The significance of extreme floods in the transformation of mountain valleys and causing flood risk, on the example of the July 2001 flood that occurred in the upper catchment of the river Skawa

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Abstract

In July 2001, in the Carpathian Basin of the Vistula, there was a lot of rainfall and storms. The meteorological situation of that time was similar to that of 1934 when a great flood occurred. On 25 July 2001, in the upper part of the Skawa catchment, a violent storm occurred. Its centre was located right at Makowska Góra. The daily precipitation in Maków Podhalański was 190.8 mm that day. Most of the precipitation occurred during a storm. Although the precipitation was much lower in the other stations located in the drainage basin, the flow of the Skawa in Sucha Beskidzka was 660 m^3/s, while the constructed dam in Świnna-Poręba – 1019 m^3/s. Precipitation was so abundant that the floodplains terraces of the Skawa have been inundated, and made the streams flowing down the Makowska Mountain spill out of the trough. The centre of Maków Podhalański and the neighbouring streets were destroyed. The main current flowed through the streets of Źródlana, Krótka, Kościelna, Rynek, and Wolności. The biggest losses were caused by the Księży Potok and several smaller streams (Rzyczki, Grabce, and Czarny Potok) that poured out of the trough and flowed through them. The biggest losses have been incurred by the Budzów and Zembrzyce municipalities located on the other side of the mountain. The losses were caused by a small Paleczka stream.

Keywords: flood, flood hazard, the Skawa catchment, the Carpathians

Introduction

Floods are one of the most devastating natural disasters on Earth. They are responsible for 32% of losses resulting from extreme natural phenomena and 26% of the total number of fatalities [1]. Floods are the only natural disaster that occurs in Poland on an almost monthly basis (except November) [2]. Catastrophic floods and the intensive precipitations that cause them are responsible for, besides material losses, significant transformations of the terrain of valley floors and slopes. These phenomena are typical of mountain areas [3], which have repeatedly resulted in significant transformations of the terrain in the Beskidy catchments [4–14], Sudetes [15, 16], in the Tatra Mountains [17], and many other mountains in the moderate climate zone [5, 18–24]. While considering the occurrence of catastrophic floods in small catchments, most authors focused on the study of geomorphological transformations within the river bed or the slope. The research was also carried out on the parameterisation and regionalisation of catchments in which flash floods occurred [25–28], on the spatial development of floodplains [29, 30], and on the impact of floods on the functioning of local communities and the perception of them [31, 32]. Attempts to take a holistic view of the issue of floods, especially those occurring in small catchments, have, however, seldom been made.

Heavy rainfall of low likelihood often occurs in small catchments up to 100 km^2, with most not exceeding 25 km^2 [33, 34]. They are responsible for floods occurring in small catchments, the area of which usually does not exceed 40 km^2 [28, 29]. Sometimes, however, floods occurring in small mountain catchments are not caused only by short-term rainfall (lasting up to several hours) [35], but they occur as a result of heavy torrential rainfall overlapping with long-term heavy rainfall. Then, in heavily damp catchments, catastrophic floods occur, during which almost all rainfall turns into surface runoff.

In July 2001, in the upper Skawa catchment area, a catastrophic flood, during which most of the watermark profiles recorded

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the highest flow, took place. It was the highest flow ever recorded. The flood was caused by a dozen or so days of heavy torrential rainfall, which was overlapped with several hours of heavy rainfall.

The purpose of the study was:

- to determine the meteorological causes of the flood and its course;
- to identify the geomorphological transformations caused by the flood;
- to assess the resulting material losses.

Materials and Methods

The meteorological situation of the area in the study in the period immediately preceding the occurrence of the precipitations that caused the flood, and during their duration, was documented based on synoptic maps of the meteorological situation in Europe at sea level on the scale of 1:7,500,000, baric topography maps, and satellite images (METEOSAT). The analysis of the precipitation and the course of the flood wave were reconstructed based on data from the monitoring network of the IMWM-NRI. The data on the amount of the precipitation was obtained from measuring stations located in the catchment areas of Lachowice-Krale, Maków Podhalański, Spytkowice, Zawoja, and from the adjacent watershed in the area of the neighbouring catchments of Bogdanówka, Krzeczów, and Rabka. Hydrological data (water levels and flows) were obtained for the hydrological posts in Skawa River (the village) in Jordanów, Osielec, and Sucha Beskidzka, and for its tributaries: the Skawica (in Skawica Dolna and Zawoja) and the Stryszawka (in Sucha Beskidzka) (Fig. 1). Historical data on the maximum annual water levels (1913–2012) and flows (1970–2012) were obtained as well.

