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MORPHODYNAMIC EFFECTS ON LACUSTRINE DEPOSITS IN THE HIGH TATRA MTS

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Abstract

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The trend of present geomorphic processes in the area of the High Tatras´ alpine belt demonstrates the growth in intensity, frequency and influence on the environment in connection with climatic conditions which transform the alpine landscape. One morpho-dynamic phenomenon of the Tatras´ glacial valleys is the infilling of alpine lakes by sediments and their gradual shrinkage. Important factors include slope gravitational processes such as rock falls and toppling, hydro-gravitational debris flows and the nivational processes ground avalanches. Each of these processes transfers a different type and amount of material of various grain composition and accumulation in the hydric zone of these alpine lakes. These important factors all influence the structural-lithological and morphogenetic conditions in surrounding slopes and ridges. Dynamics and frequency of these processes closely correspond with seasonal occurrences of extreme meteorological conditions, and their sudden changes have been confirmed by the current research of morpho-dynamic processes affecting the timberline in the High Tatra Mts. The aim of this paper is to emphasize the spatio-temporal extension of geo-morphologic processes and to demonstrate the development of alpine lake sedimentary deposition in selected valleys in the High Tatra Mountains.

Key words: alpine lake, geomorphic process, lake sedimentation, Tatra Mts

Introduction

The alpine lakes represent one of the most important geomorphological-hydrological phenomena in the High Tatra Mts. Forming a part of the glacial valleys, they play very important roles in ecosystem services such as water retention and accumulation, local climate regulation, ecological, environmental and landscape aesthetic functions. The valley environments here have continuously changed since glacial retreat. Slope stability has decreased because of the activation of significant morpho-dynamic processes. Integrated geomorphological-hydrological systems determined by the climatic and geological conditions are still being formed, with the development of tarns in the post-glacial period subjected to sediment accumulation in their drainage basins. It is currently evident that mountain-cirque lakes trap a high portion of allochtonous mineralogenic material flowing in from the surrounding slopes (Owens, Slaymaker, 1994; Kotarba et al., 2002). Sedimentary filling contains the clastic material from chutes and un-vegetated open slopes in all particle-size categories; from boulders and coarse debris fragments to the sand and clay-silt fractions. The glacial erosion has significantly participated in the mountain lake morphogenesis with specific features such as the relatively large depth and noticeably regular circular or elliptical shape of the lake shoreline. Some of the alpine lakes have been formed by deep abrasive erosion of the glacier mass into granite bedrock as cirque lakes, and also others, by retreating moraine barriers as moraine-dammed lakes, or by combination of both these processes. Several mountain lakes have been formed in moraine depressions behind the moraine mounds, thus blocking outflow from the melting glacier (Lukniš, 1973). The Holocene development of the Tatra Mts alpine lakes has been directly influenced by hydrological processes connected with gravitational, hydro-gravitational, cryogenic and also nivational processes. The spatio-temporal analysis of the mentioned landforms and processes is considered a basic step in research into changes in tarns in the Tatra Mts.

Geomorphic and hydrological processes in the drainage basins of the alpine lakes simultaneously affect the ecosystem of the glacial valleys and cirques. These especially create irreversible effects on the reduction and gradual extinction of the open water area of the lake, and this limits important sources of water supply in the valley's ecosystem. This deposition began with the de-glaciation of valleys by means of hillslope processes in the periglacial climate of the alpine environment, for example by niveo-fluvial silting, fluvio-gravitational debris flows, the gravitational rock fall scree progression and also by ground snow avalanches. A very special case is the rock-glacier debris movement, induced by inner-ice changes which enter the lake body via the frontal rampart. This occurred especially at the Veľké Hincovo pleso lake in the Mengusovská dolina valley. The rock glaciers are most likely one of the first processes participating in the alpine lake deposition. Their genesis requires an almost glacial climate, thus ensuring that the subsoil is permanently frozen (Nemčok, Mahr, 1974). A much greater amount of lake deposits has been caused by hillslope gravitational and hydro-gravitational processes. The most important activity of debris flow was dated from The Little Ice Age (about AD 1400–1900) connected together with a higher frequency of periods with the occurrence of catastrophic hydro-meteorological events (Kotarba, 1992, 2006). A correlation between the increased trend of debris flow activities and extreme precipitation in the 1980's and 2000's has been reported in previous research in the Tatra Mts (e.g. Raczkowska, 2006; Kotarba, 2007; Kapusta et al., 2010). The permanent rock falls and toppling of detached rock fragments on scree accumulation formed a more or less continuous zone of screes and debris cones around the cirques and glacial valley floors with a slope inclination of more than 25 degrees. Rock walls and screes with a high production of fragments have induced convex lobes in the water body, and these are gradually being inhabited by vegetation. Similarly, the debris flows with material emanating from high production predisposed to mylonite zones significantly supported lake sedimentation.

