Contemporary geomorphic processes in the Polish Carpathians under changing human impact

The paper presents activity of contemporary geomorphic processes in the Polish Carpathians, taking into account human impact on relief transformation in the past several centuries.

Landsliding in the flysch Carpathians is a principal process in slope transformation, posing the most serious threat to man, both in the mountains and the foothills. On the other hand, unsuitable housing on slopes initiates mass movements, frequently with catastrophic consequences. Land use changes, in particular deforestation, have over the past 200 years fostered intensive slopewash and linear erosion, with this playing an important role in shaping foothill relief. Following changes in land use and channel regulation initiated at the beginning of the 20th century, a tendency to river bed deepening prevails. Moreover, floods, and not only extreme instances, continue to pose a threat to man, with their effects enhanced by housing in floodplain areas.

A tendency consisting in the reduction of arable land and an increase in grassland and forest area, observed over the past two decades, will lead to a gradual limitation of slope-wash and wind erosion as well as a simultaneous increase in linear erosion on slopes and river bed deepening.

Introduction

Geomorphic processes, both secular and – more spectacular as far as their effects are concerned – extreme or catastrophic, are continually transforming the landscape of the Polish Carpathians, albeit with varying intensity. Beyond climate and geological setting, the results of such processes depend on type of relief. Starkel (1972) distinguished five relief types in the Carpathians: high mountains, middle mountains, low mountains and high foothills, middle and low foothills, and valley bottoms (Fig. 1A and 1B). The new concept of the influence of geological structure on Carpathian relief zonation (Jankowski and Margielewski, 2012) allowed for a reduction in the number of relief types to four: high mountains, middle and low mountains, foothills (including high foothills) and valley bottoms.

The Polish Carpathians are relatively densely populated (127 persons/km²), and more than 65% of the population live in rural areas (Długosz and Soja, 1995). For this reason man exerts a strong influence on the course of geomorphic processes, but recent processes and their effects also pose a threat to man. According to Slaymaker (2010), human activity is a key driver in present-day landscape evolution in mountain areas.

The aim of this paper is to present such mutual relationships within areas showing four types of relief, indicating the most important processes, type of geomorphic hazard and type of human influence on relief transformation, as well as tendencies in these interrelationships under a changeable climate over the past several centuries, particularly with regard to the last 200 years.

In this period, from the 13th century onwards, important changes occurred in the intensity of various types of anthropopressure (extent and duration of human impacts) in the Polish Carpathians. Some of these gained in intensity (for instance river channel regulation, construction works both on slopes and in valley bottoms, increasing road density and remedial works), while others fell in importance (such as agriculture since the mid-20th century) or disappeared entirely (pasturing). All of these factors resulted in increased forestation (Lach and Wyzga, 2002; Kozak et al., 2007). In the western part of the Polish Carpathians, human impact on the intensity of geomorphic processes has tended to increase, while in the eastern part it halted temporarily owing to the depopulation of this area in the mid-20th century for political reasons.

The human role in landform evolution and modification of geomorphic processes has been a subject of increasing attention in geomorphic literature (e.g. Nir, 1983; Goodie 2006; Gregory, 2006). Many papers focus on human modification of particular geomorphic processes and landforms, for example fluvial (Brooks, 1988; Bravard and Petts, 1996; Wohl, 2006) or particular relief type, e.g. mountains (Messerli et al., 2000; Remondo et al., 2005; Slaymaker and Embleton-Hamann, 2009).

History: progress and regress of human impact on the Carpathians in recent centuries

The types of human impact that have affected relief and intensity of geomorphological processes in the Polish Carpathian Mountains includes: (1) deforestation, human settlement, agriculture (valley floors, later slopes), since the 13th century (Gerlach, 1966; Adamczyk, 1978; Raczkowska et al., 2012); (2) animal grazing (mainly sheep in...
Figure 1. Polish Carpathians: A – geology (after Zytko et al., 1989); symbol explanation: Inner Carpathians: WT – Western Tatra Mts; HT – High Tatra Mts., PB – Podhale Basin; PKB: Pieniny Klippen Belt; Outer Carpathians: MG – Magura Unit; DU – Dukla Unit and their equivalent; SS – Sub-Silesian Unit; SL – Silesian Unit; SK – Skole Unit; ST – Stebnik Unit; CF – Carpathians Foredeep; N – Neogene deposits on flysch. B – types of relief in the Carpathians (after: Starkel, 1972) 1 – high mountains; 2 – middle mountains; 3 – low mountains and high foothills; 4 – middle and low foothills; 5 – bottom of valleys; 6 – Carpathians boundary. C – geomorphological units of the Polish Carpathians (after: Starkel, 1972; Gilewska, 1986). Symbol explanations: 1 – Central Western Carpathians: TTM – Tatra Mts.; PD – Podhale; ONB – Orawa-Nowy Targ Basin; PN – Pieniny Mts.; 2 – Outer Western Carpathians: BSL – Beskid Slaski Mts.; BM – Beskid Maly Mts.; JD – Jablonkow Depression; BZ – Beskid Zywiecki Mts.; BSR – Beskid Sredni Mts., OU – Orawa Upland; SG – Sieniawa Gate; BW – Beskid Wyspowy Mts.; GC – Gorce Mts.; BSD – Beskid Sadecki Mts.; BN – Beskid Niski Mts.; JSD – Jaslo-Sanok Depression; DF – Dynow Foothills; STF – Strzyzow Foothills, CF – Ciezkowice Foothills; NSB – Nowy Sacz Basin; WF – Wieliczka Foothills; SLF – Silesian Foothills; 3 – Outer Eastern Carpathians: HBM – High Bieszczady Mts., LBM – Low Bieszczady Mountains; SM – Slonne Mts., WU – Wankowa Upland.
forest clearings), since the 15th century (Mirek and Piekos-Mirek, 1979); (3) forest management (mixed forests replaced with spruce monocultures at lower elevations during the 19th and early 20th centuries); later efforts to restore mixed forests; increased forest cover since the 1950s (Raczkowska et al., 2012); (4) mining (stone quarries, gravel extraction, oil extraction), since the 19th century (Raczkowska et al., 2012); (5) glass-making and steel production, locally (15th - 19th centuries) (Raczkowska et al., 2012); (6) large-scale potato farming in the 19th and 20th centuries (Klimek and Trafis, 1972; Raczkowska et al., 2012); (7) transportation infrastructure (a large number of dirt roads and forest roads; railroads since the early 20th century; expansion and modernization of roads for automobiles since the 1950s) (Froehlich and Slupik, 1986); (8) construction of buildings on slopes (large houses since the 1950s; weekend houses since the 1990s) (Raczkowska et al., 2012); (9) river and stream regulation and dams (20th century), river shipping (late 19th and early 20th centuries) (Wyzga, 1993; Lajczak, 2006; Krzemien, 2003); (10) summer tourists (20th century) and winter tourists (since the 1930s) (Lajczak, 2002).

