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GEOMORPHIC EFFECT OF THE CATASTROPHIC SUMMER FLOOD OF 1997 IN THE POLISH TATRA MOUNTAINS

INTRODUCTION

Precipitation is an important relief-forming factor in the Tatra Mountains. This idea is documented in numerous works both in the Polish and Slovak part of the mountains (i.a. Staszic 1815; Dudziak 1969; Lukniš 1973; Kaszowski 1973; Ziętara 1974; Nemčok 1982; Midriak 1984; Krzemień 1985, 1988, 1991; Kotarba et al. 1987; Kotarba and Stromquist 1984; Kaszowski et al. 1988; Kotarba 1992). Reliable precipitation monitoring, set up within the framework of the Institute of Meteorology and Water Management (IMWM) tasks, provided the basis for a detail characteristics of precipitation conditions in the Tatras, especially of extreme rainfall being particularly important for rapid mass movement development (Orlicz 1962; Cebulak 1983). Monitoring of rainfall induced morphologic changes occurring on the Tatric slopes is set up in the western and eastern parts as well (Kotarba et al. 1979; Borowiec 1996). All these premises lead to a question: how do various kinds precipitation influence a mode and rate of the Tatric slope modelling? This question embraces the purpose of this article. Moreover, the article aims at showing a peculiarity of the catastrophic flood which happened in July 1997 in comparison with other geomorphic events which took place in the past in the area of the Tatras.

THE FLOOD OF JULY 1997 IN THE TATRAS

A specific character of the flood of July 1997 in the Tatras was associated with a pattern and duration of precipitation which occurred in the entire Western Carpathians. From 5 July there was an inflow of moist air masses from the north. A stationary front had developed and resulted in a steady rainfall on the northern slopes of the Carpathians. Condensation of water vapour occurred and, at the same time, there was at continual advection of cool air. On 7 July an air mass swirl developed between the Cracow Upland and western Ukraine. A cool air mass from the north was mixing with a warmer and moister air mass from Ukraine. On 8 July the axis of this structure moved from the Western Beskidy Mts (ranges of the Silesian Beskid and Żywiec Beskid) towards east and entered the Tatras. Therefore, maximum daily precipitation totals in the Tatras and Podhale were recorded by IMWM meteorological stations on 8 July. On 5–7 July the Tatric precipitation stations recorded the totals from 75.3 mm (Chochołowska Valley), 89.3 mm (Kasprowy Wierch summit station), 90.4 mm (Hala Ornak) to 100.5 mm (Hala Gąsienicowa). On the next day, 8 July 1997, the daily precipitation totals were: 163.0 mm, 166.1 mm. 162.7 mm and 223.5 mm, respectively. On the same day, the sub-Tatric precipitation stations (Kiry, Zakopane) recorded rainfall slightly exceeding 100 mm. Such enormously high rainfall totals were recorded in the past only exceptionally. For example, in Zakopane higher rainfall totals occurred between 15 and 18 July 1934 (288.9 mm) and between 4 and 8 June 1948 (233.7 mm). In July 1934, on 16–18 July rain amounting up to 422 mm fell on Hala Gąsienicowa (Orlicz 1962). On the other hand, on 4–7 July 1997 continuous rainfall of low intensity occurrred. This rainfall preceded a heavy rainstorm of 8 July which was crucial for modelling the Tatric slopes. Figure 1 presents rainfall totals from the stations in Zakopane, Chochołowska Valley, Hala Ornak, Kasprowy Wierch and Hala Gąsienicowa. The rainfall totals from 4 to 8 of July exceeded 200 mm everywhere, yet in Hala Gąsienicowa reached 330.3 mm (Fig. 1). The diurnal rainfall recorded by the pluviograph in Hala Gąsienicowa station on 8 July 1997 was 223.5 mm (Fig. 2). Here, a characteristic feature was a relatively low instantaneous intensity of the order of 0.7 mm $\cdot$ min^{-1} and a high hourly value (39 mm $\cdot$ hour^{-1}). The relationship between the rainfall total and its duration during the July 1997 flood showed that the threshold values, as determined by N. Caine (1980) and J. L. Innes (1983), have been exceeded (Fig. 3). The rainfall of 8 July lasted 18 hours while the ratios between the rainfall totals and duration are very close to the highest values known from geomorphic literature and compiled by J. L. Innes (1983). It demonstrates that the Tatric flood was an exceptional phenomenon, with extreme parameters, also beyond the European level.

