Shrinkage of the tarns in the High Tatras (Slovakia, Poland)

Juraj KAPUSTA, František PETROVIČ, Juraj HREŠKO, Zofia RĄCZKOWSKA

Abstract: *This paper assesses the shrinkage of glacial lakes in the High Tatras by analysing the series of historical and actual orthophotomaps from 1949 to 2018. The shoreline dynamics during this period were established by detailed retrospective remote sensing, and the decrease in the former surface of the water was caused by intensive interaction between morphodynamic processes and the lake basins. Herein, we have identified 38 tarns with an assumed decline in the area. This assumption was based on a comparison of initial visual analysis of the historical aerial photographs and the current orthophotomaps which capture all High Tatras tarns. We selected ten tarns with the largest or most representative changes and performed detailed cartographic analysis on them. We also attempted this analysis over shorter periods whenever possible and herein we established from 2.5 to 32.2% decrease in lake water surface area during the monitored period. This decrease in shallow lake basins was accompanied by the presence of accumulated debris flows, fine fraction fluvial-proluvial deposits, and vegetation. The shallow glacial lake basins are sensitive indicators of irreversible changes in their catchment areas and this study, therefore, highlights the effectiveness of combining detailed orthophotomaps and historical aerial photos and GIS tools in researching glacial lakes shoreline dynamics in the alpine landscape. Retrospective shoreline analysis facilitates the assessment of the effects of morphodynamic processes on the development of tarns from the postglacial period until today.*

Keywords: *lake shrinkage, basin filling, shoreline changes, tarns, retrospective analysis, morphodynamic processes, High Tatras*

Introduction

While changes in glacial lake shorelines are a significant indicator of lake-basin and micro-catchment development in the glacial and post-glacial periods, lake infilling is the most important determinant of the High Tatras deglaciated alpine landscape because it promotes gradual drying-up of lake basins in corrie and trough conditions.

From the early Holocene, a variety of exogenous geomorphological processes have generated deglaciated relief around glacial lakes, and the lakes in the High Tatras and other high mountains are now considered complete because deglaciated relief occurred 22,000 to 8,500 years ago (Lukniš 1973, Králiková et al. 2014, Zasadni and Kłapyta 2014). The relief is responsible for the transport of large amounts of weathered rock from the slopes towards the valley floor (Lukniš 1973, Kalvoda 1974), and a lot of this erosion is traped in lake basins, resulting in decreased glacial lake volume and shrinkage of lake surface area. Erosion has also affected natural processes in alpine watercourses and micro-catchments areas.

The post-glacial development of lakes and their shorelines in deglaciating high mountains does not constitute a threat to nature, as is currently in many mountains with existing mountain glaciers (e.g. Bajracharya and Mool 2009, Emmer and Vilímek 2013). Rather, it is now considered an interesting and valuable alpine landscape element from ecological, hydrological, geomorphological, aesthetic, and tourist viewpoint. Owens and Slaymaker (1994) and Hreško et al. (2012) add that the lakes form an integrated fragile geomorphological-hydrological system.

DOI: *https://doi.org/10.33542/GC2021-1-01*

Geophysical research of sedimentation in valley beds has included indirect observations on alpine glacial lake infillings by fragments and wastes from surrounding slopes (Owens and Slaymaker 1994, Hinderer 2001, Schrott et al. 2003, Götz et al. 2013). Besides, the first geomorphological research and lake mapping in the High Tatras highlighted these lake infilling processes (Rehman 1892, Schaffer 1930, Szaflarski 1933) and they were also thoroughly covered in the first comprehensive relief studies and detailed geomorphological mapping of both Slovak and Polish mountain aspects. Authors have also provided indirect evidence of decreased lake volume and water surface area caused by the High Tatras morphodynamic processes (Lukniš 1973, Hreško and Boltižiar 2001, Hreško et al. 2003, Gregor 2005, Gregor and Pacl 2005, Hreško et al. 2008, Kapusta et al. 2010, Boltižiar et al. 2016, Gallik and Bolešová 2016, Kłapyta et al. 2016).

In contrast, direct evaluation and evidence of mountain glacial lakes shrinkage based on the retrospective analysis of satellite and aerial photos have been rare, with shrinkage only noted in studies where it is peripheral or a secondary outcome of other land phenomena (Kapusta et al. 2010, Hreško et al. 2012, Necsoiu et al. 2016a, b, Kapusta et al. 2018). These changes capture shoreline development over time from exposure to current exogenous geomorphological processes in glacial lakes and their catchment areas. The shorelines changes show that glacial lakes are open and dynamic systems, rather than being stable and unchanging.

Direct research methods include:

(1) Remote Earth Sensing (RES) offers a high resolution for studying the processes and changes in high mountains. This is very effective in the following mapping, glacier and snow cover changes, geomorphological processes and forms (Druga et al. 2014, Necsoiu et al. 2016b, Onaca et al. 2016), and vegetation and landscape structure (Boltižiar 2001, Falťan and Bánovský 2004, Boltižiar 2007, Kaczka et al. 2015).

(2) Satellite and aerial photos are very suitable for mapping lake and wetland changes, with many types of research documenting short term changes (Giardino et al. 2010, Delparte et al. 2014) and especially long term changes (Falťan et al. 2011, Necsoiu et al. 2013, Song et al. 2014).

(3) Glacial lake area changes established from a retrospective analysis of satellite and aerial photos were documented in high mountains by Quincey et al. (2005), Bajracharya et al. (2007), Komori (2008), Quincey and Glasser (2009), Ye et al. (2009). Kääb and Haeberli (2011) and Strozzi et al. (2012). While these studies are focused mainly on the increased lake surface from climate change and melting mountain glaciers (Ageta et al. 2000, Watanabe et al. 2009, Ives et al. 2010, Byers et al. 2013), other authors reported catastrophic rupture of unstable moraine dams and rapid release of water from lakes caused by Glacial Lake Outburst Flood (GLOF) effects with subsequent floods and slope movement (Clague et al. 2000, Bajracharya and Mool, 2009, Janský et al. 2010, Emmer and Vilímek 2013, Schaub et al. 2013, Emmer, 2017).

Most other available literature focuses on mountain lake growth. Capturing small changes is difficult because only high-resolution orthophotomaps provide the reguired quality and cartographic precision. Therefore, accurate documentation of high-mountain glacial lakes infilling with sediment from a comparison of historical and current orthophotomaps has rarely been achieved. Also, Necsoiu et al. (2016a) record that cartographic accuracy and the reliability of capturing lake shrinkage from historical maps is questionable compared to the precise retrospective analysis of historical and current orthophotomaps (Kapusta et al. 2018).

Although deposition in the High Tatras lakes has been tacitly accepted for a long time, no potential or actual lake shrinkages have been systematically examined, or proven. The main objective of our research, therefore, is to directly identify cartographic evidence in detail and thus evaluate tarns shrinkage. Our method is a systematic multitemporal analysis of all remote sensing data concentrating on the area and geomorphological processes (Kapusta et al. 2018). To the best of our knowledge, this is the first research in the High Tatras assessing changes in the lake infilling by retrospective analysis of historical and actual RES materials. It shows the systematic nature of irreversible changes from all available materials from the territory. On this basis, even today, it presents the most intense ways of tarns' extinction.