The most rapid anthropogenic relief changes in the Polish Carpathians have occurred in the past 200 years. All of the forms of human impact listed above came to exert pressure on Carpathian relief during this period (Mirek and Piekos-Mirek, 1979; Raczkowska et al., 2012). Some forms of human impact grew stronger while others remained weak. Today the most active forms of human impact in the Polish Carpathians include building and road construction and tourism. Declining forms of human impact include sheep herding, mining and agriculture. Glassmaking and steel production no longer take place. The abandonment of agriculture on mountain slopes in the region has led to mountain slope reforestation (Fig. 2). The eastern part of the Polish Carpathians underwent depopulation in the late 1940s resulting in almost 100% increase in the forest cover (Lach and Wyzga, 2002; Wolski, 2007; Nowak, 2012). Reforestation in the western part of the Polish Carpathians began on a smaller scale in the 1990s (Ostafin, 2009; Bucala, 2012). The greatest human impacts on Carpathian relief have been from rock quarrying, dam construction (delta formation in reservoirs), house construction on valley floors and slope agriculture at lower elevations (Raczkowska et al., 2012). The effects of human impact on relief decrease significantly at higher elevations. While some types of human activity have declined in the region over the years, the relief transformation caused by these is still visible.

**Figure 2.** Transformation of landscape of small Carpathian valley during last forty years. A – year 1968, B – year 2008. Note increased range of forest and changes in stream channel pattern (photo A – M. Niemirowski; photo B – A. Bucala).

### Geological setting

The Polish Carpathians are divided into the Inner Carpathians (consisting of the Tatra Mountains and the Podhale Basin) and the Outer Carpathians (also called the Flysch Carpathians), separated by the Pieniny Klippen Belt (Fig. 1A, Ksiazkiewicz, 1972). The Tatra Mountains are composed of a central crystalline core and a cover of sedimentary rocks. The core, formed of intrusive carboniferous granitoids and metamorphic rocks (gneisses, amphibolite, metamorphic shale), is rimmed by allochthonous High Tatric Nappes and Sub-Tatric Nappes, consisting of quartzites, dolomites, limestones, marls, shales and sandstones of the Triassic-Middle Cretaceous age. The Podhale Basin is filled with conglomerates, nummulitic limestones, and Podhale flysch formations (shales and sandstones of the Palaeogene period), 2,500 m thick within a widespread syncline.

The Pieniny Klippen Belt, a narrow but deeply rooted tectonic structure, is formed of Upper Cretaceous-Palaeogene deposits: limestones, radiolarites, marls, sandstones and shales (Birkenmajer, 1986). Occurring along the boundary of the Pieniny Klippen Belt and the Outer Carpathians are andesite intrusions of the Miocene period.

The Outer (Flysch) Carpathians are formed of flysch sediments (and, occasionally, marls and hornstones) of the Late Jurassic-Early Miocene age (Ksiazkiewicz, 1972; Oszczypko, 1995). Flysch rocks, strongly folded, jointed and faulted, form several nappes/units (the Magura, Dukla, Silesian, Sub-Silesian, Skole and Stebnik Units) thrust over each other horizontally toward the north. On the northern foreland of the Carpathians, a large tectonic depression called the Carpathian Foredeep formed and became filled with Miocene deposits (Fig. 1A) (Oszczypko et al., 2006).

In the Tatars and the Pieniny, coarse debris predominate in slope cover, while in the Podhale Basin and the Outer Carpathians slope cover is mainly formed of silt and clays. The relief of the Carpathians is apparently conditioned by geological structure, both lithology and tectonic (Fig. 1A and 1B) (Starkel, 1960, 1972). However, landform transformation in each type of relief (high mountains, middle and low mountains, foothills and valley bottoms) is a result of processes induced by climate and human activity (Fig. 3).

### High mountains

High mountains with relief remodelled by glaciers include the
and intensive sheep grazing, which resulted in deforestation and destruction of continuous covers of alpine grass and dwarf pine communities (Mirek, 1996). Almost 20 years after sheep grazing was abandoned, erosional processes had slowed (Jahn, 1979), while anthropogenic landforms such as quarries, mine shafts and roads remained. Moreover, monoculture forests introduced in place of natural forest communities are conducive to erosion involving tree toppling linked with foehn or bora-type winds (Fig. 4, Kotarba, 1970).