The greatest geomorphological transformations occurred as a result of flooding the valley floors, therefore geomorphological changes were analysed within them. The research was used to identify quantitative changes due to floods. For this reason, orthophotos from 1998 and 2003 were obtained from the Marshal's Office of the Małopolska Region. The maps were imported on a scale of 1:1,000 and the coordinate system of PUWG1992, which made it possible to measure the actual distances of individual forms. For the analysis of landslide forms, data from LiDAR obtained from the Geodetic and Cartographic Documentation Center (Centralny Ośrodek Dokumentacji i Geodezji) were used.

Material damage caused by the flood was estimated based on the data obtained from the municipal offices in Budzów, Maków Podhalański, and Zembrzyce.

Research area

The research was carried out in the upper catchment of the Skawa, located according to the physical and geographical division of J. Kondracki [36] on the border of the Żywiec and Makowski Beskids, which belong to the Western Carpathians macroregion. The Skawa, a 96 km long river of the second row, starts below the Spytkowicka Pass and flows into the Vistula at the level of the village of Podolsze (Fig. 1). Flowing through several physico-geographical units, it is characterised by the presence of two different sections: the lower one, 34 km long, characterised by slight drops (2.3‰ on average), and the upper one, 62 km long, with an average decline of 6.9‰ [17].

The border between both sections is usually marked between the estuaries of the Stryszówka and the Skawica [37]. In this study, the estuary of the Tarnawka above Skawica (the river) was assumed as the border of both sections. Such a defined region allows for the study of the most mountainous region of the Skawa catchment, the area of which is 730 km.

The terrain of the catchment is closely related to the geological structure of the area. The flysch pieces present there belong to the Magura series. Convex forms are established mainly within the deposits built out of the Magura sandstones, except for the source part of the Skawa catchment, where they are established within the Łącki layers and the Piwniczna sandstones. Concave forms are formed within the hieroglyphic layers, with inlays of Pasierby and Siedlce sandstone, as well as Łącko marls, and by the Belowes layers. In the river valleys, there are Pleistocene and Holocene alluvials, which also form alluvial cones in the estuary sections of the valleys. Slopes, on the other hand, are in many places full of colluvia [38, 39, 40]. The highest point of the catchment is situated in the Babia Góra range, and it is characterised by steep slopes and sharply moulded valleys. The rake angle often exceeds 15°. The only exception being the source part of the river Skawa, where it is only 5° [41]. The highest peak, Diablak, is 1725 m above sea level, whereas the lowest is located near the estuary of the Tarnawka river, at 305 m above sea level. The riverbeds in the region are usually largely indented.

The catchment under study is a part of a region with a mountainous climate, which due to a wide range of variety in its land relief, contains different microclimate areas [42]. Those are mostly shaped by polar-sea air (69%) [43]. The annual amount of precipitation is circa 800 to 1400 mm. The most can be observed at the northern slopes of Babia Góra, although during long-lasting heavy rainfall, another two centres of rain take form, above Leskowiec and Bieńkówka. The daily rainfall amounts then to 275 mm (in 1970).

Figure 1. Location of the research area

Methodological conditions of the flood

The 2001 July flood in the upper catchment of the Skawa was contributed to by heavy rainfalls, which were, in turn, a result of a low-pressure area moving to the North-East from the Hungarian Plain. Having crossed the Karpaty range, the low remained above the South-West of Poland for a few days [13]. With such an arrangement of baric assets, the warm air above Central Europe was transported northward, while the cold and moist – southward [30, 44]. The air in motion, having approached an orographic obstacle in the form of Karpaty, amassed into a thick layer of clouds, producing showering rain and sudden storms.

