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CURRENT STATE OF KNOWLEDGE AND TURNING POINTS IN GEOMORPHOLOGIC STUDIES ON THE PRESENT-DAY EVOLUTION OF THE TATRA MOUNTAINS

Abstract. Studies on the dynamics of geomorphologic processes occurring in the Tatras began in the 1950s and continue to pique the interest of researchers. The history of the study of Tatra relief morphodynamic changes is marked by certain breakthrough stages associated with the emergence of key works yielding multiplier effects. These works identified new directions and sparked new trends in geomorphologic research as well as inspired deeper analysis of the study area. A significant acceleration of geomorphologic research in the Tatras has occurred in the most recent decade. This resulted mostly from the use of complex monitoring of key dynamic geomorphologic processes and the use of lichenometric and dendrogeomorphologic methods, which enable the identification of complete event chronologies. The present study reviews the most important quantitative studies on the evolution and rate of contemporary geomorphologic processes in the Tatras as well as novel research data produced in the last several years. The authors note principal research directions and the discuss relevant works on the identification of contemporary and relict periglacial relief along with papers on the dynamics of slope and fluvial processes and anthropogenic erosion. The paper also describes certain tendencies observed recently in the realm of morphogenetic processes associated with ongoing climate change.

Keywords: morphogenetic processes, relief evolution, research history, Tatra Mountains

INTRODUCTION

The Tatras are the highest high-mountain denudational system found in Central Europe that is not currently glaciated and is characterized by substantial sensitivity to long-term and short-term climate change as well as human impact (Kotarba et al. 1987). This area constitutes a model of Alpine-type relief, and has been examined from the geomorphologic perspective numerous times. The tradition of research on mountain relief and geomorphologic processes in Poland began with S. Staszic (1815) more than two centuries ago. Hence, the state of knowledge on the Tatras is very good in terms of geomorphology when compared with other high mountain areas in Europe (Kotarba, Krzemień 1996). Given the relatively small size of this mountain range and also its easy accessibility, many researchers have pursued work here at the scale of one valley or more comprehensive works on the Tatra massif as a whole. The geomorphologic research process is made easy by the fact that one can trek from the main ridge to the foreland area within just one day. The Tatras are often called “pocket mountains” in comparison with the Alps as well as the Caucasus Mountains (Kotarba et al. 1987). At the same time, methods and perspectives often developed in the Alps were used to study morphogenetic processes occurring in the Tatras and this was done at every stage in the history of Tatra geomorphologic research.

The authors of this paper discuss the major stages of research on geomorphologic activity in the Tatra Mountains. A number of breakthrough stages may be noted in geomorphologic research in this geographic area. Important research papers produced new ideas and new directions in geomorphologic research that would yield multiplier effects in terms of their ability to generate new knowledge (Kotarba 1987). Studies of this type are important, as they stimulate new stages of research. One key outcome of “multiplier” papers on the identification of Tatra relief is a new outlook on various landforms and high mountain relief – which once triggered – yields multiple publications produced by many other authors in this field of study. Breakthrough papers or multiplier papers surface relatively rarely and may be evaluated as such only from a long-term perspective (Kotarba 1987). Multiplier papers are produced in conjunction with ideas circulating in the global research literature and the findings of researchers working in other high mountain areas across the world. The researchers’ experience abroad also made it possible for them to note certain geomorphologic landforms in the Tatras that had not been examined earlier as: debris flows or rock glaciers.

Intensive human impact as well as naturally occurring morphogenetic processes affected by climate variability generated change in the areas now known as Tatra National Park (TPN) and its sister park in Slovakia – TANAP – until the 1950s. The main period of economic activity in the Tatras (15th to 19th centuries) coincided with a major worsening in climate conditions during the Little Ice Age (Kędzia, Kotarba 2018). Hence, it was not possible to separate outcomes of natural and anthropogenic processes for earlier periods of time. The onset of legal protection of selected areas in the Tatra region has led to observable reductions in human impact, leading to reforestation and increased hillslope permanence supported by secondary plant succession (Krzemień 1991; Wasak, Drewnik 2015). This trend is not observed only along tourist trails and logging roads, but elsewhere as well. In light of this fairly recent development, it is possible to focus more on morphogenetic activity in the context of climate warming, which has already been shown to affect European mountain ranges (Beniston 2003), and identify primary natural factors driving geomorphologic change in the Tatra Mountains.

This paper attempts to summarize the present state of knowledge on geomorphologic change in the Tatra Mts. using new field data collected during the last five years as well as data obtained in periods prior. This paper does not cover all possible issues associated with the organization of geomorphologic research in the Tatras. It omits themes in glacial relief, which are covered in a separate paper in the present issue (Kłapyta, Zasadni 2018) as well as geomorphologic issues associated with karst – both surface karst and underground karst. A good summary of current knowledge on Tatra karst is available in a paper by M. Gradziński et al. (2009).

STUDIES ON PERIGLACIAL RELIEF IN THE TATRA MOUNTAINS

The Tatras are an example of a non-glaciated mountain range with a well-developed periglacial zone (Rączkowska 2007). As much as 64% of the surface area of the Tatras was affected by a periglacial morphogenesis during the last glaciation (Klimaszewski 1988; Zasadni, Kłapyta 2014). Research on periglacial relief in the Tatras began in the 1950s, although initial studies were only qualitative in nature. These focused on the identification of the distribution of periglacial landforms and the characterization of their origin and relief. The first studies on the Polish side of the Tatras were carried out by A. Jahn (1950, 1958, 1970), while on the Slovak side it was J. Sekyra (1950, 1954, 1960). Additional studies were actively pursued in the years that followed (Ksandr 1953, 1954; Pelišek 1953; Andrusov 1954; Lukniš 1973; Rączkowska 2004, 2007; Gądek et al. 2009). Significant progress was made in the study of periglacial relief in the 1960s thanks to the utilization of quantitative methods (Gerlach 1959; Kłapa 1963, 1966; Kotarba 1976). These made it possible to determine the rate of each given periglacial process and the mechanism of action in each case. Quantitative research on periglacial processes is being continued at a number of sites shown in Figure 1. The current state of knowledge along with a characterization and distribution of Tatra periglacial landforms are available in Z. Rączkowska (2007, 2015).

Both large and well-developed relict periglacial landforms (relict rock glaciers, blocky covers, sorter circles and polygons) as well as a small number of small and currently active landforms such as very small sorter polygons (Rączkowska 2007) are present in the Tatra Mountains. The present-day activity of periglacial processes is connected with diurnal and seasonal ground freezing. A lower elevational limit for frost-conditioned landforms was set at 1,900–2,000 m a.s.l. (Rączkowska 2007), which roughly corresponds to the lower limit of the potential presence of present-day permafrost (Dobiński 1997, 2004).

