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The geomorphological effectiveness of extreme meteorological phenomena on flysch slopes

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Abstract: Extreme events tend to cause large-scale slope system changes. During the last ten years, a series of extreme meteorological events caused considerable transformation of the slopes and valleys in various parts of the Carpathian Mountains. This paper presents the geomorphological effects of extreme rainfall and thaw events on the slopes of two catchments: the Łososina catchment (Beskid Wyspowy) and the Hoczewka catchment with an area around the Solińskie Lake (Bieszczady Niskie). The bulk of the discussion concerns a study carried out in the Łososina catchment after three separate extreme events that were followed by a considerable transformation of the slopes due to landsliding. The studies carried out in the Bieszczady Range, where a single extreme event produced only spatially limited effects, were mainly used for comparison. The disparity between the responses of the two slope systems was a result of differences between the systems themselves, including their geology, geomorphology and landslide record, and of the difference in the scale of the extreme events.

Kay words: extreme events, heavy rainfall, landslies, flysch slopes, Beskid Wyspowy, Bieszczady Niskie

Introduction

While extreme events normally occur very seldom, they tend to constitute a powerful factor in the development of the local relief. During extreme events, threshold values are exceeded for the occurrence of various processes and a high landform building potential disturbs the equilibrium of natural systems, such as slope and channel systems (Thornes & Brunsden, 1978). Extreme meteorological events can have a simple or complex nature, different durations and geographical extent (Starkel, 2003). Simple extreme events include short and intensive downpours of limited coverage. Complex extreme events may include situations where a torrential rainstorm coincides with long-duration rainfall, or where a spring thaw is accompanied by intensive rainfall (Starkel, 2003). A series of events occurring in a short span of time (days, months or years) are know as clusters of events (Starkel & Sarkar, 2002). If the interval between the events is short enough, the system may have insufficient time to recover the balance and fails to return to its prior status. Subsequent extreme events contribute to the evolution of a new balance in the natural system.

A recent increase in popularity among researchers of extreme events began after the disastrous rainfalls of July 1997, which caused flooding in the Vistula and Odra river catchments and a reactivation of slope mass movements. The studies undertaken at the time were continued, as intensified landsliding activity was recorded in various parts of the Carpathian Mts. during subsequent years (1998, 2000, 2001, 2002 and 2005). In 1997, geomorphological effects of extreme rainfall events were recorded in several areas including the Polish Tatras (Kotarba, 1998), the Beski Wsypowy range and the Wielickie Foothills (German, 1998, Poprawa & Rączkowski, 1998, Gorczyca, 2004). During subsequent years, extreme events produced both new landslide forms and a further development of those originated in 1997 in many areas of the Flysch Carpathian Mts. (Beskid Sądecki, Beskid Średni, Beskid Wyspowy, Beskid Niski and the Wielickie, Ciężkowickie and Strzyżowskie Foothills; Sądecka

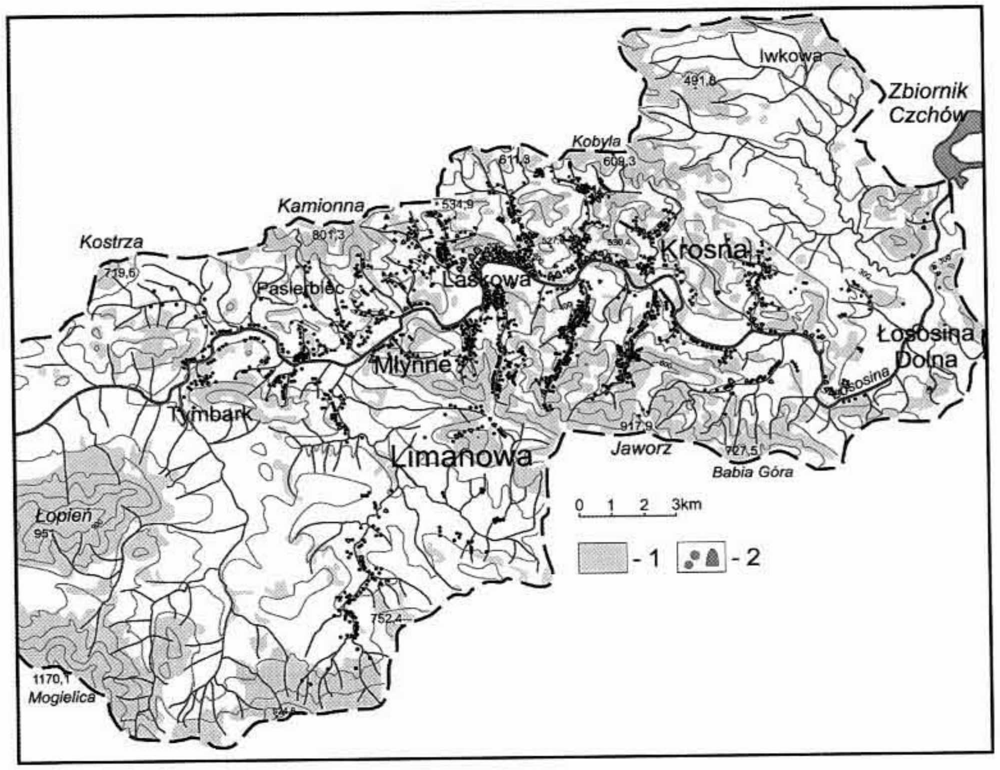

Fig. 1. Location of landslides developed or activated during 1997-2000 in the Łososina catchment:
1 – forests, 2 – small slumps and landslides.