The first 10 days of July had two outbursts of precipitation, with the rainfall ranging from 37 to 78 mm (per diem). However, with another moist atmospheric centre arriving at the studied area, the first heavy rainfall was observed between 16–17 July (30–65 mm). During the next few days, the intensity of the rain dropped down, although it still amounted to between 1 and 13 mm each day [30]. Such a situation remained until 22 July, except the most elevated fragments of the catchment (Babia Góra range), where in Zawoja, on 19–20 July, the noted amount was 46.3 mm. Beginning with 22 July, heavy rainfall was present in the whole area of the catchment, and their two-day amount ranged from 45 to 73,5 mm. The biggest amount of rainfall was observed between 24 and 27 July [45].

On 24 July, in the source part of the Skawa, the rainfall amounted (35–40 mm), whereas in its other parts it reached much higher values, from 61.9 mm in Zawoja to 94.6 mm in Maków Podhalański. On the next day (25 July), the rainfall in most parts of the catchment amounted from 12.4 mm in Lachowice to 41.8 mm in its source fragment. However, its central part has been subject to a catastrophic showering rain reaching up to 190.8 mm in Maków Podhalański [30, 31, 44, 46]. The most extensive rainfall from the atmospheric centre located above Makowska Góra was observed between 3:00 and 6:00 p.m. – circa 150 mm [47]. In the station in Bogdanówka, situated at the edge of the centre (7 km to the east), the 24-hour sum of rainfall was 68.7 mm. The next few days the rainfall continued, reaching 64 mm the very next day, lasting until 28 July (Fig. 2).

July 2001 was notable due to having some of the biggest rainfalls in history [45]. During the thirteen-day-long period of extensive rainfall (15–27 July), its amounts in most of the parts of the catchment reached between 243 and 316 mm, whereas in Maków Podhalański – it was 457.8 mm. During the 5 days of the most extensive rainfall, the same station has noted 392.7 mm (521.1 mm during the entirety of July) [44, 45, 48].

The rainfall which has contributed to the flood of July 2001 in the upper catchment of the Skawa was among the highest to have ever been noted since keeping record started. A higher amount for 24 hours in the last century was noted in the year 1970. In the atmospheric post on Leskowiec, on 18 July, the amount of rainfall was 275.1 mm. Furthermore, diurnal rainfalls exceeding 100 mm occurred in the Skawa catchment only 11 times between 1913 and 2013 (during a flood in 1934, 1958, 1960, 1970, 1983, 2001, and 2010). During the whole precipitation period of July 2001, the station at Maków Podhalański has noted the largest total amounts of rainfall in the 100 years between 1913 and 2012. The rest of the area, however, has experienced much lower totals. The largest rainfall in the overall catchment was during the May 2010 flood, when the post at Zawoja has noted 456.6 mm. However, the whole precipitation period then 1–4 May, 2010), despite having only two rainless days, was noted by the same post to have a total amount of 619.5 mm.

