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GEOMORPHIC ROLE OF EXTREME RAINFALLS IN THE POLISH CARPATHIANS

INTRODUCTION

The purpose of the paper is to synthesize the knowledge about extreme rainfalls and their role in relief transformation of the Polish Carpathians in the current century. We are witnessing the 90th anniversary of formation of the largest Carpathian landslide in Duszatyn where 10 million m^3 were moved (Zuber and Blaut 1907; Schramm 1925). It has been 80 years since Sawicki published (1917) his fundamental work on landslides in Szymbark and Muszyna which were triggered by continuous rainfalls in 1913. Effects of heavy downpours and of the flood of 1934 were described by Klimaszewski (1935) and Stecki (1934). In the 1950s, 1960s and in the early 1970s the impact of extreme rainfalls on soil erosion was emphasized by Figuła (1960), Gerlach (1966), Gil and Słupik (1972). The relationship between landslides and precipitation was studied by Jakubowski (1964, 1967, 1968), Starkel (1960), Ziętara (1968), Dauksza and Kotarba (1973). Fluvial processes and the role of floods in selected catchments were analyzed by Kaszowski (1973), Niemirowski (1972), Ziętara (1968) and Froehlich (1975).

Several notes on the influence of continuous rain of 1970 in various parts of the Carpathians (Niedźwiedź, Brykowicz *et al.*, Niemirowski, Soja, Welc, Froehlich) were published in Studia Geomorphologica Carpatho-Balcanica in 1972.

In 1976, 20 years ago, the author published a general paper about the role of extreme meteorological events in the evolution of relief of the mountain slopes and classified the events as follows: local, short-lasting downpours, continuous rains, rainy seasons and periods of rapid melting (Starkel 1976). This classification was developed in the Carpathian context and presented in later papers (Gil and Starkel 1979; Starkel 1979, 1980).

During the recent 20 years the mechanism of processes undergoing during the extreme rainfalls has been learnt better, mainly due to monitoring in research stations and thanks to a thorough registration of the events (Fig. 1). Cebulak's studies (1983, 1991, 1992a, b) on spatial distribution of maximum daily precipitation in the Polish Carpathians as well as the analyses of the duration of precipitation in Szymbark (Wit-Jóźwik 1978) were important contributions to the study on precipitation pattern. The studies on washing did not provide too much new information (Gil 1976), yet the role of cart roads in degradation of slopes was determined quantitatively (Froehlich 1982). Kotarba (1992, 1994) studied the role of heavy downpours in formation of debris flows on the Tatra slopes. The mechanism of water circulation and the role of water in development of landslides were studied on experimental slopes in Szymbark during a moist year 1974 (Gil and Kotarba 1977; Gil and Starkel 1979). These studies were then continued under the framework of the inter-disciplinary programme led by K. Thiel (Thiel 1989; Gil 1994). Fluvial studies aimed at determination of threshold values that have to be reached to trigger bedload transport and transformation of channels. Such studies were carried out in the Biały valley in the Tatras (Kaszowski 1973), in the Białka valley in the Tatra foreland (Baumgart-Kotarba 1983), in the Ropa valley near Szymbark (Dauksza *et al.* 1982; Soja 1977) and were progressing in the Kamienica and Homerka (its tributary) since 1970 (Froehlich 1982).

Table 1 — Tabela 1

Processes active during various extreme rainfalls over different slope and channel systems

Procesy działające podczas różnych opadów ekstremalnych w obrębie systemów stokowych i korytowych

Types of extreme rainfalls	Alpine rockwall–debris slopes	Steeper sandstone slopes with debris, forested	Steeper shale-sandstone slopes with thick regolith or colluvium	Gentle slopes with thick regolith or colluvium	Steep-gradient mountain channels	Low-gradient channels of foothills
heavy downpours	debris flows	small slips, and debris flows	small slips and slumps, soil flows	slope wash, soil flows	high suspended load, debris flows local erosion	high suspended load
continuous rains	subsurface runoff, piping	linear erosion piping	earthslides linear erosion	earthslides. earthflows piping	deep and lateral erosion, formation and shifting of bars	extension of channel, vertical accretion of flood plain
rainy seasons		deep rock–slides	deep earth and rock–slides	earthslides		

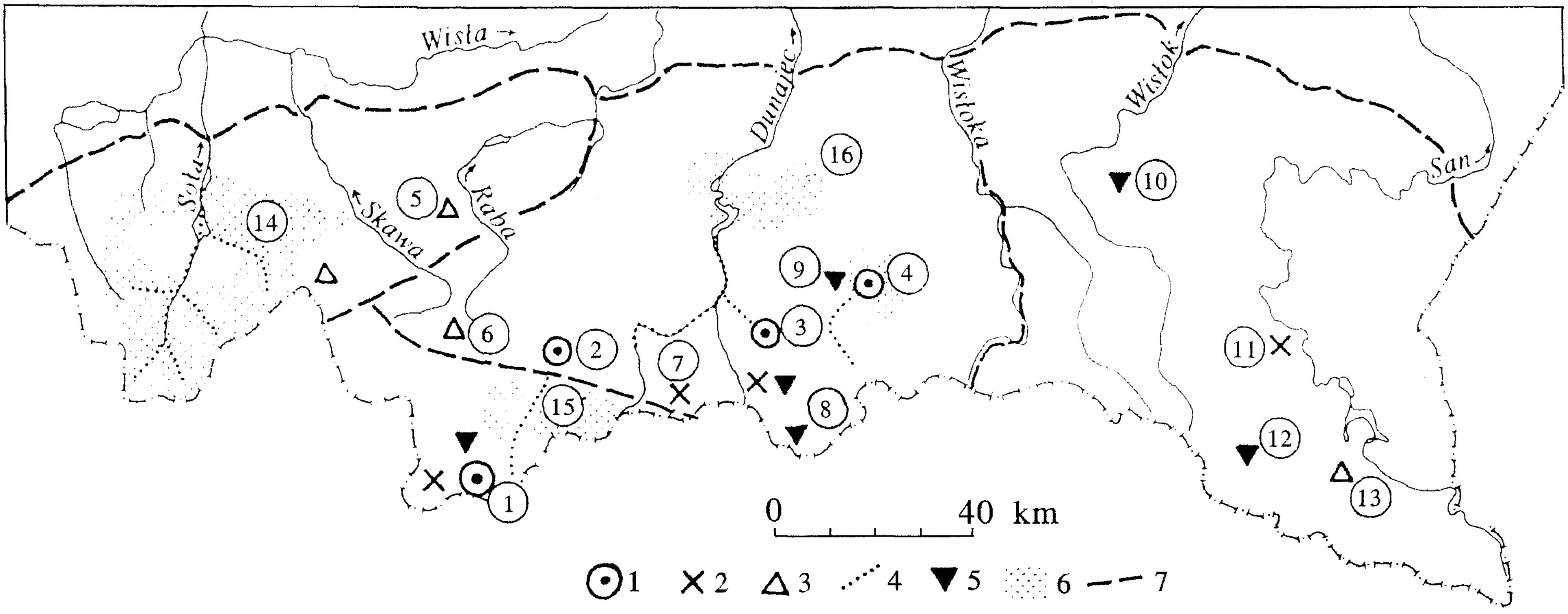

Fig. 1. Areas of investigations on effects of extreme rainfalls in the Polish Carpathians. 1 — monitoring stations of extreme geomorphic processes, 2 — localities with registered effects of heavy downpours, 3 — localities with registered effects of continuous rains, 4 — river channels with registered flood effects, 5 — landslides created during rainy reasons, 6 – regions with survey of active landslides, 7 — boundaries of main Carpathians regions presented on Fig. 7.