In contrary to the rainfall pattern described above, catastrophic rain falling down from *Cumulonimbus* clouds during summer thunderstorms of a convection type are short-lasting and their instantaneous intensities reach 1.3 mm $\cdot$ min^{-1}. During the rainstorm, on 9 August 1991, hourly total was 60 mm and rainfall instantaneous intensity was 1.5 mm $\cdot$ min^{-1}. In such the synoptic situations, the rainstorms resulted in spectacular debris flows on debris-mantled slopes above the upper timberline. Erosional gullies formed during such rainfalls are c. 5 m deep and up to 25 m wide, while the volume of the transferred debris material is of the order of 3,000 m^3. Rapid mass movements during such downpours cause

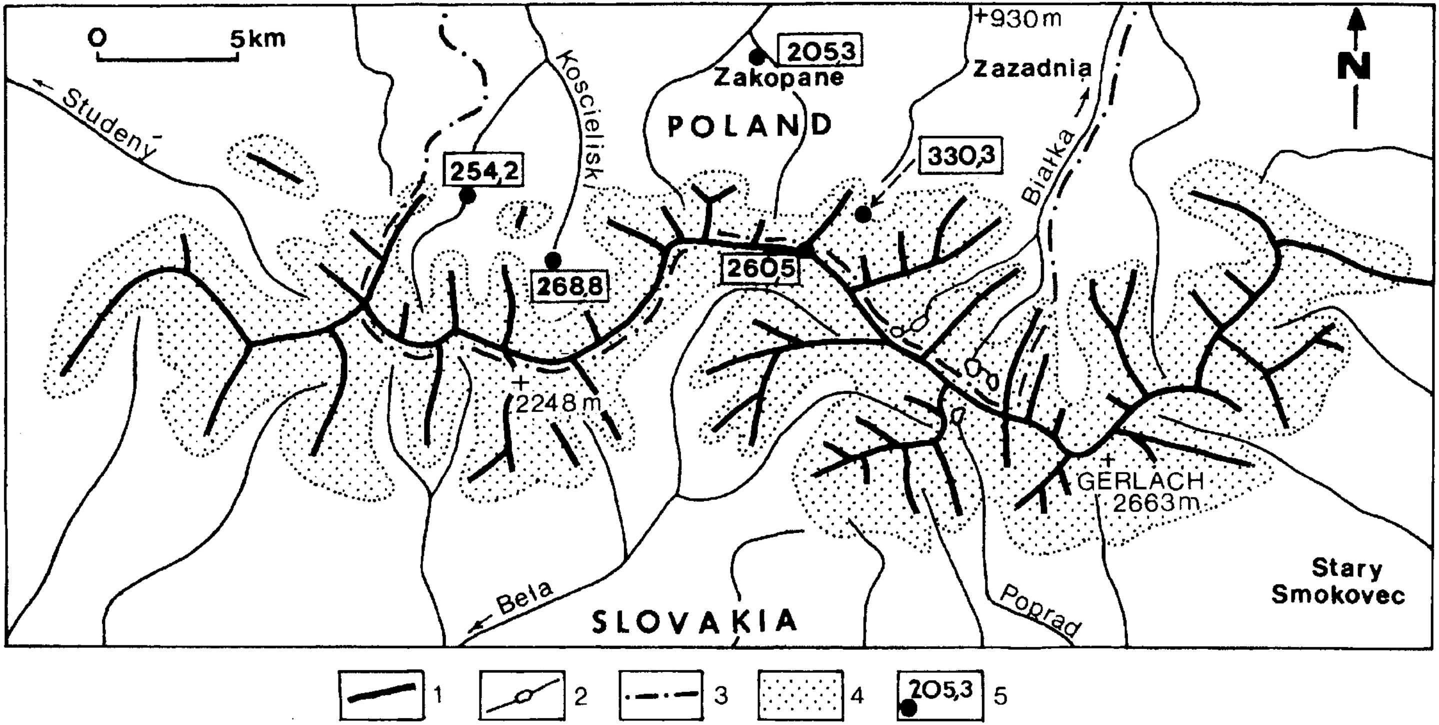

Fig. 1. Sketch map of the Tatra Mountains with location of precipitation gauges. Rainfall totals for the period 4–8 July, 1997. 1 — mountain ridge, 2 — river and lake, 3 — state boundary between Poland and Slovakia, 4 — areas above the upper timberline, 5 — precipitation gages: rainfall totals 4–8 July 1997