Study area

The Tatry Mts. are the highest range in the 1,200 km long mountain range of the Carpathians. In particular, Tatry Mts. cover 785 km^2 of the northern arc of the Western Carpathians, with 78% (610 km^2) situated in Slovakia and the remaining 22% (175 km^2) in Poland. The manifold activity of the mountain glaciers during the Pleistocene formed the morphology of glacial troughs separated by sharp ranges and peaks. Two-thirds of the area is located at an altitude above 1,500 m a.s.l. The Tatry Mts. are geomorphologically divided into Western and Eastern. The High Tatras are a geomorphological sub-unit of the Eastern Tatry Mts. and are also the highest part of the Tatry Mts.

The Tatry Mts. are the most glaciated massif of the Carpathians, glaciated at least three times in the Quaternary and 55 mountain glaciers covered 279 km^2 of its area in the last ice age (Lukniš 1973, Zasadni and Kłapyta 2014). The last glaciation lasted about 60,000 years, with a decline commencing approximately 19,000–22,000 years ago and ending 8,500–10,000 years ago (Lukniš 1973, Baumgart-Kotarba and Kotarba 2001, Engel et al. 2015, Makos 2015). The largest glacier was 13.4 km long and almost 400 m thick (Zasadni and Kłapyta 2014). The High Tatras are mostly composed of granodiorites, which emerged as the crystalline core. They are tectonically disrupted in many places, and this resulted in the formation of mylonite zones with high production of rock scree. The scree is the source of unstable detritus which accumulated under rock walls in the form of massive Holocene cones with a height from a few metres to almost 450 m (Lukniš 1973, Kalvoda 1974). The characteristic glacial relief forms were transformed in the Holocene by exogenous morphodynamic processes and their intensive modelling is still in progress. Debris flow induced by extreme rainfall produced the most dynamic and influential current processes (Raczkowska 2006, Kotarba 2007, Kapusta et al. 2010, Gadek et al. 2016, Šilhán and Tichavský 2016).

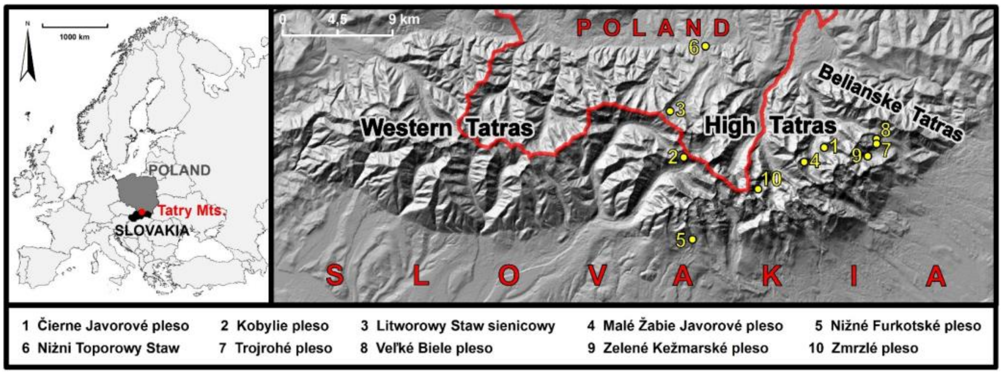

Fig. 1. *Location of the Tatry Mts. and the studied tarns in the High Tatras*

The tarns in the Tatry Mts.

There are approximately 300 different-sized lakes in the Slovak and Polish parts of the Tatry Mts. (Paryska-Radwańska et al. 2004, Kłapyta et al. 2016). The majority of them are located in the High Tatras, mostly concentrated in the alpine portion above the upper forest limit of 1,500 m a.s.l – (221 lakes, including 116 permanent ones). Many are seasonal, and there are also several extinct lakes in the form of upland peat-bogs and lake basins filled with detritus. Pociask-Karteczka et al. (2014) record the total surface of the Tatry lakes at 3.23 km^2, and small lakes with less than 1 ha surface area and up to 2 m deep predominate (Gregor and Pacl 2005). The largest lake is Morskie Oko with an area of 0.35 km^2 and the deepest lake Wielki Staw with a depth of 79.3 m. Both these lie in the northern Polish part of the High Tatras. The highest permanent lake is Modré pleso at 2,189 m a.s.l., and the seasonal 2,207 m a.s.l. Baranie pliesko lake lies in the Malá Studená dolina valley.

There are lakes in almost every High Tatras´ valley, mostly in corries at the end of the valleys (Lukniš 1973). Their surface is covered by ice from 130 up to 330 days annually, depending on the elevation, lake basin morphometry, and topographic and microclimatic conditions (Pacl and Gregor 2010, Novikmec et al. 2013). The Tatry lakes are relatively well supplied with water most of the year, with low water-level fluctuations and levels varying only temporarily in longer droughts (Gregor and Pacl 2005, Kapusta et al. 2010, Kłapyta et al. 2016).

Lake types

The larger lake basins most likely result from several glaciations, but formation of their base surface and depth ended 20,000 years ago at the climax of the High Tatras last ice age (Pacl and Gregor 2010). The highest lying lakes are the youngest and these are divided into the corrie, moraine-dammed, and mixed, dependent on the formation processes.

(1) Corrie lakes are situated at the uppermost parts of valleys where glaciers hollowed noticeable depressions. This often occurred at the tectonically disrupted parts of rocks, and they are therefore usually deeper with a simple shoreline shape (Lukniš 1973, Gregor and Pacl 2005).

(2) Moraine-dammed lakes mostly lie in the middle and lower parts of the valleys, at the lower valley levels. They were formed by moraine ramparts damming of the valley with consequent water accumulation, or by heating the dead ice floes buried under the detritus. Their basins are more shallow, from a few tens of centimetres to several metres. The shape of the shoreline is usually more complex through the influence of Holocene morphodynamic processes (Lukniš 1973, Gregor and Pacl 2005, Kapusta et al. 2010, Kłapyta et al. 2016).

(3) Combined, mixed, lakes predominate in the High Tatras. The original glacier-hollowed basins were dammed and covered with moraine ramparts (Lukniš 1973, Klimaszewski 1988). Several smaller lake basins had developed in rock glaciers or by the karst processes. Increased water levels from changes in natural moraine dam permeability by peat sediments are rare (Rybníčková and Rybníček 2005).

Lake development underwent different dynamics after the decline of glaciers. While some lakes altered only slightly from the beginning of the Holocene, others succumbed to significant changes over thousands of years and even dried-up. Major shoreline changes included processes involved in gravitational slope, water, gravity, cryogenic, nival, and organogenic conditions. Material accumulation and transport led to lake basins infilling, with irreversible area reduction and gradual loss of open water surface area. Kłapyta et al. (2016) record that this lake basin sedimentation began 8,000–9,000 years ago.

The disruption to unstable moraines by river flood flows contributed to the gradual drying-up of many lake basins. Disruption gradually sliced through natural lake dams producing lower water levels, and lake sediments infilling led to conspicuous alluvial plain formation, thus providing indirect evidence of their initial larger size.