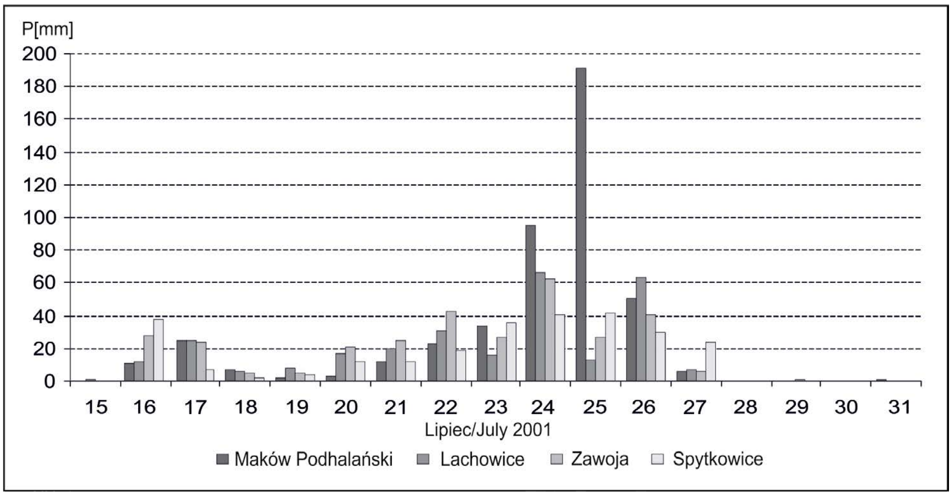

Figure 2. Daily precipitation on 15-31 July 2001 in the study area

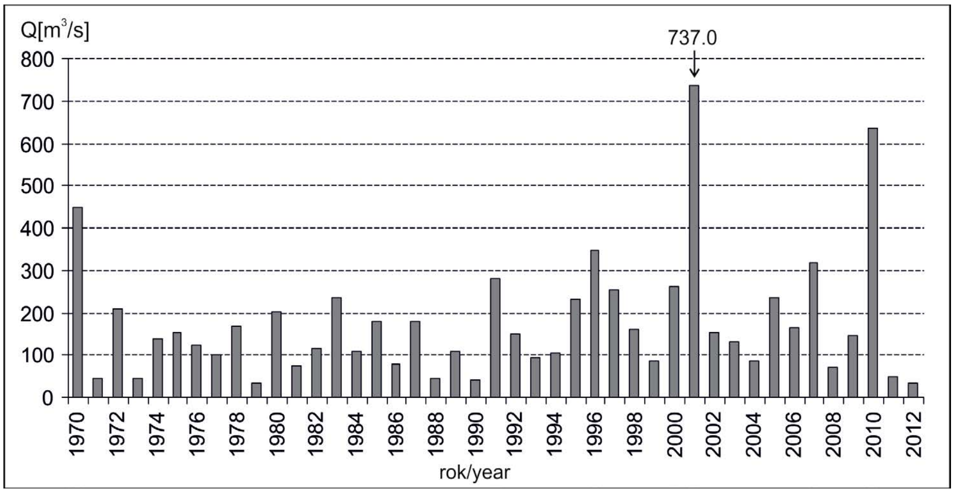

Figure 3. The maximum outflow unit from the catchment of the Skawa on 1970–2012

The course of the flood wave

The flood of July 2001, in the catchment of the Skawa, was the largest in history ever since the post in Sucha Beskidzka started recording data in 1887 [30]. During the period prior to the flood, the water level of the rivers in the Skawa catchment was considered average (flux of the Skawa in Sucha Beskidzka: circa 3.0 m^3/s). As a result of the rainfall in the middle of the month (17–18 July), the flux of the rivers increased (up to 22.2 m^3/s in the Skawa in Sucha Beskidzka).

Then, after a slow return of the watercourses to their average state, another major increase in the flux of the Skawa, below the estuary of the Skawica, took place on 22 July. The rest of the area was noted to have experienced an increased water level several hours later. On 24 July, after about a dozen hours of extensive rainfall, the flux of the overflowing Skawa in Sucha Beskidzka was 180 m^3/s. At the same time in Osielec, the flow of the Skawa increased to 157 m^3/s, and of the Skawica to only 31.7 m^3/s. The next day in the morning the flow in the watercourses in the central part of the catchment area increased significantly. The flow of the Skawica increased to 86 m^3/s, and of the Skawa in Sucha Beskidzka to 308 m^3/s) of water. At 13:00 in Osielec, the highest flow of the Skawa ever was recorded (478 m^3/s).

However, at most measuring stations the culmination waves were recorded in the evening. The Skawica, the Stryszawka, and the upper Skawa (up to the Jordanów station), which were located on the edge of the precipitation centre, reached the maximum flow (96, 216, and 160 m^3/s) respectively) at 7:00 p.m. [44]. However, in Sucha Beskidzka the Skawa reached its highest flow (737 m^3/s) at 9:00 p.m. [30]. In the uncontrolled catchment area of Paleczka, in which the flood caused the greatest damage, the culmination of the flood wave occurred between 8:00 p.m. and 9:00 p.m. [49]. In the profile located at the dam, which was being built at that time on the Skawa in Świnna-Poręba, the maximum flow was 1019 m^3/s.

The next day (July 26), the water level in the watercourses decreased significantly, however, it remained high. The flow of the Skawa in Sucha Beskidzka was 216 m^3/s, and remained at this level for over 24 hours, as it was 212 m^3/s the next day. It was only on 28 July that the waters of the Skawa gradually descended in its middle course, and the water returned to the level before the flood at the beginning of August.

This rise was characterised by a long duration and a very high culmination. The elevation of the Skawa flood wave ranged from 2.30 m in Osielec to 3.74 m in Sucha Beskidzka. It was a complex, double wave, with a much higher first culmination, and a fast ascent time and slow descent.