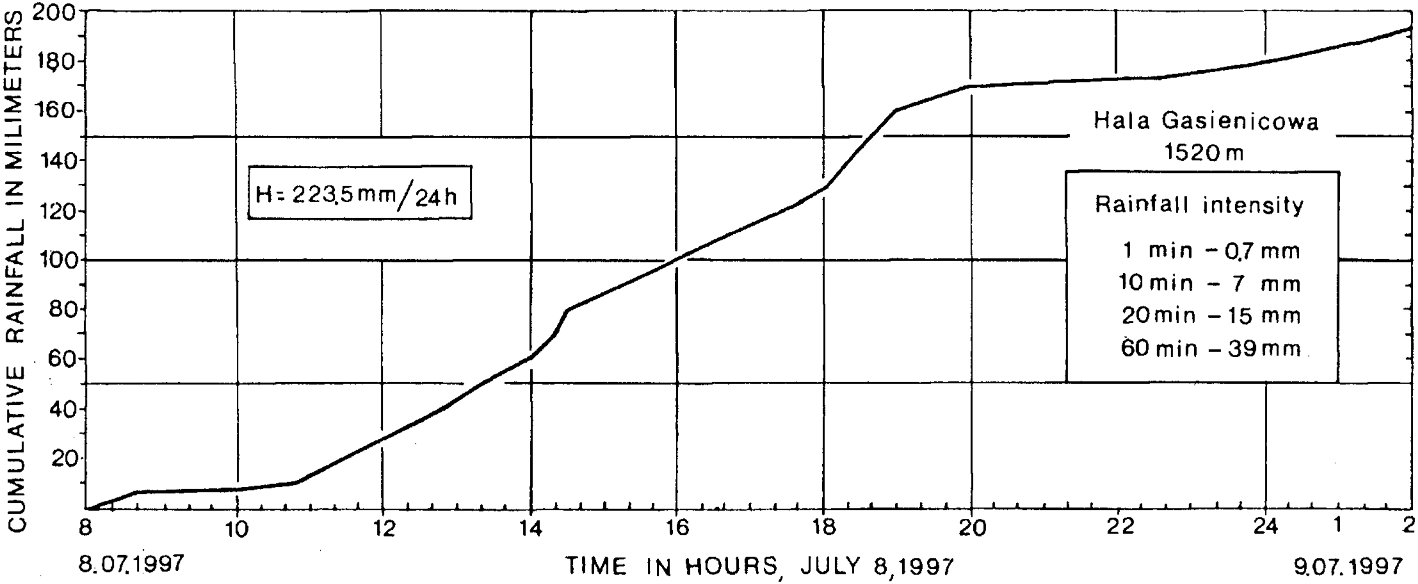

Fig. 2. Rainfall characteristics on 8 July, 1997. Data for the station located at the upper timberline

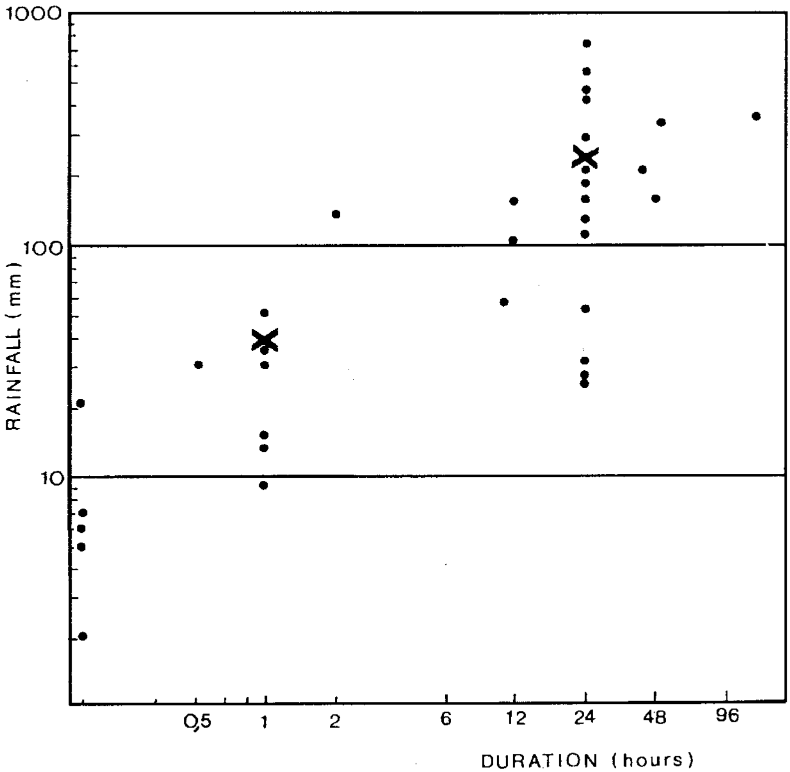

Fig. 3. The rainfall amount-duration relationship that has been reported as triggering debris-flow activity, compiled by I. J. Innes (1983), by permission of Arnold Publishers. The case of Tatra summer flood in 1997 is shown by X

washing and transfer of debris covers with maximum boulder size of 70 to 150 cm (Kotarba 1994).