During periods of average meteorological conditions, relief changes in the valley bottoms are insignificant and restricted to stream beds (Kaszowski, 1973; Krzemien, 1991). Minor modifications in the stream beds are due mainly to lateral erosion during floods (Krzemien, 1991), whereas important and permanent changes, although confined to short stream reaches only, tend to post-date extreme floods (Kaszowski, 1973; Kotarba, 1999).

Debris flows, dirty avalanches and rockfalls play the most important role in contemporary transformation of the morphology of the Tatras, by remobilising and transporting large quantities of debris material and shaping new landforms (Figs. 3 and 5, Kotarba, 1992, 1995, 1997; Raczkowska, 2008). Most significant among rapid mass movements are debris flows, which tend to occur more frequently and widely than the other processes (Kotarba, 1995; Raczkowska, 2008; Raczkowska et al., 2012). The debris flows are able to carry a load ranging from several to several tens of thousands of cubic metres of weathering material from the interfluves to valley bottoms (Kotarba et al., 1987; Krzemien, 1991; Kotarba, 1992). This activity produces newly-formed gullies (Fig. 5), several metres deep and several hundred metres long, and debris flow levees, more than 1 m in height, or it markedly changes morphometric parameters of pre-existing landforms. The resulting changes of relief are linear (debris flows, avalanches) or point-like (rockfalls) in nature (Krzemien, 1991; Kotarba, 1992, 1997). According to results of lake sediment analysis and lichenometric studies, the activity of both debris flows and rockfalls was stronger during the Little Ice Age (Kotarba, 1995).
Rapid mass movements, with the exception of avalanches, do not pose a serious threat to man in that high-mountain areas are, at present, located within uninhabited national parks. Such areas are visited by climbers, tourists and skiers, more rarely by woodcutters. In the past several decades, human-induced relief changes have tended to concentrate along tourist trails and be linear in nature. These changes are related chiefly to summer tourist activity, while climbing and skiing are of minor importance. Tourist trails tend to become deeper and wider, especially in parts where protective pavements of stones have been destroyed. Increased activity in geomorphic processes is seen in zones of up to several metres in width accompanying tourist trails (Czochanski, 2000) at sites at which vegetation cover has been destroyed.

In the forest belt, slope rills develop owing to the repeated dragging of felled tree trunks. These rills are gradually erased by natural processes, when exploitation ceases (vide Raczkowska, 2008).

Middle and low mountains

Middle mountains (800-1,300 m a.s.l.) with steep slopes (>30%) developed in the Carpathians on resistant thick-bedded flysch sandstones and include both tight mountain groups (Beskid Slaski and Zywiewicki, and Beskid Sadecki) and isolated ridges of the Beskid Wyspowy and Bieszczadz Mounts. With a variation of relief energy of 400-800 m (Fig. 1A and 1C). Low mountains tend to occur on the margins of middle mountains or represent isolated monadnock ridges of steep slopes and a variation of relief of 200-400 m, rising above depressions cut into weakly resistant flysch strata (e.g. the Beskid Niski Mounts.) (Starkel, 1972). The slopes and valley sides are mantled by slope cover, the thickness of which in the middle mountains is relatively small (70-80 cm) and increases only slightly on flat piedmont slopes (Kacprzak, 2002-03).

Mass movements (chiefly landslides), triggered by heavy rainfall, play a principal part in slope transformation in the middle and low mountains (Zietara, 1968; Kotarba, 1986; Gorczyca, 2004). Another important morphogenetic process is linear erosion which leads to deepening of river valleys, cart roads and wood cutting trails, resulting sometimes in abundant delivery of weathered material into river beds (Fig. 3). Leaching, suffusion and wind-induced toppling of trees are less important. In addition, slope wash on forested and meadow-covered slopes of the Beskid Mts. is negligible.

Under present-day climatic conditions and following deforestation, the slopes of the Polish Flysch Carpathians are dominated by shallow landslides formed in slope cover. However, in the course of extreme rainfall numerous shallow rocky-weathering landslides are formed on forested slopes of the middle and low mountains. These partly reach bedrock strata. Erosional deepening and widening of valley bottoms during floods as well as saturation of bedrock and weathering cover by precipitation waters initiate numerous mass movements which lead usually to minor changes in the relief of slopes of the middle and low mountains (Fig. 6.1, Zietara, 1968; Gorczyca, 2004).

The increasing extent of built-up areas and the related development of transport and construction infrastructure on slopes in the past several decades have led to slope overloading, undermining and changing hydrological conditions. As such, the destructive impact of mass movements on the human economy is gradually increasing. Most catastrophic is reactivation of pre-existing landslides by new periods of mass movements. Such repeated transformations of individual landforms by mass movements were observed in years including 1958-60, 1997-2002 and 2010 (Zietara, 1968; Bajgier-Kowalska and Zietara, 2002; Poprawa and Raczkowski, 2003; Bajgier-Kowalska, 2004). A poorly planned increase in built-up areas upon landslide-prone slopes, sometimes previously affected by mass movements (vide Bajgier-Kowalska, 2004), leads during extreme rainfall to initiation of landslides resulting in extensive destruction to both housing and related communications infrastructure. A peculiar feedback is to be observed: initiation and further development of mass movements, destructive to the human economy, are most frequently triggered anthropogenically (Zietara, 1968; Bajgier-Kowalska, 2004). Recent studies indicate that, in the Carpathians, the majority of the most destructive landslides originated as a result of direct or indirect human activity (Nemcoc, 1982; Kotarba, 1989; Poprawa and Raczkowski, 2003; Bajgier-Kowalska, 2004).