Names of selected research stations, sites and regions mentioned in the text: 1 — Hala Gąsienicowa Research Station in the Tatra Mts (Kotarba 1992, 1994), 2 — Jaszcze and Jamne experimental basins (Niemirowski 1972), 3 — Homerka experimental basin and Station (Froehlich 1975, 1982), 4 — Szymbark Research Station (Gil 1976; Gil and Starkel 1979; Thiel *et al.* 1989), 5 — landslide at Pcim (Jakubowski and Ostaficzuk 1962), 6 — landslide at Bielanka (Jakubowski 1967), 7 — slips and slumps at Jaworki (Gerlach 1966), 8 — landslide at Muszyna (Sawicki 1917), 9 — landslide in Szklarka valley at Szymbark (Sawicki 1917), 10 — landslide at Brzeżanka (Bober *et al.* 1977), 11 — earth-flows at Postołów (Starkel 1960), 12 — landslide at Duszatyn (Schramm 1925), 13 — landslide on Połoma slope (Dziuban 1983), 14 — landslides and channels in Western Beskid surveyed in 1958–60 (Ziętara 1968), 15 — landslides in Podhale regions surveyed in 60th (Jakubowski 1964, 1967, 1968), 16 — landslides on Rożnów Foothills (Ziętara 1974)

Ryc. 1. Obszary badań nad skutkami ekstremalnych opadów w Polskich Karpatach. 1 — stacje monitoringu ekstremalnych procesów geomorfologicznych, 2 — stanowiska rejestracji efektów ulew, 3 — stanowiska rejestracji opadów rozlewnych, 4 — koryta rzek z rejestrowanymi skutkami powodzi, 5 — osuwiska powstałe w czasie sezonów deszczowych, 6 — obszary rejestracji aktywnych osuwisk, 7 — granice regionów karpackich prezentowanych na Ryc. 7.

Nazwy stacji badawczych stanowisk i regionów wymienionych w tekście: 1 — Stacja na Hali Gąsienicowej w Tatrach (Kotarba 1992, 1994), 2 — zlewnie eksperymentalne Jaszcze i Jamne (Niemirowski 1972), 3 — zlewnia eksperymentalna Homerki i Stacja (Froehlich 1975, 1982), 4 — Stacja badawcza w Szymbarku (Gil 1976; Gil and Starkel 1979; Thiel i in. 1989), 5 — osuwisko w Pcimiu (Jakubowski and Ostaficzuk 1962), 6 — osuwisko w Bielance (Jakubowski 1967), 7 — zsuwy i zerwy w Jaworkach (Gerlach 1966), 8 — osuwisko w Muszynie (Sawicki 1917), 9 — osuwisko w dolinie Szklarki w Szymbarku (Sawicki 1917), 10 — osuwisko w Brzeżance (Bober i in. 1977), 11 — spływy ziemne w Postołowie (Starkel 1960), 12 — osuwisko w Duszatynie (Schramm 1925), 13 — osuwisko na stoku Połómy (Dziuban 1983), 14 — osuwiska i koryta rejestrowane w latach 1958–60 w Zachodnich Beskidach (Ziętara 1968), 15 — osuwiska na Podhalu rejestrowane w latach 60-tych (Jakubowski 1964, 1967, 1968), 16 — osuwiska Pogórza Rożnowskiego (Ziętara 1974)

The collected materials allowed for determination of the threshold values for extreme rainfalls during which slopes and valley floors are transformed. Characteristics of such precipitation are presented in recent papers by Froehlich and Starkel (1991, 1995), Gil (1994) and by Starkel (1986) and in the case of the Tatras by Kotarba *et al.* (1987) and Kotarba (1994).

The attached Table 1 and Figs. 1 and 7 present information on types of rainfalls and their effects in the current century.

STUDY OBJECT

The Polish Carpathians, except for a small crystalline and limestone Tatra massif protruding 2500 m a.s.l., comprise low and medium-high mountains as well as the foothills and intra-mountain basins built, almost exclusively, of the Cretaceous and Tertiary flysch (Klimaszewski and Starkel 1972). The flysch Carpathians lie within montane forest zones. The Beskidian part, 300–800 m differences in relative heights, have steep slopes (20–50°) covered with debris and skeletal soils. The hills in the foothill zone (100–200 m relative height) have more gentle (10–20°), usually convex-concave slopes with loamy soils often developed on loess.

Lithology and young tectonics are important for the Carpathian relief. In the western part of the Carpathians, predominant forms are closed, more resistant massifs with steep slopes as well as deeply incised valleys. In the eastern part, low foothills are, in majority, developed on less resistant shales, yet several isolated

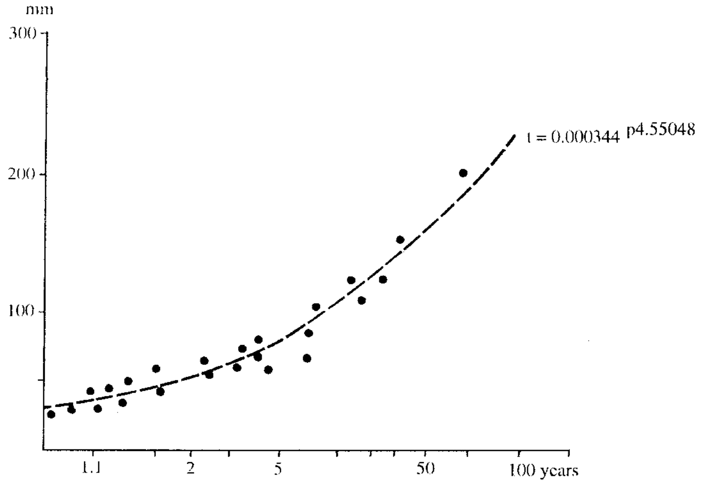

Fig. 2. Recurrence interval for maximum diurnal rainfall (1969–1988) in Łabowa near Homerka Research Station (after Froehlich and Starkel 1995)

Ryc. 2. Częstotliwość maksymalnych opadów dobowych w Łabowej w latach 1969–1988 w pobliżu stacji badawczej w Homerce (wg Froehlich i Starkel 1995) protruding ridges are built of more resistant sandstones. The heights of the ridges increase towards east, behind the transversal depression of the Beskid Niski range.