Material and methods

Methodology is based on current research in the alpine environment of the High Tatra Mts, and present knowledge of the geomorphic processes and their spatial distribution above the timberline (Hreško et al., 2008). Detailed morpho-dynamic geo-relief analysis in the area of glacial valleys represents the first step in this methodology. This research focused on both southern and northern facing valleys. The selection of representative alpine lakes has been based on preliminary spatial data analysis and geo-morphological classification and all observed geo-morphologic processes are categorized according to the standard definitions and classification systems (Lukniš, 1973). The basic dimensions of the drainage areas, consisting of catchment area, its length and transport paths were calculated by GIS techniques. Considering the high elevation amplitude of the source areas, more realistic surface area and length values were obtained by DEM analysis based on ArcGIS extension developed by Jenness (2011). Field surveying of the lake areas and vicinities was performed by time-series photo documentation to support the correct mapping and evaluation of the processes and their impact on sedimentation. The analysis of spatio-temporal changes is based on comparison of geo-referenced historical and present aerial images obtained from military topographic archives (TOPU Banská Bystrica – 1955, 1986 and 1997) and GEODIS Slovakia (2007). All images are from the beginning of autumn, with the dates varying between September 12 and September 29. Spatial resolution of all data was rescaled to 0.5 m per image pixel according to the orthophoto from 2007. Image data from near-infrared band of IKONOS (24/08/2004 © Techmex SA, Poland) was used to provide the best delineation of the water surface.

Study areas

Four alpine lakes were chosen as representative areas for the demonstration of sediment deposition processes. The Popradské pleso lake represents lake silting in the form of a fluvial delta with braided stream and successional vegetation on the surface. The Čierne Javorové pleso lake represents the unique case of sediment deposition from

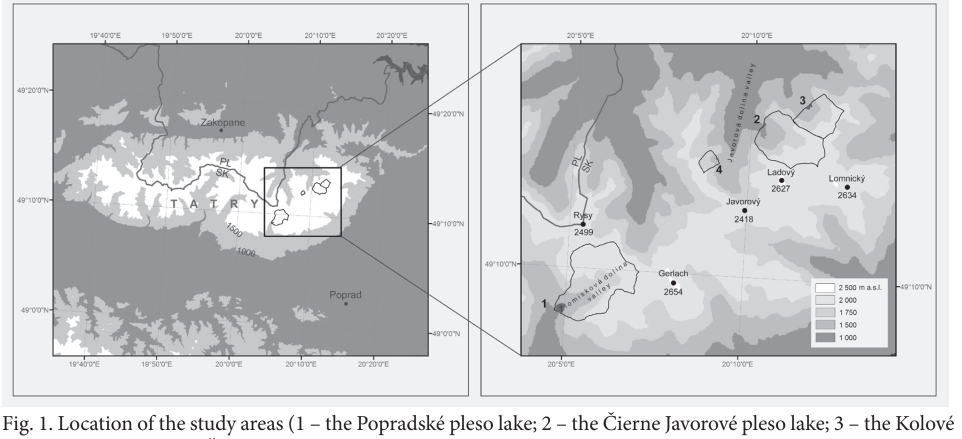

Fig. 1. Location of the study areas (1 – the Popradské pleso lake; 2 – the Čierne Javorové pleso lake; 3 – the Kolové pleso lake; 4 – the Malé Žabie Javorové pleso lake).

debris flow with well-developed transport paths and deposits ending in the stony delta. The Kolové pleso lake is partly filled by material, up to large blocky fragments, from the adjacent scree and debris flow deposits at the foot of the largest debris cone in the Tatra Mts. The Malé Žabie Javorové pleso lake is an example of the final stage of lake development before total infilling by debris cone material and recent debris flow accumulation.