Material and methods

We have identified 38 tarns with a presumed decrease in their area. This was based on the initial visual analysis of historical aerial photographs and current orthophotomaps which covered the entire Tatry mountain area. We then selected the ten tarns with the greatest or most representative changes (Fig. 1), and here we present their detailed cartographic analysis. Analysis over the shortest periods is presented wherever it was possible.

Historical aerial photos and actual orthophotos identified changes in the Tatry lake shorelines because this provides the most accurate detailed mapping and assessment of alpine landscape changes. We employed color and infrared orthophotos with 20–50 cm/pixel resolutions created in 1998, 2003, 2006, 2009, 2015, and 2018 by Eurosense Ltd. Bratislava. The infrared spectrum provided a strong contrast between the lake surface and surroundings and thus enabled reliable shoreline identification in disputed areas. The 1949, 1955, 1964, 1973, 1983, 1986, 1997, 1999, 2001, 2003, 2009 and 2015 historical aerial photographs enabled the identification of the earlier changes of shorline. The Topographic Institute in Banská Bystrica and the Polish Central Geodetic and Cartographic Documentation Center, provided high-resolution material that was easy to read even in a detailed scale (there were the panchromatic aerial black and white images, they were scanned at 1,200 dpi resolution in TIFF digital format (include citation of the format license holder).

Historical aerial photographs were not georeferenced. It was necessary to properly georeference these materials and subsequently compare them with accurate orthophotomaps from recent years and thus identify changes of the shoreline. However, due to the large vertical fragmentation of the area, the entire historical aerial photographs were not georeferenced, but their small sections (parts) were. Therefore, small areas were georeferenced, which depicted the immediate surroundings of each monitored tarn (in the order of several meters to a few tens of meters from the shoreline). Using this method, potentially significant positional errors were eliminated as much as possible.

Lake areas ascertained from historical aerial images were precisely georeferenced in the GIS environment based on a larger number of ground control points (GCPs). GCPs were placed on or near the shoreline of each tarn to be at approximately the same altitude. They were placed mainly on elements that were identified as stable. For example, significant and unchanging curvatures of the shoreline, stable large stones near the shorelines, stable solitary trees or dwarf mountain pines etc.).

Each image was spatially assigned according to a minimum of 20–30 GCPs, thus providing transformation of historical images to precise historical orthophotomaps with minimal spatial distortion. The third-order polynomial transformation was employed and the total RMS error was between 0.5 and 1 m.

Shorelines were manually vectorized by a visual on-screen interpretation of orthoimagery in GIS. The main prerequisite here was the detailed demarcation of the current extent of the lake and retrospective analysis (i.e. backdating) with the latest orthophoto time-series providing shoreline changes (Feranec et al. 1997, Feranec et al. 2005). The mapping scale ranged from 1:300 to 1:500. All operations were performed in the ArcGIS 10 environment. The retrospective analysis was complemented by DTM analysis wherever it was possible, in order to compare the most accurate 1961–1964 lake mapping and our GPS measurements and field research.

This method minimizes mapping inaccuracies, especially those resulting from the simple incorrect laying of individual map layers on each other. Retrospective analysis imposes rules for creating overlapped layers. The latest digital layer of the shoreline was taken as a basis. When digitizing the shorelines in older time horizons, no more digital layers were created in GIS. Copies were only made of the latest state, which were adjusted in places where there were logical changes during the reference period.

Small residual polygons do not appear when creating new layers, and results are not burdened by positional errors and inaccuracies. Retrospective analysis is the most appropriate method of identifying landscape structural changes over time. It has a broad use in mapping land cover and assessing glacier change (Petrakov et al. 2016) and also in identifying geomorphological dynamics (Kapusta et al. 2010, Długosz and Kapusta 2015). Although examples of a retrospective analysis of lake shorelines based on remote sensing data exist, e.g. Bajracharya and Mool (2009), Watanabe et al. (2009), Quincey and Glasser (2009), Strozzi et al. (2012), Emmer and Vilímek, (2013), Emmer et al. (2015), Tourian et al. (2015) and Emmer (2017), none of them show the shrinkage of alpine lakes/reduction of shorelines of the glacial lake caused by geomorphological processes acting on the lake basins.

We tested the reality of using backdating in the Tatry tarns in the work of Kapusta et al. (2018). In the current work, we provide the most detailed, newest, and most valuable results from a similar analysis of the tarns from the entire territory of the High Tatras. For the first time, apart from new changes caused by the systematic contribution of the debris material into the lakes, we also show the systematic nature and development of the changes, which in some lakes were caused by vegetation growth of their water surface.

The structural patterns characteristic of the landscape were identified by multitemporal orthophoto map analysis and as well as by some of the GIS properties, such as/i.e. structure, and color. Finally, the typical geomorphological processes, causing glacial lakes shoreline change had very specific patterns.

Results and Interpretation

Out of all the High Tatras tarns (221 tarns), we have identified 38, which showed an observable decrease in areas of water on orthophotomaps between the years 1949 and 2018. Thus, negative changes affected 17% of the tarns.

While most of the identified High Tatras lakes had no visible shoreline changes within the monitored period, others displayed noticeable changes (Fig. 2, 3). These were caused by large inputs of detritus to the lake basins from surrounding slopes and catchments, with a consequent decrease in open water area and level (Fig. 2, 4), or gradual vegetation overgrowth in the lake basins (Fig. 3, 5).

From the total of 38 lakes assessed in detail by prior identification of RES materials, 10 representative lakes were selected to analyze changes, and these are covered in the greatest detail (Tab. 1, Fig. 1, 2, 3). Gradual development occurred in some lake shorelines in several time horizons of the 1949–2018 monitored period. Detected shoreline changes were projected into the surface losses in lake open-water level (Tabs. 1, 2, Fig. 6). The Trojrohé pleso and Zmrzlé pleso lakes provide clear examples of specific infilling methods and developments in lake shoreline dynamics.

While some lakes showed changes only in one of the observed intervals, the shoreline of others changed relatively regularly over the entire monitored period (Tab. 1, Fig. 2, 3). The total shrinkage of Kobylie pleso, Niżni Toporowy Staw, and Trojrohé pleso lakes is shown over the entire period. This total comprises slight changes in the given time intervals, but it is dependent on possible lower quality in the older map materials and aerial photos.

Absolute changes in the monitored period covered losses in open-water surface area ranging from 100 to 1,848.3 m^2. The highest absolute surface losses were recorded in the following lakes: Veľké Biele pleso, Čierne Javorové pleso and Zelené Kežmarské pleso (Tab. 1, Fig. 7, 10). Relative changes consisting of 2.5% to 32.2% losses of original surface area were recorded in 1949 and 1955 (Tab. 2, Fig. 7). The highest percentage losses between 1949 and 2018 were recorded at 32.2% for lake Litworowy Staw Gąsienicowy, 29.7% for Kobylie pleso, 19.0% for Veľké Biele pleso and 18.0% for Čierne Javorové pleso.

