S T U D I A G E O M O R P H O L O G I C A C A R P A T H O - B A L C A N I C A
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THE ROLE OF DOWNPOURS IN TRANSFORMATION OF SLOPES IN THE POLISH CARPATHIAN FOOTHILLS

Abstract. This paper presents the influence of downpours on the transformation of slopes in the Polish Carpathian Foothills, exemplified by the slopes in the Wiśnicz Foothills. Detailed mapping of the geomorphic effects of a rainfall in May 2010 on an agricultural slope with corn (*Zea mays*) was carried out following the event. The lack of dense vegetation at the time of the downpour created favourable conditions for erosion: 102.8 t of soil were eroded from a surface of 2500 m^2, and the amount if sediment removed due to erosion of two gullies has been estimated at 634 t. The material washed from the slope accumulated on the flattened area of the footslope, creating a proluvial-deluvial fan.

Key words: water erosion, rills, gully erosion, the Polish Carpathian Foothill, southern Poland

INTRODUCTION

Intense and heavy rainfalls lead to abrupt and significant geomorphologic changes within the slope catena. This is when the threshold value of the geomorphological processes is exceeded and the balance of the geoecosystem is disturbed (S t a r k e l 2008). Soil particles are torn away as a result of the impact of raindrops and the erosive forces of water. They move downslope under the influence of gravity and constitute the main source of the material carried by surface runoff (S z p i k o w s k i 2003, R e j m a n 2006).

The intensity of wash depends on, for example, the amount and energy of the water flowing down the slope, soil resilience, slope gradient, land use, agrotechnology, and vegetation (G e r l a c h 1966, 1976; G i l 1976, 1998, 1999, 2009; G i l, S ł u p i k 1972; T e i s s e y r e 1992, 1994; J ó z e f a c i u k, J ó z e f a c i u k 1995; S t a r k e l 1997; S z p i k o w s k i 1998, Ś w i ę c h o w i c z 2001, 2002, 2008; W i e j a c z k a, K i j o w s k a 2011). The largest amounts of wash and runoff can be observed during extremely heavy and intense rainfall. Arable lands respond very quickly to rainfall (T e i s s e y r e 1992, S t a r k e l 1997, R o d z i k et al. 1998, Ś w i ę c h o w i c z 2002), however, the washing process rarely occurs simultaneously on all slopes in the catchment. Erosion rates commonly vary along the hillslope profile (Ś w i ę c h o w i c z 2004).

Recognition of above-average events, or extreme events, as well as the identification of determinants of surface runoff, is crucial because such knowledge may contribute to the reduction of economic losses that accompany such phenomena (S t a r k e l 1996). Soil erosion often leads to the long-term depletion of humus compounds and plant nutrients, lowering crop yield and increasing production costs (J ó z e f a c i u k, J ó z e f a c i u k 1996).

In recent years, the problem of extreme hydrometeorological events has gained particular significance. The rate of geomorphic processes during extreme hydrometeorological events is several times larger than at average weather conditions (R o d z i k et al. 1998). In May 2010, downpours with considerable geomorphologic effects occurred all over southern Poland. Rainfall recorded at that time in the Carpathian Foothills was uniquely large in scale, and resulted in the formation of extensive erosion cuts. The purpose of this article is to analyse the geomorphological effects of an extreme rainfall, including the characteristics of large erosional forms created by rill wash and erosion on a foothill slope with a sweet corn (*Zea mays*). The results of the study form the basis for the explanation of the role of extreme rainfalls in shaping of the slopes in the Carpathian Foothills.

STUDY AREA AND METHODS

The erosional forms were recorded about 2 km west of Brzesko, in the locality of Jasień, near national road number 4 (Fig. 1). The study area is situated within the marginal part of the Carpathians, in the northern part of the Wiśnicz Foothills, and within the Brzesko Foreland (S t a r k e l 1972). The Brzesko Foreland, with elevations up to 300 m a.s.l. represents typical low-foothill relief (S t a r k e l 1972, G i l e w s k a and S t a r k e l 1988). The studied slopes, located at approx. 250 m a.s.l., are typified by an average inclination of 7° (Fig. 1) and a thick cover of loess-like silty deposits that coat the older Miocene substratum. The loess covers on farming slopes are particularly prone to the processes of runoff and wash. This is confirmed by the map of erosion vulnerability (J ó z e f a c i u k, J ó z e f a c i u k 1995).