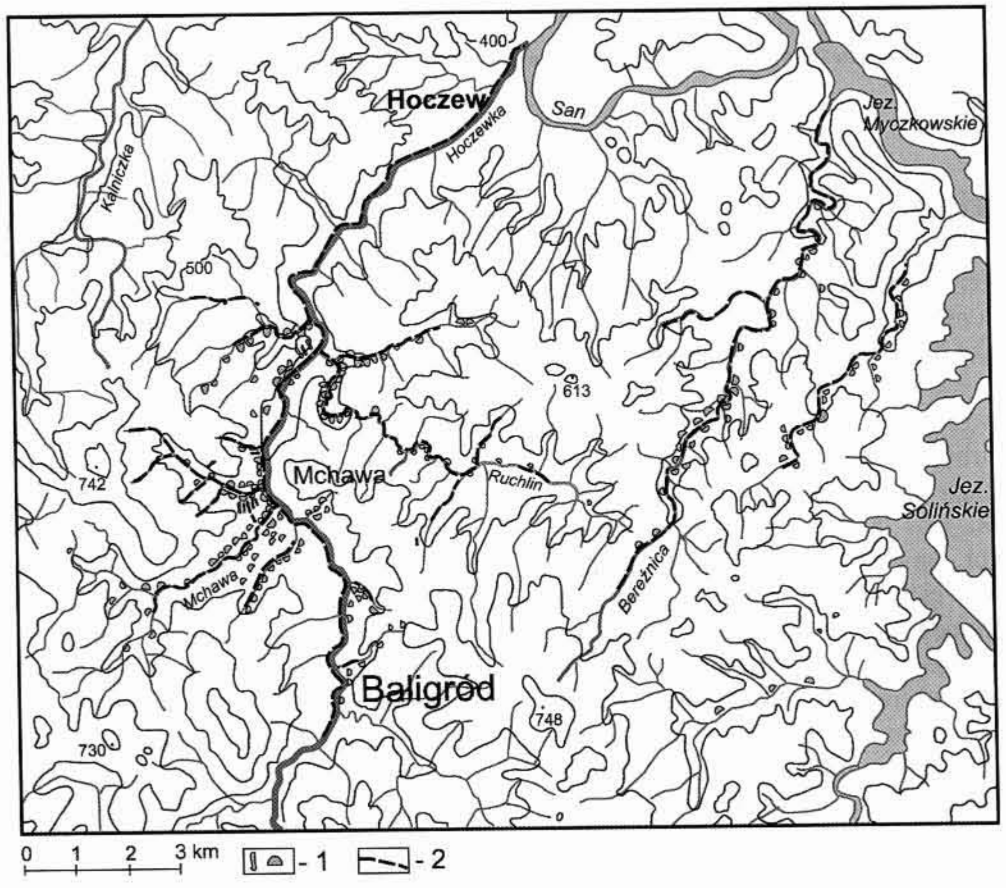

Fig. 2. Location of landslides developed in July 2005 in Hoczewka catchment and Solińskie Lake region:
1 – earth flows, landslides, small slumps, 2 – most changed valley reaches.

Basin and Bieszczady Niskie Ranges) (Mrozek et al., 2000, Lach & Lewik, 2002, Rączkowski & Mrozek, 2002, Ziętara, 2002, Gorczyca, 2004, Gorczyca & Krzemień, 2006). It therefore seems plausible that the intensive rainfall of July 1997, occurring after a long dry period (1981-1995), marked the beginning of a wet period (Niedźwiedź et al., 1999).

Located in the Beskid Wyspowy Range, the Łososina river catchment was one of the areas affected by the slope system transformations caused by extreme meteorological events (Fig. 1). During 1997-2000, three rainfall events contributed to the activation of mass slopes processes. In the first event of the series, on 9 July 1997, a torrential rainstorm ensued after several days of prolonged rain. As a result, landslide processes started in the slope covers saturated with rainwater. A subsequent event of June 1998 failed to activate any landsliding. The third event involved rapid snow melt further accelerated by intensive rains at the beginning of April 2000. Again, the slope covers were highly saturated and landsliding was reactivated.

In July 2005, the other study area experienced an extreme rainfall event that contributed to a large scale transformation of the land relief in the catchment of Hoczewka near the Solińskie Lake (Bieszczady Niskie) (Fig. 2). As a result of a torrential rainstorm lasting two and a half hours, the valley slopes were largely transformed and gravitational processes on the slopes revived.