Results

The Popradské pleso lake

This alpine lake is situated in the southern part of the High Tatra Mts at an altitude of 1494.3 m a.s.l. It has an area of 6.87 ha and maximum depth of 17.6 m (Gregor, Pacl, 2005). The catchment area is the upper part of the Zlomisková dolina valley, and the total area of the drainage basin is 4.8 km^2 in planar dimension (surface area calculated from DEM is 5.7 km^2). The tarn is a type of flow-through lake, dammed by the moraine accumulation and supplied with water from the Zlomiskový potok creek. Lukniš (1973) highlighted the washout of finer fractions from the boulder moraine accumulation which are considered the main source of lake deposits. The mouth of the creek is formed by a relatively large delta, 150 m wide.

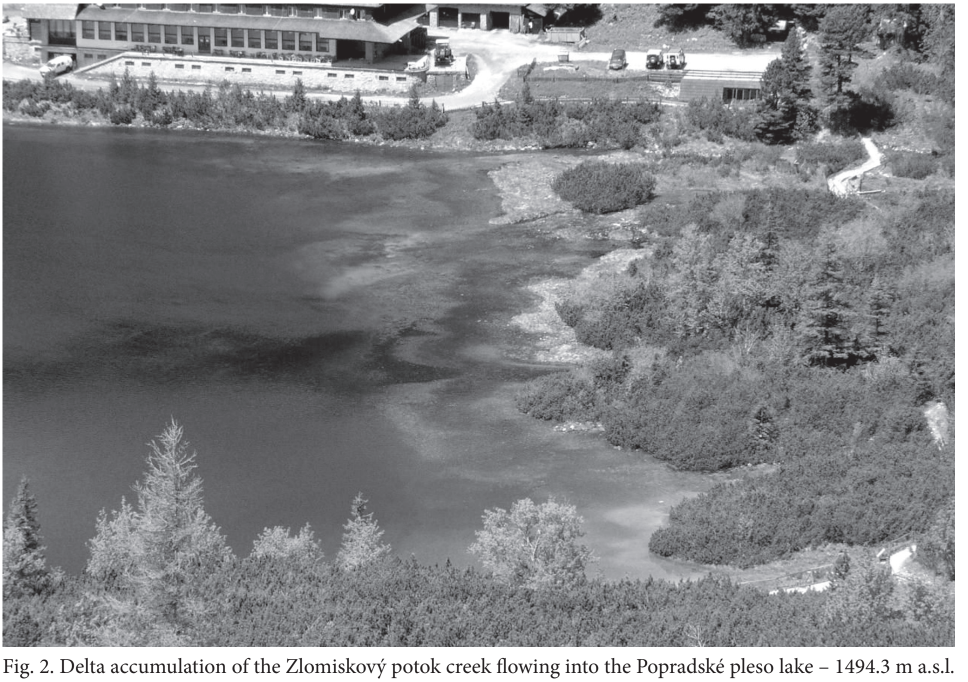

Fig. 2. Delta accumulation of the Zlomiskový potok creek flowing into the Popradské pleso lake – 1494.3 m a.s.l. (Photo: J. Košťál, 2008).

The braiding stream translocates its bed load deposits and freshly-transported material accumulates in a shoreline zone of the delta. The comparison of the aerial and satellite images documents the progressive activity of lake sedimentation and the succession of vegetation which covers delta depositions down to the shoreline. Expansion of dwarf pine vegetation is evident, while herbaceous vegetation covers the edges of the younger accumulations and along the stream branches. Based on the assumption of continuation of this trend, further delta spread and formation of a shallow beach area by fine-grained alluvium of sand and clay-silt fractions are expected.

