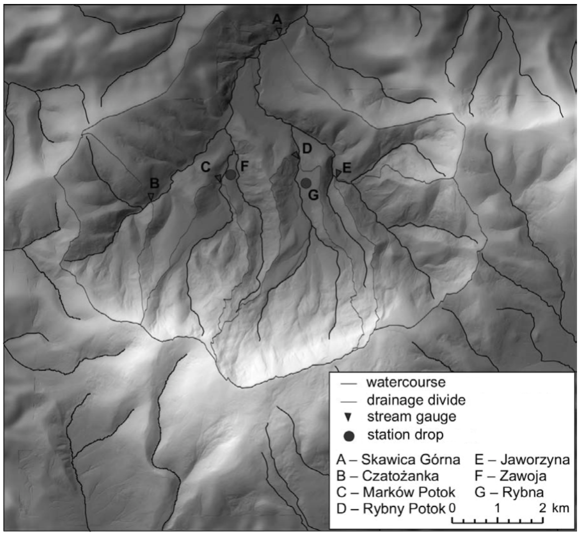

Figure 2. Location of stream gauges

Source: Author's own work

At the time of the floods of May 2014, I increased the scope of the measurements. Between 16 and 19 May 2014, the parameters of the flood wave were measured and photographic documentation was taken. Immediately after the passage of the flood wave during the field work, sites were chosen of valley cross-sections in order to calculate the maximum flow. The maximum flow was calculated according to the formula:

$$Q_{max} = P \cdot v$$

where

P – the cross-sectional area of the river bed [m^2],

v – the average flow velocity [m/s].

The average flow velocity (v) was calculated by using Manning's Equation (Manning's formula). Flow calculations were compared to the characteristic flows, calculated as recommended by IMGW-PIB using the precipitation formula (Biernat et al. 1991).

3.2. Geomorphological mapping

The second stage of the study, carried out on 22–30 May 2014, assessed the geomorphological transformations that occurred and then the geomorphological maps that were made of the Rybny and Marków streams, which experienced the greatest changes. The research was conducted using the method of field mapping based on a journal diary and instructions prepared by the Department of Geomorphology of the Institute of Geography and Spatial Management of the Jagiellonian University (Krzemień 2012). Based on the mapping, the geomorphological forms that developed were characterised and then the stream channel was divided into sections that had experienced erosion, accumulation and transport. Their quantitative and qualitative characteristics were also determined. A GPS receiver was used to map the location of trees and accumulated logs within the transformed valley floors.

4. Results

4.1. Meteorological conditions

In the second decade of May 2014, meteorological conditions over Europe were shaped by the 'Yuette' low pressure system, which moved up from the Balkan Peninsula to southwestern Romania. At the same time, from the northwest, cold polar air masses from the Atlantic began moving over Poland. This resulted in moist air masses from the southeast moving over the Carpathians, causing intensive heavy rainfall in its western regions (Franczak 2015). Over two days (13–14 May), 62 mm of rain was measured in Zawoja and caused the retention basin of the upper Skawica catchment area to fill up.

On 15 May 2014, a low pressure system from Hungary and Romania increased the intensity of the rainfall, which occurred at a rate of 9.1 mm/h. The upper Skawica catchment area (at the Zawoja hydrological station) recorded a daily precipitation of 138.0 mm. Heavy rain continued to fall the next day until 6:00 and then began to gradually taper off, although scattered showers fell during the entire day. On the second day (16 May), rainfall ranged from 41.5 mm in Zawoja to 80.1 mm in Rybny Glade. Rybny Glade also recorded the highest two-day total rainfall (204.6 mm), whilst the total precipitation over 13–16 May in the upper Skawica catchment area was from 241.5 to 243.5 mm (Fig. 3).