Research areas

The two research areas, namely the Łososina river catchment in the Beskid Wyspowy Range (Fig. 1) and the Hoczewka catchment with an area of the Solińskie Lake in the Bieszczady Niskie (Fig. 2), are part of Outer (Flysch) Carpathian Mts. that folded during the Tertiary Period. The former area is located in the catchment of the Łososina, a left-bank tributary of the Dunajec River, in the Carpathian part of the Upper Vistula catchment. Almost the entire 407.1 km^2 of the Łososina catchment is located within the Beski Wyspowy Range with the exception of its mouth reaching the Wielickie Foothills (Balon et al., 1995). The area is built of flysch formations of the Magurska Nappe of the Cretaceous and Palaeogene Age (Cieszkowski, 1992). The study focussed on the central and eastern portions of the catchment, between Tymbark and Czchowskie Lake, spanning 241 km^2, or 60% of the catchment territory ranging from 905 to 230 meters asl. The geomorphology of the Beskid Wyspowy is linked with its lithology. The less resistant thin-layered alternating shale and sandstone formations of the Podmagurska series constitute the lower and more gentle parts of the slopes, while the more resistant thick-layered sandstone of the Magurska series mainly compose the summit and ridge parts allowing high slope gradients up to 300.

The other research area includes the central part of the Hoczewka catchment and an area to the west of the Solińskie Lake (94 km^2; Fig. 2). The area, ranging from 748 to 400 meters asl., is built of the Lower Krośnieńskie strata, including primarily thin-layered sandstone and shale and to a lesser degree thick-layered sandstone with shale and Otryckie shale. The area has a foothill-type morphology with the characteristic remnant ridges 200-300 hundred meters above the rest of the area.

Methodology

The Łososina research was carried out between August 1997 and December 2002, while the Hoczewka catchment and Solińskie Lake were studied in 2005. The fieldwork involved the mapping of all landslide forms that emerged after the extreme rainfall events on 1:10 000 topographical maps. (For the purpose of this study, forms without slide surfaces, such as flows, were also included as landslides). Additionally, the following information and parameters were collected for every mapped landform:

- elevation above sea level of the top edge of the landslide scar;
- length, width and depth of a landform; tongue length and colluvium depth;
- location on the slope vis-a-vis other landforms and structures;
- threats to buildings and roads.

Selected landforms had longitudinal profiles and plan-views made at 1:5000 scale using a clinometer and a measuring tape. Photographic documentation was also produced. To determine the degree of slope transformation by the mass processes, Bober's (1984) landsliding coefficients set for the Polish Carpathian Mts. were used.

The study involved monitoring changes within the mapped landforms and recording newly developed landslides after subsequent rainfall events over three subsequent years (1998-200).

To understand the meteorological circumstances that started the landsliding processes in the Beskid

Wyspowy, rainfall data collected at the IMGW weather stations at Limanowa and Rozdziele in the Beskid Wyspowy during 1997-2000 were used. Cartographic material and a satellite image, made available by Professor T. Niedźwiedź from the Cracow Branch of IMGW, proved very useful in the timing and spatial analysis (Niedźwiedź & Czekierda, 1998). To determine the circumstances determining the initiation of the gravitational processes in the Bieszczady Niskie data from IMGW precipitation stations at Baligród-Mchawa, Lesko, Solina, Cisna, Komańcza, Szczawne, Terka and Dwernik were used.

Slope impact of extreme rainfall events

Landsliding is generally caused when the equilibrium between resistance and shear stress within a slope is disturbed in favour of shear stress (Emblenton & Thornes, 1985). Typically, the slope equilibrium can be disturbed by an external factor, often precipitation. The impact, even if indirect, of precipitation in activating mass movements is so strong because precipitation varies immensely over time and space. As a result, precipitation is the factor that drives the process of weakening the forces supporting slope covers from sliding (Crozier, 1999).

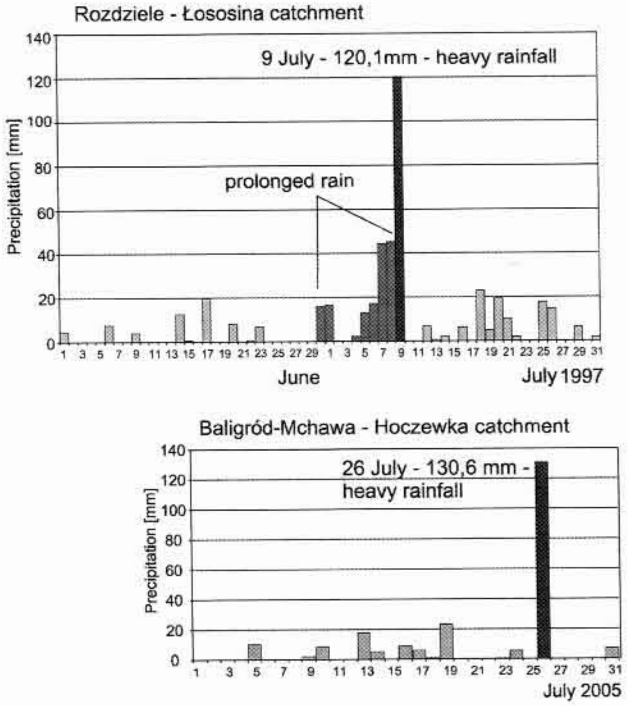

Fig. 3. Daily precipitation:
A – in June and July 1997 at IMGW station at Rozdziele (Łososina catchment); B – in July 2005 at IMGW station at Baligród-Mchawa (Hoczewka catchment).