In the Carpathians, being influenced by western circulation, precipitation varies during a year and is higher in the higher, more closed western ridges facing to the north-west. Therefore, on the windward slopes in this part of the Carpathians precipitation is 1000–1500 mm, while towards the east average precipitation decreases to 700–1000 mm. Summer precipitation predominates and its duration time amounts to 7% (Wit-Jóźwik 1978). Although the daily precipitation indicates the threshold value only indirectly, yet thanks to synthesizing work of Cebulak (1991, 1992a, 1992b) it is a better characteristics of spatial and temporal distribution of extreme precipitation. Average maximum daily precipitation in 1951–1980 varied from 40–60 mm while the daily precipitation of probability of once per 100 years varies from 90–250 mm and is the highest in the high western mountain ranges: the Beskid Śląski and Mały, Beskid Żywiecki, Sądecki and the Tatras (Fig. 2). If the highest daily precipitation in this part of the mountains comprises more extensive areas and is brought about by continuous rain (lasting usually 2–5 days), so high precipitation in the eastern part is caused by local frontal storms. The frequency curve plotted for Łabowa (the eastern margin of the Beskid Sądecki Mts) shows 100–150 mm precipitation every 10 years on average (Froehlich and Starkel 1991). Continuous rainfalls causing floods happen every 10–30 years. For example, the flood of 1970 was triggered by 3-days' precipitation of the height of 300–400 mm (Niedźwiedź 1972). When tracing precipitation pattern in the current century, with Łabowa as example (Figs 3 and 7), one can notice at least 7 years with 1150 mm precipitation. In summer months (June–August) precipitation exceeded 550 mm 15 times and was induced by continuous rainfalls.

THRESHOLD VALUES FOR TRANSFORMATION OF SLOPE AND CHANNEL SYSTEMS

The effective duration time of processes controlling transformation of relief is much shorter than it has been presumed (Thornes and Brunsden 1977; Starkel 1986). In short time spans there is a concentration of water flowing over a slope (Słupik 1973) which affects both the mode of flow over the slope and floods in the valleys. Therefore, before analysing particular types of rainfalls (of various intensity, duration time and amount) and their geomorphic effects it is worthwhile to calculate the threshold values for various processes that trigger transportation of river load or debris and permanently transform the relief of slopes and valley floors.

In the case of the slope these are: the threshold value for infiltration and initiation of surface runoff, threshold for throughflow and threshold for soil flow, plasticity limit and strain exceeding internal friction and cohesion.

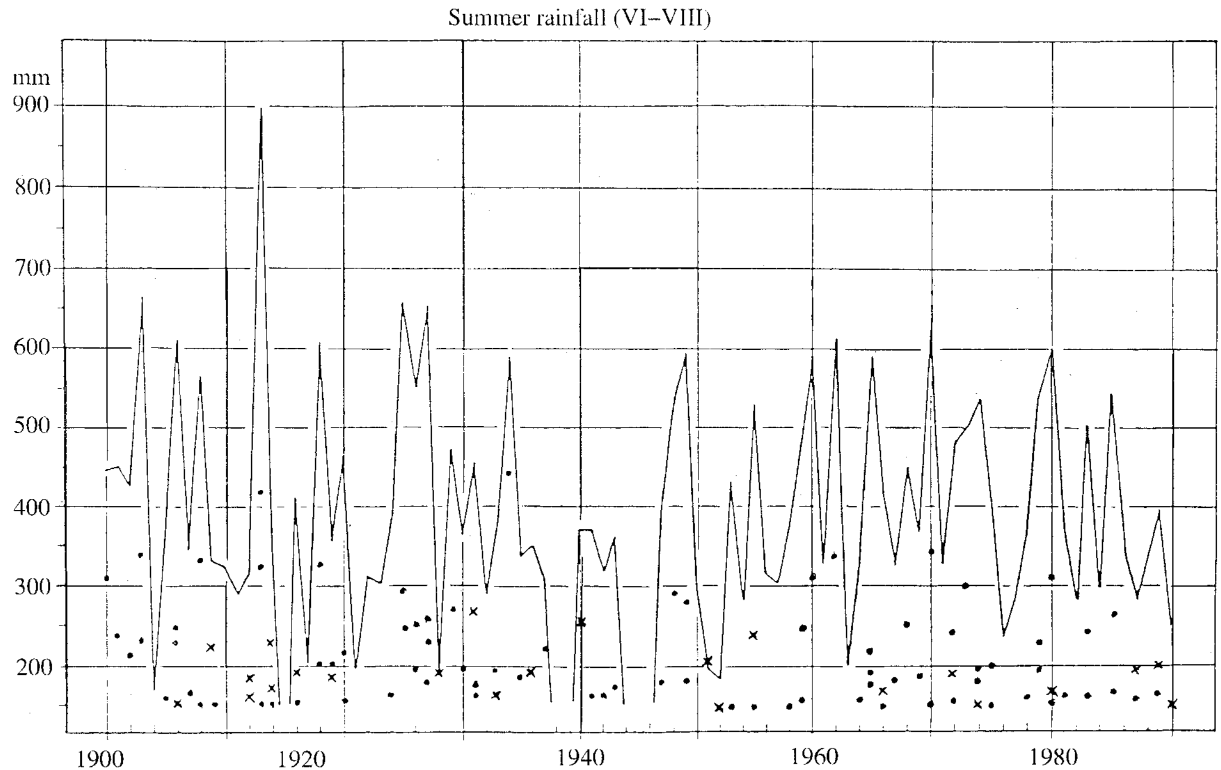

Fig. 3. Course of total summer rainfall in 20-th century at Łabowa (after data collected by Cebulak and Niedźwiedź). Dots indicate highest monthly rainfall in summer (VI–VIII), crosses — monthly rainfall in other seasons

Ryc. 3. Przebieg opadów letnich w XX wieku w Łabowej (wg danych zebranych przez Cebulak i Niedźwiedzia). Kropki pokazują najwyższe opady miesięczne w lecie (VI–VIII), krzyżyki w innych miesiącach roku

Infiltration on mountain slopes in the Carpathians varies from a part of mm per minute to 46 mm/minute (Słupik 1981) and depends on porosity and permeability of rocks. On loams overland flow is observed if precipitation intensity is 1 mm/minute while on skeletal soils infiltration continues until the threshold of throughflow is reached with the seepage pressure. The rate of flow in loamy weathered materials measured in Jaworki near Szczawnica was 1.8 m/hour (Figuła 1960). The long-lasting throughflow on the loamy deposits, related to saturation of upper ground surface, may lead to liquifacation of slope material and creeping of an arable layer or a soil cover with sward if precipitation is of the order of 30–40 mm and if its intensity is 1 mm/minute (Gil and Słupik 1972). On steep (over 30°), high-mountain scree slopes similar precipitation results in debris flows (Kotarba 1992, 1994). Friction and cohesion forces on the slopes with weathering covers may be exceeded after an increase in water content in various situations depending on slope gradient. Conditions triggering sliding of rocky material over shales and formation of rockslides (cf. Bargielewicz 1958; Jakubowski 1968) are even more complex. The threshold of the slope equilibrium is exceeded if precipitation intensity is low, less than 1.5 mm/hour, that supports deep infiltration, and if precipitation amounts to over 250–300 mm (Gil and Starkel 1979; Thiel 1989; Gil 1994).