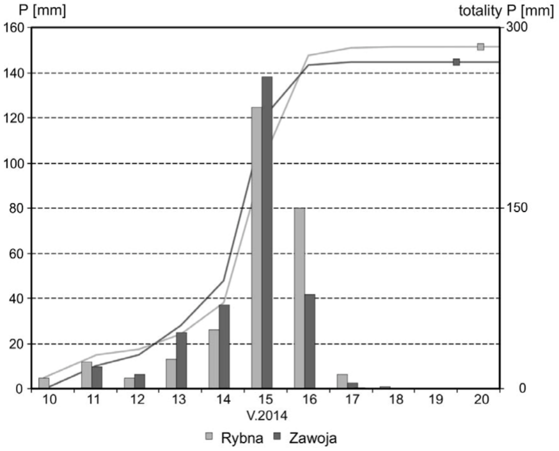

Figure 3. Daily precipitation on 10–20 May 2014 in the study area

Source: Author's own work based on data from IMGW-PIB and own data

4.2. The course of the flood wave

In the first decade of May 2014, the water level of the upper Skawica was in the low range. The water courses reacted rapidly to the intense rainfall, contributing to the formation of high flood wave. On 13 May at 19:00, the water began to continuously rise. The rapid increase in the water level of the streams began on 15 May at 15:00 and lasted until 7:00 the next day, when the flood wave culminated. The maximum flow of the Skawica River in Zawoja was 76.6 m^3/s, and the maximum outflow unit was 1.15 $\text{m}^3/(\text{s}\cdot\text{km}^2)$. The largest outflow unit occurred in the Rybny Potok catchment area at 2.15 $\text{m}^3/(\text{s}\cdot\text{km}^2)$, and the maximum flow rate reached 19.7 m^3/s. The outflow unit of the Marków Potok catchment area was slightly lower at 2.10 $\text{m}^3/(\text{s}\cdot\text{km}^2)$ (Fig. 4). The maximum outflow unit on 16 May in the upper Skawica catchment area at the Zawoja hydrological station was the highest for the upper Skawa catchment area. A slightly lower maximum outflow unit was recorded in the Stryszawka catchment area, which had the highest maximum outflow in the history of taking measurements there during the May floods (219.0 m^3/s). A much lower q_{max}, just

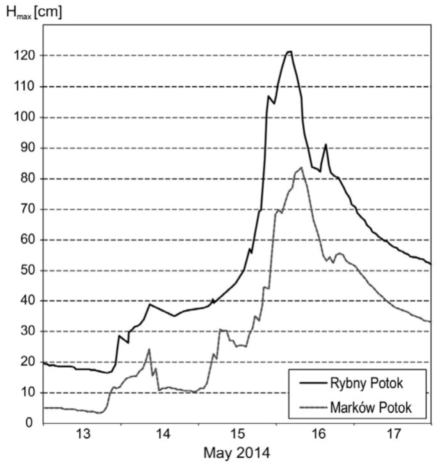

Figure 4. Hydrograph of Rybny Potok and Marków Potok on 13–17 May 2014

Source: Author's own study

0.7 m^3/(s·km^2), was observed in the Skawica catchment area at the hydrological station in Skawica Dolna (Table 1). The reason for this was the significantly less intensive rainfall in the lower part of the catchment area. The most intense rainfall occurred over the Babia Góra Massif and the adjoining Mędralowa Mountain Group to its west.

4.3. Geomorphological transformations

The swollen streams in spate from 15 to 16 May 2014 resulted in major transformations of the Skawica's upper catchment area, but the extent of the changes in the sub-catchments was very diverse. The greatest changes were found in the Rybny Potok catchment (Fig. 5), whereas other catchments had much less extensive geomorphological changes, mainly affecting the lower sections of the streams. Amongst them, the greatest changes occurred in the Marków Potok catchment (Fig. 6A), whilst the smallest were found in the Czatożanka catchment.

There were no significant changes in the structure of the water channels, and there was only a marked increase in the number and sizes of the forms of geomorphological transformations. In the upper sections of the streams, forms of erosion increased in length and height, whilst in the lower parts, many new forms of erosion were observed and the surface area of existing forms of accumulation increased, accompanied by the creation of forms of erosion.