This paper regards the capacity of precipitation to activate landsliding in terms of the extreme rainfall event potential. In analysing this potential, the author took into account the total rainfall, its duration, intensity and variation over time, as well as the area affected by precipitation.

In the Łososina catchment, the first complex type of rainfall event was observed in July 1997. The event combining long duration and torrential components led to a general activation of mass processes and, consequently, to a vast remodelling of the local slopes.

During 4-7 July 1997, Beskid Wyspowy experienced a long-duration rainfall of 10-30 mm per day (data from the IMGW Limanowa weather station and the IMGW Rozdziele precipitation post). On 8 July, the rain intensified and the Limanowa station recorded 85 mm, including half from a violent rainstorm lasting ca. one hour (Fig. 3). On the following day, 9 July, a thunderstorm, the nucleus of which formed on the previous the evening, produced at least 150 mm of rain over two hours at its centre. Overall, during 4-9 July the Limanowa station recorded 218.4 mm and the Rozdziele station recorded 241.8 mm of rain, or 0.123 mm per minute in the average rainfall intensity (Fig. 3). When the final thunderstorm of 9 July is separated from the long-duration rainfall, the six days of rain between 4-8 July produced 138 mm at Limanowa and 122 mm at Rozdziele with the average intensity of 0.1 mm per minute. The combined total of the six days of rain accounted for 20% of the annual precipitation in the Łososina catchment. The average intensity of the 9 July rainstorm (according to the Chomicz classification of 1951), which had been the main reason for starting and reviving mass movements, was ca. 1.25 mm per minute at the centre, ca. 1 mm per minute at Rozdziele and 0.504 mm per minute at Limanowa. While during the entire 4-8 July period rain was also observed across southern Poland and the northern Czech Republic, the rainstorm of 9 July only covered the eastern Beskid Wyspowy and the bordering sections of the adjacent: Wiśnickie and Ciężkowickie Foothills and of the Gorce range. The thunderstorm was centred at the border of the Beskid Wyspowy and Wiśnickie Foothills near Laskowa.

The second important impulse activating mass processes produced by the rainfall was the swollen Łososina river and its tributaries. The 1997 flood event was classified as 'catastrophic-great' with the peak discharge of a 5% likelihood. On 9 July, at the Piekiełko hydrometric profile the culmination wave reached 430 cm and at Jakukowice it reached 585 cm.

During the catastrophic rainfall of July 1997, the Łososina catchment slopes crossed their stability threshold, as expressed in the intensified mass and erosion processes. As a result, landforms such as landslides, land-slumps, systems of debris-and-mud flows and multiple erosion cuts emerged. Old landslides and creeping surfaces were also reactivated. Around 1300 landslides, or more than 98% of landforms mapped during the entire study, either first emerged or were reactivated in July 1997. The majority of the landslide forms investigated emerged during the single event of 9 July 1997. The intensity and pattern of waste mantle movement was uneven. The sliding began during the thunderstorm of the 9 July 1997, the most spectacular displacements occurring ca. 1-2 ours after the rain. At that moment, the sliding masses were the most oversaturated with water and were transformed into mud and rubble flows. Poorly discernible sliding surfaces were a characteristic feature of the landforms that emerged at that stage, alongside the uneven surface of the scar and the displacement of the sliding masses of material over very long distances.

A clear majority of the new landslide forms developed in July 1997 are small land-slumps (786 forms or 60%). They are located principally along slopeside roads or buildings, agricultural terraces and valley slopes. Another highly characteristic landslide type landform that emerged at the time are long, narrow and shallow earthslides (417 forms or 32%). Those shallow landslides developed mainly on turf-covered slopes. As a result, the waste-mantle, typically no deeper than 1-2 meters, was virtually entirely removed in the process. Many of the landforms developed as a result of both sliding and flow mechanisms, thus combining features characteristics of a landslide and a debris-and-mud flow or torrential flow (13% of landforms). The few landforms – featuring deeper slip surfaces, such as rock and rock-and-debris landslides – were mostly old reactivated landslides.

The landslide forms that originated in 1997 are highly diverse in size. The new or reactivated landslides ranged between just a few to nearly 20 000 m^2 in area and two to 240 meters in length.