One important research direction in this area consisted of the determination of elevation-based differences in selected processes and periglacial relief in the Tatras. A. Jahn (1975) employed criteria used in the Alps (Furrer 1965) to divide the periglacial zone in the Tatras for the first time – the entire area above the upper timberline. He noted certain landmark relief features in the

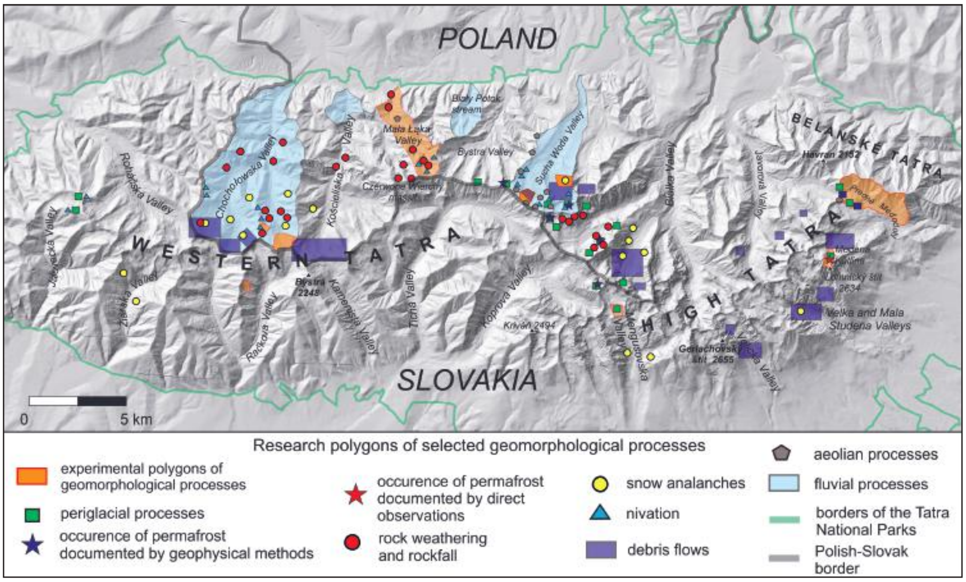

Fig. 1. Research polygons of selected geomorphological processes in the Tatra Mountains.

periglacial zone to identify a tuffur zone (1,500 to 1,800 m a.s.l.), solifluction zone (1,800 to 2,000 m a.s.l.), and active structural grounds (above 2,000 m a.s.l.). This research was continued later by A. Kotarba (1976), A. Kotarba et al. (1987) as well as Z. Rączkowska (2004).

PERMAFROST RESEARCH

A separate place in Tatra periglacial studies is occupied by works on contemporary and relict permafrost occurrence. A comprehensive history of ground freezing and permafrost research in the Polish Tatra Mountains was recently published by S. Kędzia (2015). As permafrost material is not visible from the surface, its very existence in the Tatra Mountains has been documented primarily by geophysical surveys. At the same time, certain reliability-related problems were reported in relation to permafrost detection in the Tatra Mountains by W.J. Mościcki (2010b) as well as B. Gądek and S. Kędzia (2009). These studies highlighted internal limitations and the ambiguity of popular and commonly used geoelectric and BTS methods, and indicated that the potential permafrost occurrence documented by these surveys may become called into question (Gądek 2014).

Multiproxy investigations on permafrost occurrence in the Tatra Mountains began in 1993 and are facilitated by Poland’s membership in the International Permafrost Association (IPA). W. Dobiński was the first to note the presence of permafrost both in the Polish and Slovak parts of the High Tatras using geophysical surveys and climatologic methods (Dobiński et al. 1996; Dobiński 1997). Via the thawing and freezing index, he determined potential climate conditions for the occurrence of permafrost above 1,930 m a.s.l., while continuous permafrost was noted above 2,500 meters of elevation in the High Tatras (Dobiński 1997). Additionally, using the BTS method, he identified the lowest places of potential permafrost occurrence at an elevation of 1,650 m a.s.l. (Dobiński et al. 1996). These were interpreted as relict patches of Pleistocene permafrost that had formed during the last stages of the last glaciation (Dobiński 1997, 2004). The potential extent of permafrost in the Tatra Mountains was estimated at nearly 100 km^2, which comprises about 3.2% of the entire area of the Tatra Mountains (Dobiński 1997). The works of W. Dobiński led to a major increase in the number of Tatra permafrost studies, thus generating a multiplier effect.

Advanced monitoring of Tatra permafrost sites was initiated by S. Kędzia and J. Mościcki in the Kozia Dolinka Valley in 1995, and B. Gądek in the Medená Kotlina Valley in 2003 (Gądek et al. 2009; Kędzia 2015). Currently, these sites represent the most comprehensively studied permafrost polygons in the Tatra Mountains. The presence of permafrost in the Kozia Dolinka Valley was confirmed by multiproxy geophysical and ground temperature survey studies (Mościcki, Kędzia 2001; Lamparski, Kędzia 2007; Gądek, Kędzia 2008, 2009), which pointed to a permafrost occurrence in the form of isolated patches of frozen debris and soil on the northern-exposed debris slopes of Mount Kozi Wierch at elevations of 1,955 to 1,965 m a.s.l.

The Medená Kotlina Valley (Fig. 1) remains the only place in the High Tatras and the entire Carpathian mountain chain, where permafrost existence has been directly documented (Gądek, Kotyrba 2003; Gądek et al. 2009). A 4-meter layer of buried massive ground ice was found under 2.0–2.5 m of thick rubble material covering the right half of a glacierette at elevations of 2,025 to 2,350 m.

According to the current state of knowledge, contemporary active permafrost is present in the form of sporadic and discontinued patches above 1,950 m of elevation in the lower sections of selected northern-exposed debris slopes in the High Tatra Mountains. Both its preservation and development are controlled by local micro-topography, and are more related to exposure and local circulation of cold air over the given surface and low solar radiation than elevation and development of snow cover (Gądek, Kędzia 2008, 2009). The high porosity of blocky slope cover at such sites facilitates the deep penetration of cold air leading to a progressive ground cooling effect (Mościcki 2008, 2010a; Gądek 2012). The thickness of the permanently frozen layer is estimated to range from 0.5 to 25 m (Dobiński 1998; Mościcki, Kędzia 2001; Gądek, Grabiec 2008), while its active layer ranges from 0.5 to 6 m in thickness (Dobiński et al. 1996; Lamparski, Kędzia 2007). However reflection of permafrost in talus structure and landforms morphodynamic was proved (Gądek et al. 2009). The absence of permafrost indicative landforms in the Tatra periglacial zone was linked with the high activity of avalanches and gravitational processes as well as the significant thickness of the active permafrost layer (Rączkowska 2007, 2008b).

Recently acquired quantitative data based on the presence of coarse crystalline cryogenic cave carbonates (CCC) in Tatra caves (Žák et al. 2004; Orvošová et al. 2013), have enabled a reconstruction of the Pleistocene permafrost extent for the Tatra Mountains. These studies revealed widespread alpine permafrost extent during the Last Permafrost Maximum (20–18 ka BP) in the Western Carpathians – with the lower limit of discontinuous/sporadic permafrost at an elevation of 800 m (Orvošová et al. 2013). The thickness of permafrost in the High Tatra Mountains at elevations close to 1,800 m was at least 285 m. The earliest published suggestion of the possibility of the survival of Pleistocene permafrost in the contemporary periglacial zone of the Tatra Mountains was made by T. Czudek (1986), and further developed by W. Dobiński et al. (1996, 2008). However, the problem of the possible occurrence of relict (Pleistocene) permafrost in the Tatras remains an open issue, and additional research is needed in order to ascertain the veracity of this theoretical finding.