This study uses the results of geomorphological mapping of erosional features that were formed on an agricultural slope (a cornfield, *Zea mays*) after the rainfall of May 2010. The lack of dense vegetation cover created favourable conditions for erosion. Rainfall data for the present study were obtained from the Field Research Station at Łazy (a part of the Institute of Geography and Spatial Management, Jagiellonian University) located around 5 km from the analysed slope. Mapping of the geomorphological effects was conducted immediately

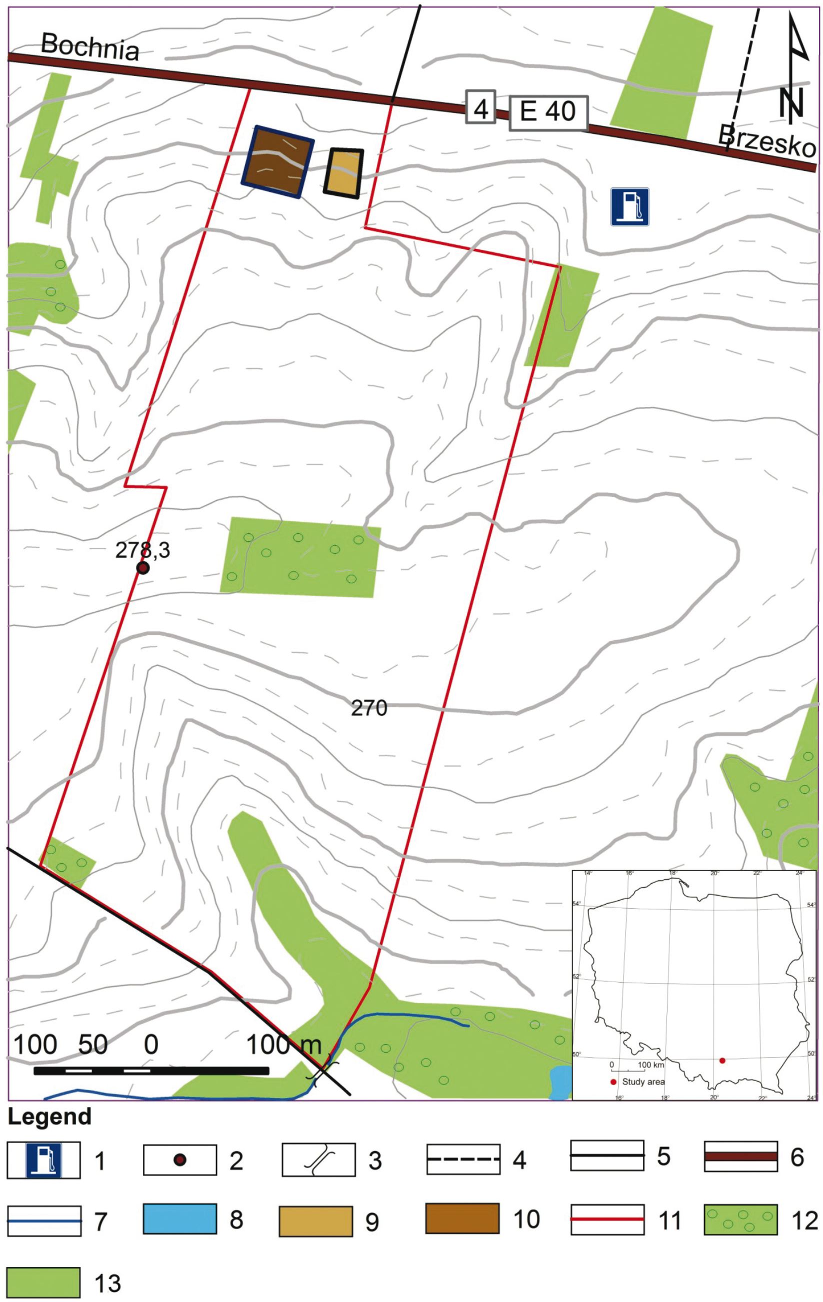

Fig. 1. Location of the study area — and research plots on the cornfield in Jasień near Brzesko:1 — petrol station, 2 — point altitude, 3 — footbridge, 4 — rural road, 5 — local road, 6 — main road, 7 — watercourse, 8 — pond, 9 — the plot with gullies, 10 — the plot with rills, 11 — parcel boundary and the area of the observed erosion, 12 — forest, 13 — shrubber

after the event, on 26 May, 2010, and the volume of surface runoff was estimated. The mapping focused on gullies, up to 3 m deep, and more shallow rills that were measured in detail on a surface of 2500 m^2. Their depth, width, and number were assessed. Cross-sectional profiles were made for two newly created deep channels19 profiles within gully A, and 9 in gully B, to enable monitoring of the rates and direction of the transformation of these forms during the next intense rainfall.