Torrential, mud and debris-and-mud flows, alongside landsliding, played a considerable role in the transformation of the Łososina catchment. Torrential flows featuring the dominance of fluid over solid material contributed mainly to the transformation of V-shaped valleys. The latter were considerably deepened, sometimes up to two meters, and any fluvial or rubble material accumulated in their beds as a result of prior landslides was mostly transported away. Some of the torrential fans produced in the process at the valley mouths had considerable depth, up to two meters, and area. Mud flows on the Łososina catchment slopes tended to occur as complex forms, as a result of a combination of sliding and flow mechanisms. And finally, debris-and-mud flows only reshaped old rock landslides and headwaters of the Łososina tributaries. Because of the large bedload supply and considerable gradient of slopes within the old landslides, numerous corrasion chutes at their mouths with debris fans appeared.

The mapped landforms covered 8.4 km^2 of the study area of 202.4 km^2, yielding the landsliding ratio of 4%. Additionally, for comparison purposes, the landsliding ratio was calculated for just the landforms developed from July 1997 to the end of 2000. The 1214 landslides covering 0.63 km^2 produced the ratio of 0.31%, or just one thirteenth of the ratio for all of the landslides. The landslide density ratio for all of the landslide forms stood at 6.6 per km^2 and was just a fraction smaller for the new landforms at 6 per km^2.

In 1998 and 1999, the total annual precipitation in the Łososina catchment was greater than the long-term average (Mrozek et al., 2000). However, the average monthly precipitation was much lower than in July 1997. While certain mass movements were observed in the study area, they were much smaller in scale than in July 1997. One event worthy of note was the thunderstorm of 4 June 1998 that might be classified as a simple-type extreme event. It produced 83.1 mm in Limanowa at the centre of the rainfall, which was comparable to the amount of 9 July 1997. The geomorphological effect of the downpour was, however, virtually limited to erosion by the swollen streams. The saturation of the slope covers with water contributed primarily to the activation of secondary landsliding within the landforms developed during the previous year. Newly emerged landforms included a dozen small land-slumps on valley sides and on the sides of roads cutting into slopes, mainly in the Sowlina catchment. Slope processes included primarily secondary landsliding within ca. 70 landforms developed during the previous year. The secondary mass movements mainly affected the lower parts of landslides, i.e. the tongues and colluvial bulges. Minor displacements were observed within the material accumulated in the landslide scars. The 1998 rainfall also contributed to the continued development of old landslides reactivated in 1997.

In the spring of 2000, the Łososina catchment experienced yet another phase of heightened mass movement activity. This was a result of the saturation of the slope covers by the precipitation and thaw waters. A detailed description of the meteorological situation that had led to this landslide event is based on data made available by the IMGW and on the publication by Mrozek et al., (2000). In the winter of 1999/2000, the snow cover in the Łososina catchment persisted from November to March. During that time, it would increase in thickness (reaching a maximum thickness of 40-50 cm at the IMGW sites in Limanowa and Rozdziele) and thaw altogether several times. This cyclical pattern was caused by spells of above zero air temperatures separating periods where the minimum or average daily temperature dropped below the freezing point. With every period of higher temperature, the thawing snow gradually saturated the slope covers with water.

This meteorological pattern contributed to the weakening the stability of the slope covers. Under these circumstances, the stimulus that triggered the landsliding processes was provided by an intensive rainfall of 5 April 2000 that, after several hours, turned into an equally intensive snowfall. The event of 25 April 2000 produced the greatest total precipitation at 51.8 mm at the IMGW Limanowa and 41.2 mm at Rozdziele. On the same day, a cold front moved over the area carrying snow. These peculiar weather conditions, which could be described as an extreme event of the complex type, triggered landsliding processes that were then observed for several days while the snow melted. A number of new landslide forms emerged (e.g. at Stańkowa), alongside a further considerable development of 22 landforms originated in 1997. In 2000, secondary landsliding was commonly observed in more than 100 landslide forms. The slopes where landslides developed in 2000 displayed certain evidence of instability such as cracks and small land-slumps (e.g. at Stańkowa) as early as in 1997. The secondary landsliding was very common and covered landslides almost in the entire study area. Specifically, they affected the lower parts of the landslides: the tongues and especially the colluvial bulges. Minor displacements were also found in the landslide scars.

During the study period, only one extreme rainfall event was observed in the Hoczewka catchment in the Bieszczady Niskie range. An isolated thunderstorm of 26 July 2005 lasted for two and a half hours and produced 130.6 mm recorded at the IMGW precipitation station at Baligód-Mchawa (Fig. 3). This extremely intensive rainfall, displaying evidence of a torrential rainstorm, caused floods in the Hoczewka and its tributary valleys and activated gravitational processes that produced 191 landslide forms.

Small land-slumps (135) account for a clear majority of the total landforms. They are located primarily on the valley sides, along roadside undercuts and agricultural terraces. The remaining landforms included mud and debris flows (26) and mud and debris landslides (26). A very characteristic feature of the sliding and flow landforms was the fact that all of them had developed on slope edges, whether natural or man-made, principally on turf-covered surfaces. Almost all of the landforms classified as landslides emerged as a result of both the sliding and flow mechanisms, thus combining features of landslide and mud, or torrential, flows.