ROCK GLACIER STUDIES

Rock glaciers are a common features of periglacial relief in the Tatra Mountains, and are also considered valuable diagnostic landforms, useful in the detection of past permafrost conditions. Rock glaciers represented the subject of greatest interest among all the different landforms in the Tatras. Initial studies focused on the identification of rock glacier landforms in the relief of the Tatras. While the characteristic porridge-like topography of rock glaciers (Fig. 2) was identified in the early stages of research in the Slovak part of the High Tatras (Partsch 1923; Lukniš 1973), the lack of appropriate research methods prevented the proper study of these landforms, and in many cases these landforms were not even identified as a separate category of periglacial relief based on origin (eg. Klimaszewski 1948, 1988).

A breakthrough paper in the study of rock glaciers in the Tatras was that of A. Nemčok and T. Mahr (1974) who were inspired to pursue this avenue of research by a landmark research study by C. Wahrhaftig and A. Cox (1959) on rock glaciers in mountain areas in Alaska. This was the first examination of Tatra rock glaciers based on the interpretation of aerial photographs; a total of 31 locations with rock glacier occurrence were reported in the glacial cirques of the Slovak Tatra Mountains. The relief of rock glaciers on the Polish side of the Tatras was studied much later. Research experience gained in the course of fieldwork in Spitsbergen and the Hindukush (Kaszowski 1985) made it possible to identify and also classify rock glaciers in the crystalline relief of the Polish Western Tatras (Kaszowski et al. 1988) and the Polish High Tatras (Dzierżek, Nitychoruk 1986). Significant progress in the study of Tatra rock glaciers was

Fig. 2. Relict rock glacier body at the Malé Hincovo pleso (Mengusovska Valley, High Tatra Mountains, Slovakia). A-massive, convex frontal slope, B-collapsed blocky surface of relict rock glacier located above the presumed lower limit of contemporary permafrost (1930 m a.s.l.).

also made by A. Kotarba (1986, 1991–1992, 2007) who examined problems associated with the proper identification and classification of relict debris landforms in the Tatras. He defined a pure rock glaciers as only those associated with the flexible creeping of debris together held by interstitial ice, which form under permafrost conditions and without any contribution from glacier ice. A cartographic analysis of the occurrence of rock glaciers was produced using field data and LiDAR laser scanning data collected in selected valleys in the Polish and Slovak parts of the Tatras by P. Kłapyta (2015) and J. Zasadni (2015). A recent paper also covers results of identification efforts focused on rock glaciers located throughout the Tatras based primarily on the analysis of digital satellite data (Mareková 2013; Uxa, Mida 2017b).

A total of 122 rock glaciers were identified in the Tatra Mountains by T. Mareková (2013). These landforms occur approximately between 1,400 and 2,200 m a.s.l., with the majority found between 1,600 m a.s.l. and 1,900 m a.s.l. Rock glaciers occur more frequently in the Western (75 landforms) than in the High Tatras (47 landforms). On the other hand, T. Uxa and P. Mida (2017b) identified 379 rock glaciers, which were almost evenly distributed between the Western Tatras (48%) and the High Tatras (52%). These differences in the distribution of rock glaciers reflect the view of A. Kotarba (1991–1992) that in many cases it is almost impossible to unequivocally identify the origin of relict landforms, and arbitrary classifications are the ultimate result. One additional difficulty in interpretation consists of the fact that many different geomorphologic processes produce landforms similar in shape and local microrelief; also known as the principle of equifinality (Slaymaker, Owens 2004). For this very reason, relative morphologic criteria based on an analysis of aerial photographs and satellite images become subjective as means of the classification of these types of landforms.

The discovery of permafrost occurrence in the Tatra Mountains (Dobiński 1997) marked the beginning of research on the activity of rock glaciers in this geographic area. In earlier works, all Tatra rock glaciers were classified as relict landforms of the Latest Pleistocene age (Kaszowski et al. 1988; Kotarba 1991–1992). Measurements of bottom snow cover temperature (BTS) and electro-resistivity soundings carried out by W. Dobiński (1997) pointed to the possible occurrence of relict Pleistocene permafrost within selected rock glaciers found in the High Tatra Mountains and also their classification as inactive rock glaciers. In contrast, the monitoring of ground surface temperature at rock glacier sites with supposed permafrost carried out by B. Gądek and S. Kędzia (2008, 2009) did not confirm such an interpretation. Similarly, BTS measurements made at a rock glacier site near Hincovo Pleso in the Mengusovská Valley suggested anomalous ground temperatures (Kędzia et al. 2004), although these were not low enough to consider this rock glacier as “inactive” (Kotarba 2007). Although the results of geophysical investigations are ambigious, it cannot be excluded that permaforst patches are present in at least some Tatra rock glaciers, as this is supported by the negative mean annual ground surface temperature (MAGST) measured at rock glaciers in the Slavkovská and Vel’ká Studená valleys in the Slovak High Tatras (Uxa, Mida 2017a). However, the possible presence of permafrost in some rock glaciers precludes the use the of term “intact rock glaciers” with respect to such landforms, what falsely suggest its fresh microrelief convex profile with high amount of massive permafrost body and relatively recently completed activity. In fact, all Tatra rock glaciers exhibit a collapsed surface (Fig. 2b), and do not show any evidence of movement in the last few thousand years, as shown by lichenometric studies by S. Kędzia (2014), and more recently, preliminary results of cosmogenic nuclide dating (Zasadni et al. 2018).

Studies on the activity of rock glaciers were also concerned with the age of the rock glaciers. However, contradictory opinions have been expressed regarding their age and the final timing of their activity. Their age was initially determined based on morphostratigraphic relationships and their most recent activity was linked with the Younger Dryas cold period (12,9–11,5 ka BP) (Kaszowski et al. 1988; Kotarba 1991–1992). A different interpretation was noted by J. Dzierżek and J. Nitychoruk (1986) who linked the youngest rock glaciers with climate cooling during the Little Ice Age. The first relative age chronology of Western Tatra mountain rock glaciers was formulated by P. Kłapyta (2011, 2012, 2013) based on a weathering index determined by the Schmidt hammer test. Three different rock glacier morphosystems were identified, which fall into two relative Late Glacial age categories: LG-2 and LG-3. Similarly, relative age relationships were established for the rock glacier assemblage of the Five Polish Lakes (Zasadni, Kłapyta 2016). Recently, ^{10}Be exposure dating shed new light on the chronology of Tatra rock glaciers. Z. Engel et al. (2017) provide the first chronological evidence for the Late Glacial activity of moraine rock glaciers in the Salatínska Valley (Western Tatra Mountains), which surface was stabilised around 13 ka BP, at an elevation of 1,650 meters. Additionally, the most recent preliminary results of ^{10}Be dating of rock glaciers found at the highest elevations in the Tatra Mountains (1,980 to 2,150 m a.s.l.) (Zasadni et al. 2018) indicate that the youngest rock glaciers in the Tatra Mountains were formed during the Younger Dryas. Instead, dated rock glaciers occur above the presumed lower limit of contemporary permafrost (1,930 m a.s.l.) the Younger Dryas served as the last cold episode of its activity. This finding strongly supports the earliest views of L. Kaszowski et al. (1988) as well as A. Kotarba (1991–1992).