Tab. 1. *Total reduction of open water surfaces of tarns in 1949–2018*

	Tarn (Country)	Elevation (asl.)	Depth (m)	Surface (m^2) 1949	1955	1973	1986	1998	2003	2009	2018	Total reduction (m^2) 1949/1955*– 2018
1	Čierne Javorové pleso (SK)	1492,1	3,2	8069,8	x	7401,5	7148,3	7001,5	x	6796,0	6614,3	-1455,5
2	Kobylie pleso (SK)	1734,3	1,0	1045,2	x	xx	xx	xx	xx	xx	734,9	-310,3
3	Litworowy Staw Gąsienicowy* (PL)	1618,0	1,1	-	3517,1*	x	3087,1	x	2864,1	2711,5	2381,6	-1135,5
4	Malé Žabie Javorové pleso (SK)	1704,2	3,1	1727,1	x	x	x	1727,1	1527,3	x	1527,3	-199,8
5	Nižné Furkotské pleso (SK)	1626,0	1,2	1406,4	xx	xx	xx	1262,4	xx	xx	1184,3	-222,1
6	Niżni Toporowy Staw* (PL)	1089,0	5,9	-	5067,5*	xxx	xxx	xxx	xxx	xxx	4565,9	-501,6
7	Trojrohé pleso (SK)	1610,8	1,4	1811,5	x	xx	xx	xx	xx	xx	1711,4	-100,0
8	Veľké Biele pleso (SK)	1615,4	0,8	9726,8	x	xxx	9289,2	8910,7	x	8429,7	7878,5	-1848,3
9	Zelené Kežmarské pleso (SK)	1546,0	4,5	17509,5	x	16776,1	x	x	16245,1	x	16153,8	-1355,7
10	Zmrzlé pleso (SK)	1762,2	12,5	20843,4	x	x	20843,4	xxx	20312,9	x	20312,9	-530,5

** – the oldest historical aerial photos of particular lakes*
x – interpretation was not necessary
xx – interpreting of photographs in shorter time periods would be inaccurate due to minor changes
xxx – photos are not possible to be reliably interpretable

Tab. 2. Relative reduction of open water surfaces of tarns in 1949–2018

Tarn (Country)		Initial state		Reduction of open water surfaces (%)						
		1949	1955	1973	1986	1998	2003	2009	2018	1949/1955*–2018
1	Čierne Javorové pleso (SK)	100,0	-	-8,3	-3,1	-1,8	x	-2,5	-2,3	-18,0
2	Kobylie pleso (SK)	100,0	-	x	x	x	x	x	-29,7	-29,7
3	Litworowy Staw Gąsienicowy* (PL)	-	100,0	x	-12,2	x	-6,3	-4,3	-9,4	-32,2
4	Malé Žabie Javorové pleso (SK)	100,0	-	x	x	x	-11,6	x	x	-11,6
5	Nižné Furkotské pleso (SK)	100,0	-	x	x	-10,2	x	x	-5,6	-15,8
6	Niżni Toporowy Staw* (PL)	-	100,0	x	x	x	x	x	-9,9	-9,9
7	Trojrohé pleso (SK)	100,0	-	x	x	x	x	x	-5,5	-5,5
8	Veľké Biele pleso (SK)	100,0	-	x	-4,5	-3,9	x	-4,9	-5,7	-19,0
9	Zelené Kežmarské pleso (SK)	100,0	-	-4,2	x	x	-3,0	x	-0,5	-7,7
10	Zmrzlé pleso (SK)	100,0	-	x	x	x	-2,5	x	x	-2,5

* – the oldest historical aerial photos of particular lakes

Observed changes of the tarn area

One of the main reasons for the changes in the High Tatras lake shorelines and the loss of their open-water surface area was the accumulation of lake sediments in the shallow, peripheral parts of their basins. This formation of lake sediments is a typical morphodynamic phenomenon in the High Tatras alpine landscape. Field observation, retrospective shoreline analysis, and debris flow identified the following, (1) formation of sediments in tarns mainly involve debris flows, (2) the flows include sedimentation of fine fractions in the shallow parts of the lake basins (Fig. 2, 4 and 10) and (3) fine fractions are drained from adjacent debris cones, moraines and gutters during the high water saturation caused by extreme precipitation (Lukniš 1973, Gregor 2005, Gregor and Pacl 2005).

The valleys of the High Tatras often have areas with a slight angle or flat relief near the tarns and also below the debris flow fans. Lukniš (1973) records these as typical alluvial plains. They consist predominantly of gravel, sand, and fine fractions, and are often infilled former lake basin areas (Fig. 9). The alluvial plain formation consisted of debris flows of bifurcating streams with saturated suspended loads, and also sand and fine particles drained by water pressure from the alluvial fans of detritus cones. A gradual increase in this material produced shallower lake-basin coastal margins and debris accumulation up to the water surface level. Alpine vegetation is also well-rooted in the soft, damp loam soil and this contributes to lake sediment formation and increased alluvial plain area (Fig. 4).

All these processes interact with cumulative effects. The sediments of the debris flow fill the peripheral parts of the lake basins and fine fractions of both older and younger accumulations are washed out in basin glacis. Debris flows also provide rapid transport of weathered rock fractions from distant gutters to the lower parts of lake basins and debris cones' alluvial fans. They produced erosion gullies which changed after heavy rainfall into temporary watercourses, and these added alluvia to the lake basins. Debris flows sporadically penetrated lakes during sudden extreme precipitation. While a sufficient volume of sediments flowing into the shallow lake basin areas causes swift reduction of open lake water surface area (Fig. 10), flow into a deep and voluminous lake basin causes only reduction of water volume.