The slopes of the study area have 94 km^2 and the 191 mapped landslide forms cover 0.035 km^2. The resulting landslide ratio is very small at 0.04% and is eight times lower than in the Łososina catchment. (Compared to the ratio calculated only for the new landforms developed in 1997, excluding rejuvenated old landslides). The density ratio for the total landslide forms was 2 per one km^2.

Flood water and torrential flows had a much greater impact on the land relief than the landsliding processes in the Hoczewka catchment and the Solińskie Lake area. Considerable transformation affected the combined total length of 56 km of watercourse channels. New landforms that developed during the process within the channels included erosion chutes, rocky thresholds and vast bars with rocky rubble.

CONDITIONS: Change in slope stability	
NATURAL	ANTHROPOGENIC
Increase in slope gradient and length	
- natural valley side erosion dissecting the bed and undercutting valley sides by watercourses - scars of old landslides	- excavation of material during earthwork - field terraces
Removing of lataral support	
- violent cutting into the valley bed and sides by watercourses - mining for rocks (quarrying)	digging into slopes for development (roads, buildings, etc.)
Overloading slopes	
- accumulation of colluvia	- development (roads, buildings)

Table 1. External conditions on the Łososina catchment slopes favourable to mass movements. Based on Brunsden (1985) and own research.

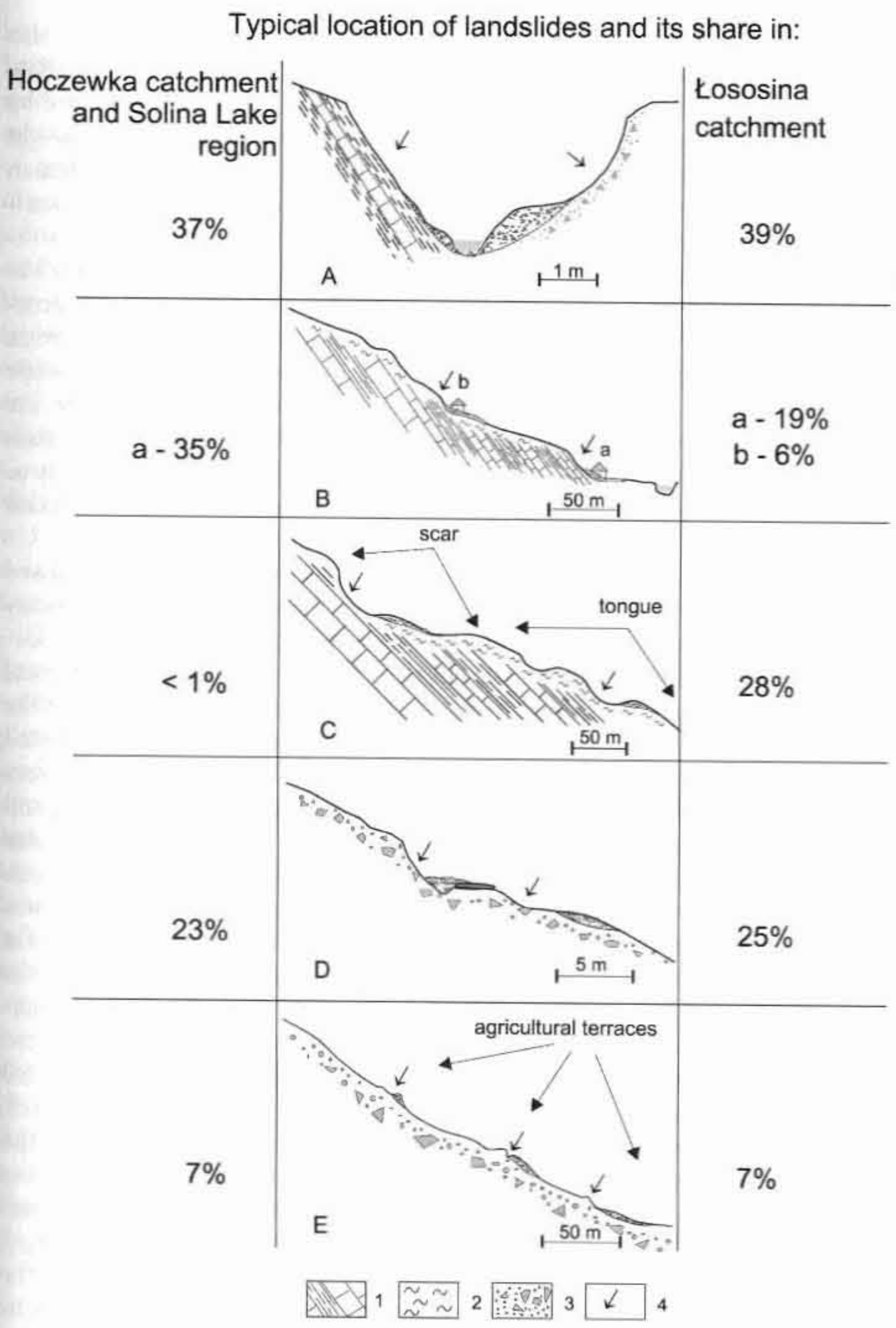

Fig. 4. Typical location of landslides and its share: in the Łososina catchment (Beskid Wyspowy) and in the Hoczewka catchment and Solińskie Lake region (Bieszczady Niskie);
1 – shale-sandstone layers; 2 – colluvial covers; 3 – waste-mantle covers; 4 – location of slope failure:
A – transformation of V-shaped valley sides;
B – transformation of higher-level terrace slope edges and denudational undercuts (a), undercuts approaching buildings (b);
C – reshaping of old landslide;
D – regress of roadside undercut edges;
E – transformation of agricultural terraces.