In contrary to the weather phenomena mentioned above, the rainfall of July 1997 did not resulted in numerous and new debris flows above the upper timberline. Only the gullies formed earlier were widened and deepened, yet in principle they had not changed their general forms. During the July 1997 flood only one immense debris flow developed on the slopes of Wołoszyn Mt. Formed in the source niche down the arête it entered the Roztoka Valley bottom after passing through the Suchy Żleb Wołoszyński trough. It reached the length of c. 1 km. The maximum width of the debris deposition in the frontal part was 30 m and newly formed debris ramparts were up to 4 m high. The lack of other spectacular, new forms of debris flows above the upper timberline during the July 1997 flood might be attributed to a relatively low rainfall intensity, not exceeding 1 mm · min^{-1}, although the hourly totals reached the threshold values that were sufficient for triggering debris flows.

GEOMORPHIC AND ECONOMIC EFFECTS OF THE JULY 1997 FLOOD

The magnitude of geomorphic effects and economic losses depend not only on rainfall totals and precipitation distribution but also on peculiarities of the environment in which these changes occur. In the Tatras, a specific variability of the environmental features corresponds closely to geological differentiation (a crystalline core and metamorphic in the high-mountain area, and Mesozoic mantle in the middle and lower parts which have a medium-high mountain nature), type of relief (glacial, erosion-denudational, fluvial, karstic) and the appropriate weathering covers. Finally, a zonal vegetation pattern also controls water circulation and determines storage capacity of the area. Therefore, rainfall of similar parameters might result in various qualitative and quantitative effects. Rainfall data shown in Figure 1 indicate that precipitation of the order of 250–330 mm occurred in a whole territory of the Tatras. The rainfall as heavy as that occurred previously in 1934 and caused the largest flood registered in chronicles not only for the Tatras but also for the entire Polish Carpathians. Not only were geomorphic effects and material losses of the July 1997 flood in the Carpathians as profound as in the case of the previously occurring floods in the 19th century, yet they were even more extensive. Similar conclusions might refer to the Tatras based on the evidenced damages registered and estimated by the administrative board of the Tatra National Park. The evidence of the material losses and geomorphic effects, documented just after the flood, indicated that detrimental consequences had a very irregular horizontal and vertical pattern. A peculiar feature was a concentration of losses in the forested areas and a relatively small damages above the upper timberline. The most spectacular changes in the relief and harm to vegetation occurred in the central part of the middle-mountain forest belt of the Tatras, in the valleys of Sucha Woda and Olczyska. There, the main stream channels, valley bottoms and valleys dissecting slopes became remodelled to the highest degree. Numerous slides, flowing movements of soil-debris masses came into being and the transfer to the valley bottoms occurred. Even whole trees were moved. The lower reaches of the channels and valley floors of the Sucha Woda and Olczyska had been completely remodelled, and numerous sections of mountain local roads, forest pathways and tourist trails had been totally destroyed. A primary evaluation of the damages in the Tatra National Park amounted to 6.1 million zlotys. The highest detrimental consequences referred to the roads (5.7 million zlotys) and tourist trails (0.243 million zlotys). It has been stated that in majority of the registered damages, geomorphic processes were most effective in the human-made objects, i.e. on the local roads and pathways, ski tracks and tourist trails.

Continuous rain of the period from 4 to 7 July 1997 caused the soil-debris covers on the forested slopes to be saturated with rainwater, and the rainstorm of the following day (8 July) brought about oversaturation leading to triggering

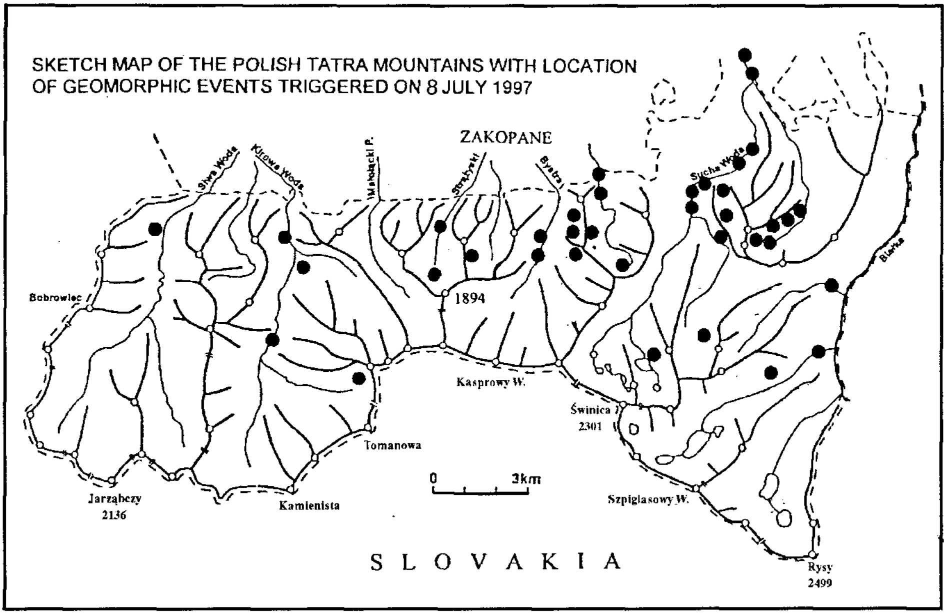

Fig. 4. Sketch map of the Polish Tatra Mountains with location of geomorphic events triggered on 8 July 1997