A good example of extremely unsuitable construction planning in mountain areas is provided by Lasnica near Lanckorona (Wieliczka Foothills) where, following intensive rainfall in May 2010, 34 houses were seriously damaged. These houses were located in an area in which in July 1960 a landslide destroyed 15 houses and damaged a further nine (largely wooden at that time) (Zietara, 1969). Similarly, a landslide at Lachowice (Beskid Makowski Mounts.), originating in July 2001, destroyed 15 houses located on a pre-existing landslide (Fig. 6.3) (Bajgier-Kowalska, 2004; Osyczyno et al., 2002). The most extensive recent landslide at Kłodne near Limanowa (Beskid Wyspowy Mounts.), reactivated at the beginning of June 2010, also destroyed 17 houses built upon its surface (Fig. 6.2 A–C). Beyond catastrophic rainfall, reactivation was determined by slope overloading related to newly-constructed buildings situated in the uppermost part.
Figure 6. Examples of recent landslides transforming slope relief of catastrophic impact on economy: 1 – small weathering landslide in Młynne (Beskid Wyspowy Mts.), transformed over-road area (July 1997), 2 – catastrophic landslide at Klodne (Beskid Wyspowy Mts., June 2010): A – vast colluvial swell and destroyed buildings; B – slip surface exposed on ground surface; C – pushed colluvial swell with destroyed buildings in lower parts of the landslide; 3 – catastrophic landslide in Lachowice (Beskid Makowski Mts), in July 2001; 4 – small landslide at Kamionka on the Lososina River valley side, in July 1997, which destroyed a house (photo W. Margielewski)
of the landslide zone. Gravitational sliding was also fostered by a dip in bedrock strata parallel to slope inclination. In some cases, landslides have tragic consequences: in July 1997 a small landslide at Kamionna near Limanowa (Beskid Wyspowy Mts.) resulted in the destruction of a part of a house in which one resident died (Margielewski et al., 2008) (Fig. 6.4). Many landslides develop also in marginal zones of water reservoirs, both due to changes in hydrogeological conditions and through abrasion at the reservoir shore.

Beyond the clearly serious economic losses, contemporary mass movements (frequently anthropogenic) may also lead to minor relief transformation by steepening or smoothing of geomorphic escarpments, broadening and minor changes in the shape of river valleys, slight retreat of valley head niches and the formation of an undulating slope profile (Zietara, 1968; Kotarba, 1986; Gorczyca, 2004; Margielewski et al., 2008). These processes are, however, restricted to very small areas (Fig. 6). The Klodne and Lachowice landslides mentioned above produced, beyond large-scale destruction, significant relief transformation of isolated slopes (Fig. 6.2 and 6.3). Nevertheless, overall transformation of slopes in the Beskidy Mts. occurs only within a longer cycle (of thousands of years) leading, together with other denudation processes (e.g. erosion), to retreat of valley heads, elongation of river valleys, shaping of incipient tributary valleys and, finally, the formation of concave-upwards landslide slope profiles (Starkel, 1960; Zietara, 1968; Kotarba, 1986). In general, contemporary landslides induce other denudation processes, such as creeping, flows, slopewash, suffusion, erosion and weathering (Zietara, 1968). The dominant role of mass movements in shaping the Carpathian landscape is confirmed by a detailed landslide inventory, including recent landforms, which takes into account the number, area and activity classes of landslides. This inventory is currently being conducted on 1:10,000 topographic maps, as part of the SOPO (Anti-landslide Screen System) project (Grabowski, 2008).

Terracing of cultivated slopes reduces slope-wash processes considerably (Gerlach, 1976). Weathering material is delivered directly to river beds only during strong downpours and long-term rainfall via natural erosional cuts and cart roads (Slupik, 1981; Froehlich, 1982; Froehlich and Slupik, 1986). Intensification of linear erosion occurs along wood-cutting trails during intensive rainfall. Road cuts then deepen rapidly. In the Beskid Makowski Mts., following rainfall in June and September 2010, axial parts of cart roads became dissected by 30–40 cm.

**Foothills**

The foothills occupy 47% of the Polish Carpathians. They are a belt of hills and intra-mountain depressions ranging from a dozen or so kilometres in width in the western part to several tens of kilometres in the east (Fig. 1A and 1C). The Carpathian Foothills rise to 300-500 m a.s.l. and slope via a distinct step to the north, towards the Sandomierz Basin. The region is composed of folded flysch strata. The eroded bedrock is covered by thick weathering mantles, and low foothills on the Carpathian margin are capped by loess. The middle Foothills are identified by narrow intervals (50.5%) and low (31.8%) foothills which, together occupying ca. 82% of the Carpathian Foothills in Poland (Margielewski et al., 2008). In this region, arable land comprises 45.5%, meadows and pastures 12.7% and forests 25.4% of the area (Soja, 2002). This distribution results from settlement in the Middle Ages (13-15th centuries) and deforestation, which was most intensive in the 18th and 19th centuries (Margielewski et al., 2008). The structure of cropland is dominated by cereals and such crops as potatoes, beetroots and corn. Farms of an average area of ca. 3 ha are usually composed of several separate fields ranging in area from 0.5 to 0.7 ha (Guzik, 1995). The division of farmland into plots requires a high density of roads (7 kmkm-2), which in the foothills greatly exceeds drainage density (2 kmkm-2) (Soja, 2002; Kroczak, 2010).