In the Rybny Potok catchment, the largest transformations of the watercourse and flood zone occurred in the lower section of the stream (section V), where the area occupied by accumulation forms increased from 1,000 to 5,730 m^2 (Table 1; Fig. 6B). The largest of these measured 2,170 m^2. The large increase in the number and area of the accumulation forms (fourfold) also appeared along the entire remaining length of the valley, but they typically had an area of no more than 50 m^2. The greatest

Table 1. The maximum outflow unit from the catchment of the upper Skawa on 10–20 May 2014

Date	Name of the river (hydrological stadion)					
	Skawa (Jordanów)	Skawa (Osielec)	Skawa (Sucha Beskidzka)	Stryszawka (Sucha Beskidzka)	Skawica (Skawica)	Skawica (Zawoja)
	96.6 km^2	244.0 km^2	468.0 km^2	139.7 km^2	139.0 km^2	48.6 km^2
	q_{max} [dm^3·s^{-1}·km^{-2}]					
10.V	7.1	5.5	9.0	4.9	12.9	17.9
11.V	6.4	5.0	8.2	4.5	11.7	16.1
12.V	7.9	5.8	9.1	5.5	13.6	19.5
13.V	7.4	5.4	8.7	5.3	13.3	19.5
14.V	13.6	8.6	24.8	43.0	57.6	67.5
15.V	332.3	227.0	114.7	458.3	295.7	539.1
16.V	1480.3	881.1	1149.6	1575.5	697.8	1576.1
17.V	156.3	150.0	237.2	313.0	94.2	216.1
18.V	70.3	69.7	120.1	130.9	67.6	116.5
19.V	38.5	41.4	52.1	75.5	49.2	74.5
20.V	23.1	28.8	33.3	48.3	38.1	65.0

Source: Author's own work

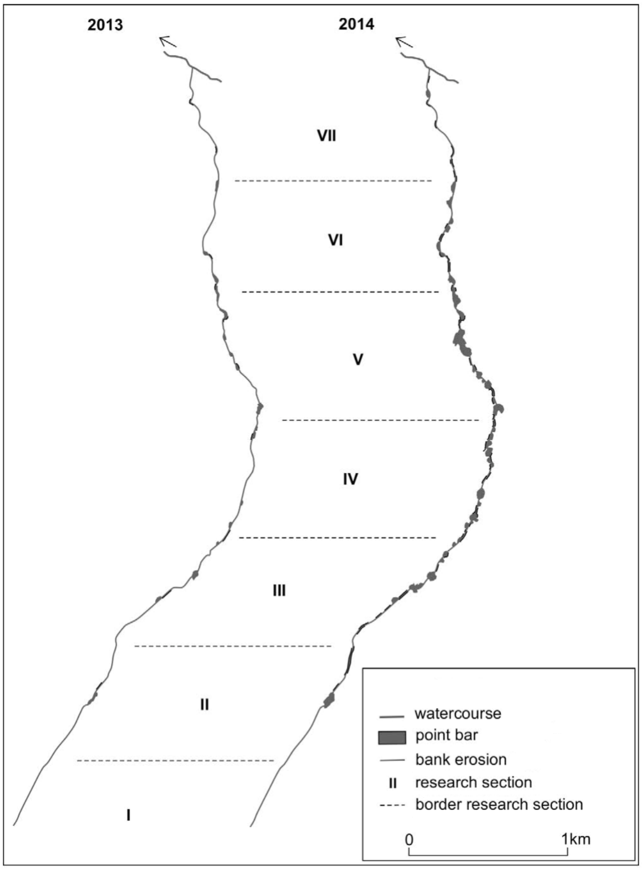

Figure 5. Geomorphological transformations in the Rybny Potok catchment

Source: Franczak (2015); changed

increase in the number of sites experiencing bank erosion occurred in the upper channel (above Stonowa), where their total length grew two- to threefold (Table 2). The longest bank erosion with an average length of 80 m was recorded in section II. As a result of the creation of numerous bank undercuts reaching a height of up to 7 m in a narrow section of the valley, a large number of trees fell into the channel, causing extensive large woody debris accumulations. In the middle and lower sections of the stream, the lengths of the eroded banks ranged from 12 to 20 m and their height was 1−1.5 m. Heights reaching 6 m were found only within meanders, at the foot of high fluvial terraces.