The Kolové pleso lake

The basin of this alpine lake was formed in the higher level of the glacial trough of the Kolová dolina valley below the large scree of debris cone running from the rock gully of the Kolový štít peak (2418 m a.s.l.). The total area of the drainage basin is 1.42 km^2 in planar dimension, with a surface area of 1.80 km^2. The present tarn area is a residue of the original glacial lake that used to fill the entire cirque depression behind the moraine mound during the Late Würm period. The lake's water level is at an elevation of 1565.4 m a.s.l., with 1.8

Fig. 3. Drainage basin of the Kolové pleso lake, highlighting the direct impact of debris cones (the main photo – J. Hreško, 2010), with sand and clay-silt fractions deposited underwater along the right bank (the inserted frame with modified image is from IKONOS, 2004).

ha area and a maximum depth of 1.2 m (Gregor, Pacl, 2005). Rock falls, topples and dry debris flows have especially participated here in lake sediment deposition (Figs 3 and 4). Recent gravitational processes, and mylonitised fault failures mentioned by Lukniš (1973), have led to intensive disintegration of the Kolový štít peak ridges. Debris cones grooved by debris flow tracks entered the lake from the left branch of the glacial cirque and a relatively wide delta formed in the foreground supplying the lake with sand and clay-silt sediments. A further significant source of silting is located on the right side of this alpine lake, in the form of a small but sediment-rich delta of Kolový potok creek, flowing into the lake from the right branch of the glacial cirque. Small-debris fragments and fine-grained deposits, with gradual transition into sand and clay-silt fractions deposited underwater along the right bank, prevail here (Fig. 3 – upper right inserted frame).

Fig. 4. The dominant lake sediment facies of recent debris falls and topples (Photo: J. Hreško, 2010).

The Malé Žabie Javorové pleso lake

This lake represents the final stage of alpine lake development with an almost full lake body of sediments, located in the glacial cirque over the Javorová dolina valley at the elevation of 1704.2 m a.s.l. The lake depth ranges from 1.14 up to 3.1 m (Gregor, Pacl, 2005). The substantial part of lake deposits consist of material from the debris flow in the form of a progressive debris cone, shrinking the open-water area from the axial direction (Fig. 5). The particle size of recent coarse accumulations entering the open water varies from 5 cm to 30 cm in diameter. On the left, the lateral banks are in contact with the scree slope and with older debris-moraine accumulation partly covered by herbaceous vegetation. The edges of the shallow lake are filled with fine-grained sand and clay-silt fractions which evidently drifted

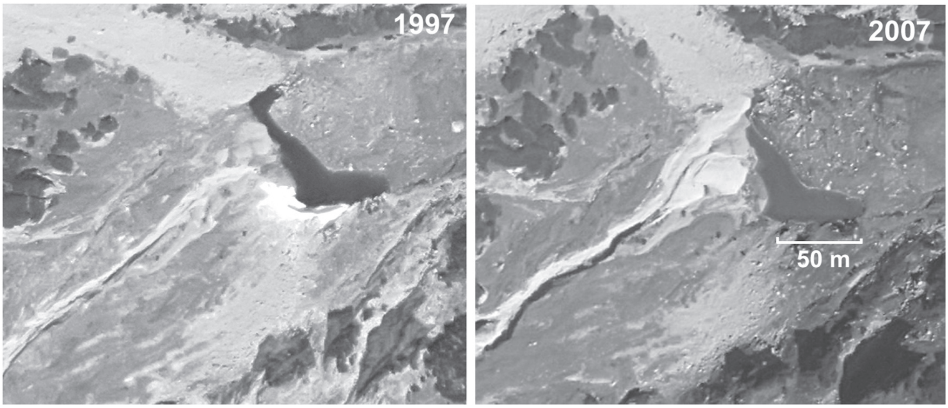

Fig. 5. The process of lake infilling by debris flow deposits in the 10-year span (aerial images by TOPU Banská Bystrica, 1997 and Geodis Slovakia, 2007).

from the debris flow accumulation (Fig. 6). The length of the youngest accumulation of the debris flow is approximately 80 m with maximum width of 40 m. The erosional furrow has two branches with a total length of 430 m and width of 3 to10 m. The source area of debris flow is formed from two morphologically different parts with a total width of more than

Fig. 6. Sandy accumulations on the lake bed, washed up by debris flow deposits (Photo: J. Hreško, 2011).