The flood occurred in the entire catchment area of the upper Skawa, but the absolute maximum water levels and flows were not exceeded in the entire area. In its upper reaches, above the Jordanów, the water level on the Skawa was lower than the maximum recorded during the flood in 1934 by 0.60 m (the flow was lower by 60 m^3/s) [50]. In turn, on the Skawica, the maximum water level was lower than the peak recorded during the flood in 1983 by 0.70 m (the flow was lower by 83 m^3/s). In the upper reaches of the Skawica river, there was only an average flood (maximum flow in 2001 – 24.3 m^3/s) at 120 m^3/s during the flood in 1983; Fig. 3). The hitherto maximum water levels were exceeded in the rest of the catchment area. In Sucha Beskidzka, the culmination wave on the Skawa exceeded the maximum level from 1931 by 0.10 m, and in Osielec exceeded the level from 1948 by 0.30 m.

A comparative analysis of the flood concerning other events of this type that took place in mountain catchments allows us to state that it is one of the events of the largest scale of this type. The highest unit runoffs were recorded in small catchments exposed to heavy torrential rainfall. Under Polish conditions, it is assumed that in such catchments, unit runoff during a flood may amount to approx. 30,000 $dm^3/s/km^2$ [51, 52]. However, for most of the profiles studied by A. Bartnik and P. Jokiel [42, 53] (for 2/3), unit outflows were lower than 500 $dm^3/s/km^2$. In the upper Skawa catchment area, during the flood in 2001, the recorded unit outflows in the water gauge profiles closing the catchments up to about 100 km^2 were not the highest in history. In Jordanów, the maximum unit outflow of the Skawa was 1656 $dm^3/s/km^2$, of the Stryszawka in Sucha Beskidzka 1546 $dm^3/s/km^2$, and of the Skawica in Skawica – 691 $dm^3/s/km^2$, which resulted from the fact that these catchments were located on the edge of the most intense rainfall. However, in small uncontrolled catchments located in the centre of rainfall, this outflow certainly reached several thousand $dm^3/s/km^2$ (Fig. 4). In medium and large catchments, the maximum unit outflow during the flood was one of the highest recorded in Poland. Out of the catchment areas ranging from 100 to 1000 km^2 the Skawa in Osielec achieved the tenth highest maximum unit runoff (1959 $dm^3/s/km^2$) in Poland.

On the other hand, for the Skawa in Sucha Beskidzka, this coefficient was 1574 $dm^3/s/km^2$ (Fig. 5). These two water gauge profiles also had one of the highest K flood indices, which amounted to 4.13 in Osielec and 4.12 in Sucha Beskidzka. According to P. Jokiel's and P. Tomalski's [42] calculations, the Łopuszanka in Piaski had the highest value of the K index (4.64). However, in Poland as a whole, only in less than 10% of cases the calculated K indices were higher than 3.5, and those exceeding 4.0 were rare and calculated mainly for the Carpathian rivers. Higher unit runoff coefficients and K flood indices were recorded only for very small, uncontrolled mountain catchments [26, 33].

Figure 4. Maków Podhalański during the flood in 2001

Figure 5. The Skawa River in Maków Podhalański during the flood in 2001

Geomorphological transformations during the flood

In the upper Skawa catchment area, the greatest geomorphological transformations occurred in the Paleczka catchment area and on several short right-bank tributaries of the Skawa flowing into it between Maków Podhalański and Sucha Beskidzka. Numerous fresh erosive undercuts and sandbanks up to 50 m^2 in size were created within these watercourses. The largest transformations took place in the river bed of the regulated Księży Potok flowing in its lower section through the centre of Maków Podhalański. Within the narrow valley bottom, the concrete and stone retaining walls protecting the shore and the communication routes leading alongside it, from which the material was accumulated below, were destroyed. Numerous erosive undercut up to 5 m high was formed, and erosion gutters up to 20 m long and 1m deep were created within the valley bottom. Waterfall thresholds ranging in height from 0.5 to 1.5 m have formed in the longitudinal profile of the bed on the shoals of Magura sandstones. Meanwhile, in the lower sections of streams flowing down the Makowska Góra in sections with a smaller longitudinal decrease and in the areas of rapid change in the direction of the river bed (transformed by humans), wide alluvial fans with an area of up to 5100 m^2 were formed (Fig. 6).