The greatest transformation of the Marków Potok channel occurred in the lower sections of the stream, where a series of point bars formed with an area of several to 490 m^2 (Fig. 6A). The average point bar area formed there was 60 m^2. These bars were accompanied by undercutting erosion with an average length of 11 m and a height of 4 m. After the flash flooding, the highest forms measured 9 m in height.

One hundred and twenty-nine tree logs were deposited in the lower section of the Rybny Potok water channel (Fig. 7B). Most of them (67%) were deposited into the channel from the immediate vicinity as a result of bank erosion. However, 33% of the deposited logs in the Rybny Potok channel were transported from the upper sections of the catchment (Fig. 8B). Spruce (*P. abies*) (89%) accounted for the vast majority of the deposited large woody debris, with 11% made up of grey alder (*A. incana*) logs (Fig. 8A). Twenty-five tree logs (Fig. 7A) were inventoried in the studied area of the Marków Potok catchment, of which 72% were grey alder logs and 28% spruce (Fig. 8A). About half (52%) of the large woody debris deposited in the Marków Potok channel originated from the

Table 2. Changes to bank erosion length [m] and b point bar area [m^2] in the trough Rybny Potok as a result of flash flood in May 2014

Number of tested zone	Bank erosion length [m]		Point bar area [m^2]	
	Years			
	2013	2014	2013	2014
I	0	0	0	0
II	50	420	150	665
III	60	136	200	850
IV	130	290	300	1 455
V	100	280	1 000	5 730
VI	20	106	150	770
VII	10	72	40	200