In river channels suspended load transportation may increase slowly but continually, and depends mainly on a character of a flood wave and on material supply from slopes. Here, the threshold value is triggering the bedload transportation which leads to a shift of bars, bank erosion and transformation of river channel. These threshold values depend on a size of bedload and on a channel gradient. Average changes are initiated if specific runoff reaches 1 $m^3s^{-1}km^{-2}$ (Niemirowski 1972; Froehlich 1975; Baumgart-Kotarba 1983).

The changes are even more spectacular if the bankful discharge is reached and river enters its floodplain. Then, avulsion of the channel and transformation of the entire floodplain floor are possible, although the final stage is usually accumulation of the madas (alluvial loams) in the middle courses of rivers.

TYPE OF RAINFALLS AND THEIR EFFECTIVENESS

Based on observations of precipitation of various amounts, intensity and duration it is possible to provide the following classification: local, short-lasting downpours, continuous rains and rainy seasons (Fig. 4).

a) Local, short-lasting downpours that are morphologically effective in the Carpathians amount to 30–70 mm and have intensity of 1–3 mm/minute. They usually occur every few years. However, there are also downpours amounting to 100–120 mm during 3–4 hours when a large proportion of rain has intensity exceeding 1 mm/minute. Two such downpours that occurred in Szymbark in 1969 were described by Gil and Słupik (1972), Słupik (1973), and Gil (1976).

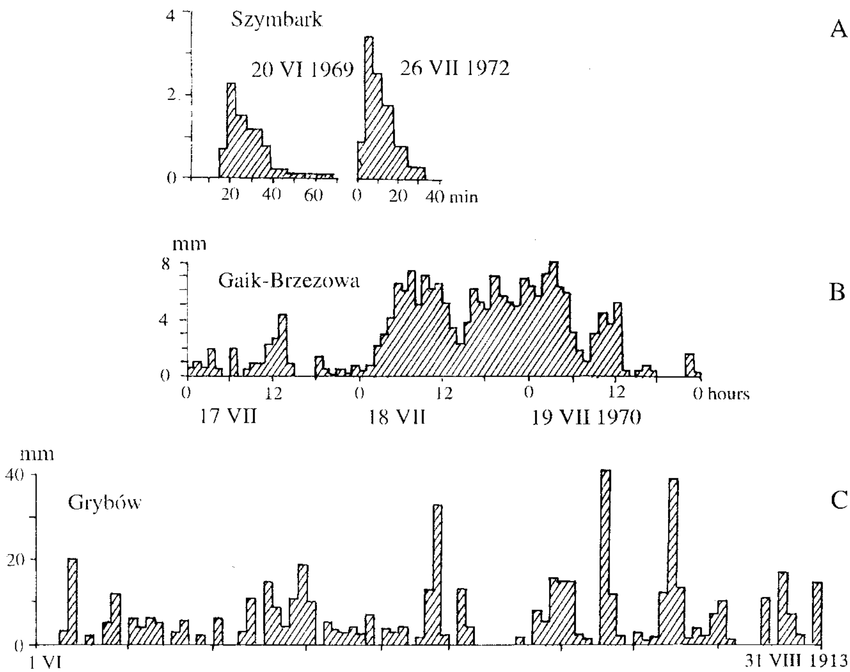

Fig. 4. Course of rainfall intensity during various types of extreme rainfalls in the Carpathians. A — heavy downpour in 1969 at Szymbark (Gil and Słupik 1972), B — continuous rain in 1970 at Gaik-Brzezowa, Carpathian Foothills (Niedźwiedź 1972), C — rainy season in 1913 at Grybów (when great landslide in Szymbark was formed)

Ryc. 4. Przebieg natężenia opadu w czasie różnych typów ekstremalnych opadów w Karpatach: A — ulewa w 1969 roku w Szymbarku (Gil, Słupik 1972), B — opad rozlewny w 1970 roku w Gaiku-Brzezowej na Pogórzu Karpackim (Niedźwiedź 1972), C — pora deszczowa w 1913 roku w Grybowie (gdy powstało wielkie osuwisko w Szymbarku)

During these downpours water infiltrated only 25 cm deep and a part of water flowed over the ground surface (to 25%). Such downpours produce rills in arable fields, deepen cart-road incisions (Froehlich 1982) and may lead to earthflows of arable soil layer (Figuła 1960). Several tons of soil may be carried away from 1 hectare of arable fields. Simultaneously, slumps may form on the inter-field escarpments that was already pointed out by Łoziński (1909). In 1953 numerous soil flows and weathered material slumps were formed on steep slopes after the 110.7 mm downpour near Zagórz and Postołów on the San river (Starkel 1960). In 1958 in Jaworki (the Małe Pieniny Mts range) 355 slumps and flows were identified after the downpours which exceeded 100 mm and which transferred ca 7000 m^3 of material (Gerlach 1966). In small river catchments, where specific runoff may exceed 10 $m^3s^{-1}km^{-2}$, debris flows sculpturing channels may be triggered (Soja 1981).

On 18 August 1988, in the high-mountain part of the granitic Tatras, the 95 mm precipitation that lasted 3.5 hours and had maximum intensity over

1 mm/minute resulted in debris flows, forming troughs on 200–600 m long scree slopes. The largest of these flows transferred ca 3645 m^3 of debris (Kotarba 1992, 1994). In the western, lower energy part of the Tatras up to 100 m^3 of material is transferred in troughs if precipitation is of the order of 80–100 mm (Kotarba *et al.* 1987).

b) Continuous rainfalls in the Carpathians comprise large parts of the mountains and are related to movement of cyclonic systems (Niedźwiedź 1972, Cebulak 1992b). Such rainfalls lead to morphological changes if precipitation reaches 150–400 mm during 2–5 days and if the rainfall intensity does not exceed 3–12 mm/hour (daily precipitation of the order of 100–250 mm). During such continuous rainfalls, occurring every 5–20 years in the Carpathians or happening sometimes in 2–3 consecutive years (Ziętara 1968), morphological changes undergo on slopes, in river channels and on floodplains. The effects of continuous rainfalls of 1934, 1958–1960 and 1970 belong to the better investigated ones.