600 m. The left part is related to the higher level of the glacial cirque (Lukniš, 1973). The slope to the valley floor is formed due to gravitational processes, evidently induced by the existing horizontal mylonitised fault failure which separates the lower accumulation part. This debris accumulation ends at the mounds of abraded bedrock and peri-glacial scree with discontinuous vegetation of dwarf pine. The bedrock step in the middle of the slope is intersected by two erosional furrows from the lateral debris flows which join at an elevation of 1760 m a.s.l., and approximately 160 m from the lake. This debris flow is supplied with fragmented material from the very deep rock chute of the Žabí Javorový štít peak (2203 m a. s.l.) and also from the smaller secondary channels on the right side of this source area. This portion of the glacial cirque can be classified as a gravitational-debris morpho-dynamic system, with a high production of fragments and debris cones formation.

Arising from the actual trend of increasing frequency of extreme precipitation events, there is a legitimate assumption of continuing shrinkage of this alpine lake by debris flows towards its extinction. The left side of the lake is already filled with coarse debris and fine-grained fractions in its foreground.

The Čierne Javorové pleso lake

The drainage basin of the alpine lake is located on the right side of the glacial valley floor (the Čierna Javorová dolina valley), surrounded by moraine mounds in the frontal

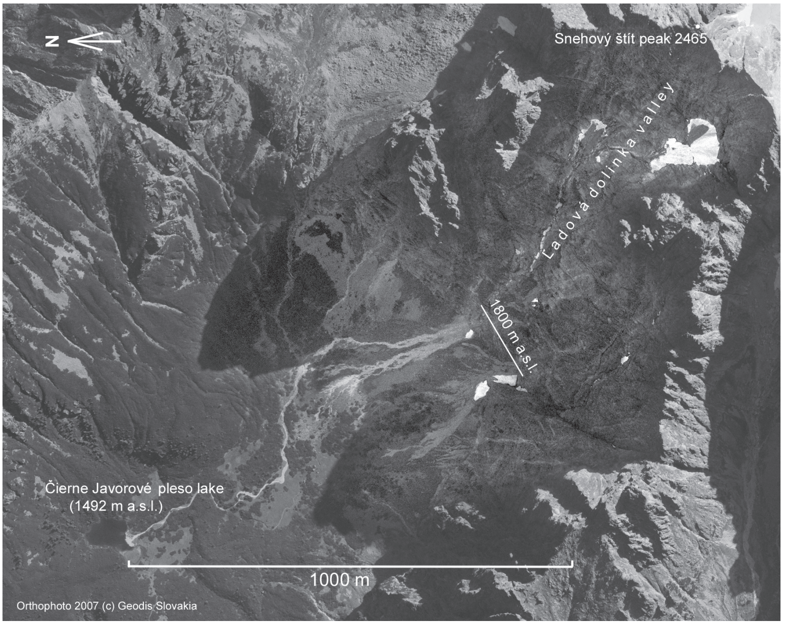

Fig. 7. The drainage basin of the Čierne Javorové pleso lake with debris flow course (adjusted orthophoto, 2007).

zone. The total area of the lake catchment is 2.92 km^2 measured in planar dimension, and 3.74 km^2 as surface area derived from DEM. The original extent of the lake was evidently larger, indicated by the flat valley floor; however it has been filled with the accumulations of debris flows. The morpho-dynamic system of debris flows, originating in branched rock chutes in the cliff relief of the Veľká ľadová veža peak (2387 m a.s.l.) and the Snehový štít peak (2465 m a.s.l.), is typical in this lake catchment area (Fig. 7). The enormous potential source of debris fragments is produced by the higher occurrence of crack structures and mylonite zones in the granite massif. Kinetic energy of the flows is expressed by the elevation amplitude of 800 up to 900 metres between the source area and the lake water level (1,492.1 m a.s.l.). The maximum measured depth of the lake is 3.2 m (Gregor, Pacl, 2005).

The gradual shrinkage of the alpine lake is caused by two main sedimentary facies. The first is the coarse fragmented debris up to 30 cm in size transported from rock cliffs and chutes. The total length of this main debris flow is to 1950 m in planar dimension, and 2350 m as surface length derived from DEM. Of this, 660 m corresponds to the floor of the valley. Due to the transportation distance, the debris fragments show evident signs of abrasion in the form of rounded edges. Meandering and furcation of the flow with patchy accumulations of rock fragments along the channels are typical features in the valley floor, from vertical "down-cutting" and lateral erosion processes. Considerable impact on delta deposits by flow down-cutting and channel enlargement was observed in 2011, with alternating effects of channel transfer and removal of the older sediments or overlay by fresh accumulations. The frontal edge of the delta slopes steeply into the lake, in curved and finger shaped offsets of these coarse fragments.