The two main rills can be treated as the first stage in gully development. There is no single criterion that would allow differentiation between a gully and other eroded forms. A frequently used definition by C. J. H a u g e (1977) states that gullies have a cross section larger than 1 square foot (sq ft), or 929 cm^2, and only carry water during and right after a torrential rain or after a violent thaw. This threshold is perceived by farmers as the critical value for the onset of rilling, and above it, driving conditions on the field are poor (S o u c h è r e 1995). A few authors (P o e s e n, G o v e r s 1990; P o e s e n 1993, V a n d a e l e 1993) apply this definition to ephemeral gullies which are wide but shallow. J. P o e s e n (1993) suggests a parameter describing width dependence on depth (w/d). Gullies width/depth ratio exceeding 1 are easy to remove, but cause the worst damage by moving fertile soil. S. S o b o l e w (1948) distinguishes four stages in gully development. The first stage is connected with the formation of shallow rills, however, this is not a prerequisite for the formation of gullies. The second stage refers to a deep slope cut in a place located quite far away from the watershed, whose route depends on the pre-existing rills, ploughing rills, rotational landslides, and suffosion sinkholes. Suffosion plays an important role in the process of gully formation (C z e p p e 1960). At the third stage, dissection of the gully floor stops nearly completely, and is followed by undercutting of the sidewalls, parts of which break off and slide. The fourth stage is dominated by deposition.

Considering these assumptions, the term gully was used in the article to define the two deep rills.

CHARACTERISTICS OF MAY 2011 RAINFALL EVENT

In May 2010, a very intense rainfall was observed in southern Poland. The rainfall was particularly heavy in the marginal and western part of the Carpathians (Fig. 2). In the period between 15 and 20 May, a low-pressure system that moved from the Gulf of Genoa through the Pannonian Basin and towards Ukraine, developed over Poland. This system brought cool and humid air mass extending from the North Atlantic to western Poland; while very warm and humid air masses extended from the Mediterranean Sea to eastern Poland (T o k a r c z y k 2011). The high humidity of the air masses over Poland, as well as the considerable thickness of layered clouds connected with the air masses, had the greatest

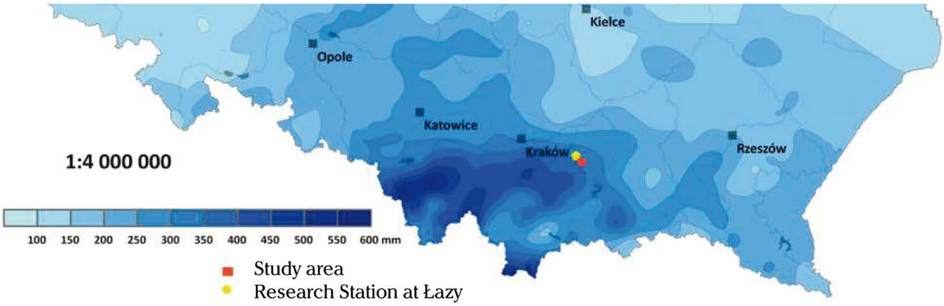

Fig. 2. Total monthly rainfall in May 2010 in Poland (Source: Institute of Meteorology and Water Management)

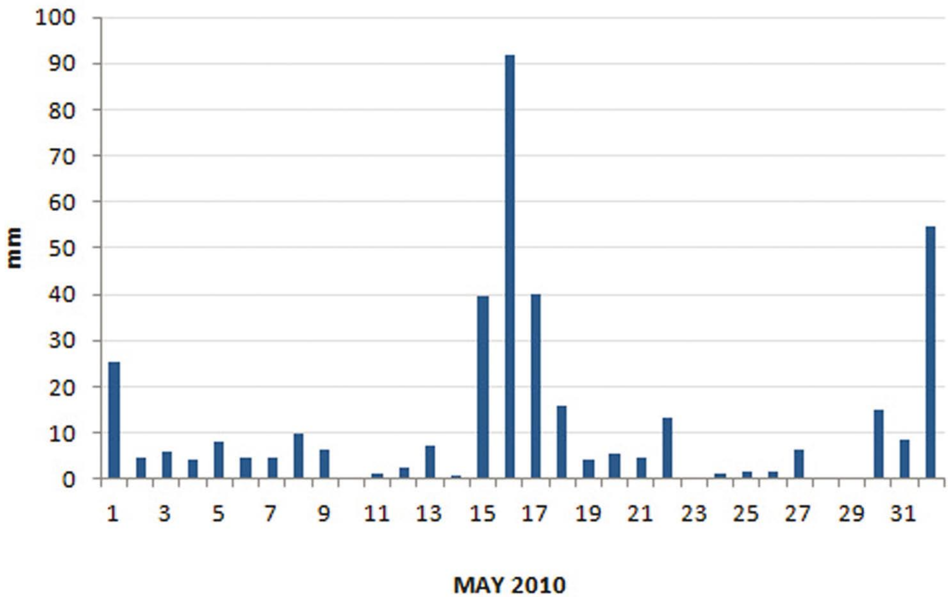

Fig. 3. Total daily rainfall in May 2010 recorded by the Field Research Station at Łazy near Bochnia (Source: the Field Research Station in Łazy)

influence on the intensity and amount of the precipitation. Such conditions supported the occurrence of heavy rainfall. Total monthly rainfall in May 2010 in Poland was characterized by a large spatial diversity; monthly values ranged from below 100 mm in the western part of the country to over 500 mm in southern Poland (Fig. 2).