Morphological effects on the slopes depend on the substratum. Surface washing is limited to steeper slopes (Gil 1976). Erosion of cart-roads is intensive (Froehlich 1982). The most frequent are earth slides which occurred commonly in the Beskid Śląski and Beskid Żywiecki Mts in 1958 and 1960. Then, 10% of landslide susceptible slopes, which amounted to 20–30% of the total area, were re-activated (Ziętara 1968, Fig. 5). In 1970, the 3-days' precipitation reached 400 mm which is a record value for a century (Niedźwiedź 1972). In the case of skeletal soils on sandstone slopes of the Beskid Śląski Mts throughflow led to formation of episodic springs. The density of these outlets was 600 per 1 km^2 (Brykowicz *et al.* 1973). Specific runoff in the mountain course of the Vistula was 2 $m^3s^{-1}km^{-2}$. The flowing water moved blocks of diameters of 1.5 m. Similarly, throughflow during the extreme daily precipitation (continuous rain — 300 mm) on Hala Gąsienicowa in the Tatras in 1973 contributed to rise in discharge of mountain streams and to transformation of stream channels (Kaszowski and Kotarba 1985).

During the continuous rainfalls of 1970 described above, specific runoff exceeded 1 $m^3s^{-1}km^{-2}$ everywhere in the Western Carpathians to the Ropa river (e.g. discharges of the streams in the Gorce Mts were: Jaszcze — 1.3 m^3s^{-1}, Jamne — 1.6 m^3s^{-1} according to M. Niemirowski 1972; but that of Bystrzanka near Szymbark 3 m^3s^{-1} (Soja 1972). Froehlich (1975) calculated that suspended load and bedload transported during flood in that particular year was 20 times larger than in a normal year and that the flood accounted for 90% of the annual sediment load. In the drainage basin (203 km^2) of the braided river Białka Tatrzańska rises in discharges of the order of 200–250 m^3s^{-1} occurred every 5 years on average and transformed systems of bars, and pools and riffles (Baumgart-Kotarba 1983). The floods of the discharge of 400–450 m^3s^{-1} and 2% probability are able to transform the whole bed of the braided Białka river (e.g. in 1934).

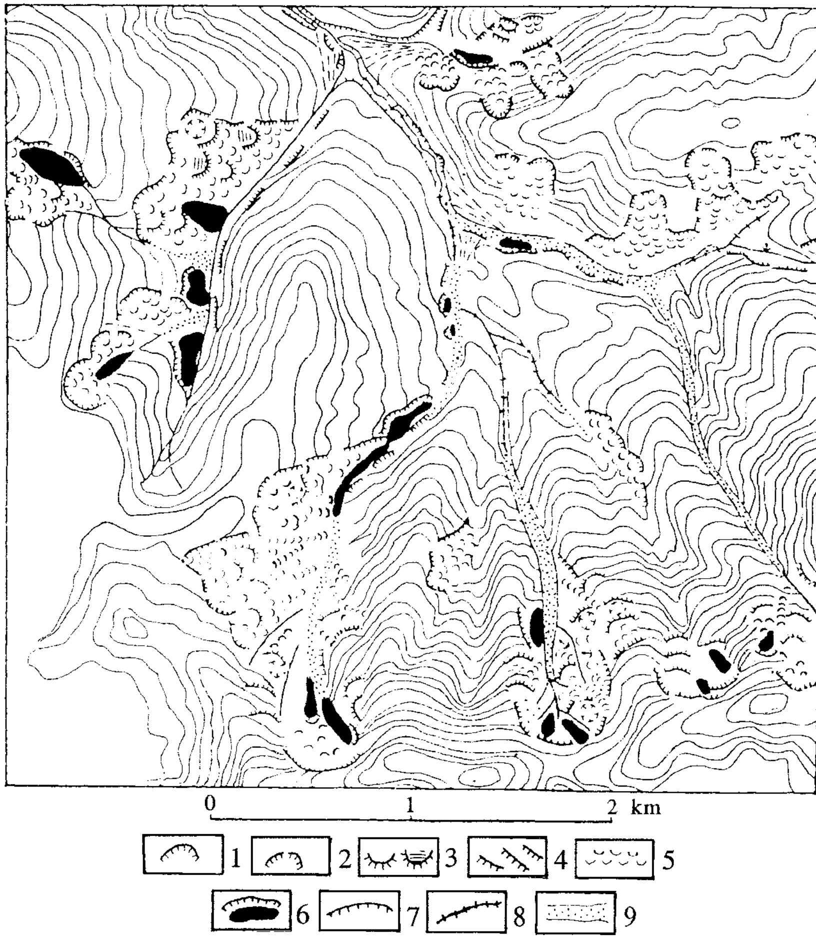

Fig. 5. Transformations in the Żabnica catchment in the Żywiecki Beskid (after Zi ę t a r a 1968). 1 — well preserved slide scars, 2 — poorly preserved slide scars, 3 — slide ridges and steps, 4 — scarps over landslide, 5 — landslide tongues, 6 — newly formed or rejuvenated landslides in 1958–60, 7 — undercuttings, 8 — rocky steps and rapids in the stream channels, 9 — bottoms of valleys filled by debris or gravels bars during heavy rains in 1958–60

Ryc. 5. Przekształcenia w zlewni Żabnicy w Beskidzie Żywieckim (wg Z i ę t a r a 1968). 1 — dobrze zachowane nisze osuwiskowe, 2 — słabo zachowane nisze, 3 — grzędy i stopnie osuwiskowe, 4 — krawędzie osuwiska, 5 — jęzory osuwiskowe, 6 — osuwiska nowopowstałe lub odmłodzone w latach 1958–60, 7 — podcięcia, 8 — progi i bystrza w korytach rzecznych, 9 — dna dolin wypełnione rumoszem lub odsypami żwirowymi w czasie ekstremalnych opadów w latach 1958–60

c) Rainy seasons. In moist years, precipitation in the Beskidy Mts may reach 1500 mm. Moreover, precipitation in particular summer months reaches 200–500 mm while in autumn and winter months (excluding vegetation period) — 100–200 mm. Except for the years with continuous rainfalls and floods, intensity of precipitation is low and does not usually exceed 1–1.5 mm/hour. If such precipitation infiltrates it gets down to the bottom of weathering and slope covers and then enters cracks in the bedrock. Not only loose deposits are saturated with water and it starts throughflow but the surface of sliding becomes plasticized and seepage pressure increases. Then, even a slight impulse such as increased precipitation intensity is able to trigger movement of soil and rocky material on the slope. Experimental studies (Thiel 1989; Gil 1994) showed that in 1974, 1980 and 1985 precipitation exceeding 250 mm and lasting 10–30% of time in several weeks activated landslide masses. A good indicator is permanent throughflow at the depth of 1 m, registered in autumn and winter of 1974/1975 (Gil and Starkel 1979). The mass movement was initiated if the throughflow exceeded 5000 litre per hour from 1 hectare (Fig. 6). At that time the rate of movement of the continually creeping landslide "Zapadle" increased 3 times (Gil and Kotarba 1977). New landslides were registered in other parts of the Carpathians (in Brzeżanka Bober et al. 1977). In 1980 in the eastern part of the Carpathians precipitation was high again. Precipitation registered in Terka on the Solinka stream was 1427 mm, out of which 718 mm fell in June and July, and out of which 289 mm on 21–27 July. This continuous rain coincided with a rainy season and gave in effect a deep rocky-debris landslide in forest near Połoma (Dziuban 1983; Gil 1994).