STUDIES ON PRESENT-DAY GEOMORPHOLOGIC PROCESSES

Studies on the dynamics of present-day geomorphologic processes in the Tatras are not easy to carry out due to difficult field conditions and the need to utilize long-term monitoring as well as specialized research methods. For this very reason, the number of publications on this issue is smaller and has always been smaller than the number of publications on other themes in the area of geomorphology (Kotarba, Krzemień 1996). Studies in this specialized area began quite late – in the mid-1950s – in the Hala Gąsienicowa Valley, which happens to be in the general area of the research station operated by the PAN Institute of Geography (Gerlach 1959; Kłapa 1963). This research was made possible by the fact that meteorologic parameters were already being collected in this site. Subsequent studies on geomorphologic processes were performed in many other study areas whose distribution is shown in Figure 1.

Most of these studies focused on individual morphodynamic processes. However, several study areas were also used to conduct comprehensive studies and measure rates of change in several different geomorphologic processes. In the Polish part of the Tatras, this included experimental slopes on Skrajna

Turnia and Żólta Turnia in the Sucha Woda Valley (Kotarba et al. 1979, 1983), Mała Łąka Valley (Kotarba 1976), and the Starobociański and Dudowy glacial cirques in the Chochołowska Valley (Krzemień 1985, 1991; Kaszowski et al. 1988) (Fig. 1). Comprehensive research was conducted also in Slovak part of the Tatra Mountains in the Vyšna Magura study area (2,093 m) in Račkova Valley (Midriak 1983) and the Predné Meďodoly valley catchment (Hreško, Boltižiar, 2001; Hreško et al. 2003, 2008; Boltižiar 2007, 2009, 2010) (Fig. 1).

SLOPE PROCESSES

The first publication on frost heaving and movement of weathering material by needle ice as well as creeping was that of T. Gerlach (1959). This work initiated a series of papers on selected morphogenetic processes occurring at the present time in the Tatra Mountains and also provided the first quantitative data. Subsequent papers by A. Kotarba (1972, 1976) examined the activity of geomorphologic processes such as physical weathering, rockfall, chemical denudation, creeping, debris flows, and morphogenetic action of the wind and snow in the Czerwone Wierchy Massif (Fig. 1). Rates of change were measured at multiple sites on different types of parent material and in different geoecological zones. The study also underscored that Tatra slopes are shaped by a set of processes whose intensity depends on geo-ecological zones and seasons of the year.

The latter concept was further developed by M. Kłapa (1980) who identified four unique morphogenetic seasons: nival, nival-pluvial, pluvial, pluvial-nival. Each season is characterized by a distinct set of processes and different duration. Subsequent studies on relief change due to morphogenetic processes focused on the role of time and extreme weather phenomena in the shaping of high mountain denudational systems (Kotarba et al. 1987; Kotarba 1997, 2002). The focus on morphogenetic research helped identify changes in the frequency of the occurrence of extreme processes in the last few decades (Kotarba 1997, 2002) as well as over longer periods of time (Kaszowski et al. 1988; Kotarba 2004). The spatial differentiation of selected processes is shown on maps that also illustrate the progress made in geomorphology research (Kaszowski, Kotarba 1985; Kotarba 2002).

Physical weathering, rockfall, and debris accumulation are associated with rocky slopes and rock walls. The best conditions for these processes to occur are found in the cold zone on slopes with western exposure (Kotarba 1976, 1984). The current method of quantitatively determining the effectiveness of weathering processes in the Tatras is based on the average rate of rock wall recession, which depends on lithology and elevation. The highest rock wall recession rate was determined to be 3.0 mm per year in the case of limestone and dolomite in the Western Tatras (Kotarba 1972; Koszyk 1977). This is a much higher value than that for the Belanské Tatras and the carbonate part of the Western Tatras in Slovakia (0.43 to 0.95 mm/yr) (Midriak 1983). The highest rate of rock wall recession is substantially lower (0.26 to 0.7 mm/yr) for granite as well as metamorphic rocks (Rączkowski 1981; Kotarba et al. 1987). The rate of material weathering and rockfall decreases below the upper timberline.

The study on frost-related weathering and associated rockfall processes taken by E. Lubera (2014) in the Western Tatras has shown that the mean rockfall rate was greater for north-facing rock walls at 0.0117 mm/yr. This is a lower value in comparison with that provided by A. Kotarba (1972), and the reason for this may be that the more recent study was carried out at lower elevations reaching only 1,645 meters. Calculations for gelation cycles performed for each test site show that the highest rockfall rate does not correspond to the largest number of gelation cycles found on the southern-facing slopes (91.8/year). The rockfall process occurs following a delay and its activation is dependent on heavy rainfall and snowmelt events that trigger the breaking away of fragments of previously loosened rocks (Lubera 2014). In general, the rate of breaking away of material from rock walls is low, and the resulting rock pile below may be described as the outcome of a low intensity process. The rate of deposition of debris on talus slopes ranges from 0.1 to 10 cm per year (Rączkowska 2008a). The main area of deposition is the apex part of the talus slope as well as the middle, part of talus cone. The values associated with this process for granite areas are several times lower than values for carbonate areas – assuming the same elevation (Kotarba et al. 1983).

Chemical denudation is a commonly occurring process associated with the dissolution of rocks by precipitation water and snowmelt water. The intensity of this process varies with elevation. Studies by A. Kotarba (1971, 1972) performed on the carbonate Czerwone Wierchy Massif shows that the lowest values of chemical denudation occur at moderately cold elevations and very cool elevations above the upper timberline. The highest values occur in the woodland zone or the cool zone and moderately cool zone. Values noted for the crystalline relief of Tatra are several times lower (Krzemień 1984, 1985; Kot 1996). Chemical denudation does not play a significant morphogenetic role in the study area at the present time. However, it may be described as a process linking hill slope systems and river channel systems (Rączkowska 2008a). It produces karst landforms such as karst niches, karst funnels, and underground landforms of the karst type (Kotarba 1972; Głazek, Grodzicki 1996).

If we consider the morphometry of the talus slope above rock walls and rock slopes and the type of process responsible for debris movement, then we may generate at least a dozen unique models of slope formation (Kotarba 1984; Kotarba et al. 1987). Debris-mantled slopes are affected by slow mass movements such as creeping or solifluction. The highest rates for these processes were calculated for the alpine zone and range from 1.7 to 2.0 cm per year (Kotarba et al. 1987; Rączkowska 2008a). Rates of change are much lower in the woodland zone reaching 0.5 mm per year (Kotarba 1976).