Rainfall of 334.1 mm, recorded in May 2010 at the Field Research Station in Łazy, constituted 48.3% of the total annual rainfall in this area (mean annual rainfall for the period of 1987–2010 amounted to 692 mm) and at least 377% of the multi-annual average monthly rainfall in May. Additionally, a considerable variation of the total daily rainfall sums was recorded. Total daily rainfall on 16

May 2010 amounted to 91.9 mm (Fig. 3) with the maximum rainfall intensity reaching 0.26 mm min^{-1}. Total daily rainfall on 16 May exceeded by 3.3 mm the average May rainfall recorded in the period from 1987 to 2010 and was the largest daily sum in the last 20 years. Total sum for the period 15–18 May 2010 was 187.5 mm (the Research Station in Łazy).

THE GEOMORPHIC EFFECTS OF EXTREME RAINFALL ON A FOOTHILL SLOPE

The high rainfall recorded from 15 to 18 May 2010 resulted in surface runoff and rill wash, which formed a system of rills and very deep erosive cuts that were turning into gullies that directed the drainage of the soil material on the cornfield (*Zea mays*) (Photo 1). Corn is normally sown in Poland in the first week of May; thus, during the intense rainfall, corn on the studied field was only a few centimetres high, and its root system was not well developed. The initial growth of corn is slow, and it only grows faster after producing 6–7 leaves. In the analysed area, corn was sown in rows according to the slope gradient, which created favourable conditions for the concentration of rainfall and intensified erosion. The fairly uniform microtopography of the surface between the rows of corn

Photo 1. Rills on the cornfield in Jasień, which occurred after intensive rainfall in May 2010 (by M. Kijowska)

created favourable conditions for the occurrence of rill wash on the whole field, and the entire structure of soil was destroyed due to ponding.

Around 53 rills were created on a field of 2500 m^2. The depth of the rills ranged from a few centimetres to a maximum of 40 cm centimetres, while their depth was connected with the depth of tillage (±35 cm). The rills cutting through the slope had a parallel arrangement that was in accordance with the gradient and direction of the rows of corn; junctions occurred only in a few places, increasing the size of the rills. Farming not only directly influences the surface, but also the condition of the soil down to the depth of the agro-technological works, namely to the plough pan (G i l 1976, R o d z i k et al. 1998). The detachment and transport of soil particles is mostly connected with runoff intensity (T h o r n e et al. 1986, W a t s o n et al. 1986). It has been estimated that 102.8 tonnes of soil was eroded from the surface of 2500 m^2 (Photo 1), which equals 411.2 tonnes per hectare.

The transition from surface runoff into rill wash and later into deep cuts, similar to gullies, could be observed along the farmed slope. Rapid concentration of water runoff results in the rill wash on the larger part of the slope. The rill wash is observed in parallel rills that depend on the direction of the crop. Deep erosional cuts, which resemble gullies, occurred below the middle part of the slope.

Formation of deep erosional cuts is connected with an array of factors including complete saturation of soil covers, local reduction of their thickness, and the increase of the slope gradient. Saturation of the soil in this part of the slope forced the throughflow and water in the pipe channels up to the surface where it again changed into overland flow. The silty soil cover on the almost impermeable substratum was liquefied due to the shear stress of the runoff. As a result, Miocene shale-sandstone series were exposed in the floor of the upper part of the gully. At the same time, concentration of the overland flow from several rills increased the erosive effect and caused deep cuts in the slope surface. Channels of biotic origin (connected with the activity of moles, mice, and rabbits) (P o e s e n 1989) play an important role in the development of the gullies. Piping as well as the pipe tunnels that were formed on the contact of residual soil and substratum rocks, play an important role during the process of the deepening of rills and the creation of gully-like forms (C z e p p e 1960) (Photo 2).

Two deep erosive cuts formed on the slope with the corn crop. The first cut (gully A) was 39 m long and 270 cm deep (Photo 3, Fig. 4). It has been calculated that around 384 tonnes of soil were eroded from this form. In comparison, around 250 tonnes were eroded from the other cut, which had a more complex shape but smaller length and depth (maximum depth was 185 cm). The latter form — gully B (Photo 6, Fig. 5) was characterised by the occurrence of rills in the side branches and the numerous traces of wash on the slopes. In the bottoms of those two channels numerous stepped profile emerged. They consisted of rock steps of heights up to 200 cm as well as 80-90 cm deep erosional depressions resembling plunge pools. Side walls of the two gullies were significantly

Photo 2. Suffosion processes on the contact of residual soil and bedrock (by M. Kijowska)