Other quite important facies are the sandy lake deposits accumulated in the left part of the lake. These form a relatively isolated island covered by herbaceous vegetation, with continually expanding beach-like sandy facies around the perimeter (Fig. 8). Formation of this island is likely connected with turbulent processes of sediment accumulation by the sudden input of material in the foreland of the debris flow delta, or it may be related to the jet or funnelling effect of water flowing from the lake. The less visible sandy and clay-silt facies on the lake bed are not so important in this stage of lake silting.

The trend of the lake sediment deposition was documented by the comparison of aerial image series over a 50 year span (Fig. 9). There is an evident increase in accumulation visible in the delta frontal zone and in channel transfers of recent debris flow. This trend still continues, with observations in 2009–2011 identifying three different debris flow activities and fresh debris deposits. These processes will most likely continue with the expectation of the trend of higher frequency of precipitation anomalies, with sediments therefore temporarily or permanently blocking outflow from the lake.

The total areal extent of the Čierne Javorové pleso lake was 6461 m^2 in 1955 (Table 1). The comparison of the next evaluated periods indicates a decrease in the water level between 1955 and 1986 by 22.1%; to 5032 m^2. Since 1986, the water area increased in each of the following periods; to 5615 m^2 in 1986–1997 (by 11.6%) and to 5664 m^2 in 1997–2007 (0.6%) (Table 1).

Fig. 8. The delta of active debris flow entering the lake (Photo: A. Sedlák, 2010).

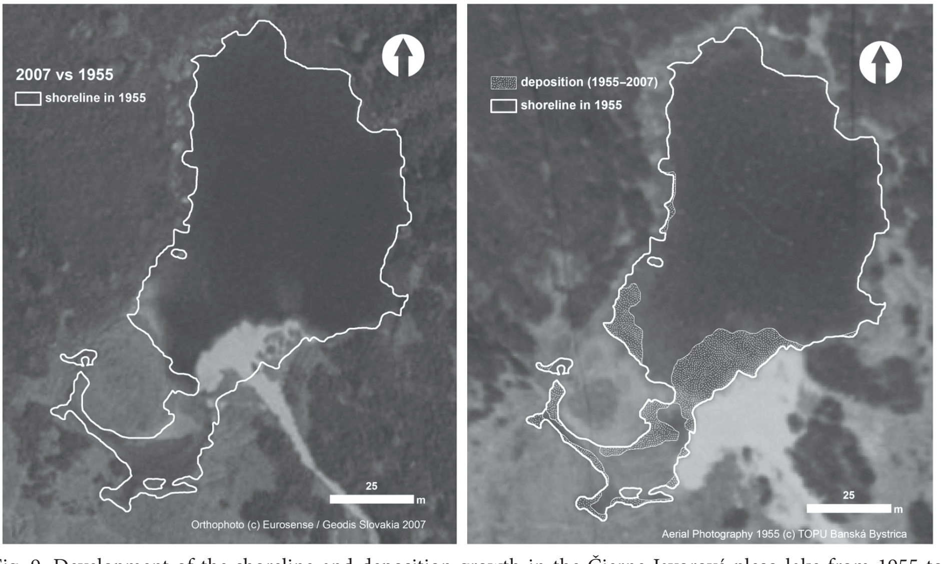

Fig. 9. Development of the shoreline and deposition growth in the Čierne Javorové pleso lake from 1955 to 2007.

T a b l e 1. Water area changes of the Čierne Javorové pleso lake in reference periods (N – number of water patches; Area (m^2) – area of water patches in square metres; Area (%) – ratio of area in 1955; Δ – difference in area (%) between the related years).