The physico-chemical properties of flysch strata and large thicknesses of weathering mantles are conducive to the development of landslides, the principal type of mass movement in the Carpathian Foothills (Fig. 3). Numerous small, mostly shallow, weathering and rocky-weathering landslides tend to form quite frequently. These landslides usually occur within denudation escarpments, on valley sides and in valley heads, leading to local transformation of these landforms (Kotarba, 1986; Michno, 1998; Poprawa and Raczkowski, 2003; Margielewski et al., 2008). Mass movements also induce changes in slope profiles. Initial slopes of straight convex-upwards or convex-concave-upwards profiles undergo change into slopes showing concave-upwards undulating or irregular profiles. Strong transformation of foothill ridges by mass movements results in local narrowing of interfluves and even their fragmentation into a number of separate segments (Kotarba, 1986; Michno, 1998). The succession of mass movements leads to gradual slope fragmentation and formation of small tributary valleys (Kotarba, 1986). Moreover, valley-side landslides provide source areas for delivery of weathering material for fluvial transport. Blocking of river beds by colluvium intensifies lateral erosion, leading thereby to the widening of stream beds, the steepening of their banks and the sinuous trace of the beds themselves (Kotarba, 1986; Michno, 1998; Swiechowicz, 2002; Margielewski et al., 2008).

Intensive deforestation and replacement of forested areas with crops results in a periodic absence of tight vegetation cover, which would protect the ground surface from local downpours, long-term rainfall and rapid thaws. In the Carpathian Foothills, soil susceptibility to erosion is greater, particularly in those areas where soils develop on loess. Slopewash and linear erosion on cultivated slopes result in partial or, in extreme cases, total removal of the arable layer (Fig. 3). Most of the material washed from the upper and middle parts of slopes is deposited as thick deluvial cover on flat areas or depressions within the slopes and at their feet (Swiechowicz, 2008). The annual amount of slopewash varies and depends on crop type (Table 1, Gil, 2009; Swiechowicz, 2012a, b). Slopewash also varies greatly across different crops during individual falls of rain (Table 2, Swiechowicz 2012a, b). Isolated, extreme episodes of slopewash may account for >90% of the annual value (Gil, 2009). Long-term slopewash leads to a lowering of the slope surface and changes in its inclination, shape and length (Gil, 1999, 2009).

**Table 1. Comparison of slopewash [tha−1] on differently used plots in Szymbark and Lazy near Bochnia in summer half-year**

| Region, author, study period | Crop or land use | Annual values of slopewash [tha−1] |
|-----------------------------|-----------------|-----------------------------------|
|                            |                 | min. | max. | average |
| Szymbark: the boundary between the Beskid Niski Mts. and Ciezkowice Foothills; Gil, 2009; 1969-2000 | potato cereal meadow | 0.003 | 0.346 | 0.048 |
| Lazy near Bochnia; Carpathian Foothills margin; Swiechowicz, 2012a, b; 2007-2009 | potato cereal meadow | 0.000 | 0.418 | 0.259 |

27 Episodes Vol. 37, no. 1
During high-energy falls of rain or rapid thaws, concentration of overland flow leads to linear erosion which shapes a rill network (Fig. 7A, Swiechowicz, 2012a). These rills range from several metres to several hundred metres in length, and their courses are either straight, parallel or irregular, with a tendency to anastomose. Rills may reach several tens of centimetres in depth, locally even 2 m. They usually concentrate along lines of natural water flow and anthropogenic landforms related to land use (e.g. along field boundaries, roads, ruts left by agricultural vehicles) (Fig. 8, Swiechowicz, 2010). Deluvial fans tend to form at the outlets of rills and ephemeral streams, merging sometimes into deluvial plains at the feet of the slopes.

The mosaic of variably cultivated fields, separated by ridges, furrows and cart roads, characteristic of the Carpathian Foothills, means that the mechanism of material delivery from slopes to river beds is complex (Gerlach, 1976; Froehlich, 1982; Swiechowicz, 2002). This material reaches valley bottoms or river beds only during downpours and long-term rains, the main role being played by cart roads close to river beds and by natural erosional cuts, with the role of footslopes being negligible (Froehlich, 1982). Most of the material is deposited upon slopes and deluvial plains situated at the feet of slopes, or is trapped by valley bottoms occupied by permanent green crops, which separate poorly interconnected slopes and river beds (Fig. 7B, Swiechowicz, 2002).

The presence of shallow landslides, intensive slopewash and linear erosion on cultivated slopes makes land management difficult, leads to considerable material losses, and frequently necessitates exclusion of vast areas from cultivation and other economic activity (such as construction).

**Valley and basin bottoms**

Valley bottoms and intramontane depressions, comprising 10% of the Polish Carpathians, reveal the most dynamic relief changes (Fig. 1B). These areas are occupied by Pleistocene and Holocene meadow terraces, frequently preserved as fragments and in floodplains and river beds, as well as old and young, still developing, alluvial fans (Starkel, 1972). The rate of modelling of active fluvial landforms depends on the frequency and size of floods, amounts of material transported and grain size. Locally, valley head bottoms are modelled by landslides approaching river beds and by raised bogs located on high terraces. In recent centuries, the morphogenetic role of man has become increasingly important (Fig. 3). Longitudinal and cross-profiles of river channels are determined by type of relief of host catchment and by bedrock lithology. The parameters of channels become disturbed first due to indirect, and later direct, human impacts on water circulation, transfer of weathering material down the slopes and its further fluvial transport, which developed on a larger scale in the 19th century. Finally, adjustment of channel geometry to changing over-bank discharge has been identified in the study area (Wyzga, 1993). The frequency of large floods has fluctuated over the last 200 years, but considerable economic losses due to such floods have greatly increased since the mid-20th century (Starkel et al., 2007; Lajczak, 2007b). Housing development in valley bottoms leads to further increase in such losses during floods, despite partial river regulation and construction of numerous water dams in the Carpathians (Grela et al., 1999).