Source: Author's own work

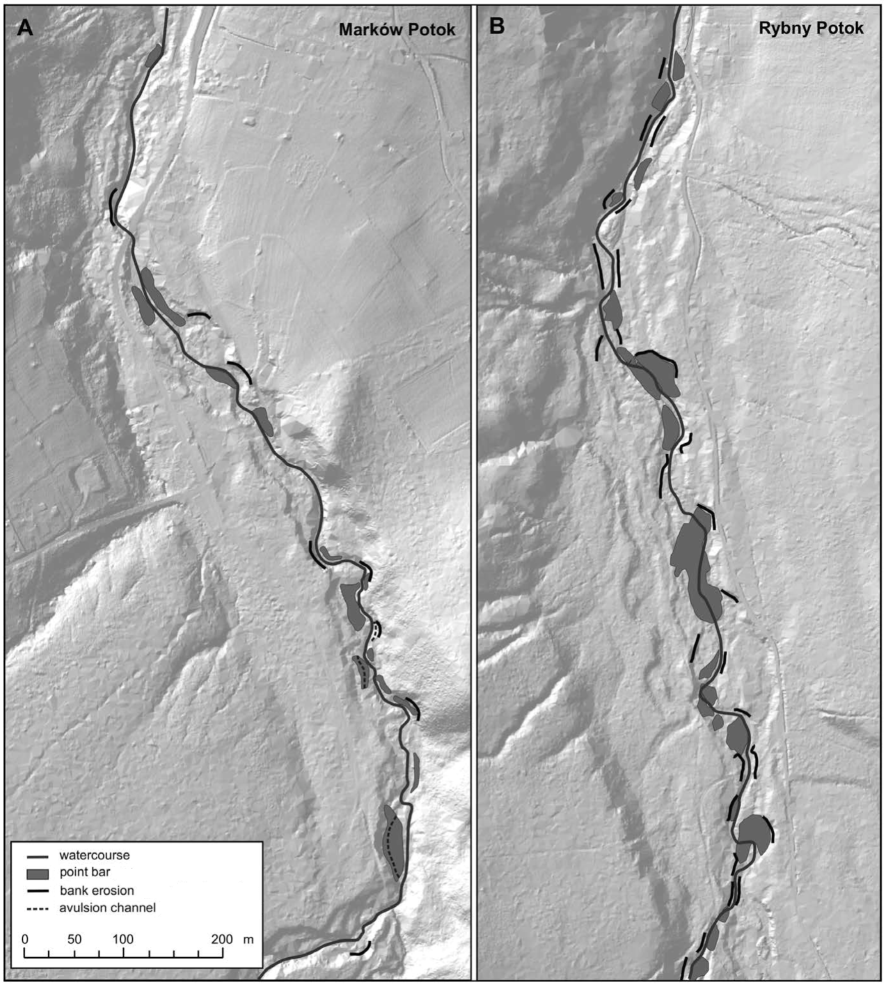

Figure 6. Geomorphological transformations of the lower part of Marków Potok (A) and Rybny Potok (B) channel in 2014.

Source: author's own work

area in which the accumulation was found, whilst 48% was transported from the upper part of the catchment (Fig. 8B).

5. Discussion

The intense rainfall that occurred in mid-May 2014 in the Babia Góra region was one of the highest in the history of the Zawoja hydrological station (measurements from 1961), and the precipitation of 138.0 mm on 15 May was the highest. Precipitation was 15% higher than the previous highest daily rainfall from July 1970 (120.1 mm), whilst the upper Vistula basin experienced one of the largest floods in its history (Franczak 2013, 2014b). Similarly, high daily rainfall amounts were recorded in the Skawa catchment area during seven other events in 1934, 1958, 1960, 1970, 1983, 2001 and 2010 (Franczak 2013). The total daily precipitation that fell in the Skawica upper catchment on 15 May 2014, however, was much lower than the rainfall recorded on 18 July 1970 in Laskowiec (275.1 mm). On the same day, Bieńkówce (Paleczki catchment) recorded a daily total precipitation of 209.1 mm, and the Zubrzyca Górna (Orava catchment) had 226.0 mm (Stach 2009). However, as mentioned earlier, during that particular flood wave, the maximum daily rainfall in the upper Skawica catchment area was lower than that in 2014. The rainfall noted at Zawoja in May 2014, however, did not occur in the months with the highest monthly totals of precipitation reported in the Western Carpathians. In this area, they most often occur in June and July. Despite this, May is still included in the period (May to September) with the highest monthly totals of precipitation. It was in May that the nearby station in Maków Podhalański recorded the highest monthly rainfall total of 521.1 mm (Cebulska, Twardosz 2012; Woźniak 2013). In May 2014, the total amount of rainfall in Zawoja was 354.1 mm.

The flood wave that formed as a result of the torrential rainfall was characterised by a very steep slope during the flood phase, concentrated over only 14 h. The flow of the Skawica in Zawoja increased to 76.6 m^3/s and the maximum outflow unit was 1.57 $m^3/(s{\cdot}km^2)$. Higher values of q_{max} were