Year	N	Area (m^2)	Area (%)	Δ1986	Δ1997	Δ2007
1955	2	6461	100.0	-22.1	-13.1	-12.3
1986	6	5032	77.9		+11.6	+12.6
1997	3	5615	86.9			+0.9
2007	2	5664	87.7			

These results show the evident impact of alluvial deposition of debris flow running from the south-east into the lake between 1955 and 1986, although this may be inaccurate in absolute detail due to the seasonal climatic effects on the areal extent of the water body. Some approximations are possible by correlation with climatic data for the investigated years. These include the mean monthly precipitation and also snow water content data from the preceding winter.

Precipitation activity and its influence on the alpine lake sediment deposition

Precipitation represents the most important factor controlling formation, frequency and intensity of hydro-gravitational processes in alpine environments. This participates, directly or indirectly, in the morpho-dynamic activity in the Tatras in the form of snow and rainfall. The higher intensity and frequency of occurrence predispose formation of morphologically active avalanches, debris flows and flood events observed during the latter decades. On the basis of present knowledge and observations, these additional inputs with minimal intensity of 30 mm per day are considered to be morphologically active. To fulfil this precondition as naturally as possible, only the data measured in the period from May to October was selected. Between 2008–2010, daily rainfalls over 30 mm were recorded at the Lomnický štít peak on 20 days, and at the Skalnaté pleso lake on 26 days (Table 2).

For threshold precipitation values with higher morpho-dynamic potential, rainfalls over 30 mm in 24 hours can induce the local mass transport and accumulation of debris fragments in chutes. Where values exceed 50 mm in 24 hours, there is the expectation of debris transport in chutes and existing debris flow channels. Kapusta et al. (2010) give the example of precipitations over 80 mm in 24 hours triggering the morpho-dynamic activity of debris flow in a range greater than the extent of the debris cone. Such a large amount of water can release enough energy to initiate and sustain movement of coarse-grained rock fragments even on gentle slopes from the valley floors. This can result in meandered and braided channels and also newly-generated accumulation forms such as deposition lobes in forelands of debris cones and finer debris accumulations on the flat valley floors. Heavy rainfalls in July 2010, with two days of precipitation values over 40 mm, a further two days over 50 mm, plus one exceeding 90 mm in 24 hours have proven this morpho-dynamic action. These events correspond with activities of debris flows documented in the basin of the Čierne Javorové pleso lake.

T a b l e 2. Daily precipitations over 30 mm at the Lomnický štít peak – LS (2634 m a.s.l.) and Skalnaté pleso lake – SP (1778 m a.s.l.) meteostations from 2008 to 2010 (Data source: SHMI).

Month/ Station	IV.		V.		VI.		VII.		VIII.		IX.		X.	
	LS	SP	LS	SP	LS	SP	LS	SP	LS	SP	LS	SP	LS	SP
			53.8	53.3			36.7	47.3		44.9			34.1	35.2
							33.4	39.3		34.1			33.0	
2008	–	–						51.8						
				50.8	40.6	35.9	33.6		42.9	57.2			31.8	31.4
2009	–	–			44.5	61.8			30.5	33.3			42.8	62.8
			65.9	48.9	31.3	42.6	39.5	32.1	31.7		**85.6**	32.7		
				46.3		72.5	39.8	58.7						
				42.4		30.6	39.3	45.9						
2010	–	–					31.8	58.5						
								93.2						
								41.6						

Discussion

The formation of lacustrine deposits and the shrinkage of the alpine lakes represent the important morpho-dynamic phenomena in the high-mountain environment of the Tatra Mts. The study of this topic is usually supplementary to existing research activities such as; geomorphological analysis (Lukniš, 1973), the geodetic and cartographic surveys (Gregor, 2005; Bartoš et al., 2006), analysis of time variability in lake accumulation by using sediment dating techniques (Owens, Slaymaker, 1994; Kotarba et al., 2002; Irmler et al., 2006) and hydrological research (Gregor, Pacl, 2005). Alpine lakes represent a specific type of water ecosystem and important source of surface water. Their formation and development is closely connected with the morphogenesis of the Tatra Mts during alternating glacial and interglacial periods in the Pleistocene and after ultimate retreat of the glaciers in the post-glacial period in the Older Dryas stadial (Lukniš, 1973; Ložek, 1973). Some lakes are in the stage of extinction as a natural process, especially in areas with a surfeit of material sources in close vicinity to the lake. Where total infilling by sediments occurs, the lake residuum and its drainage basin keep the retention capability of surface water to a reasonable extent. However, the rate of water accumulation and redistribution usually decreases over time. This change not only has a crucial impact on freshwater habitats of the alpine lake, but also on habitats along the out-flowing water stream, because the water supply is then limited to sources from precipitation and sub-surface flow.