The western part of the Polish Carpathians is dominated by gravel-bed rivers typified by a high dynamism in channel landforms. Rivers to the east of the Dunajec River valley (Fig. 1B and 1C), draining lower topographical areas are characterized by fluvial transport restricted almost exclusively to suspended load. For this reason the upper reaches of such rivers frequently have broad channels cut into solid bedrock (Klimek, 1979).

Human-induced changes in the morphology of valley bottoms and depressions in the Polish Carpathians were initiated by deforestation, agricultural settlement and introduction of root plants. The dense network of cart roads built at that time have led, since at

---

**Table 2. Slopewash [t ha⁻¹] on differently used plots in summer half-year during single rainfalls (Lazy near Bochnia, 2007–2009)**

| Year | Crop or land use | Annual values of slopewash [t ha⁻¹] |
|------|-----------------|-----------------------------------|
|      |                 | min. | max. | average |
| 2007 | bare fallow     | 0.025| 19.432| 3.642   |
|      | potato          | 0.031| 16.164| 3.338   |
|      | cereal          | 0.000| 0.024 | 0.002   |
|      | meadow          | 0.000| 0.016 | 0.003   |
| 2008*| bare fallow     | –    | –    | –       |
|      | potato          | –    | –    | –       |
|      | cereal          | –    | –    | –       |
|      | meadow          | –    | –    | –       |
| 2009 | bare fallow     | 0.000| 96.439| 19.056  |
|      | sugar beet      | 0.000| 16.094| 2.496   |
|      | cereal          | 0.016| 0.111 | 0.017   |
|      | meadow          | 0.000| 0.026 | 0.004   |

* there were no slopewash events in 2008
At least the 17th century, to intensification of outflow and increasing delivery of weathering material from slopes to river beds. In the 19th century, mixed forests of the lower forest zone were replaced by monoculture fir forests, contributing to increased flood risk in the Carpathian valleys and higher dynamism in fluvial landforms. The dense network of forest roads built in the 19th and 20th centuries intensified water outflow from slopes and fostered increased delivery of weathering material into river beds. Over the past century, geomorphic changes in valley and basin bottoms have resulted chiefly from purposeful measures aiming at reducing the extent and intensity of floods as well as channel dynamism. Partial channel regulation was conducted in this period to stabilize channel banks and reduce the amount of bed load in deepened channels. Flood embankments were built along some river reaches, resulting in a narrowing of the flooded zone. Artificial water dams on large rivers, exploited since 1932, provide traps for the entire bed load and up to 99% of suspended load (Lajczak, 2006).

Increased delivery of water and weathering material from slopes to valley bottoms via the dense network of cart and forest roads, and in the case of narrow valleys directly into river beds (Froehlich, 1982) contributes to an increasing dynamism in fluvial processes. Grain size studies of bed load material point to increasing waves of floods in the western part of the Polish Beskidy Mts. as early as the 19th century. Carrying capacity of bed load increased and thus coarse-grained material was transported (Niemirowski, 1974; Wyzga, 1993). These tendencies continued in non-regulated streams as late as the mid-20th century (Zietara, 1968). As a result, in the western part of the Polish Carpathians (including the Dunajec River valley), the dominant tendency to aggradation and broadening of river beds prevailed until the end of the 19th century (Fig. 2). These beds were situated even higher than adjacent floodplains and underwent a transformation into broad, gravel braided channels (Klimek, 1979). On the other hand, through the 19th century and at the beginning of the 20th, large-scale water transport of wood and gravel was carried out in headwater segments of numerous streams and rivers of the Beskidy Mts., which resulted in exposure of solid bedrock within such channels. Material removed from these sites built alluvial fans and braided channels within main river valleys. The processes leading to a shallowing and broadening of gravel river channels, lasting until the end of the 19th century, can also be explained by climate changes during the Little Ice Age. Gravel bed shallowing in the Carpathian rivers grew in intensity in the 19th century following the large-scale introduction of potato crops. Further downstream, over-bank sedimentation during individual floods extended beyond the active flood plain.

The channel regulation of the Carpathian rivers initiated at the turn of the 20th century, and still continuing, replaced the previously dominant tendency of channel shallowing with channel deepening. Processes leading to channel shallowing and broadening are observed only upstream of dams. The upper river reaches, together with their tributaries, now have step-like profiles following construction of numerous stone debris-control dams. Boulder-gravel alluvial fans intercalated by silt-sandy material tend to form in shallow water dams. Gabions stabilize the channels and, in the case of broad braided channels, a narrow regulation route leads to channel deepening and narrowing and, consequently, increased river competence with regard to long-distance transport of material (Wyzga, 1993). In the lower, and even middle, reaches of the Carpathian rivers, this process is also induced by channel straightening in the lowland segments of meandering courses (Lach and Wyzga, 2002). As registered by numerous water gauges, these river segments deepened in the 20th century by 2-3 m, with more than 50% of this change in the second half of the 20th century. Local extraction of coarse-grained bed load led to exposure of solid bedrock within the channels (Lach and Wyzga, 2002; Krzemien, 2003; Zawiejska and Krzemien, 2004).