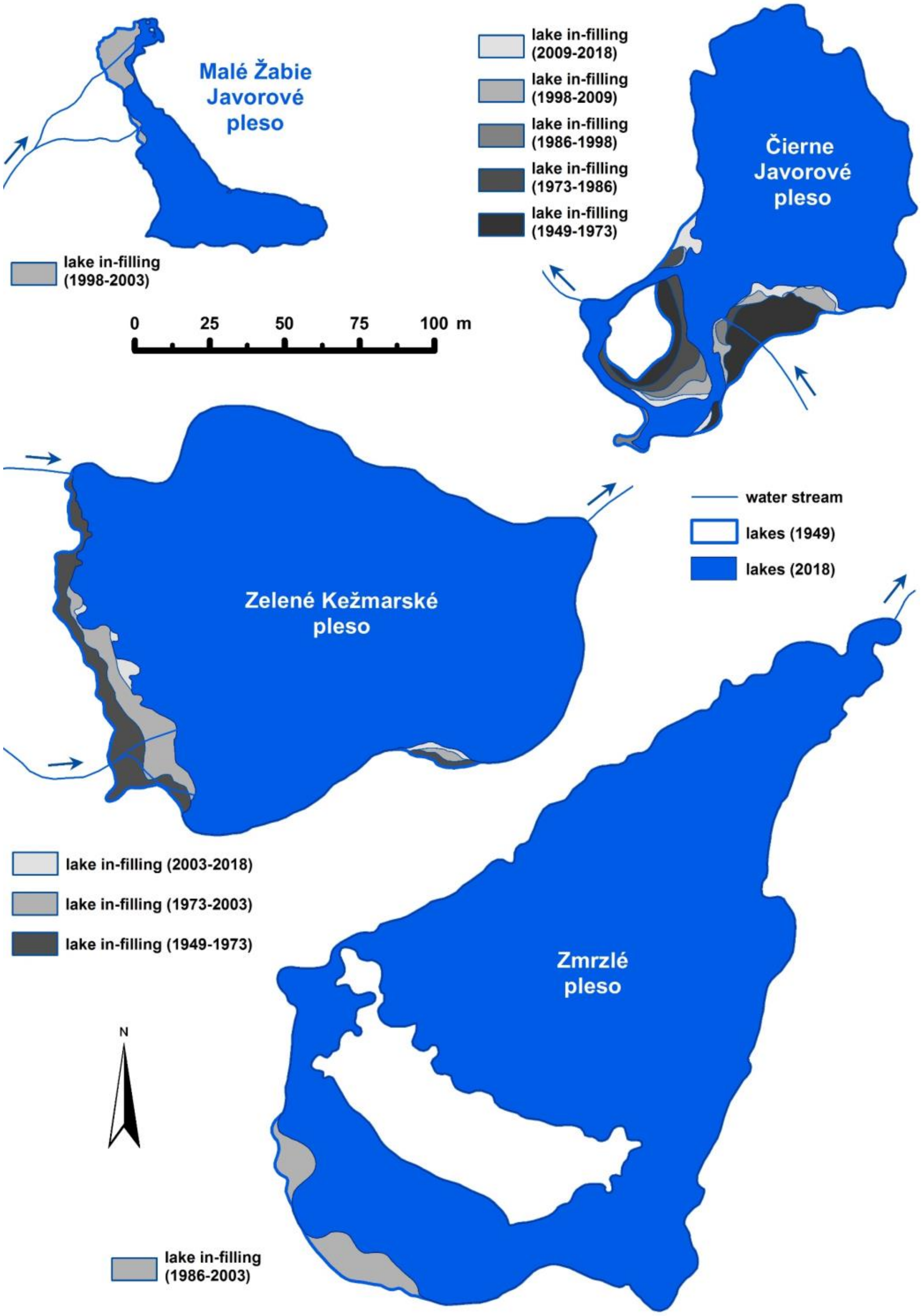

Fig. 2. *Shrinkage of tarns caused by material input from adjacent slopes in 1949–2018*