of an overland flow and flowing movement of soil-debris masses. Even in the case of the slopes overgrown with middle-mountain forests, sliding, earthflows and shallow landslides were triggered on a mass scale when referring to the area affected. The transferred material formed tongues and lobes whose fronts were leant against tree trunks, and locally benches and steps built of colluvia had developed. Such forms appeared in different parts of the slopes, in the sub-ridge part, middle one and close to a valley floor. Especially on the steep slopes and in old erosion undercuts, the slope processes transported weathered material to the floors of the main valleys.

Due to the flowing movement of the slope covers, previously continuous vegetation mantle became truncated and transferred together with the weathered masses. However, the main source of the material supplied to the valley bottoms were tiny valleys dissecting the slopes. Transportation of the weathered material concentrated in tiny basins and incisions which are dry during a year. Prior to the flood, the floors of the valleys were filled up with weathered material, often a coarse one, and their slopes were overgrown with the middle-mountain forests. Excess of precipitation water, accumulated in the covers, was concentrated in the valley axes, and during the flash rainfall on 8 July the weathered material was washed together with whole trees; dry ones in the foehn-fallen forest areas or even living ones (Photo 1). In numerous small valleys, especially in the surrounding of Kopy Sołtysie Mt, the wood-mineral debris was washed rapidly and denuded down to the

Photo 1. Frontal view to woody debris cone formed at the outlet of small V-shaped valley, Filipka Valley, Kopy Sołtysie Mt

bedrock. Here, rocky floors that have not been observed for many years in the middle-mountain forest belt of the Tatras, developed. The wood debris mixed with mineral debris, removed to the floors of the main valleys (Filipka, Złota and Olczyska valleys), was deposited in the form of cones. In the cone composition predominated the fallen and transferred trees which in most often cases had the bark stripped off during transportation (Photo 2). In the Filipka Valley natural dams were formed across the main valley. That had slowed down the water outflow. High turbulence in the zone of the tree dams added up to erosional effect. That is evidenced by numerous erosional gullies and evorsion hollows being 1.5–2.0 m deep. The erosional power was as high as the roads reinforced with gravel became washed out and wooden bridges were either destroyed or covered with transported rubble (Photo 3 and 4).

The most devastating effects of the fluvial processes have been stated in the valleys of the middle-mountain forest belt of the Tatras, and especially in the Sucha Woda and Olczyska Valleys (Fig. 4). In the Sucha Woda Valley, in the 2.5 km long reach, i.e. from the junction of the Sucha Woda and Pańszczycki Streams to the outlet from the Tatras, the main channel had been remodelled over its entire width. This re-modelling was associated with a rise of water level of the Sucha Woda Stream. During the flood, the water level rose by 2.5 m. That was infered from tracks of the bark stripped off from the trunks and branches of the living trees that grew around the channels and that