Among the slope processes debris flows play a major role in the present-day and past evolution of Tatra slopes and glacial cirque floors (Kotarba 1992a,b, 1997; Rączkowska 2006). Weathering material is carried by debris flows from ridges to cirque floors, where it overbuild and fossilize glacial relief and is deposited in form of several meters thick sediments (Libelt 1988; Kłapyta 2012; Kotarba et al. 2013). Material triggered by debris flows fills in depressions in cirques and across valley floors. This explains how alluvial talus slopes become extended thanks to the "sinking" of moraines and relict rock glaciers by debris flow sediments. The average sinking rate increased between 7 and 10 times over the last 200 to 300 years – a period of human impact and climate change – in comparison with the previous period of about 8,000 years (Kaszowski et al. 1988). A morphology of slopes shaped by debris flows are referred as distinct type of "alluvial talus slopes", which are thought to be a principal slope forms across the whole Tatra (Kotarba et al. 1987). In the earliest geomorphological studies the authors did not note and appreciate the relevance of these rapid high-energy gravitational processes. On a geomorphologic map of the Tatra Mountains (Klimaszewski 1988), only single distinct debris flows in the area of Morskie Oko Lake were depicted. However, debris flows occur in almost every glacial cirque and may number into the dozens (Kotarba et al. 1987; Krzemień 1988, 1989; Kotarba 1992b; Długosz 2015). According to A. Kotarba et al (2013) 3,580 debris flows track are present in the entire Tara Mountains, most of them were registered in the High Tatra (2,300) and only have of that number (1,127) in the Western Tatras. Debris flow activity has been studied in the High Tatra Mountains since 1975, when field experiments on talus slopes of Skrajna and Żółta Turnia in the Sucha Woda valley were started (Kotarba et al. 1979, 1987; Kotarba, 1988b) (Fig. 1). The multiplier works of M. Lukniš (1973) on the Slovak side and those of A. Kotarba (1976) on the Polish side helped spark strong interest in these processes and their resulting landforms (Midriak 1983; Kotarba et al. 1987; Krzemień 1988; Kaszowski et al. 1988; Kotarba 1992a, b, 1997; Krzemień et al. 1995; Rączkowska 1999, 2006).

Our understanding of the history of debr is flow activity in the Tatra Mountains is based on periodical photogrammetry of selected slopes (Kotarba et al. 1979, 1983), sedimentological studies of lacustrine deposits, dated by ^{14}C and ^{210}Pb (Kotarba 1992a, 2004; Baumgart-Kotarba, Kotarba 1990), lichenometric dating (Kotarba 1989, 1991, 1992b; Gądek et al. 2016), historical orthophotomaps (Kapusta et al. 2010), incomplete archival records (Kapusta et al. 2010), and recently also a first continuous dendrogeomorphic reconstruction with annual resolution (Šilhán, Tichavský 2016, 2017). Given a daily precipitation total of 80 to 100 mm, debris found on slopes may migrate as much as 500 meters, and the volume of the migrating material may range from 100 to 25,000 m^3 (Kotarba et al. 1987; Krzemień 1988, 1989). In most cases, debris flows are triggered by a short, high-magnitude precipitation events. Debris movement affecting entire hill slopes require precipitation magnitudes of 35 to

40 mm per hour or at least 80–100 mm/day (Kotarba 1992a, 1994), however such thresholds vary with lithology and relief (Kotarba et al. 2013). One of the longest debris flows in Polish Tatra Mountains reaching 1,700 meters was observed in the course of a 5-hour rainstorm event in the Kościeliska Valley yielding 73.8 mm of rainfall (Krzemień et al. 1995).

According to A. Kotarba (1992b), the rate of sedimentation in High Tatra lakes during the LIA (ca. 0.37 mm/yr) was significantly higher than that calculated for other phases of the Holocene (0.2 mm/yr). The debris flow sediment preserved in the High Tatra indicates that the last Holocene phase of intense slope processes started in ca. 1400 AD (Kotarba 2004), while in the Western Tatras, beginning of intense mass movement on mountain slopes started in the second half of the 15th century (Kłapyta 2012).

Research on the morphogenetic effect of snow aims to discover more about the morphogenetic effects of snow avalanches and nivation defined as a set of processes associated with an extended duration of snow patches (Kotarba 1976; Embleton, Thornes 1979). Snow avalanches are a less often studied extreme, high-energy, geomorphologic process in the Tatra Mountains (Fig. 3). The first scientific reports on snow avalanche activity date back to the early

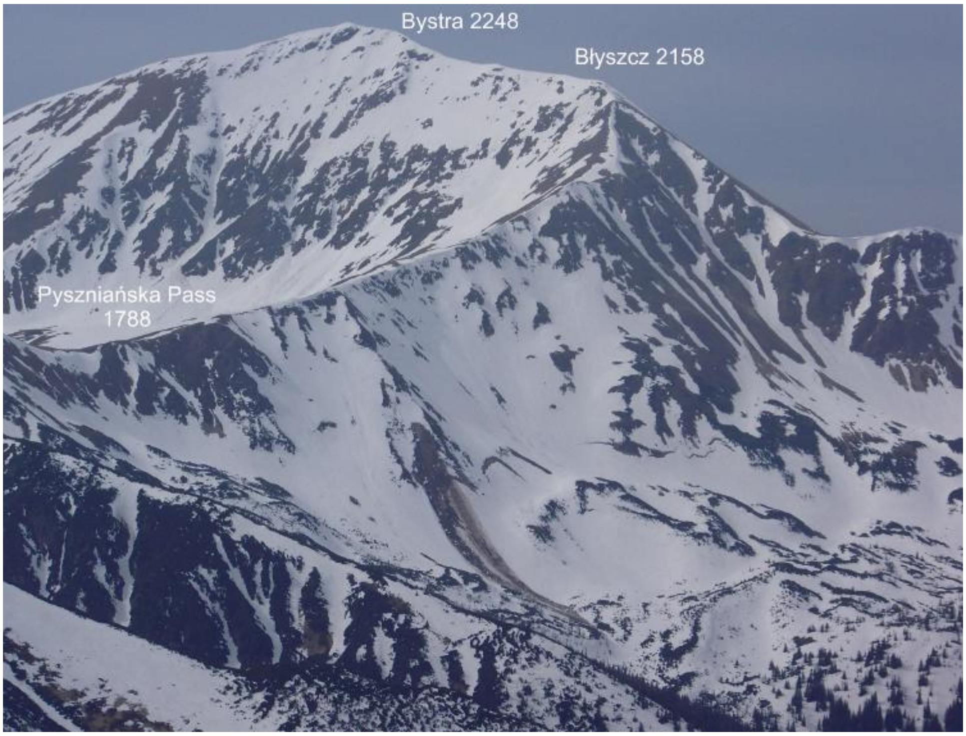

Fig. 3. Dirty avalanche track in the Pyszniańska Valley, Western Tatra Mountains (photo taken in April 2018).