Increased accumulation in valley bottoms upstream of water dams results in the formation of extensive sandy and silty deltas, within which landforms previously unknown in the Carpathians develop, such as sinuous stream beds, islands, levees, interleeve basins, crevasses and crevasse splayls. Deltas formed in water reservoirs tend to possess three zones: topset, foreset and bottomset. Owing to high-amplitude water level changes within the reservoirs (up to 12 m), longitudinal profiles of such deltas differ from those of typical Gilbert-type deltas (Klimek et al., 1990; Lajczak, 2006). The deltas continue towards the dam into the basin bottom which becomes aggraded with the finest-grained material, usually clayey. Immediately below water dams, river channels are deepened by under-loaded waters; moreover, fine-grained material is washed out from coarse-grained alluvium (Malarz, 2002).

River regulation and construction of water dams induced changes in the distribution of erosional, transporting and accumulative river bed segments in the Polish Carpathians. This distribution was previously determined by variable proportions of different kinds of bed load transport, channel gradient and catchment relief type.
Deforestation and land use have over the past 200 years fostered intensive slopewash and linear erosion which played an important role in shaping foothill relief. Extreme processes of slopewash and linear erosion on cultivated slopes usually lead to economic losses in agriculture.

Different dynamic types of river longitudinal profile and floodplain formation coexist in the Carpathians. Following changes in land use and channel regulation initiated at the beginning of the 20th century, a tendency to river bed deepening prevails. Moreover, floods, and not only extreme instances, continue to pose a threat to man, with their effects enhanced by housing in floodplain areas.

A tendency to reduction of arable land and an increase in grassland and forest area, observed over the past two decades, will lead to a gradual limitation of slope-wash and wind erosion as well as a simultaneous increase in linear erosion on slopes and river bed deepening, and activation of shallow landslides. Because, following the Second World War there was no permanent collectivization of land in the Polish Carpathians, in contrast to the other parts of the Carpathian chain, the relationships described between geomorphic processes and human activity cannot be applied directly to Carpathian regions in other countries.