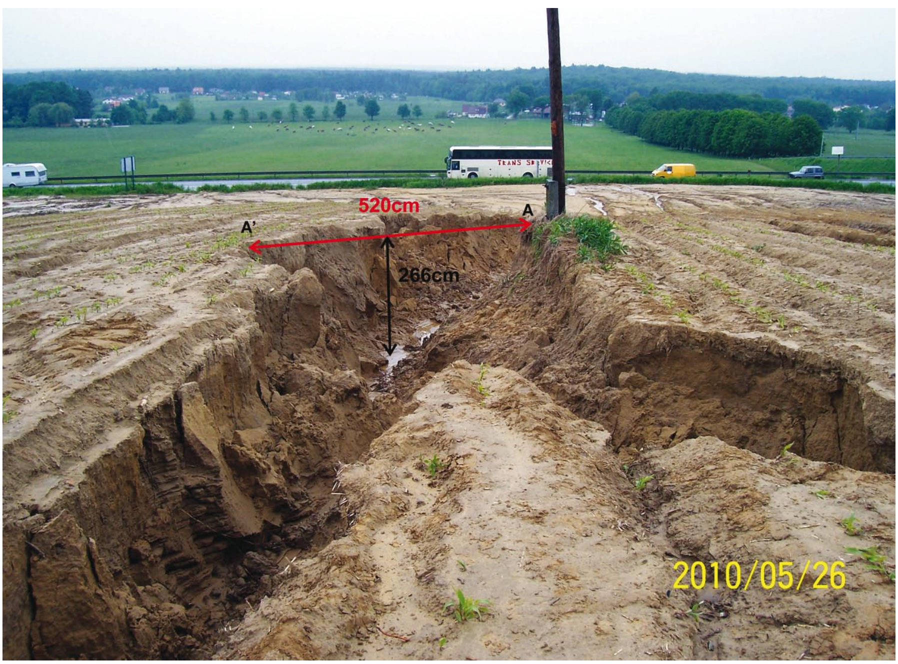

Photo 3. Effects of intense erosion on the cornfield and a cross-section of the gully A (by M. Kijowska)

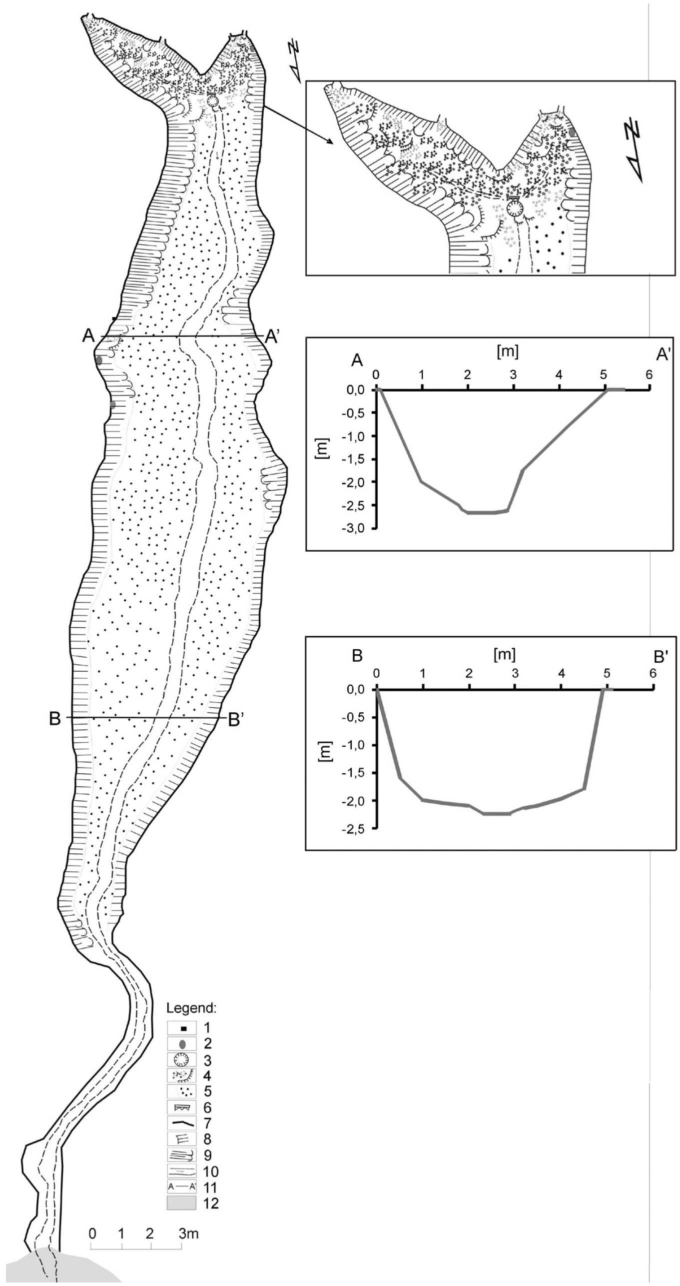

Fig. 4. Geomorphological sketch of the gully A. 1 — telephone pole, 2 — biotic channel, 3 — pothole, 4 — detached soil packets forming the mound at the foot of gully walls, 5 — accumulation of fine material, 6 — shale-sandstone series of Miocene, 7 — the edge of the gully, 8 — steep gully wall, 9 — gully wall with detached material, 10 — channel, 11 — cross section, 12 — proluvial-deluvial fan