20th century (Zaruski 1911; Smoleński 1932). However, the first systematic studies on the snow cover and avalanches of the region were conducted later – between 1928 and 1930 – at the High Mountain Climatologic Station of the Institute of Geography of Jagiellonian University in the Dolina Pięciu Stawów Polskich Valley (Leszczycki 1929). Papers on the morphogenetic role of snow avalanches in the Tatras include L. Kňazovicky (1970), A. Kotarba (1976), M. Kłapa (1980), A. Kotarba et al. (1983) and K. Krzemień et al. (1995), who underscored the relevance of these processes in the evolution of the upper timberline. More than 3,770 avalanche tracks have been identified thus far in the Tatra Mountains (Žiak, Długosz 2015; Rączkowska et al. 2016; Boltižiar et al. 2016). More than 70% are located on slopes with gradient values over 26°. Both the length of avalanche tracks and the size of avalanche starting zones decrease with increasing slope inclination (Rączkowska et al. 2016). According to historical records of snow avalanche activity in the Tatra Mountains (Kaczka et al. 2016), a total of 3,406 avalanche events have been recorded since 1900, of which 2,033 were noted in the Polish part of the Tatras and 1,373 were noted in the Slovak part. One important turning point in the study of avalanche processes was the introduction of dendrogeomorphologic methods that help yield complete chronologies of avalanche activity. A 150-year long reconstruction of snow avalanche activity was produced for the Biały Żleb chute (Lempa et al. 2014) and the Żleb Żandarmerii chute (Gądek et al., 2017) in the Rybi Potok Valley. Avalanche history was also reconstructed via a multiproxy approach, where remote sensing techniques, geomorphologic and dendrogeomorphologic methods, and mathematical modeling produced a comprehensive picture of the occurrence, timing, and magnitude of large avalanches in the Żleb Żandarmerii chute in the Tatra Mountains (Gądek et al. 2017).

The morphogenetic activity of snow patches was observed much later than avalanches (Kotarba 1976; Kłapa 1980; Bochniak 1988; Rączkowska 1992, 1993, 1995, 2007). According to the work of Z. Rączkowska (1992, 1993, 1995) on multiplier effects, we know that the pattern and intensity of nivation in the Tatras depend mostly on slope type and degree of turf coverage. Research by Z. Rączkowska (1993) has shown that the present-day evolution of nival niches is the outcome of nival erosion on slopes covered in weathering material or nival accumulation on debris-covered slopes. However, the role of nivation on the annual scale is limited to changes in relief (Rączkowska 1992, 2008b).

The morphologic effects of wind in the Tatras is another area without sufficient field research (Kotarba, Krzemień 1996). Deflation affects slope fragments devoid of vegetation and areas located primarily close to the main ridge and in mountain pass areas. Areas with dried soil cover are affected by wind erosion at speeds as low as 6.4 m/s (Pasak 1967; Kotarba 1976). B. Izmaiłow (1984a,b) studies of wind activity in the alpine zone of the High Tatras show that the deflation rate in this geographic area reaches 163.7 g/m^2/yr and the accumulation rate reaches 70.5 g/m^2/yr. In forest zone, foehn winds may even uproot

Fig. 4. The geomorphological impact of tree uprooting after a foehn wind occurrence, in December 2013 in Kościeliska Valley, Western Tatra Mountains (photo taken in April 2018).

trees. Events of this type may also trigger and transport large amounts of weathering material (Kotarba 1970, 1992; Rojan 2010).

D. Strzyżowski et al. (2016) founded that post-uprooting craters in the Kościeliska Valley in the Western Tatras, formed in December of 2013, occupy an average of 3.9% of the area of the windfall – and at some locations as much as 14.5%. The mean volume of a stump and root network per hectare was 378.4 m^3 (Strzyżowski et al. 2018), what represent relatively high value per single event (Fig. 4). In some small catchments (second and third order), the slope system may become linked with the channel system via weathering material transport from post-uprooting craters as well as stump and root networks formed in the close vicinity of river channels.

FLUVIAL PROCESSES

L. Kaszowski (1970, 1973) was the first researcher to study fluvial patterns and fluvial process intensity in the Tatras using quantitative methods. His study involved Biały Potok Stream (Fig. 1) whose main morphodynamic function was found to be the erosion of the floor of its channel. Hence, loss of debris from the Biały Potok channel exceeds or equals the influx of debris. The shortage of debris in this stream channel is a precondition for channel erosion, which occurs via two distinct processes that appear to counteract one another – evorsion and progressive erosion. Evorsion is more commonly encountered and leads to point increases in channel depth or increases in the height difference between consecutive channel sections. Progressive erosion occurs rarely and equalizes the longitudinal profile of the stream channel, and reduces height differences between each consecutive channel section. The two processes occur one after the other and counteract each other leading to reverse reductions in channel depth and the maturing of the longitudinal channel profile. The highest water stages occurring in a given geographic area play the greatest morphodynamic role in the river channel – yielding major quantitative changes as well as relatively small qualitative changes (Kaszowski 1975).

On the other hand, K. Krzemień (1991, 1992) aimed to study fluvial system dynamics in terms of the balance of three types of transported material (dissolved and suspended matter, bedload) at the scale of the entire Western Tatra massif from mountain peaks to its foreland. The structure of the material transported in the high mountain channel system – currently non-glaciated – is characterized by a marked excess of dissolved matter (91.78% to 95.58%) with respect to suspended matter (4.35% to 8.05%) and bedload (0.07% to 0.23%). This structure does not change even at high water stages – only the proportions between the types of material change. The very same structure is noted for material carried towards the foreland (Krzemień 1991, 1992). The entire high mountain channel system in the Western Tatras changes rarely – once every three years, on average. Lower elevations of the system are affected by change in more cases than are upper elevations – one to eight times per year, on average. Debris transport occurs over distances up to 20 meters in stream channels in glacial chutes affected by medium-size floods and large floods. Debris travel distances may reach 200 meters in the course of a catastrophic flood event. Debris transport is 4 to 6 times longer in stream channels carving into glaciofluvial material in valleys that were not glaciated in the Pleistocene compared to channels in glaciated niches.

Bedload transport is always longest in middle mountain stream channels – reaching 160 meters during medium-size and large floods. It may reach hundreds of meters in the course of catastrophic floods (Kaszowski 1973). The environmental conditions in these streams are best described using regression equations for the relationship between the largest pebble fraction in relation to the speed of water. The following water speed is required in order to move 30 cm pebbles in Starobociański Stream flowing through a glacial valley: 5 m/s. For movement in the Biały Potok stream flowing in a middle mountain area, the required water speed is only 3.7 m/s. At similar water speeds, the debris transport distance is about 16 times greater in the Biały Potok stream compared with the Starobociański Stream (Kaszowski et al. 1984). Recent studies on the functioning of denudation valleys in the Western Tatras have produced bedload transport models for the denudation valleys (Płaczkowska 2016, 2017). Bedload transport rarely occurs in the middle mountain sections of these valleys and the high mountain sections of these valleys: once per 1 to 3 years. Bedload transport distances vary from several meters in high mountain channels to more than a dozen meters in middle mountain channels (Płaczkowska 2017).

New studies on the structure of the slope-fluvial system were initiated in the Western Tatra Mountains in order to explore the slope-to-channel transition zone or the dominance of slope processes versus the dominance of fluvial processes. The transition from slope process dominance to fluvial process dominance may be either smooth over a longer distance (>50 m), with a transitional reach or abrupt over a shorter distance (<50 m), without a transitional reach (Płaczkowska 2017).