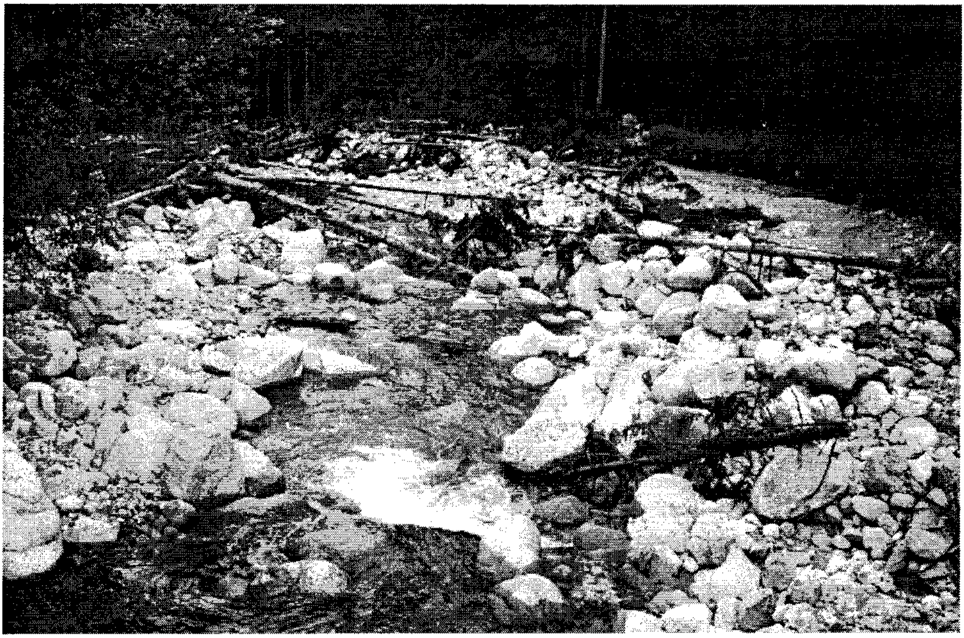

Photo 2. The Sucha Woda valley bottom after flood. Spruce tree trunks are bark-free due to transportation by flood water

Photo 3. Streamside debris slides within glacial drift deposits of the Toporowe Stawy. Large organic and mineral supply to the main channel of the Sucha Woda valley

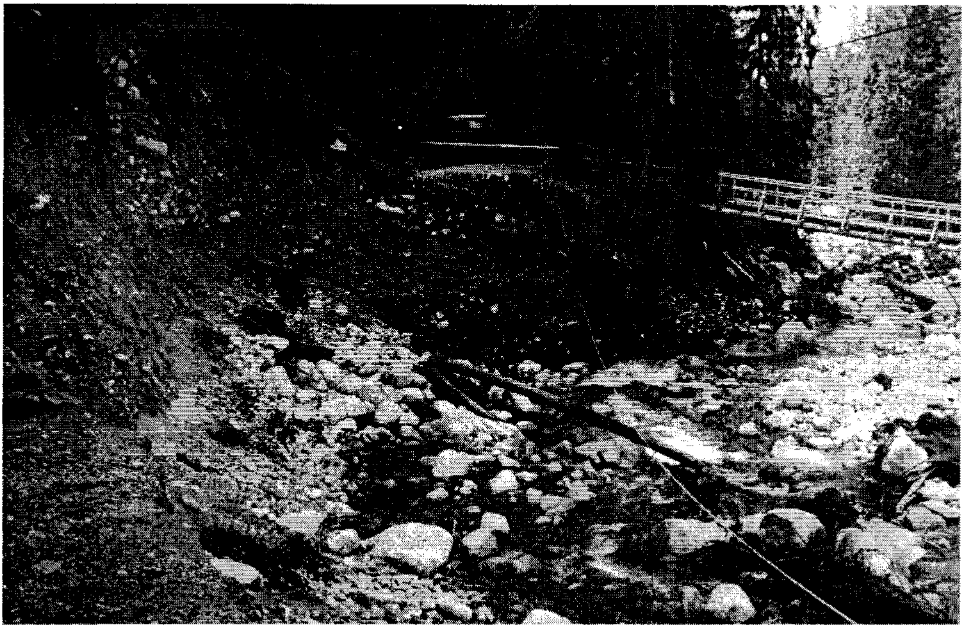

Photo 4. Erosion undercut 30 m long and 10 m wide within the main road from Brzeziny to Hala Gąsienicowa. The volume of eroded material is calculated to be around 1,200–1,400 cu. m

withstood the flood (Photo 5 and 6). At the overall channel gradient of c. 70% (Wit-Jóźwik 1974) the water flowing over its entire width undercut glacio-fluvial and fluvial terraces as well as a moraine mound of the Toporowe Stawy. Due to washing of the terraces and moraine slopes, the lateral retreat of the banks, including those built of coarse material of diameters of 1–1.5 m, occurred and was followed by the longitudinal transportation of the material in question. On the other hand, the slopes built of moraine deposits rich in sand-silty particles, provided as much of the fine material as the density of the water medium was sufficiently high to support transportation of the blocks up to 2 m in diameter over the distance of 20–30 m from their original position. The transportation of as coarse debris could have occurred only if the material transported in the channel had a high content of fine particles, i.e. silty and clayey ones, and fluvial transportation environment was enriched by debris and mud flows. Given all these circumstances, even the coarsest material was subjected to longitudinal transportation and transverse selection. This way had developed a system of levees built of boulders exceeding 1 m in diameter and showing imbrication features. The material in question had been intermixed with wooden debris originating from destruction of the trees growing close to the channels and growing on the valley sides undercut by the main stream. The trees collapsing and falling down into water together with their root system became local barriers on the river transporting rocky debris. Therefore, the river current pushed toward the sides of these natural dams was directed to