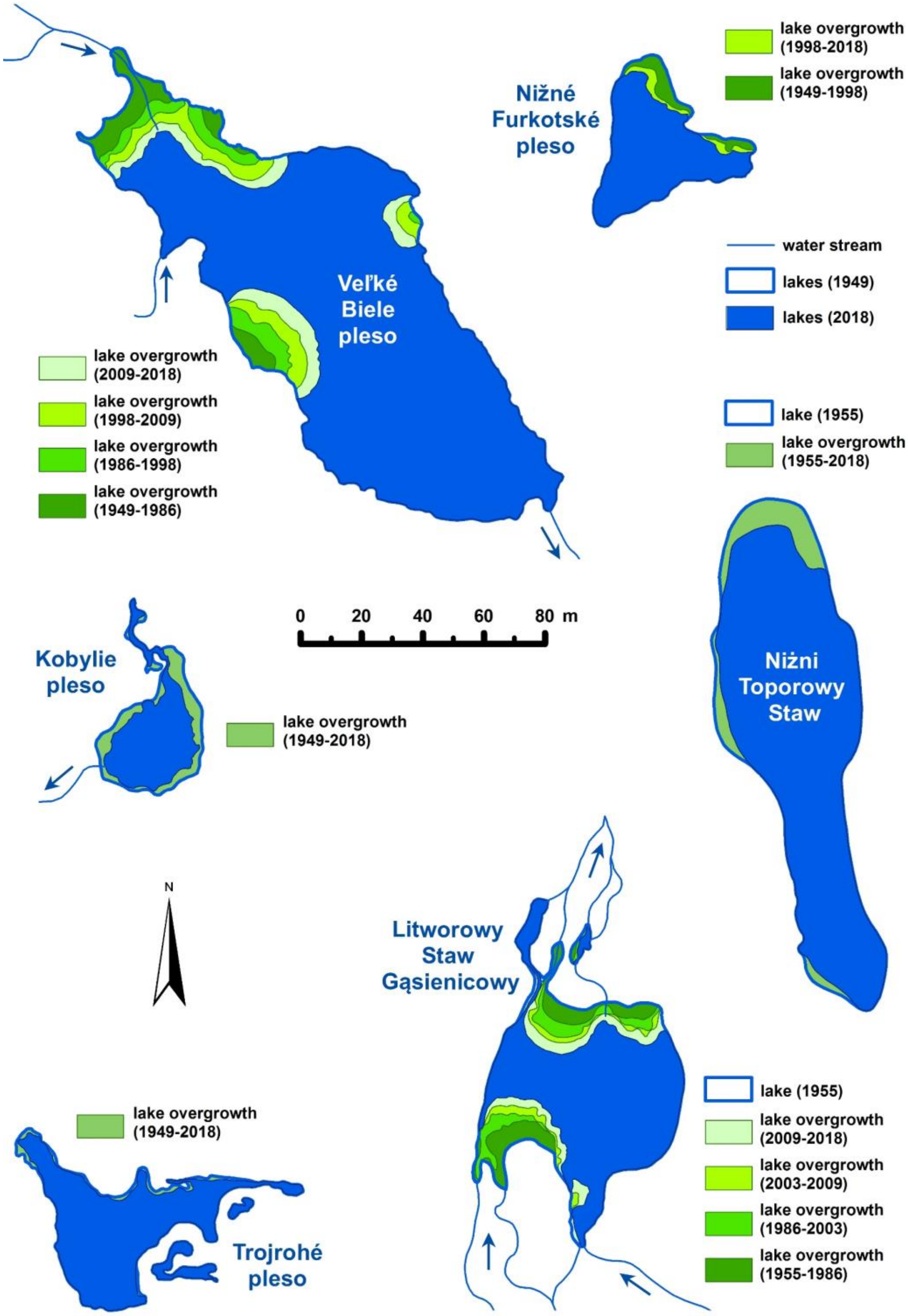

Fig. 3. *Tarn overgrowth by vegetation in 1949–2018*

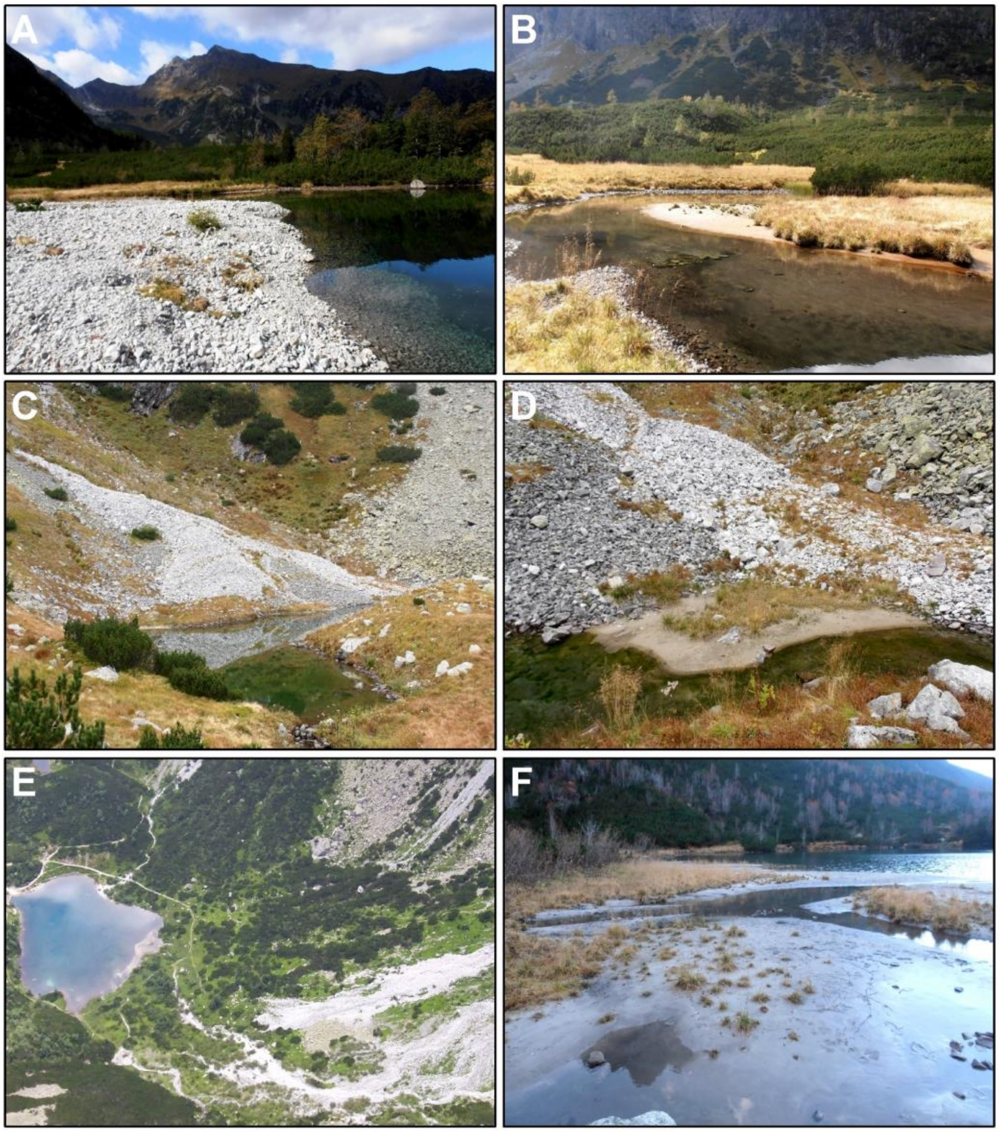

Fig 4. *A – Long-range, direct filling of Čierne Javorové pleso lake basin in the Javorová dolina valley by coarse debris flow fractions (photo: J. Kapusta, 2016), B – The formation of an island from fine fractions flooded out by water pressure from the debris flow and cone sediments into the lake basin. Fine sediments stabilised by vegetation over several years (photo: J. Kapusta, 2016), C, D – The Malé Žabie Javorové pleso tarn in the Javorová dolina valley is sporadically but directly filled with debris flows, from which fine fractions were flooded out during extreme precipitation (photo: J. Kapusta, 2016), E – The Zelené Kežmarské pleso tarn in the Dolina Kežmarskej Bielej vody valley is being intensively filled by debris flow sediments, by flooding out of fine fractions with the water pressure of adjacent cones and by alluvia of water flows, E – During extreme precipitation, debris flows reach the lake basin (photo: J. Kapusta, 2010), F – Fine fractions forming typical alluvial plain and comprise an ideal substrate for vegetation succession, which gradually stabilizes them (photo: J. Kapusta, 2014).*

The Čierne Javorové pleso tarn presents specific and relatively rare lake sedimentation and debris infilling (Fig. 4, 10). This tarn has several fault and mylonite zones with great amounts of wastes from gutters and cones during extreme precipitation and these are rapidly transported through water-courses into the lake. While coarse detritus fractions were gradually deposited at the point of inflow and caused the loss of relatively large water-level areas, the sand and fine fractions were washed further into the lake basin by water pressure, rapidly making the basin more shallow. Turbulent water flow caused fine sediment transmission over the lake bed, and this water flow in the Čierne Javorové pleso tarn enabled sediments to settle and gradually form a distinct island on the left side of the lake. The fine fractions were then gradually overgrown by herbaceous vegetation, and this further stabilised the island over the past decades. The gradual vegetation rise is obvious at the periphery, and its spread has enlarged the island to such an extent that the lake area has decreased by 1,455 m^2 since 1949 (Fig. 4).

The Zmrzlé pleso tarn also has specific lake dynamics. A typical island was created by sedimentary detritus from the surrounding slopes (Fig. 2, 8), and when the lake surface is frozen, the lake basin around the debris island creates "protalus ramparts". In contrast, in the summer absence of snow and ice, the peripheral SW portion of this tarn is silted by debris during extreme precipitation.

While the accumulation of lake sediments in the shallow, peripheral parts of the basins formed the main reason for shoreline change and lake shrinkage in 1949–2018, a further major cause was basin overgrowth by vegetation (Fig. 3, 5, 7, 10). This process mainly affected shallow basins with an average depth around 0.5 m, and with tens of centimetres or less at some edges. The shallowest basin margins are rapidly overgrown by aggressive vegetation, especially sedges and herbaceous species, and grass remnants accumulate under the water surface and gradually increase lake shallowness by forming a humus layer.

The greatest changes occure in shallow tarns such as Veľké Biele pleso and Litworowy Staw Gąsienicowy (Fig. 5, 10). The arms of these lakes strongly bifurcate where waters flows into them, and this allows a lot of fine suspended loads and sand from the higher parts of the catchment into the lake basins. These particles accumulate in the basins and create excellent substrate conditions for sedge root systems which can gradually expand in shallow areas at the expense of the open-water level (Fig. 5). In contrast, tarn Trojrohé pleso has lost a relatively small 5.5% of shoreline during the monitored period (Fig. 3). This is despite its complicated shape which has undergone significant change. Only the very shallow peripheral areas of this tarn have overgrown the sedge because its depth of approximately 1.4 m ensures that most of its periphery is too deep to accommodate vegetation.