Among the main tributaries of the Skawa River, the greatest geomorphological changes occurred in the Paleczka catchment area. In its middle and lower reaches, the riverbed widened and deepened. In its middle current (in Budzów between the hamlets of Nowakówka and Spolnikówka) at a length of 2.8 km and the lower part of Jachówka (from the hamlet of Radwanówka to its estuary to Paleczka), at a length of 2.4 km, there was a significant remodelling of the riverbeds. There was an increase in their surface, and the riverbed was widened in places 2, 2.5 times (even by 65 m) (Fig. 7). The transformations in the riverbeds resembled the changes that took place during the catastrophic floods of 1958, 1960, 1970, and 1972, when the beds of the channels were very intensively remodelled, and the banks were washed out (Madry 1974; Painter 2000). In turn, in the Księży Potok catchment area, they were similar to the floods in 1934 [44] and 1853 [54]. The so-called Antoni Schneider's files, kept in the National Archives in Cracow, contain a description of the flood that hit the then Maków on 22 June 1853, as a result of heavy rains that occurred over Makowska Góra. The collected waters of Księży Potok flooded the Maków market, covering it with sediments, including boulders weighing up to 1 t [54].

Figure 6. Alluvial fans in the Księży Potok catchment

Landslides have also become active in the catchment area. The largest one was formed on the southern slope of the Beskidówka mountain (Chelm Range) as a result of the undercutting of the slope by the right bank of Paleczka eroding in this section. The landslide with an area of 3.25 ha was 285 m long and from 70 m to 190 m wide. The landslide tongue crawled 40 m into the floodplain terrace (Fig. 8). One of the largest landslides, which