Photo 5. The material carried from the cornfield to the trench at the footslope (by M. Kijowska)

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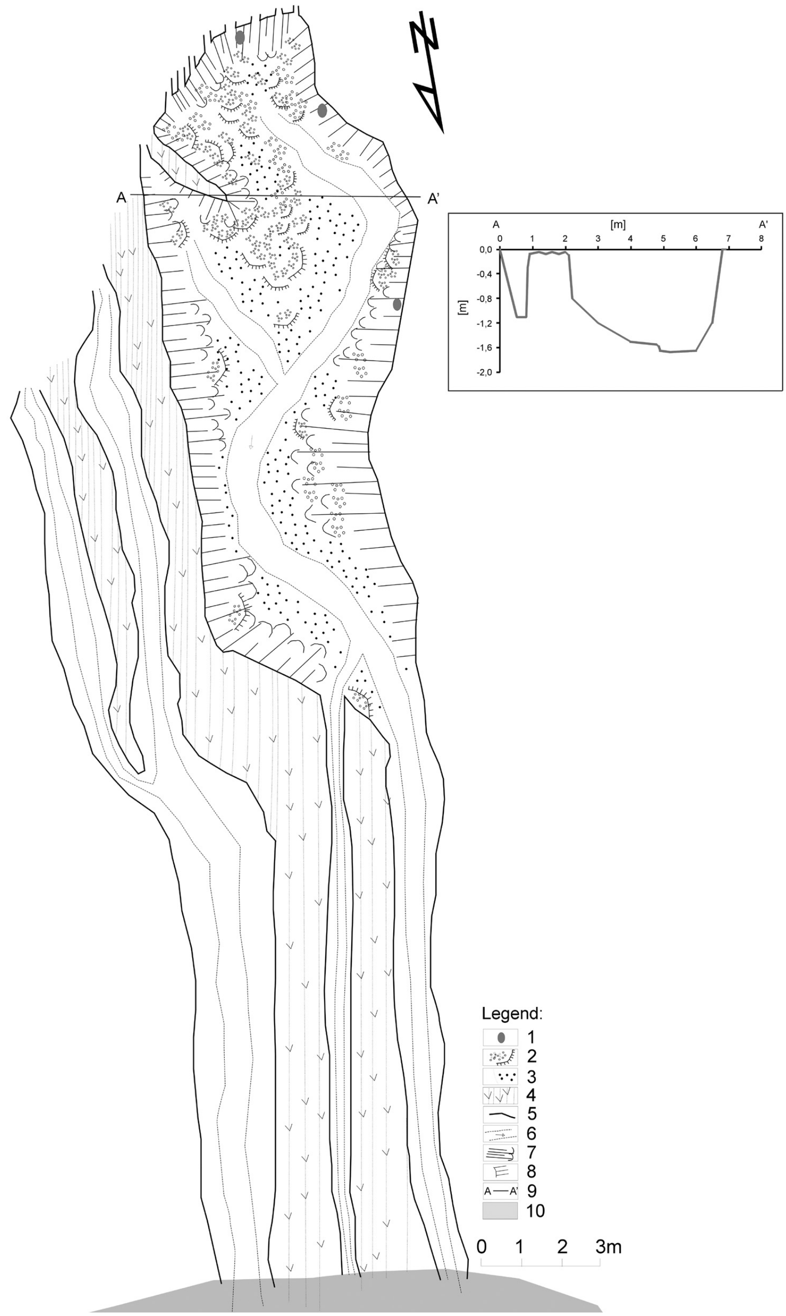

Fig. 5. Geomorphological sketch of the gully B. 1 — biotic channel, 2 — detached soil packets forming the mound at the foot of the gully walls, 3 — accumulation of fine material, 4 — rill erosion, 5 — the edge of the gully, 6 — channel, 7 — gully wall with the detached material, 8 — steep gully wall, 9 — cross section, 12 — proluvial-deluvial fan

transformed by soil slumps. The size of detached soil packets forming mounds at the foot of the gully walls reached up to $^3/_4$ of their height. A similar situation was observed in the Kalinka catchment, the Miechów Upland (W o l n i k 1981, C z y ż o w s k a 1996). In gully B in place with a small slope sporadic channels were formed with staggered erosive and accumulative sections.