Formation of the largest Carpathian landslides in the current century is related to moist years. In April 1907 the rock slide in Duszatyn (Fig. 1, Schramm 1925) replaced 10 million m^3 in the valley head. In the preceding year, 1906, in the nearby site Wetlina, precipitation amounted to 1474 mm, and extra 371 mm precipitation added to that during the first four months of 1907 and saturated the substratum during snowmelt. In summer of 1913 the deep landslide in the Szklarka valley near Szymbark transferred 3.5 million m^3 of material (Sawicki 1917). This and some other landslides in the Carpathians were related to long-lasting summer precipitation (precipitation in July and August was 500–600 mm), and an additional impulse was a continuous rainfall. Per analogy to 1974 one should assume that numerous small landslides and displacements within the large old landslide were also formed in 1907 and 1913.

THE ROLE OF EXTREME EVENTS IN RELIEF EVOLUTION

The collected information on the effects of rainfalls in the current century is presented in Fig. 7 and in Table 1. Here, processes characteristic of various types of extreme rainfalls in different parts of the Carpathians may be traced. On this background the author discusses the differences in activation of slope and channel systems, frequency of extreme events in the 20th century and degree as well as direction of transformation of the slopes and channels.

From the comparison of suspended load on the slopes and in the river channels it is evident that there is negative correlation related to intensity and

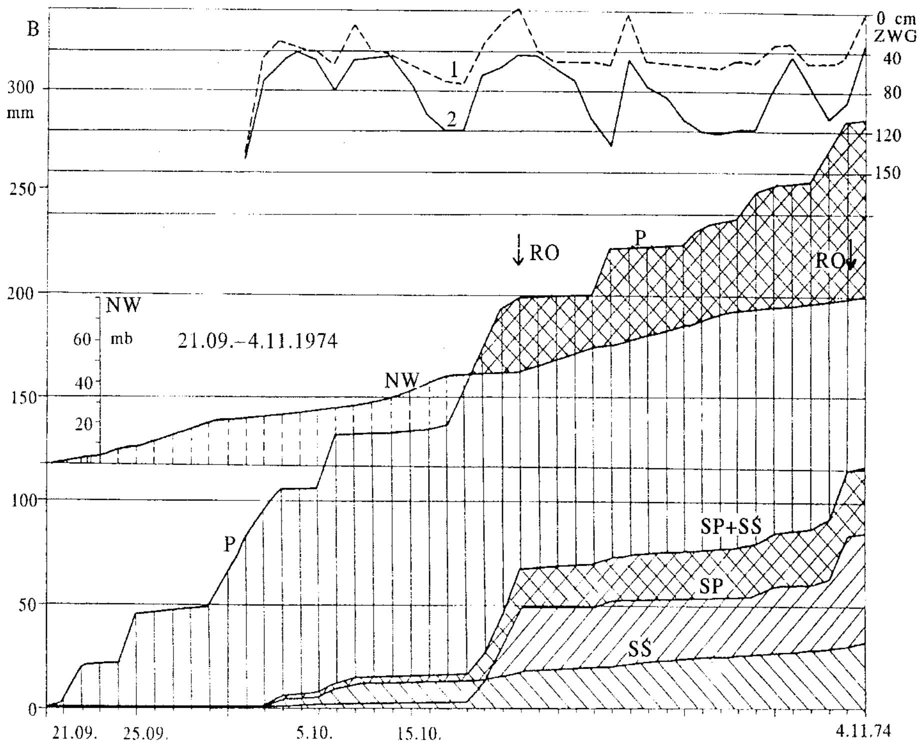

Fig. 6. Elements of water circulation on experimental slope at Szymbark in autumn 1974 (after Gil 1994). P — cumulative curve of precipitation in mm, SP — surface runoff, SS — subsurface flow at the depth of 100 cm, SP+SS — total water outflow, NW — cumulative curve of air moisture deficit in mb+mm, ZWG — oscillations of ground water table to the depth of 150 cm (1 — upper part of slope, 2 — lower part), RO — moment of the occurrence of mass movements: solid line — intensive movement, dashed line — weak movement

Ryc. 6. Elementy obiegu wody na stoku eksperymentalnym w Szymbarku jesienią 1974 roku (wg Gil 1994). P — krzywa kumulatywna opadu w mm, SP — spływ powierzchniowy, SS — spływ podpowierzchniowy na głębokości 100 cm, SP+SS — całkowity odpływ, NW — krzywa kumulatywna deficytu wilgotności, ZWG — wahania zwierciadła wody gruntowej do głębokości 150 cm (1 — w górnej części stoku, 2 — w dolnej części), RO — moment wystąpienia ruchu osuwiskowego: linia ciągła — ruch intensywny, przerywana — ruch słaby

duration of precipitation (Starkel 1980). During the 42 mm downpour in 1969, washing of 40 tons of material per hectare was registered on the experimental plots located on a cultivated slope while the material transported out of the Bystrzanka catchment (13.5 km^2) amounted only to 9.5 tons from 1 km^2. The washed-out material was usually accumulated at the foot of slopes. Another downpour (80 mm) removed ca. 770 tons from 1 km^2 from the Bystrzanka catchment (Welc 1972). Material entered the stream channel. On the other hand, continuous rain resulted in removal of 0.43 t from the 1 hectare field while 70 t of material per 1 km^2 was removed by the Bystrzanka channel (Gil 1976). The material was likely to originate from the channel itself and from cart-roads that is confirmed by precise measurements by W. Froehlich (1982). During the floods induced by continuous rain in large drainage basins the role of slope in the supply of material is not very significant. Such material originates from cart roads and singular landslides which are usually associated with channel undercuttings (Ziętara 1968; Dauksza and Kotarba 1973). However, the changes in the channels themselves are very important if over 90% of suspended load and bedload are transported during a flood lasting no more than 1–2% of time (Froehlich 1975, 1982). The amount of material depends on degree to which a catchment is deforested (Niemirowski 1972; Froehlich 1975, 1982).

As the slopes respond to the high intensity downpours with washing and soil-flow, and continuous rain disturb the slope equilibrium by local landslides, then the larger floods and changes in the channel pattern take place usually during continuous rains. In the High Tatras the slope and channel systems also reach the threshold values in different situations. Daily precipitation not lower than 200–300 mm is able to cause the synchronism of the changes (Kotarba *et al.* 1987). An analogous synchronism of transformation was also observed during continuous rain in the Beskid Żywiecki in 1960 (Ziętara 1968), when, in drainage basins of an area to several tens of km^2 and with landslides, there were shifts of bars, transformation of stream channels and undermining of slopes causing reactivation of landslides.