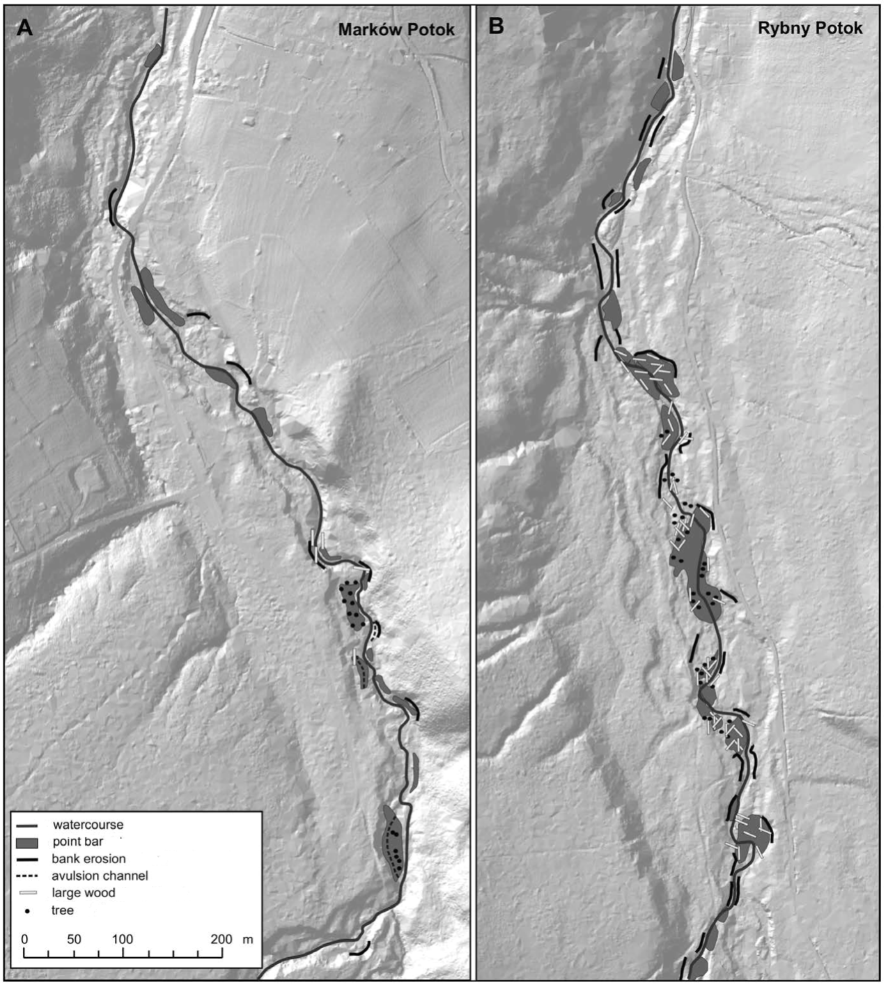

Figure 7. Accumulation places of large wood the lower part of Marków Potok (A) and Rybny Potok (B) channel after flash floods in May 2014

Source: Author's own work

recorded in its sub-catchments, and a maximum outflow unit value of 2.25 $m^3/(s \cdot km^2)$ was reached in the Szumiąca Woda catchment. These values, however, were much smaller than the average maximum outflow unit calculated by Bryndal (2014) for the Polish Carpathians.

As the flood wave advanced, the Babia Góra stream channels were significantly transformed, with the greatest changes occurring in the Rybny Potok catchment. Extensive changes in the morphology of the stream bed were also recorded in the lower section of the Marków Potok and Jaworzyna Potok. These changes were similar to those demonstrated by numerous other authors studying the impact of floods on morphological changes to the river beds of the Polish Carpathians (including Ziętara 1968, Krzemień 1992; Starkel 1996; Gorczyca 2004; Izmaiłow et al. 2008; Krzemień, Gorczyca 2010; Gorczyca et al. 2013). By far, the smallest transformation occurred in the Czatożanki catchment, where only the channel was deepened in some places. No changes were recorded in the Czatożanki catchment to the terrace. The largest transformations of the valley floor occurred in the middle of the Rybny Potok channel in the aforementioned section V (Fig. 5B). Several extensive accumulation forms developed in places where the valley bottom distinctly expanded. The intensive growth of patches of grey alder and spruce along the banks and on the flood plain contributed to this by accumulating the debris carried by the flood wave. Large accumulations of organic matter were formed, reaching a height of 3 m, and their blockage of the flood waters caused the formation of large areas of gravel deposits in front of them. Below the large woody debris, on the other hand, undercuttings formed up to a depth of 1.5 m. As already demonstrated by many authors (including Mosler 1981; Wyżga et al., 2003; Wyżga, Zawiejska, 2005; Kasprzak 2010), the dams resulting from woody debris are the main cause of the transformations within stream channels.