The location of plunge pools in the gullies is connected with the flow turbulence and variation in the lithology of the substratum, observed in the sections with exposed bedrock. The falling water swirls, causing the undercutting of the steep gully walls and their periodic, yet rapid erosion, a process previously described by S. S o b o l e w (1948). With limited protection from poorly branched plants, ploughing and cultivation along the slope facilitated erosion of such large amounts of residual soil. This allowed a direct contact between the rainfall (with the intensity of several dozen millimetres per hour) and the slope surface causing water dispersion, which, together with intensive overland flow, resulted in intense erosion.

The calculated denudation index, excluding deep gullies, amounted to 21 mm; after the gullies have been taken into account, the index equalled 55 mm.

A proluvial-deluvial fan, approximately 122 m wide (Photo 4), was formed at the mouth of the rills and gullies, at the foot of the slope. The material eroded from the cornfields was also carried to a nearby trench, and then transported to a stream, as evidenced by the traces of overland flow: flattened grass with the soil on the side of the trench (Photo 5).

Similar geomorphological results of rainfalls in May 2010 were observed on the southern slopes of the Sowiniec Graben (in Cracow) in the "Srebrna Góra" vineyard. In this area, the slope surface lacked tight plant cover. The new grapevines were planted in rows in accordance with the slope gradient. Due to rainwater erosion, gullies, 1.5 m to 2 m wide and about 290–300 m long, developed on the whole slope (Z. R ą c z k o w s k a, personal communication).

In the Carpathian Foothills, similar transformation of slopes and the emergence of a deluvial fan was observed in the catchment of the Dworski Stream (the Wiśnicz Foothill) in 2002 (Ś w i ę c h o w i c z 2004). After intense rainfall, with a daily sum up to 43 mm, the emergence of a system of convergent rills that were 30 m long and up to 68 cm deep, was noted on sugar beet fields during the initial phase of the plant growth (Ś w i ę c h o w i c z 2004). During the subsequent rainy days, due to the linear ablation, the rills were deepened to 120 cm and their width increased. However, the new erosional forms were filled after harvesting by means of agro-technological methods. J. Ś w i ę c h o w i c z (2004) noted that in the neighbouring catchment of the Brzeźnicki Stream, where there are both narrow and long fields with small plots of various land use, such heavy rainfall did not cause changes of the slopes, as both the surface runoff and the relocation of the material that was washed away took place at small distances.

The emergence of numerous rills transformed into gullies was observed in the Lublin Upland (Z i e m n i c k i, N a k l i c k i 1971, R o d z i k et al. 1998). The

Photo 6. Effects of intense erosion on the cornfield in the gully B (by Z. Rączkowska)

maximum amount of material activated during the disastrous rainstorms in the Lublin Upland is estimated to have been between a few thousand to several thousand t ha^{-1} (B u r a c z y ń s k i, W o j t a n o w i c z 1974). Rainstorms in this area have a decisive influence on the development of gully forms, both the natural ones as well as the anthropogenic (road cut) (R o d z i k 1998). Deposition on the floors of hollows and dry valleys is observed in a large part of the loessic areas in the Lublin Upland (K l i m o w i c z 1993); however, in the Sudetes Foreland (T e i s s e y r e 1992) somewhat opposite processes take place. After a heavy rainfall in May 1996, G. J a n i c k i et al. (1999) observed numerous erosional forms, up to 2 m in length, in the northern part of the Sokal Plateau-ridge. The erosion value calculated for this region was 382.3 t ha^{-1} and was a little lower than those described in the literature, mainly due to the efficiency of the rainfall and the degree of slope dissection. The effects of rainfall on loessic areas were also described by J. B u r c z y ń s k i and J. W o j t a n o w i c z (1974) who estimated the amount of material evacuation at 622.2 m^3 km^{-2} following a single rainfall in Dzierzkowice. In Piaski Szlacheckie this value was higher and amounted to 1432.5 m^3 km^{-2} (Tab. 1).

Table 1

The compilation of the selected erosion episodes

Locality	Geographical region (macroregion/mezoregion)	Amount of erosion [t ha^{-1}]	References
Jasień	Zachodniobeskidzkie Foothill/ Wiśnicz Foothill	411,2	Author
Kolonia Celejów	Lublin Upland/ Nałęczów Plateau	1,29	J. Rodzik (2008)
Around Zubowice	Wołyńska Upland/ Sokal Plateau	382,3	G. Janickiet al. (1999)
Giebułtów/ Nidzica river basin	Niecka Nidziańska/ Miechów Upland	255–292 (the upper part of the slope); 357–425 (the middle and lower part of the slope)	E. Czyżowska (1996)
Dzierzkowice	Lublin Upland/ Urzędowskie Elevation	12,4	J. Buraczyński, J. Wojtanowicz (1971)
Piaski Szlacheckie	Lublin Upland/ Giełczew Elevation	24,56	H. Maruszczak, J. Trembaczowski (1956)
Parchatka	Lublin Upland/ Małopolski Vistula Gap	462	A. Reniger (1959)