Frequency of events disturbing the equilibrium of the slopes and river channels is various in different parts of the Carpathians in the current century (Fig. 7). Local downpours and their effects have usually been registered in the region of research stations and in the areas of detailed studies. Therefore, their frequency is seemingly high in the region of Szymbark (Gil 1976) and near Hala Gąsienicowa in the Tatras (Kotarba 1992, 1994). Years with continuous rainfalls, large floods, shallow landslides and slumps are known from large regions, usually from western and central parts of the flysch Carpathians as well as from the Tatras and Podhale region. Such were the years: 1903, 1925, 1934, 1948, 1958, 1960, 1970 and 1980. All together there were registered 17 years when continuous rainfalls covered large areas and had far reaching effects. In smaller mountain catchments transformation of the channels is recorded every 2–5 years (Baumgart-Kotarba 1983).

In the Carpathians, particularly moist years supporting formation of deep landslides were: 1906/1907, 1913 and 1974.

A scale of transformation of relief during the extreme precipitation varies in a wide range (Fig. 7, 8). During the downpours, washing out and linear erosion on the slopes lead to denudation of the upper surface that can reach to a few millimeters per one event or can locally comprise the whole arable layer providing soil flow. The role of precipitation of a given type, extensive downpours, in development of suffosion forms is not exactly known

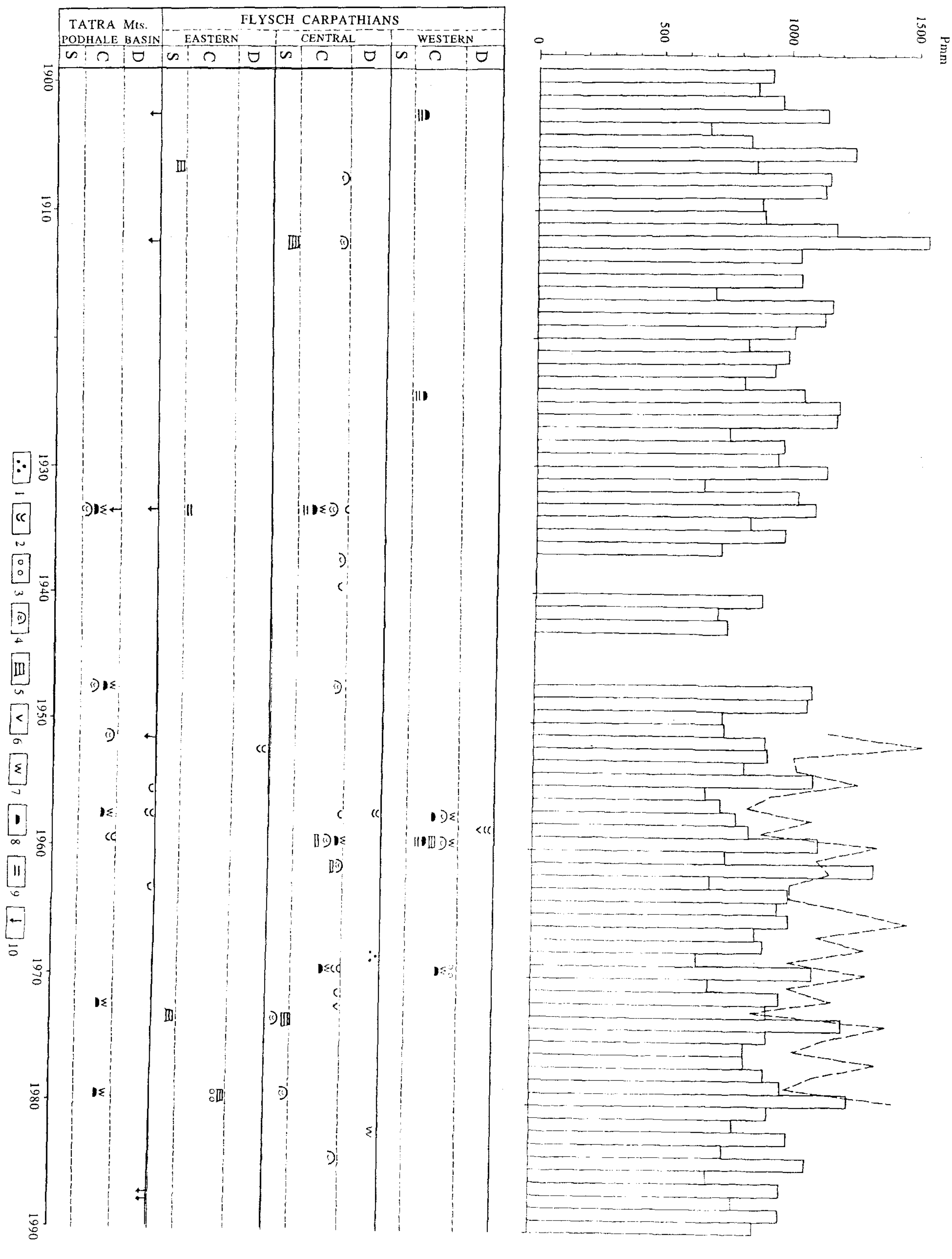

Fig. 7. Extreme rainfalls in Łabowa and Wisła (western part) and their geomorphic effects in various parts of the Polish Carpathians registered in 20-th century. D — downpours, C — continuous rains, S — rainy seasons, 1 — heavy slope wash, 2 — soil flows and slumps, 3 — piping, 4 — earth slides, 5 — great rockslides, 6 — channel erosion (local), 7 — channel erosion (intensive regional), 8 — formation of channel bars, shifting of channel, 9 — overbank deposition, 10 — debris flows

Ryc. 7. Opady ekstremalne w Łabowej i Wiśle (część zachodnia) i ich efekty geomorfologiczne w różnych częściach Polskich Karpat, zarejestrowane w bieżącym stuleciu. D — krótkotrwałe ulewy, C — opady rozlewne, S — pory deszczowe, 1 — intensywne spłukiwanie, 2 — spływy glebowe i zerwy, 3 — sufozja, 4 — osuwiska ziemne, 5 — wielkie osuwiska skalne, 6 — erozja korytowa (lokalna), 7 — erozja korytowa (intensywna, regionalna), 8 — świeże odsypy korytowe, 9 — akumulacja pozakorytowa, 10 — spływy gruzowe

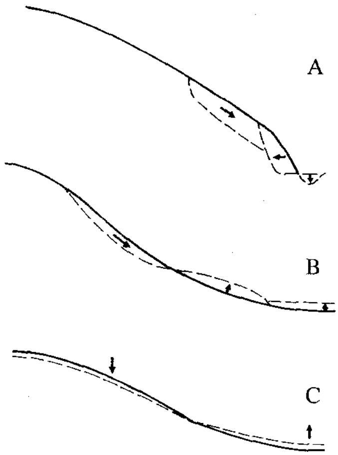

Fig. 8. General trends of slope transformation during extreme rainfalls. A — mountain slope (upper valley section), B — mountain slope (lower valley section), C — foothill slope

Ryc. 8. Ogólne tendencje przekształcania stoków w czasie ekstremalnych opadów: A — stok górski (górny odcinek doliny), B — stok górski (dolny odcinek doliny), C — stok pogórski