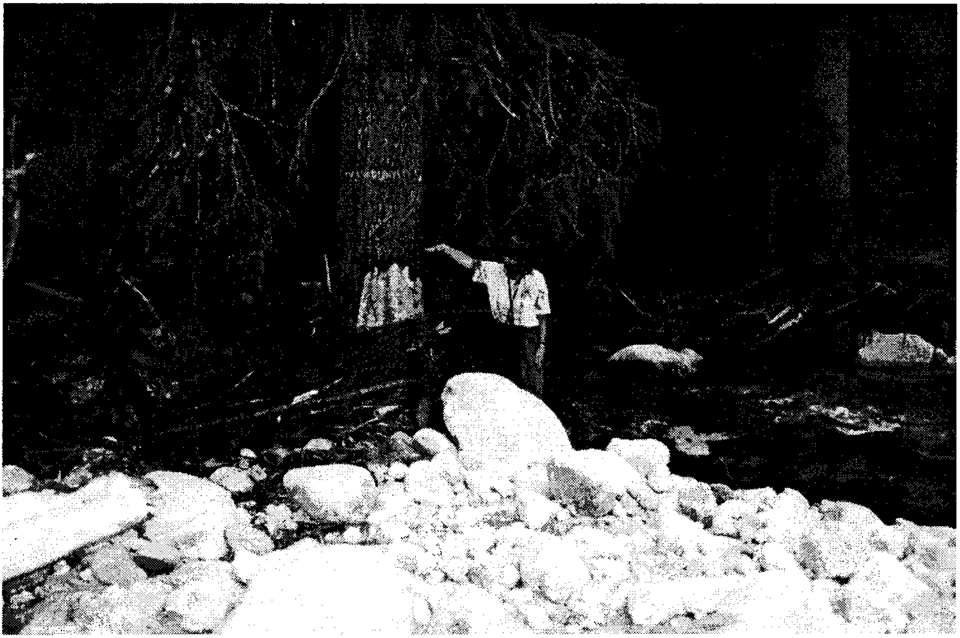

Photo 5. An extent of high water stage in the main channel of the Sucha Woda valley marked by stripped bark

Photo 6. Stripped bark on spruce trunk due to large woody and mineral debris transport on the margin of flood plain, Sucha Woda valley

the banks causing again farther undercutting of the sides and a new supply if the trees and mineral debris to the channel. This feedback between the channel and slope processes caused the very stable edges of terraces, built of blocky fraction and not bearing the traces of washing in a historical scale, to retreat laterally by a few metres. A similar processes of the lateral channel widening took place on the expense of the moraine slope from the Toporowe Stawy aside. The most spectacular erosional form developed this way, resulted in destruction of the road from Brzeziny to Hala Gąsienicowa. Over the c. 30 m long section, the road running at the height of 6 m above the channel level was completely cut off and the stream bank retreated by c. 10 m (Photo 4). A simple calculation showed that, here, the volume of the washed material together with the road amounted to 1,200–1,400 cu. m. The Sucha Woda Stream, flowing over the entire valley floor width, washed many sections of the local road to Hala Gąsienicowa.

FINAL REMARKS

The Tatric flood of July 1997 significantly differed from other catastrophic hydro-meteorological phenomena. The rainfall that occurred on 8 July was sufficiently heavy to cause serious rises in water levels of the Tatric streams. Yet, this rain fell onto the area which had been saturated with water in the preceding days. The described sequence of precipitation triggered one of the highest floods in the Tatras in historical times. The highest recorded instantaneous intensities, expressed in millimetre per minute and calculated from pluviograms, did not exceed 0.7. A much higher rainfall intensities, of the order of 1.5–1.7 mm $\cdot$ min^{-1}, are often observed in the Tatras during short-lasting flash rainfall of convectional type. Such rainfall result in spectacular changes in morphology of the Tatric slopes, especially in the high-mountain cryonival domain. During the July 1997 flood, new forms in the cryonival domain have been stated only occasionally while the gross of the geomorphic work took place in the middle-mountain forest domain (Fig. 5). The geomorphic processes in this part of the Tatras had the extent and magnitude which had not been observed on a historical scale. Quantitatively this phenomenon manifested in competence of the forest belt streams, i.e. in capacity for boulder transportation during a flood. The studies carried out after the flood of 1 July 1973 when the diurnal rainfall total on Hala Gąsienicowa reached the absolute maximum of 300 mm showed that the material whose maximum diameters varied from 20 to 60 cm was transported in the channels (Kaszowski and Kotarba 1985). At that time, the maximum fraction transported in the Sucha Woda Stream amounted to 20–40 cm. However, during the last flood boulders of up to 2 m in diameter were also transported. The transportation was controlled not only by fluvial processes but also by debris flow-like process. An important component of the transported material was wooden debris that have not been observed in the Tatras on a such

LONGLASTING CONTINUOUS RAIN
Duration > 3 days, max. intensity < 1 mm/min
+
SHORT LASTING DOWNPOUR