Slopes prone to landsliding

While the location of the new landforms developed on the slopes of the Łososina and Hoczewka catchments was affected by a whole range of factors, the key influences included the amount, timing and distribution of precipitation. However, the geomorphological effectiveness of the precipitation at any given site was determined by a set of physical geography factors.

In general, the commonness of landslides on the slope of the flysch Carpathian Mts. is a result of the peculiarity of the flysch formations, especially the shale and the shale-derived covers. Landslide forms, however, are not evenly distributed on the slopes. This is not just a result of the spatial limitation of impulses activating mass movements, but also of diverse internal conditions determining the susceptibility of a slope system to the landsliding. The diversity includes the slope gradient, lithology of the strata, their gradient, the depth of the waste-mantle, the existence of remains of old landsliding activity, as well as the land use and land cover.

In analysing the impact of those factors on the activation of the mass movements, the concept of "localised instability" was employed (Crozier, 1986). According to this concept, certain portions of the slope are more predisposed to landsliding than others. In these parts, the initiating factor's potential is focussed due to the properties of the slope system, while in other parts this potential becomes dispersed and the mass movements either do not occur or are delayed in comparison to the more exposed parts.

Based on the location of the landslide forms in the Łososina and Hoczewka catchments compared to other terrain forms and man-made infrastructure, external circumstances were identified that would favour mass process activity. Natural and anthropogenic factors determining the emergence and development of landslide forms are summarised in Table 1.

Most of the 1300 plus mapped landslide forms in the Łososina catchment developed on turf-covered slopes. Valley sides (39% of all forms) and roadside undercutting edges (25%) proved to be particularly prone to landsliding. They were followed by old landslide surfaces (28%), higher terraces sides (19%), agricultural terraces (7%) and man-made digs for buildings (6%). A similar location pattern was observed in landslide forms mapped in Bieszczady Niskie. In this area, the landforms had developed mainly on valley and upper terraces sides (70% of landforms) in road undercuts (23%) and agricultural terraces (7%) (Fig. 4).

The large number of landslides within various slope undercutc was caused by the abrupt increase in the slope gradient resulting in a higher relief energy. The origin of the common occurrence of landslides on valley sides seems to be similar.

A slightly different and more complex condition may be a reason for the preferred activation of mass movements within old landslide forms. This location of landsliding was caused by the concave features of these landforms concentrating the surface and ground water flow. Thus, the local saturation with water of the waste mantle may have been quicker than elsewhere on the slope, as pointed by Crozier (1986). Other factors contributing to the occurrence of landslides within older landforms include the existence of 'sleeping' slip surfaces and the typically greater local depth of the waste mantle than elsewhere.

Shallow ground and debris landslides are also helped by turf vegetation. Grass impedes sheetflow and retains rainwater longer. The ground covered by grass can therefore considerably increase in weight while the cohesion of the cover is reduced. Human activity is also extremely important in its large contribution to the upsetting of slope stability.

Slope stability tends to change not just in space, but also over time. One of the crucial factors in this process is the progressing weathering of the slope covers. This contributes to the increased exposure of the slope covers to sliding because, due among others, to the increased waste mantle depth. External factors, such as slope fragmentation as a result of human activity or river erosion may also weaken the stability of certain parts of slopes.

The four extreme meteorological events discussed in the previous section (three in the Beskid Wyspowy and one in the Bieszczady Nieskie) had various degrees of impact on the transformation of the local slopes. In July 1997, the complex type event had the greatest landform building potential and contributed to the intensification of landsliding processes on a very large scale in the Łososina catchment. The subsequent events not only had a much lesser potential, but also occurred in an area where the most landslide-prone slopes had already been transformed. Indeed, it was likely that the slope systems of the Łososina catchment were less prone to the landslide-triggering factors in 1998 and 2000 than in 1997. In the Hoczewka catchment, only one simple type rainfall event occurred - in July 2005 - an isolated thunderstorm that fell on the slopes unprepared by a long-duration rainfall. Compared to the complex type event of 1997 in the Łososina catchment, its landform generating role was minor. Alongside the lesser potential of the triggering factor, internal conditions, including lithology, relative height and gradients all played a role in the lesser exposure of the Hoczewka catchment slopes to landsliding.