(Czeppe 1960). The material washed from the slopes is accumulated at their foot and does not get to a river channel except for very narrow valleys lacking floodplains. Landslides leave behind traces which are difficult to reclaim. Some of the landslide reactivate or permanently creep (Ziętara 1968; Gil and Kotarba 1977). Proportion of the landslides in the Carpathians is small, of the order of 2–3% (Bober 1984) yet in some regions it reaches 10–50% of a total area of a catchment (Starkel 1960; Ziętara 1968; Kotarba 1986). Permanently activated landslides in headwater areas develop most vigorously. Of this type are the largest, young landslides in Duszatyn (Schramm 1925) and in Szymbark-Szklarka (Sawicki 1917). The other type are landslides on the slopes undercut by rivers which carry away the transferred material. They were monitored for several years (Dauksza and Kotarba 1973; Gil and Kotarba 1977). Kotarba (1986) assigns them to "delapsive type". The sizes of slumps and mudflows depend on a shape and length of slopes, therefore, these are usually small forms and the transferred material rarely enters a valley floor and even more rarely is carried away by a stream (cf. Starkel 1960; Jakubowski 1968).

Nevertheless, such movements are able to transport large masses of material of the order of thousand of cubic metres from an area of 1 km^2. If large landslides change the relief of slopes and of headwaters, then shallow flows and slumps do not lead to dissection of the slopes.

Similarly, the size of debris flows in the Tatras depends on the length of scree slopes on foot of which alluviation takes place (Kotarba *et al.* 1987; Kotarba 1992).

The scale of transformation of river channels and floodplains during extreme events varies. Ziętara (1968) observed deepening and widening of the Beskidian river channels after the flood in 1960 and formation of new bars downstream that provide evidence of removal of 6000 m^3 of bedload from 1 km^2 of a catchment. Erosion during the flood in 1970 gave in effect deepening of rocky channels to 1 m (Brykowicz *et al.* 1973; Niemirowski 1972). Floods in the Ropa valley occurring one after the other (1970, 1972, 1973, 1974) resulted in removal of the river load and then in incision into a solid rock (Soja 1977). That gave in effect a change in evolution from an aggrading to erosional channel. In the braided channel of the Białka Tatrzańska each flood causes shifts of the bars and channel branches (Baumgart-Kotarba 1983). Based on the analysis of low water levels of the Dunajec river in the current century, it was shown that large floods lead to step-like changes in the channel depth, to deepening by scouring in the gravels or to aggradation by input of a new migrating bar (Froehlich 1975).

The analysis of the extreme events and of their morphological role shows that they are responsible for transformation of relief in the Carpathians. Maturity of the slopes and presence of slope covers which were left by periglacial morphogenesis cause the slope systems to react with a delay; disturbance of equilibrium comprises small fragments of the slopes. On the other hand, the channel systems, modified by rivers rising during continuous rainfalls are permanently adjusting to hydrologic regime of rivers of temperate climate and to increased supply of material induced by deforestation (Starkel 1986; Froehlich and Starkel 1991).

The threshold values may be exceeded once or several times (Selby 1974). Shallow earth slides which formed only once are being overgrown and levelled out (Jakubowski 1968), it can also be the case of rock slides where subsequent mass movements even out the surface (Sawicki 1917). However, phenomena of activating of landslides, known from the region of Szymbark, or their permanent movement (Ziętara 1974; Gil and Kotarba 1977; Gil and Starkel 1979) are equally frequent. If the stimulus in a form of inflow of groundwater or undercutting by a river is permanent, it is difficult to talk about "adjustment" or "recovery time" (Selby 1974), time necessary to reaching maturity increases. If so, one cannot talk about an extreme event; sliding becomes a secular process similarly to leaching (cf. Starkel 1986).

Based on the studies of the extreme precipitation evident is a specific role of series of events occurring one after the other. Such "clusterings", observed by Ziętara (1968) in the case of landslides and bars of boulders (1924, 1925, 1926, as well as 1958, 1959, 1960), lead to consolidation of new forms or their elements. The discussed floods of the Ropa river in 1970–1974 enhancing the tendency to channel deepening (Soja 1977) played a similar role.

Kotarba (1994) pointed to so called "intrinsic thresholds" in high-mountain slopes which are related to the amount of weathered material needed to trigger, for example, a debris flow. Similar is the role of shallow sliding of weathered material on steep flysch slopes described by K. Jakubowski (1964) in the case of Podhale and by L. Starkel (1960) in the case of Zagórz. Only weathering of shale or sandstone after many centuries (millennia) can lead to restoration of movement.

Complexity of inherited relief and lithology as well as differentiated tectonic activity leading to the deepening of the valleys give way to diversified action of extreme processes induced by precipitation. The latter comprises a wide range of rainfalls of various intensity, amount, duration and spatial distribution. Mutual superposition of these pattern leads to temporal exceeding of equilibrium of the slope or channel systems that is usually spatially limited and rarely synchronous in both the systems.

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STRESZCENIE

L. Starkel

GEOMORFOLOGICZNA ROLA EKSTREMALNYCH OPADÓW W POLSKICH KARPATACH

Niniejsza praca podsumowuje stan wiedzy o ekstremalnych opadach i ich roli w przekształceniu rzeźby. Omawia historię badań od początku bieżącego stulecia, zwracając uwagę na prace ostatnich 20–25 lat, pozwalające rozpoznać mechanizm procesów i określić wartości progowe opadów, w czasie których dochodzi do transformacji stoków i den dolin.

Wysokość rocznych sum opadów waha się od 700–1500 mm, zmniejszając się ku wschodowi i w strefach cienia opadowego. Opady dobowe o częstotliwości 1–2% wahają się od 80–300 mm.

Autor wydziela 3 podstawowe typy opadów, w czasie których dochodzi do przekroczenia wartości progowych. Krótkotrwałe lokalne ulewy o natężeniach 1–3 mm/min uruchamiają intensywne spłukiwanie, spływy glebowe, a w Tatrach spływy gruzowe. Opady rozlewne — 150–400 mm w ciągu 2–5 dni — prowadzą do tworzenia osuwisk ziemnych, przekształceń koryt rzecznych i akumulacji mad na równinach zalewowych. Pory deszczowe o opadach miesięcznych 100–500 mm powodują nasycenie podłoża i uruchomienie głębokich osuwisk skalnych.

Ryc. 7 ilustruje zróżnicowanie regionalne i różną częstotliwość opadów ekstremalnych. Skala przekształceń bywa szeroka. Systemy stokowe zwykle reagują z opóźnieniem a zaburzeniu ulegają nieliczne fragmenty stoków. Natomiast systemy korytowe ustawicznie dopasowują się do przepływów ekstremalnych. Wyjątkowo przekształcanie stoków i koryt może odbywać się synchronicznie. Częste przekraczanie wartości progowych prowadzi do zmiany kierunku ewolucji form.