⇓ ⇓ ⇓ ⇓ ⇓

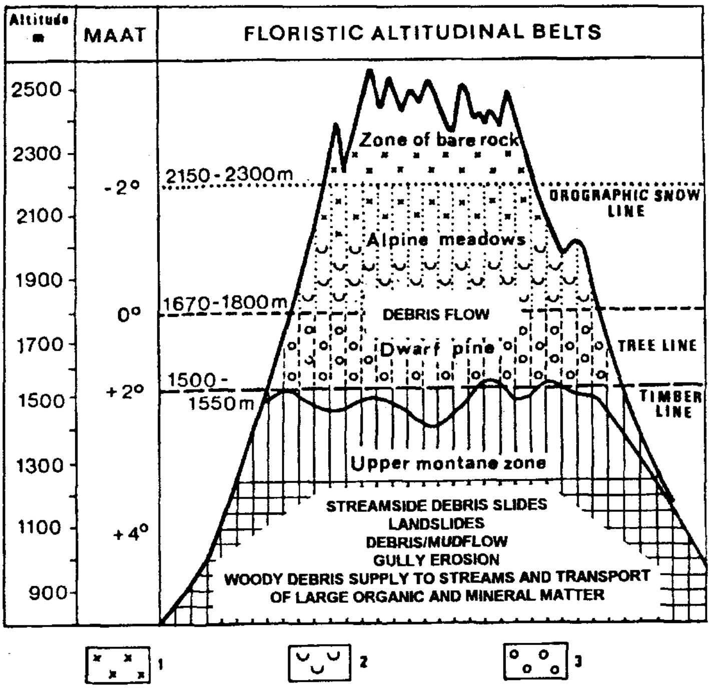

Fig. 5. Dominant geomorphic processes within geoecological belts of the Tatra Mountains during summer flood of 1997

scale yet. These exceptional geomorphological changes may be explain also by substantially large organic debris displacement and storage in the active stream channels. Such large organic debris move only rarely and are semipermanent parts of channel morphology, and play a significant role in the routing and storage of mineral sediment. Residence time for such debris in channels could exceed 100 years, and in some circumstances even 200 years (Keller et al. 1995). In the Tatra National Park large organic debris is evacuated by forest service after flood of 1997, for nature protection purposes.

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STRESZCZENIE

A. Kotarba

GEOMORFOLOGICZNE SKUTKI KATASTROFALNEJ POWODZI W 1997 ROKU W TATRACH POLSKICH

Powódź w lipcu 1997 roku była wyjątkowym zdarzeniem w Karpatach Zachodnich. W Tatrzańskim Parku Narodowym największe opady wystąpiły podczas 6 dni, w okresie od 4 do 9 lipca, przy czym kulminacyjny opad miał miejsce w dniu 8 lipca. W tym dniu stacja IMGW na Hali Gąsienicowej zarejestrowała opad 223,5 mm. Największe przekształcenia rzeźby wystąpiły w Tatrach Reglowych, szczególnie w doliniach Suchej Wody, Olczyskiej i Filipka, gdzie procesy geomorfologiczne osiągnęły niespotykany w skali historycznej zasięg i rozmiary. Poziom wody w korycie Suchej Wody podniósł się o około 2,5 m, a rzeka płynęła całą szerokością dna doliny, podcinając brzegi i niszcząc zarówno terasy glacifluwialne jak i zbocza wysoczyzny morenowej Toporowych Stawów. Podcinane zbocza wysoczyzny morenowej Toporowych Stawów dostarczały do koryta zarówno materiał głazowy jak i frakcje pylasto-piaszczyste, przez co gęstość ośrodka wodnego była na tyle wysoka, że transportowi podlegały głazy o maksymalnej średnicy do 2 metrów. Za transport były odpowiedzialne nie tylko procesy fluwialne, lecz również procesy o charakterze turbulentnych spływów gruzowych. Drzewa padające do koryta wraz z systemami korzeniowymi były lokalnymi barierami dla wód powodziowych. Zwiększały turbulencję w rzece i były lokalnie przemieszczane wskutek transportu podłużnego i poprzecznego. Powstały nowe systemy korytowe. Na stokach pokrytych przez lasy reglowe dochodziło do uruchamiania złazisk, spływów ziemnych i płytkich osuwisk, a w nieckach i dolinach wciosowych nastąpiło wyprzątnięcie pokryw zwietrzelinowych do litej skały. W stożkach napływowych utworzonych u wylotów tych dolin do doliny głównej, dominowały drzewa powalone i przemieszczone. Powstały niespotykane w Tatrach stożki drzewno-gruzowe. Straty materialne spowodowane przez powódź w Tatrzańskim Parku Narodowym osiągnęły 6,1 mln złotych i dotyczyły głównie dróg i szlaków turystycznych.