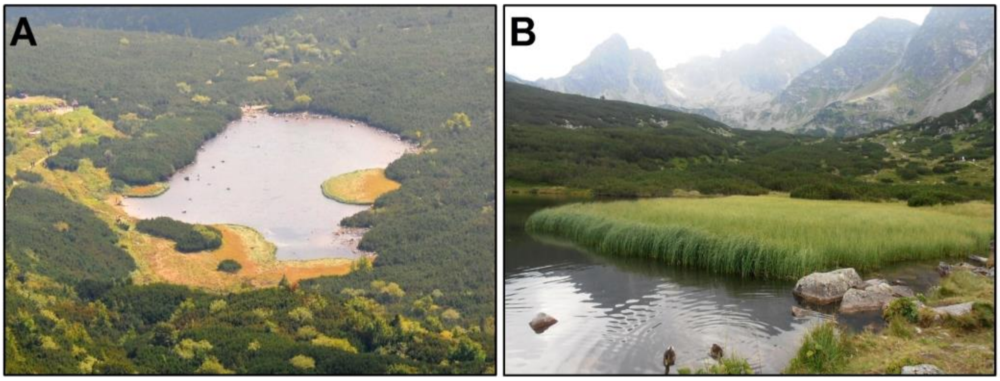

Fig 5. *A – The Veľké Biele pleso tarn in the Dolina Kežmarskej Bielej vody valley is intensively overgrown with vegetation. Ideal conditions for a rapid succession of vegetation are mainly created by the input of fine sediments transported into the tarn by inflows. (photo: J. Hreško, 2016), B – The Litworowy Staw Gąsienicowy tarn in the Dolina Suchej Wody valley has a small shallow basin, through which water flow flows. Peripheral shallow parts in the inflow and the outflow part of the tarn are overgrown with vegetation (photo: J. Kapusta, 2015).*

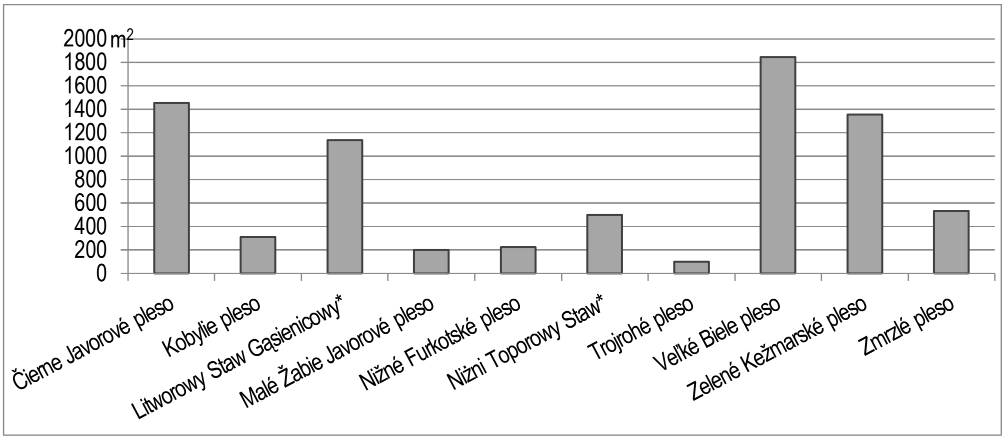

Fig. 6. *Total reduction of tarn surfaces in 1949–2018*

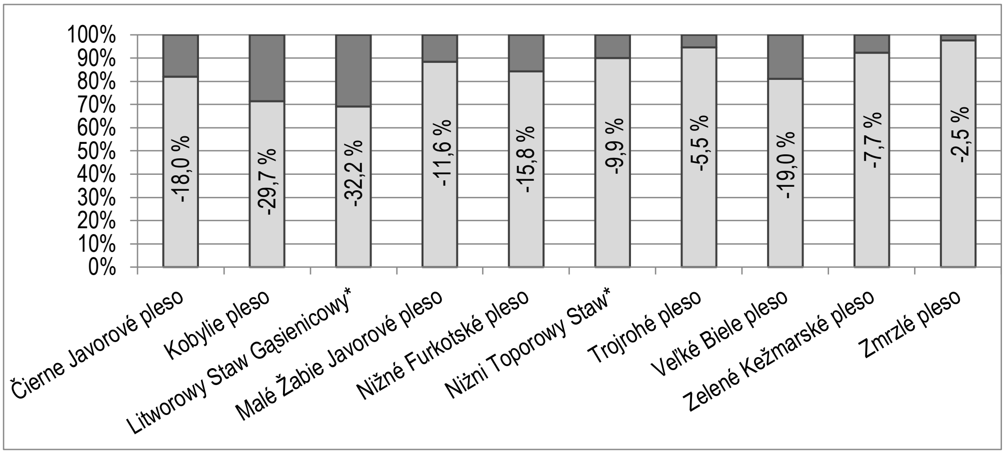

Fig. 7. *Relative reduction of tarn surfaces in 1949–2018*

Discussion

While the Tatry tarns shoreline shapes are important indicators of postglacial effects, they especially highlight current lake development by silting and morphodynamic processes. Shorelines significantly changed during the Holocene by the encroachment of vegetation, debris cones, and alluvial plains. The complicated shoreline shape in many lakes is evidence of past intensive morphodynamic processes, but some shorelines still continue to experience relatively high dynamics (Fig. 2, 3). These glacial lakes become arid, not through negative water balance but due to combined morphodynamic factors, especially geological conditions and extreme precipitations.

The influence of geological conditions on shoreline development and changes is reflected in localisation of mylonite and fracture zones which range from a few metres to 200–300 m. The largest sediment volumes are normally transported to lake basins from catchment areas with vast free-waste material. Relief geomorphological conditions determine the formation and development of some lake catchment morphodynamic processes. Here, the most suitable condition is gutters with substantial free and unstable detritus which rapidly drain the Tatry slopes and provide waterways for avalanches, loose stones and debris flows (Lukniš 1973, Kalvoda 1974, Hreško 1994, Klimaszewski 2005, Kapusta et al. 2010).

Field surveys highlight that favourable substrate conditions and water depth in peripheral basin areas are significant factors in lake shrinkage. The fine sediments in shallow lake areas enable strong vegetation expansion and consequent rapid overgrowth of the open-water surface, and this significantly influences the intensity of organogenic morphodynamic processes.

The current High Tatras tarns shoreline shapes and dimensions result from the interaction of both older and more recent relief forms and hydrological balance. In particular, the shapes of glacial lakes in the High Tatras are the most important indicators of both postglacial development and the intensive interaction of lakes and morphodynamic processes.

Fig. 8. *The Zmrzlé pleso tarn in the Bielovodská dolina valley with a characteristic detritus island. It is situated in a shady location under the main ridge of the High Tatras (view from the Vysoká peak (2,547.2 m a. s. l.), photo: J. Kapusta (2016).*

Causes of the lake area changes

High Tatras lake shrinkage is predominantly due to lake basin infilling with material from surrounding slopes and gradual vegetation overgrowth. While negative hydrological balance can cause drying-up and subsequent alluvial plains or vegetation overgrowth, combined influences, including climate and moraine rampart tightness, can help ensure that more water accumulates in the lake than flows out. However, some of the High Tatras lakes have their total surface area and water volume systematically decreases over time. Hence, a large number of already extinct lakes have been identified in valley depths, and these are now filled with lake sediments or completely overgrown with vegetation (Fig. 9).