In general, high mountain areas of the Tatra Mountains evolve differently than wooded middle mountain areas. High mountain areas are affected by a set of morphogenetic processes determined by the local climate, with debris flows as the most important of processes. On the other hand, in woodland areas in middle mountains, the most important processes are material transport via water, loose weathering material, as well as organic substances in the direction of lower elevations (Kotarba 1999; Gorczyca et al. 2014). Blocks ranging in size from 50 to 87 cm may start to move during extreme events that occur every 20 to 30 years at the entrance of small V-shaped valleys found in middle mountain areas (Kaszowski, Kotarba 1985; Gorczyca et al. 2014). Substantially larger blocks reaching 2.0 meters in diameter may begin to move down large stream channels carved mostly into glaciofluvial material. In the course of such events, material transport may be triggered not only by fluvial processes, but also turbulent debris flows (Kotarba 1999).

Existing studies on denudation-fluvial systems in the Tatras suggest the following basic tendencies in clastic material transport: If weathering material and denudation material reach a channel system in the Western Tatras, then these materials will be transported and deposited on multiple occasions in the long term. Weathering material derived from mountain slopes in the High Tatras accumulates in outflow-free depressions and lake basins situated at a variety of elevations (Hreško et al. 2012; Kapusta et al. 2018). Slope systems and fluvial systems become linked only in the case of catastrophic precipitation events that occur once per century (Kotarba 2002). This occurs only in some regions of the High Tatras and over very short periods of time (Kotarba et al. 1987; Krzemień 1991; Rączkowska 2008a).

ANTHROPOGENIC EROSION

Contemporary human impact in the Tatras is associated mostly with tourism and wood transport following windfall events (Western Tatras) on land part of a private village belonging to the Witowska Community as well as skiing in the Mount Kasprowy Wierch area. Tourism-related human impact occurs along tourist trails and consists of gradual anthropogenic erosion (Skawiński 1993; Czochański, Szydarowski 1996; Krusiec 1996; Gorczyca, Krzemień 2002; Fidelus-Orzechowska et al. 2017). Research by P. Skawiński (1993) and M. Krusiec (1996) on human impact in the Tatras initiated a new research direction designed to determine patterns and intensities of ongoing geomorphologic processes in areas affected by human impact. This new research effort focused attention on the significant effects of human impact in areas such as Mount Kasprowy Wierch, Goryczkowa Valley, and Chochołowska Valley in the Western Tatras, and subsequently in the Polish Tatras as a whole (Gorczyca 2000; Rączkowska, Kozłowska 2010; Fidelus 2014, 2016; Fidelus-Orzechowska et al. 2017).

Tourist trails are areas affected by both morphogenetic processes and tourist land use. This can lead to the emergence of landforms of variable origin. Tourist trails have become much wider and deeper in the last 15 years along many long stretches in the alpine and subalpine zone. All tourist trails in the Tatras experience the strongest physical changes in the course of snowmelt in the spring as well as in the summer during heavy rainfall events. Forest management practices only affect small areas and last for predefined periods of time, but yield major morphologic changes, creating deep and permanent erosional incisions and produce rapid changes in slope and valley floor relief (Rojan 2015; Fidelus-Orzechowska et al. 2017). On the other hand, skiing does not produce substantial changes in slope relief due to good management practices on the part of Tatra National Park (Rączkowska, Kozłowska 2010; Fidelus-Orzechowska et al. 2017).

Human impact in the Tatras leads to accelerated circulation of material and higher energy flows across mountain slopes, and in some cases throughout the Tatra massif as a whole. In effect, weathering material (often fine material) is transported downhill to the base of the slope and leaves the slope area in the form of suspended matter and bedload moving in stream channels towards more distant destinations (Fidelus-Orzechowska et al. 2017).

DISCUSSION

Most Tatra geomorphology papers deal with selected geomorphic processes within the context of the long-term evolution of landforms, but a few (e.g. Kotarba et al. 1987; Rączkowska 2008a) contain summaries of the present-day evolution of mountains affected by ongoing morphogenetic processes.

The authors have identified several groups of multiplier publications in the area of present-day morphogenetic processes in the Tatras – including periglacial papers (Jahn 1958; Rączkowska 2007), slope process papers (Gerlach 1959; Kotarba 1972, 1976; Rączkowska 1993, 2008), debris flow papers

(Kotarba et al. 1983, 1987; Kotarba 1989, 1992a,b), fluvial papers (Kaszowski 1970, 1973; Krzemień 1991), and also anthropogenic erosion papers (Skawiński 1993; Krusiec 1996). All of these publications initiated and stimulated new research directions in morphogenetic studies with the use of quantitative methods designed to measure mechanisms and intensities associated with present-day geomorphologic processes.

An assessment of the present-day dynamics of morphogenetic systems in the Tatras requires a certain amount of information on the activity of morphogenetic processes in the past. This then requires accurate event chronologies enabling the identification of process activity tendencies. Significant progress in our understanding of active morphogenetic processes is linked with the use of lichenometric (Kotarba 1988a, 1997; Kędzia 2013; Gądek et al. 2016) as well as dendrogeomorphologic methods, which enable the generation of more robust event chronologies for rockfall sites (Zielonka, Wrońska-Wałach 2018), debris flow sites (Kotarba, 1989, 1991; Šilhán, Tichavský 2016), avalanches (Lempa et al. 2014; Gądek et al. 2017), and floods (Zielonka et al. 2008).

The Tatra Mountains represent a dynamic landscape system that is highly responsive to climate change. Studies on geomorphologic processes occurring in the Tatras conducted since the 1950s have made it possible to identify potential tendencies associated with the activity levels of key morphogenetic processes related to climate change. During the last 50 years, positive trends both in summer season temperatures and mean annual air temperatures have been observed in the Tatra Mountains (Bokwa et al. 2013; Łupikasza et al. 2016). An increase in annual air temperature of 0.14°C per decade was reported for the Polish Tatras (Łupikasza et al. 2016) and an increase of 0.21–0.30°C per decade for the Slovak Tatras (Pribullová et al. 2013) for the period 1951–2006 and 1961–2007, respectively. This has caused an upward shift in climatic zones (Melo et al. 2013), upward expansion of the timberline up to 80 m since the mid-1920s (Kaczka et al. 2015; Gądek et al. 2017) and a decrease in the duration and thickness of snow cover throughout the vertical profile of the Tatras (Falarz 2007). Although the statistical significance of observed climate change is higher for the Tatra foothills than in the Tatra alpine zone (Żmudzka 2009), recent climatologic analysis has confirmed the process of climate warming in the Tatra mountain range (Gądek, Leszkiewicz 2012).

The effects of climate warming may be especially noticeable in all the components of the Tatra cryosphere, which is very sensitive to temperature changes (Gądek 2014). The degradation of orographically conditioned permafrost and the formation of thermokarst microrelief have been recently observed in places with thin snow cover in the sporadic permafrost zone of the Tatra Mountains (Gądek et al. 2009; Gądek, Leszkiewicz 2012). According to these observations, ground temperature increases are most rapid at the least shaded sites on south-exposed slopes at lower elevations, where the snow cover is thin every winter. However, as documented by B. Gądek and J. Leszkiewicz (2012) under special orographic-nival conditions, an increase in mean annual air temperature may be paradoxically accompanied by a decline in the mean annual ground surface temperature.