The significant increase in the size of the area of the accumulation forms in the Rybny Potok valley in contrast to neighbouring valleys, where they were not as large (Fig. 8A), is due to the morphology of the Rybny Potok valley floor and the distribution of trees in its territory (Fig. 8B). The Rybny Potok catchment area has a marked dichotomy. The slopes in the upper part of the catchment are steep, and the stream bed has many inclines in excess of 350‰ (Franczak et al. 2015). On the other hand, below the Słonów meadow (Stonów), the stream flows in a relatively wide valley for approximately 1.5 km, which measures from 40 to 60 m wide, reaching even 90 m in places. The channel's incline decreases to only 80‰. The Holocene terraces extending along the channel are 0.5–1.5 m high, and their entire surface is covered with dense stands of spruce and patches of grey alder.

During the May 2014 flood, a very large amount of organic material fell into the stream channel as a result of extensive bank erosion in the upper part of the catchment, including tree logs, some of which were then transported to the lower sections of the valley. The swollen waters spilled onto the floodplain in the middle and lower sections of the stream, depositing organic matter amongst the trees growing on the terrace. In addition, the free flow of the flood water was blocked by the dams formed by the deposited large woody debris, transported to the lower parts of the valley. As a result of the accumulation of a large number of logs and fine organic matter, a number of dams were formed, holding back the transported rock material. Below the dams, plunge pools and eroded gullies were formed, up to a depth of 2 m. The same effect of extensive accumulations of large woody debris has been observed in other Carpathian catchment areas, including the Bystrzanka catchment (Kijowska-Strugała 2015).

Transported tree logs were also deposited on the resulting gravel bars and erosional undercuts. The largest amount was deposited on the gravel bars formed on the wide stream bends. Within these individual forms, several to almost 20 logs were deposited, with the largest having 20 (Franczak 2014). In the other valleys, there were no more than a few logs on the particular accumulation forms. Spruce logs dominated amongst those deposited in Rybny Potok, which had fallen into the water from the floodplain as banks experienced undercuts erosion. Grey alder, because of its overgrowth on the floodplain, dominated amongst the logs heaps found in the stream channel itself, which lacked trees transported from the fluvial terrace. Such a situation occurred in the Marków Potok catchment, where it represented 72% of the large woody debris deposited in the channel.

The large woody debris that fell into the stream channel as a result of the flood intensified the formation of extensive accumulation forms in the lower sections of the valley. The existence of very large piles of tree log debris may, however, contribute in the future to the enlargement of these forms. In the event of an extensive flood, they will interfere with the hydraulic flow, impeding the further transport of the bed load, and thereby increase in size.

6. Conclusions

The intense rainfall that occurred in May 2014 in the upper catchment of the Skawica caused significant changes in the geomorphology of the Babia Góra stream channels. The extent of the transformations, however, differed within individual valleys. The greatest transformation was recorded in the Rybny Potok catchment that drains the domed peak of Babia Góra. The data suggest that the accelerated outflow from the upper parts of the massif induced by low infiltration and steep inclines resulted in a significant increase in the energy of the water, which caused the extensive erosion of channel banks and transported the rock and organic materials that were swept away. The low floodplain with dense tree cover occurring in the middle and lower sections of the catchment set the stage for the numerous accumulations of large woody debris, with heights reaching up to several metres. Several different forms of accumulated material developed above these heaps, with erosional forms occurring below them.

The remaining valleys of the Skawica upper catchment did not have such a broad floodplain with dense tree cover, and thus the conditions were not as conducive to the development of such large-scale transformations of their stream channels. The upper parts of their catchment areas experienced extensive erosion, whilst accumulation forms developed only within stream meanders.

Sometimes extensive accumulations of large woody debris in stream channels may be the result of forest management activities. During large floods, the remains of logs and branches move and block water flow, thus contributing to further changes within the channel.

Conflict of interest

The author declares no conflict of interest.

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