References

Adamczyk, M.J., 1978, Changes in landscape of the Polish Carpathians in years 1650-1870: Wierchy, v, 47, pp. 20-24, (in Polish).
Bajgier-Kowalska, M., 2004, The role of the human activity in the incidence and reactivation of landslides in the flysch Carpathians: Folia Geographica, series Geographica-Physica, v. 36-36, pp. 11-30, (in Polish with English summary).
Bajgier-Kowalska, M. and Zietara, T., 2002, Succession of the mass movements during last 5-years in the Flysch Carpathians: Problemy Zagospodarowania Ziemi Górskiej, v. 48, pp. 31-42, (in Polish with English summary).
Birkennäger, K., 1986, Outline of the geological evolution of the Pieniny Klippen Belt; Przegląd Geologiczny, v. 34, no. 6, pp. 293-304, (in Polish).
Bravard, J.P. and Petts, G.E., 1996, Human impacts on fluvial hydrosystems, in Pets, G.E., Amoros, C., eds, Fluvial Hydrosysytems: Chapman and Hall, London, pp. 242-262.
Brookes, A., 1988, Channelised rivers: Chichester, Wiley, 342 pp.
Bucala, A., 2012, Wspolczesne zmiany srodowiska przyrodniczego dolin potokow Jaszcze i Jamne w Gorcach: Prace Geograficzne Instytutu Geografii i Przestrzennego Zagospodarowania PAN, v. 231, 145 pp., (in Polish with English summary).
Czochanski, J.T., 2000, Influence of tourism on erosional-denudational processes and forms in surrounding of tourist paths in Borowiak, D., Czochanski, J.T., edS, Z badan geograficznych w Tatrach Polskich: Wydawnictwo Uniwersytetu Gdanskiego, Gdansk, pp. 341-348, (in Polish).
Długosz, Z. and Soja, M., 1995, Population in Warszynia, J., ed., Karpaty Polskie: Uniwersytet Jagielloński, Krakow, pp. 209-215, (in Polish with English summary).
Froehlich, W., 1982, The mechanism of fluvial transport and the waste supply into the stream channel in a mountainous flysch catchment: Prace Geograficzne Instytutu Geografii i Przestrzennego Zagospodarowania PAN, v. 143, 144 pp., (in Polish with English summary).
Froehlich, W. and Sulapik, J., 1986, The role of roads in the generation of flow and erosion in the Carpathian flysch drainage basins: Przegląd Geograficzny, v. 58, no. 1-2, pp. 129-160, (in Polish with English summary).
Gadek, B., Raczkowska, Z. and Zogala, B., 2009, Debris slope morphodynamics as a permafrost indicator in zone of sporadic permafrost, High-Tatras, Slovakia: Zeitschrift fur Geomorphologie N.F., v. 53, Suppl. 3, pp. 79-100.
Gerlach, T., 1966, Development actuel des versants dans le Basin du Haut Grajcark, Hautes Beskides, Carpates Occidentales: Prace Geogr.
Instytut Geografii PAN, v. 52, 124 pp., (in Polish with French summary).
Gerlach, T., 1976, Present-day slope development in the Polish flysch Carpathians. Prace Geograficzne Instytutu Geografii i Przestrzennego Zagospodarowania PAN, v. 122, 116 pp., (in Polish with French summary).
Gil, E., 1999, Water circulation and wash down on cultivated slopes in the Polish Flysch Carpathians in Bochenek, W. and Kijowska, M., eds, Funkcjonowanie środowiska przyrodniczego w okresie przemian gospodarczych w Polsce: Biblioteka Monitoringu Środowiska, Szymbark, pp. 191-218, (in Polish with English summary).
Gilewska, S., 1986, The geomorphological subdivision of Poland: Przegląd Geograficzny, v. 58, pp. 15-42, (in Polish with English summary).
Gorczyca, E., 2004, The transformation of flysch slopes by catastrophic rainfall induced mass processes (Lososina River catchment basin): Wydawnictwo Uniwersytetu Jagiellońskiego, Krakow, 101 pp., (in Polish with English summary).
Goudie, A., 2006, The human impact on the natural environment: past, present and future: Blackwell, Oxford, 347 pp.
Grabowski, D., 2008, The SOPO Anti-landslide Screen System: Przeglad Geologiczny, v. 56, pp. 537-538, (in Polish).
Gregory, K.J., 2006, The human role in changing river channels: Geomorphology, v. 79, pp. 172-191.
Grela, J., Slota, H. and Zielinski, T., eds, 1999, The Vistula river catchment, monograph of flood in July 1997: Instytut Meteorologii i Gospodarki Wodnej, Warszawa, (in Polish).
Guzik, C., 1995, Agricultural land use in Warszynska, J., ed., Karpaty Polskie: Uniwersytet Jagielloński, Krakow, pp. 239-252, (in Polish with English summary).
Izmałow, B., 1984, Eolian process in alpine belt of the High Tatra Mts.: Studia Geomorphologica Carpatho-Balcanica, v. 13, pp. 111-129.
Jankowski L., Margielewski W., 2012. Rozwoj rzezby Karpat zewnetrznych: Beskid Niski-Beskid Podkarpacki. Prace Geograficzne Instytutu Geografii i Przestrzennego Zagospodarowania PAN, v. 74A, pp. 123-131.
Kaszowski, L., Krzemien, K., 1987, High-mountain denudational system in the Polish Tatra Mountains: Prace Geograficzne Instytutu Geografii i Przestrzennego Zagospodarowania PAN, spec. Issue, v. 3, 106 pp.
Kozak, J., Estreguil, C. and Troll, M., 2007, Forest cover changes in the northern Carpathians in the 20th century: a slow transition: Journal Land Use Science, v. 2, pp.127-146.
Kroczak, R., 2010, Geomorphological and hydrological effects of unmetalled road network functioning on the example of Cziejkowice Foothills: Prace Geograficzne Instytutu Geografii i Przestrzennego Zagospodarowania PAN, v. 225, 138 pp.
Krzemien, K., 1991, Dynamics of the high-mountain fluvial system with the Western Tatra Mts. as example: Rozprawy habilitacyjne Uniwersytetu Jagiellońskiego, v. 215, 160 pp., (in Polish with English summary).
Kozak, J., Estreguil, C. and Troll, M., 2007, Forest cover changes in the northern Carpathians in the 20th century: a slow transition: Journal Land Use Science, v. 2, pp.127-146.
Lach, J., and Wyzga, B., 2002, Channel incision and flow increase of the upper Wisłoka River, southern Poland, subsequent to the reafforestation of its catchment: Earth Surface Processes and Landforms, v. 27, pp. 445-462.
Lajczak, A., 2002, Slope Remodelling in Areas Exploited by Skiers: Case Study of the Northern Flysch Slope of Polisko Mountain, Polish Carpathian Mountains, in Allison R.J., ed., Applied Geomorphology: John. Wiley & Sons, Ltd., Chichester, pp. 91-100.
Lajczak, A., 2006, Delts in dam retained lakes in the Carpathian part of the Vistula drainage basin: Prace Geograficzne Instytutu Geografii i Gospodarki. Przestrzennjej Uniwersytetu Jagiellońskiego, v. 116, pp. 99-109.
Lajczak, A., 2007a, Natura 2000 in Poland, Area PLH120016 The Orawsko-Podhalanskie Peatlands: Institute Botany, Polish Academy of Sciences, Kraków, 139 pp.
Lajczak A., 2007b, River training vs flood risk in the upper Vistula basin, Poland: Geographia Polonica, v. 80(2), pp. 49-60.
Klimes, K., and Trafas, K., 1972, Young-Holocene changes in the course of the Dunajec river in the Beskid Sadecki Mountains: Studia Geomorphologica Carpatho-Balcanica, v. 6, pp. 85-92.
Kotarba, A., 1970, The morphogenetic role of the foehn wind in the Tatra Mts.: Studia Geomorphologica Carpatho-Balcanica, v. 4, pp. 171-187.
Kotarba, A., 1971, Coarse and intensity of present-day superficial chemical denudation in the Western Tatra Mts.: Studia Geomorphologica Carpatho-Balcanica, v. 5, pp. 111-127.
Kotarba, A., 1986, The role of landslides in modelling of the Beskidian and Carpathian Foothills relief: Przegląd Geograficzny, v. 58, pp. 119-129, (in Polish with English summary).
Kotarba, A., 1989, Landslides: Extent and Economic Significance in Central Europe in Brab, E. and Harrod, B.L., eds., Landslides: extent and economic significance: Proceedings 28th IGU Congress: Symposium on landslides, Washington: Balkema, Rotterdam, pp. 191-202.
Kotarba, A., 1992, High energy geomorphic events in the Polish Tatra Mountains: Geografiska Annaler, v. 74A, pp. 123-131.
Kotarba, A., 1995, Rapid mass wasting over the last 500 years in the High Tatra Mountains: Questiones Geographicae, spec. issue, v. 4, pp.177-183.
Kotarba, A., 1997, Formation of High-Mountain Talus Slopes Related to Debris-Flow Activity in the High Tatra Mountains: Permafrost and Periglacial Processes, v. 8, pp. 191-204.
Kotarba, A., 1999, Geomorphic effect of catastrophic summer flood of 1997 in the Polish Tatra Mountains: Studia Geomorphologica Carpatho-Balcanica, v. 33, pp.101-115.