A reduction in snow cover depth may result in a decrease in the mass and intensity of extreme avalanches, as observed along one of the most active avalanche tracks found in the Polish Tatra Mountains (Żleb Żandarmerii) in recent years (Gądek et al. 2017). However, an identification of trends in the frequency and intensity of avalanches, both of which are related to climate change, requires further research.

In line with increases in temperature, an increase in the frequency of circulation types associated with extreme precipitation was observed in the Tatras between 1951 and 2012 (Niedźwiedź et al. 2015), whereas no significant trend was found in mean annual precipitation (Bokwa et al. 2003). Additionally, an increase in the number of days with precipitation amounts of 40 to 60 mm in the warm half-year, together with an increasing frequency of long-term wet periods, was observed during the last decade (Górnik et al. 2017). As intense rainfall is the most important trigger for flood events and debris flows in mountain areas, an increase in the number of high-energy hydro-geomorphologic events was expected in the last decade. However, the observed response of the Tatra denudational system to hydro-meteorologic factors is more complex, as not all extreme events trigger morphogenetic processes leading to observable geomorphologic changes (Kaszowski 1973; Krzemień 1992; Kotarba et al. 2013).

According to a recent reconstruction of flood trends on the northern Tatra slopes for the second half of the 20th century (Ruiz-Villanueva et al. 2016), the tendency towards more extreme, but perhaps less frequent floods, is likely to reflect reality. Similarly, a literature overview on the occurrence of extreme hydro-geomorphic phenomena in the Tatra Mountains (Gorczyca et al. 2014) indicates that since the 1970s the tendency of the clustering of multiple extreme events has been replaced by the occurrence of single low-frequency, high magnitude events. Rainfall with high energy potential for floods or debris flow generation was recorded once every 6 to 9 years, while extreme hydrogeomorphologic events that simultaneously trigger floods, debris flows, and mud flows in the alpine mountain belt, and torrential flows in the middle mountain belt occur every 15 years (Gorczyca et al. 2014). These data indicate no ubiquitous increase in the frequency of hydrogeomorphologic events during the last 50 years (Gorczyca et al. 2014).

The general tendency in the present-day evolution of Tatra mountain slopes is that of stabilization by compact turf and forest, and this may help limit the effects of morphogenetic processes. This tendency was especially strong in the second half of the 20th century, and was most readily observable in the Western Tatras (Rączkowska 2008). The low activity level of these events may be related to the stabilization of slopes, which became much more prevalent following the establishment of protected natural areas in the Tatras with the establishment of Tatra National Park.

An increase in the number of small and large floods was identified in local catchments on both sides of the Tatra Mountains over the last decade, which was associated with an increase in the number of days with daily precipitation of 40 to 60 mm and a higher frequency of long-term wet periods (Górnik et al. 2017). Similarly, the latest reconstruction of rockfall activity in the Western Tatras shows an increasing trend for rockfall events since 1985, which may be linked with an increasing frequency of long-term wet periods (Zielonka, Wrońska-Wałach 2018). In contrast, a decreasing trend for the area of the river's active zone has been observed over the past 60 years on the southern Tatra slopes in the catchment of the Belá River (Kidová et al. 2016). This is the result of an overall decrease in flood size, changes in the catchment sediment supply induced by increasing forest cover in the catchment, and changes in channel boundary conditions (Kidová et al. 2016).

Debris flows are highly climate-dependent, geomorphologic processes that operate in the Tatra alpine mountain belt (Kotarba et al. 1987, 2013; Krzemień 1988). However, there is no clear relationship between periods of high daily precipitations and the triggering of this type of mass movement (Kotarba et al. 2013). No significant increase in the number and magnitude of debris flows has been observed during the last five decades on the northern slopes of the Western Tatra Mountains (Gorczyca et al. 2014). In contrast, multitemporal trend analyses of remote sensing data show an increasing frequency and intensity of debris flows since the 1980s from the High Tatra (Kotarba 1997; Kapusta et al. 2010; Kotarba et al. 2013). A local dendrogeomorphic reconstruction of the debris flow pattern in the Malá and Velka Studená valleys (Fig. 1) indicates a high concentration of debris flow events over the last decade on the southern slopes of the High Tatra Mountains (Šilhán and Tichavský 2016). This evident increase of debris flows frequency may not necessarily be related to an increase in the number of extreme precipitation events, but may be possibly an effect of enhanced permafrost thawing and increased production of loose debris sediments in debris flow source zones at high elevations on the southern Tatra side (Šilhán, Tichavský 2016).

This review reveals that there is no clear general tendency in the dynamics of geomorphologic processes occurring in the Tatra Mountains in the last 50 years. A local increase in the number of extreme events has been noted, especially over the last decade, which applies to both channel dynamics and events on hill slopes. Some of these different tendencies may be a consequence of a variable precipitation regime and different topo-climatic conditions between opposite Tatra slopes. The hydrologically unique catchments selected in the Tatra Mountains were examined in the past by Pociask-Karteczka et al. (2010). However, the assessment of the potential impact and tendencies in contemporary climate warming on patterns and dynamics associated with the geomorphologic processes occurring in the Tatra Mountains appears to be a key challenge for future geomorphologic studies.

CONCLUSIONS

An examination of the activity of morphogenetic processes in the Tatra Mountains leads to the identification of breakthrough stages associated with new and significant research studies. This type of multiplier effect in research is needed in order to place the focus on new approaches or new problems. Research designed to mark new directions, as noted in the literature review in each earlier section, was largely driven by two professors leading research work: A. Kotarba and L. Kaszowski. Significant progress in our understanding of active morphogenetic processes became linked with the use of lichenometric and dendrogeomorphologic methods, which enable the generation of robust chronologies for events such as rockfall, debris flows, snow avalanches, and floods.

Research on morphogenetic process dynamics in the Tatras indicates that this high mountain area, which is not glaciated today, is characterized by the occurrence of two weakly connected morphodynamic systems – a slope system and a channel system. Frequently these two systems operate independently of each other. This independence is based on a lack of physical linkage between the two systems under “average” hydrometeorologic conditions. The slope system is dominated by debris flows and torrential flows. Debris is transported downhill, but remains in the slope system, and is not normally transported to the fluvial system. Human impact has led to an increase in the intensity of natural morphogenetic processes and consequently increased linkages with the fluvial system. The studied system has been part of Tatra National Park since the 1950s, which has reduced human impact over time. One remaining problem is the impact of tourists on the relief of the area, especially in alpine and subalpine geocological zones. Other problems include the collection of trees felled by strong winds on private land in the Western Tatras as well as the removal of trees injured by pests and other sources of tree injury.

Research on geomorphologic process dynamics conducted in the Tatras since the 1950s does not show any general growth tendencies in morphogenetic process dynamics on slopes and on valley floors. Local decreasing tendencies in dynamic of geomorphological processes may be the effect of slope reinforcement following the establishment of Tatra National Park and its sister park in Slovakia. On the other hand the physical response of the Tatra denudational system to growth tendencies in hydrometeorologic events is complex, as not all extreme hydrometeorologic events trigger morphogenetic processes leading to observable morphogenetic changes in the field.

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