Current research results show almost all the identified hill-slope processes participate in lake infilling by sediments. Water-induced gravitational processes (as in debris flows), gravitational processes (rock falls and fragment topples) and also fluvial transport and delta accumulation significantly influence these study areas. Gregor (2005) appends the spring avalanche contents as a source of infilling sediments in these Tatra lakes. Their geomorphic impact is appreciably higher where there are dissected rock chutes on the mylonite base with a higher potential for debris material to be transported in episodic slush avalanches (André, 1990). For these types of lake sedimentation, closer contact of the water body with the avalanche accumulation zones is required. Considering these preconditions, the ground avalanches are not the presumed process directly contributing to lake sedimentation in all study areas. Moreover, in many cases it was not unambiguously possible to assign certain types of sediments to the specific process. The present morpho-dynamic effects of the ground avalanches were observed in 2010 on slopes above the Malé Žabie Javorové pleso lake by destroyed vegetational cover and the surface soil-regolith layer, with possible partial deposition in the lake.

At the Skalnaté pleso lake, abundant snowfalls in the 2008/2009 winter registered at the Skalnaté pleso meteorological station from November 17th 2008 to March 30th 2009 reached 468 mm. The value recorded in 2009/2010 winter from December 5th 2009 to March 18th 2010 was 344 mm. These values reflected the higher incidence of geo-morphologically effective nivation processes, including the various types of avalanches. Höller (2001) refers to the formation of spring ground avalanches as gliding avalanches which usually occurred on southern facing non-forested slopes where soil temperature varied between 0 °C and +2 °C, depending on the depth of the snow cover. This process resulted in the entire displacement of snow cover and it represented a driving force for erosion (Leitinger et al., 2008). Observations of these gliding avalanches in the Cascade Mountains, British Columbia, confirmed their formation is influenced by precipitations and by further conditions which cause the presence of water in the snow cover sub-layer (Clarke, McClung, 1999).

Formation and dynamics of debris flows are evidently connected with extreme rainfalls with thresholds over 25 mm per hour, or 80–100 mm in 24 hours (Fussgänger, Jadroň, 2001; Kotarba, 1994; Kapusta et al., 2010). However, some studies have reported that lower-intensity rainfalls from 30 mm per 24 hour have the potential to initiate debris flows, especially in cumulative precipitation events lasting several days (Kotarba, 2007; Lajczak, Migoń, 2007). On the other hand, Lajczak and Migoń (2007) highlighted the possible misinterpretation of the meteorological data normally acquired from the closest meteorology stations. The combined effect of orographic convection and altitude may have resulted in significantly higher daily rainfall recorded at low-altitude stations.

Conclusion

Results herein represent the initial phase of research into the lacustrine deposit sources in the High Tatra Mts region, and especially those due to present geomorphic processes. Following spatial dimensions and intensity potential, the hydro-gravitational processes of debris-flows have the greatest influence on infilling and extinction of these alpine lakes. The debris flows and avalanches are considered to be the most dynamic processes in this alpine belt of the Slovak high mountains (Stankoviansky, Barka, 2007; Hreško et al., 2008). The turning period of the reactivation and more frequent occurrence of high-volume avalanches and debris flows can be approximately dated to the year 2000. Subsequently, many debris chutes, rock gullies and avalanche tracks, which were previously relatively stable for several decades regenerated followed the trend line of precipitation activity. The state of the current knowledge indicates that a long-term monitoring network of observational and measuring plots is compulsory for the detailed evaluation of the processes inducing sediment transport and accumulation in alpine lakes. This should also include utilization of GIS techniques to detect changes, and time-series photography of the lake areas and drainage basins based on terrestrial and remote-sensed images of aerostat equipment, for instance. Support can also be provided by high-accuracy GPS locators, supplemented by sonars for lake-bed profiling and sediment dating techniques.

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