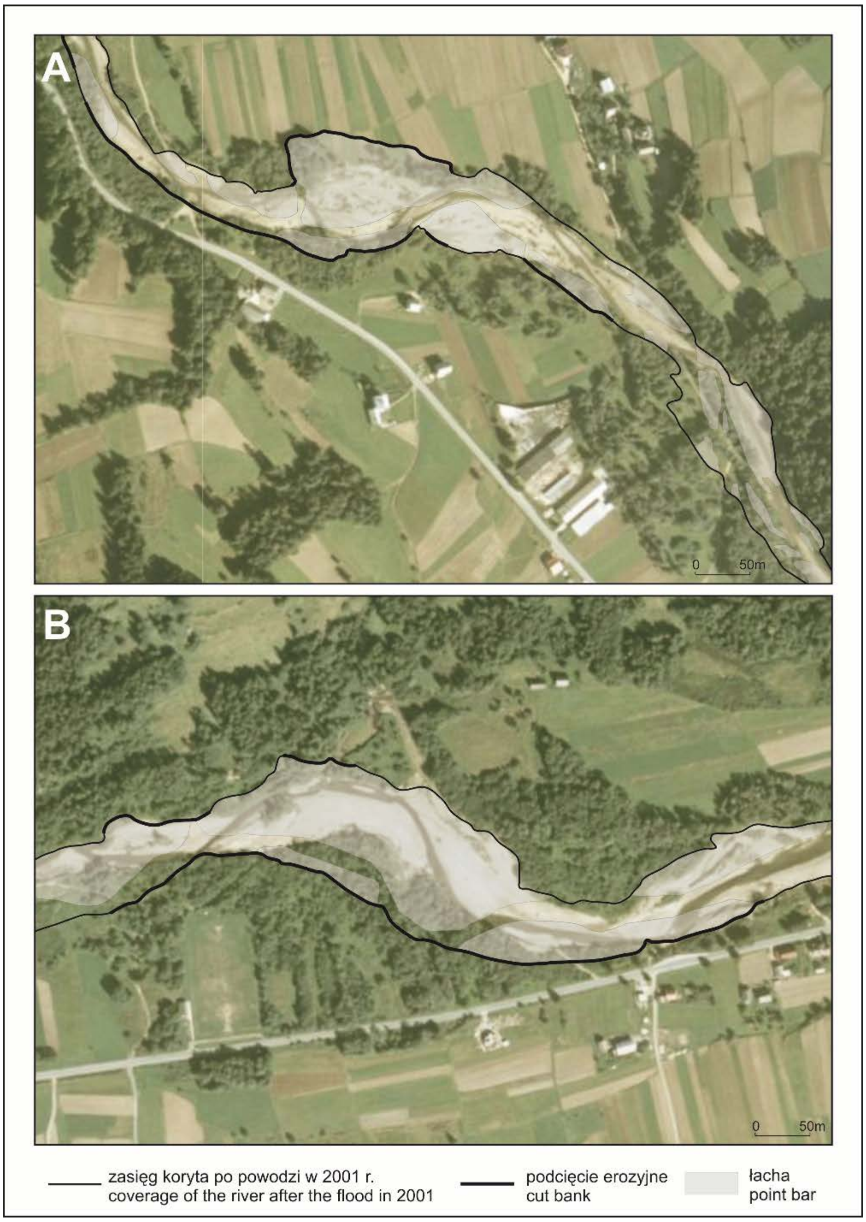

Figure 7. Geomorphological transformations in the Paleczka catchment

caused considerable losses, was activated in the Lachówka catchment in the village of Lachowice. It was established on the slope of Mount Parchałówka and was 380 m long and 160 to 280 m wide. The front of the landslide went down to the bottom of the stream, damaging it, but due to the possibility of the formation of a dam lake and flooding of the buildings above, its front was dug. Within the landslide, 10 houses were destroyed and several more were damaged [55]. On the other hand, in the Skawica catchment area, its tributary Gołyń triggered activation of a large 315 m long landslide on the slope of the Urwisko mountain, which blocked the stream bed and created a dam lake. However, in this case, the front of the landslide was dug as well, due to the above-mentioned risk of flooding residential buildings.

Flood losses

During the flood in 2001, the greatest losses occurred among all the floods that appeared in the study area in 1913–2012. The biggest losses took place in Maków Podhalański, where, apart from flooding the floodplain terraces by the Skawa River, mountain streams also caused great damage. They flooded the city centre and almost all streets and properties from Głowacki Street in the eastern part of the city as far as the border with Sucha Beskidzka. On the other hand, among the Skawa sub-catchments, the greatest losses were recorded in the Paleczka catchment, where the accumulated waters of the river flooded the entire valley bottom.