THE ECONOMIC CONSEQUENCES OF THE EXTREME RAINFALL

Development of the deep gully A and B initiated adverse slope fragmentation. Gullying caused portions of arable land to be transformed into wasteland as the fragmented surface is no longer possible to harvest. In 2010, gullies occupied about 0.10 ha (0.5%) of the agricultural land in Jasień, and about 1% of the cornfields. The new forms contributed to the decrease of arable land and affected farming. Depending on their intensity, the processes of wash, rilling and gullying, may seriously affect soils (J ó z e f a c i u k, J ó z e f a c i u k 1999), and lead to decreased soil thickness, changes in the arable-humus horizon and deterioration of biochemical and physiochemical properties of the soil.

As noted by A. J ó z e f a c i u k and C. J ó z e f a c i u k (1999), eroded soils usually have inferior mechanical composition, due to the removal of the finest soil particles, decreased porosity, permeability, and water capacity (L i p s k i, K o s t u c h 2005). It is one of the reasons for lower soil fertility. At the footslope, where the material is accumulated, increased humus thickness is observed; however soils there have unfavourable properties. Changes in soil humidity take place on arable land with numerous and large erosion rills. Hollows that frequently appear on the surface damage infrastructure. The rills near Brzesko were transformed into gullies, displacing a telephone pole.

SUMMARY AND CONCLUSIONS

Intensive rainfall plays a key role in the relief modelling of the Carpathian Foothill regions. The current formation of deep erosional forms is an incidental situation in the Carpathian Foothills. Similar precipitation amounts do not cause gullying in this region. However, studies conducted in the marginal part of the foothills suggest that such features are frequently encountered on loess-like deposits (S t a r k e l 1960). The examined rills, gullies and proluvial-deluvial fans, which developed on cornfields in the initial growth phase, exemplify the effects of runoff and slope wash following a rainfall event in May 2010, characterized by a daily rainfall total reaching 92 mm. One type of crop was sown in rows, according to slope gradient, on a cornfield with a surface of about 11 ha, thus contributing to the extensive wash. The lack of thick vegetation cover and soil scarification accelerated the runoff and the rate of wash.

The mapping, which was conducted immediately after the rainfall, allowed the assessment of the magnitude of the erosion. The gullies observed on the slope in Jasień were up to 3 m deep and up to 39 m long. In gully A (longer and deeper) erosion amounted to 384 tonnes, and in gully B equalled about 250 tonnes. About 53 rills, up to 40 cm deep, were formed on a field of 2500 m^2. The amount of eroded material was calculated to be 102.8 tonnes (411.2 t ha^{-1}), and the denudation index equalled 21 mm. The material washed from the slope accumulated in the flattened area of the footslope, creating a proluvial-deluvial fan.

The model of slope transformation into a foothill slope was similar to and fit the one proposed by T. G e r l a c h (1966) in which the upper part of the slope is lowered, while the bottom part extends. The results of the study provide a more detailed model, i.e., the upper part of the slope is lowered, but also cut, the middle part is subject to the most intensive fragmentation and degradation due to development of gullies and rills; the accumulation on the footslope is assumed in both models. However, it should be noted that anthropogenic forms, such as deep hollows and roads, disturb the model introduced by T. G e r l a c h (1966) as they limit the development of accumulation forms and reduce the amount of deposited material by facilitating channelling. They play a role of "mega" field terraces.

The study has showed that a decisive role in slope transformation is played by land use, the applied agro-techniques, the total area of the land under cultivation, and efficiency of coverage provided by plants, depending on plant growth phase and the intensity of precipitation. However, rain with similar characteristics (intensity, duration, and amount of precipitation) may have different effects, depending on the land use and the degree of plant coverage. As observed in the particular segments of the agricultural slope, the high level of soil erosion was associated with the additional supply of underground water and subsurface scouring of soil by water flowing through underground channels which formed at the contact of residual soil and bedrock.

The emergence of this kind of erosional cuts on slopes not only impedes harvesting and using of agricultural machinery but also significantly influences soil moisture conditions. Erosive activity of rainwater constitute drainage that dries up soil and worsens cultivation conditions. Intensive processes of wash also cause weeds to spread and crop yield to decrease because of the loss of significant amounts of fertile topsoil, rich in organic matter. The destructive influence of the erosional forms is also connected with flooding and silting up of the arable land, routes, and irrigation channels with loessic material. Erosion can be prevented by means of anti-erosion irrigation which limits the occurrence of erosion processes and preserves the production capacity of soil. The analysis of this single, extreme incident has shown that the rate of erosion on the slope that is used for agriculture may exceed the intensity of wash for a few years – or even several decades.

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