Role of shallow landsliding in the shaping of mountain slopes

The landforms developed in landsliding processes triggered by the extreme precipitation events were typically small in size, but their number and dense distribution contributed to a considerable transformation of the Łososina catchment slope and to a lesser transformation of the Hoczewka catchment. Landsliding exerted the greatest impact on valley sides, old landslide surfaces, road undercuts and agricultural terrace edges. Figure 4 depicts models of transformation by landsliding of slopes in medium-height, deforested and developed mountains using the example of the Łososina and Hoczewka catchments. The role of the processes chiefly involved the transformation of V-shaped valley sides. Erosion undercuts, edges of higher terraces and roads cutting into slopes, as well as agricultural terraces retreated and were modified. As a result, landforms with abrupt edges, whether natural or man-made, were evened out. Concave landforms were particularly exposed to landsliding. Those included primarily old landslide scars and hollows within the tongues of those forms. As a result of landsliding, many old landslide forms were transformed and obliterated.

To assess the role of landsliding in the shaping of the Łososina catchment, a number of cross-transects were set in the Łososina valley to help identify slope sections particularly exposed to those processes. Old and deep landslide forms, typically found close to the ridges, had developed within the Magurskie sandstone formations and were predominantly overgrown with forests and featured salient shapes. On the other hand, landslide forms developed in lower parts of the slopes, typically on the slopes of the Łososina valley and its main tributaries, had their features partly obliterated, evened out slopes within the scar edges and traces of landslide accumulation were largely invisible. These landsliding slopes were the most affected by the landsliding of the 1997-2000 period. Most of the Łososina catchment slopes are irregular in shape with alternating concave and convex stretches. The landsliding processes investigated in this study had only a minor impact on the shape of the slopes as such, but they mainly transformed various abrupt lines on the slopes by either obliterating or destroying them altogether. In the slope profiles this was expressed by the extension of irregular/undulated slope stretches, deepening of the concave forms and minor local slope build-up by colluvia.

The rate of the transformation and obliteration of the geomorphological features in the studied landslides was high, which is typical of shallow waste-mantle landslides. Most of the landforms did not modify the regime of dominating morphological processes, water circulation or the development of the valley network. Intensified denudation and erosion processes could only develop within the larger landslides that featured elongated chutes or in old but reactivated landslides. This is also where concentrated surface runoff may have started the development of new valley forms. When compared to the present day processes observed elsewhere on the slopes of the flysch Carpathian Mts. in terms of scale and the degree of relief transformation, the studied processes must be regarded as having a high geomorphological potential. Indeed, landsliding displaced considerable masses of debris material and the inclusion of the highly liquidised colluvia in torrential flows caused the material to be transported over long distances, often into the valley beds.

In the flysch Carpathian Mts., large and deep rock-and-debris landslides tend to be transformed at a much slower rate than even very large landslides developed within the waste mantle only (Jakubowski, 1974). Similar landslides - where compact and structurally unaffected packets have been displaced - are typified by a high degree of permanence in comparison with detritic landslides where the material has been mixed, crumbled and fragmented. Trees play an important role in maintaining the saliency of landslide features. Forests tend to preserve the landslide relief by considerably restricting secondary movements. In contrast, the transformation rates of contemporary landslides on deforested slopes is incomparably greater.

Shallow debris slides prevail in the current climate and land use conditions, the latter involving deforestation and slope development. Debris landslides are currently the most numerous landslide forms and are almost always linked to extreme weather conditions in their origin (Jakubowski, 1965, 1968, Govi et al., 1982, Crozier, 1986, Bălteanu, 1997). Normally, shallow landsliding plays a minor role in the long-term development of the slope shapes and the geomorphological effect of those landforms is typically short-lived. In many mountain areas, however, mass processes combined with linear erosion are attributed the greatest geomorphology role in the development of slopes and valleys (m. in.: Rapp, 1963, Govi et al.,1982, Bălteanu, 1997).

Conclusions

During 1997-2000, a cluster of extreme meteorological events occurred over a short span of time in the Łososina catchment. The precipitation and thaw events of 1997, 1998 and 2000 contributed to an increased mass movements activity on the slopes and to the maintaining of a large role of landsliding in the transformation of the Łososina catchment morphology. The activation of landsliding triggered by a single extreme event in the Bieszczady Niskie range was much smaller and the degree of slope transformation in the area was minor.

The study indicates that the extreme event potential to initiate landsliding processes depends on two factors. One is the degree of complexity of the extreme event, where the potential of a single torrential rainfall is much greater when preceded by a long-duration rainfall than that of an isolated rainstorm of even a particularly great intensity. The other factor involves internal circumstances of the slope system, such as lithology, relative elevation and slope gradients.

The shallow mass movements mainly transformed V-shaped valley sides and effaced and evened out the bends of varied origin on the slopes. As a result of the landsliding processes, large amounts of debris were dislodged and displaced. Highly liquidised colluvia were included in torrential and debris-and-mud flows causing the material to be transported over long distances, often into the valley beds.

The gravitational processes occurred only locally and involved limited amounts of slope material, but had a considerable impact on the slope morphology. Mountain slopes transformed by landsliding are characterised by irregular longitudinal and cross sections, as a result of the multitude of convex and concave parts of the sliding slope.

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