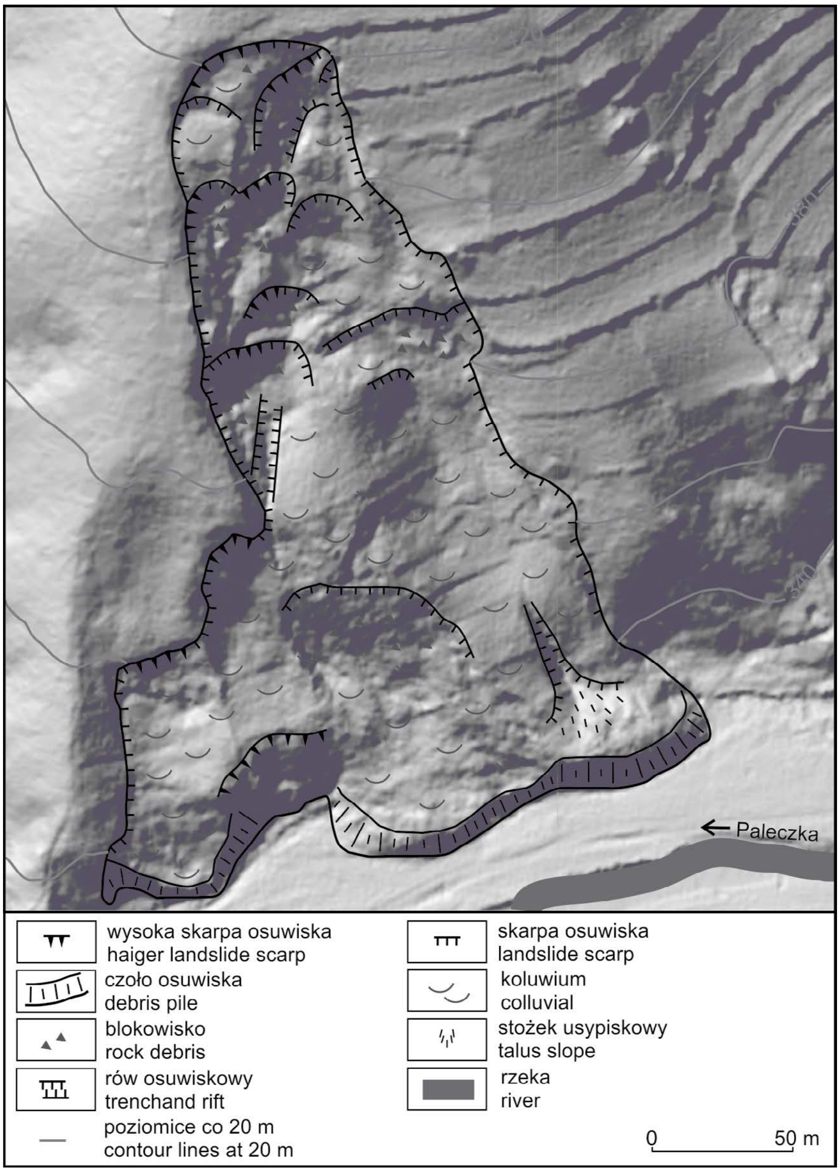

Figure 8. A landslide formed during the flood in 2001 on the southern slope of Beskidówka

The flood of 2001 caused losses in the Vistula basin, amounting to approximately PLN 3 billion, of which approximately (material losses in PLN refer to costs estimated according to the valuation from the decade of 2000) 1/3 accounted for the losses incurred by the Małopolskie Voivodeship. In the upper Skawa catchment area, the greatest material losses were recorded in the area of three communes (Budzów, Maków Podhalański, and Zembrzyce) located in Suski County. In its area, one of the largest losses in the commune and district infrastructure (approx. PLN 62.5 million) was recorded in the Małopolskie Voivodeship, which constituted by far the highest share in the local government' own revenues – 182%. Total losses in Suski County amounted to PLN 90 million. The biggest losses were recorded in the Budzów commune, where they amounted to PLN 60 million. In the Maków Podhalański commune, losses in the municipal infrastructure amounted to approx. PLN 16 million. The water supply network (0.9 km) and the sewage system (94.4 km), as well as municipal roads (58.2 km) and bridges (53), were destroyed. On the other hand, among private property losses were recorded in the case of 191 apartments, of which 8 buildings were so damaged that they were demolished after the flood [56]. In the commune of Zembrzyce, 105 residential houses were damaged, and the wooden buildings in Zamłynie (including 8 residential houses) were destroyed. Two bridges and 5.7 km of municipal roads were also damaged. As a result of the flood in Budzów, one person died, who was carried away by the swollen current of Paleczka [45, 57].

Conclusions

The flood that occurred in the upper Skawa catchment area in July 2001 was the largest one recorded since the start of the measurements in 1887. The accumulated floodwaters caused significant geomorphological transformations, which occurred mainly within the Paleczka catchment area and on smaller watercourses draining Makowska Góra. There has been a significant remodelling of stream beds and the activation of large landslides. The accumulation and erosion forms formed during the flood caused a change in the landscape within the valleys. However, the degree of the transformations that took place differs depending on the size of the formed forms and their distribution within the valley. On the other hand, their durability in the landscape depends on the type of development plan for the land they are built on. The channel forms developed in Paleczka, in a highly urbanized area (in its lower and middle reaches), were mostly removed (as a result of channel regulation) within just two years of the flood. Moreover, the forms created in the upper reaches have been preserved for a long time, undergoing a gradual succession of vegetation. In 8 years (until 2009) they completely disappeared from the landscape. The torrential cones formed in the area of Maków Podhalański were removed from the landscape the fastest. The longest-preserved forms in the landscape, created during the flood in 2001, are large landslides, the form of which was formed on the Beskidówka slope and is still preserved in the landscape in 2015.

The flood also caused significant damage to public infrastructure and private property. The resulting losses were estimated at around PLN 90 million, the largest of which was recorded in the Budzów commune and in Maków Podhalański (the number of material losses was given according to the valuation from the decade of 2000). However, it was not the Skawa, but rather its tributaries and numerous small mountain streams that did contribute to the greatest losses.

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