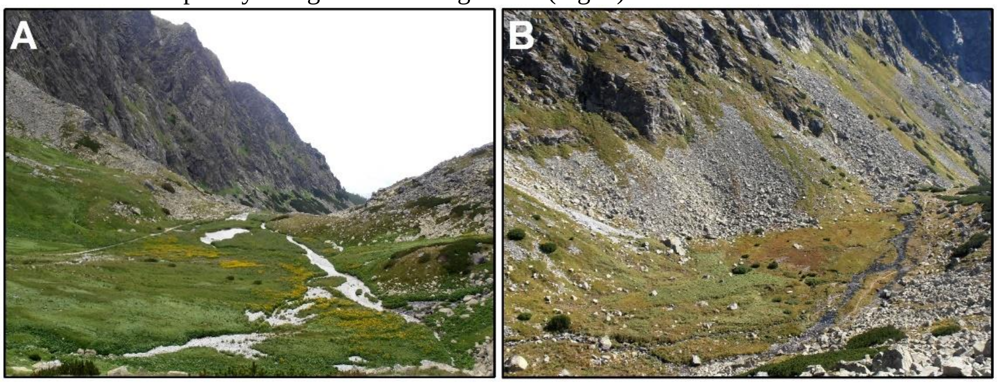

Fig. 9. *A – The almost completely filled Kvetnicové pleso great tarn basin in the Velická dolina valley (photo: J. Kapusta, 2012), B – Completely filled tarn basin of a former tarn in the Zlomisková dolina valley (photo: J. Kapusta, 2016).*

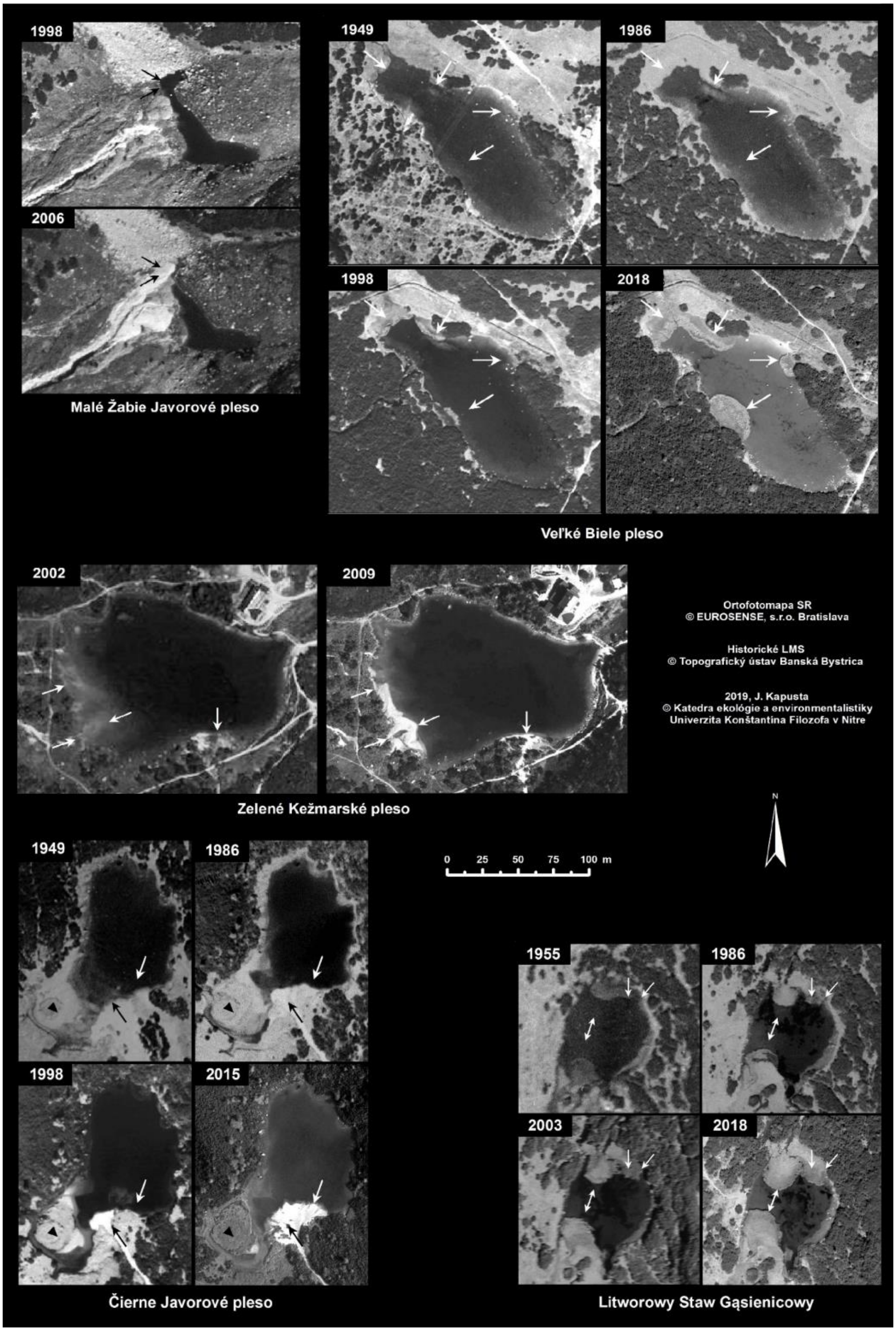

Fig. 10. *Selected tarns in the High Tatras in the series of orthophotos*

The following causes of the High Tatras lake shrinkage and shoreline dynamics were identified from orthophotomap analysis, RES, detailed analysis of geomorphological processes, and the synthesis of available literature (Lukniš 1973, Kalvoda 1974, Gregor 2005, Gregor and Pacl 2005, Klimaszewski 2005, Hreško et al. 2012, Kłapyta et al. 2016) on High Tatras lakes:

1. Infilling from debris flows – Debris flows are activated during extreme precipitation and they transport weathering products from the rock gutters and deposit them in the form of debris flow fans. The fan lower parts are gradually blown out and laid as typical debris tongues. Gradual material deposition propels the debris flow-fans foot into the lake. Where cones do not enter the lake directly, debris sedimentation of various fractions still comes from the outlying gutters at the cone foot. Consequently, this is blown into the lake during the next extreme precipitation. These processes are evident in tarns Čierne Javorové pleso, Zelené Kežmarské pleso, Malé Žabie Javorové pleso, Velické pleso, Zamrznuté pleso, Czarny Staw pod Rysami, and Morskie Oko.

2. Infilling by fine-grained fractions blown out of debris flow fans – In extreme precipitation and high water conditions, sand and small fractions from the alluvial fan foot are washed away by water pressure, and carried into lake basins. In addition, fine fractions can also be washed out of higher moraine unsustained material. Thus, lake basin coastal areas gradually become more shallow until part of the open water surface dries-up and typical alluvial plains are formed, as in Zelené Kežmarské pleso, Zelené Kačacie pleso and Kolové pleso.

3. Infilling through the delta of the water stream and its bifurcating channels – Water streams bring alluvia into lakes in the form of fine-grained fractions during flood flows and higher water conditions. Thus, flat deltas and characteristic alluvial planes form at the mouth of streams. The stream beds can also use debris flows for transport because fine fractions and sand, which usually end up in lake basins, are washed out of the debris deposited on the stream bed by debris flow. These combined methods of lake siltation with debris flows, water streams, and the outflow of fine fractions are common dynamics in tarns Kvetnicové pleso and Zelené Kežmarské pleso.

4. Overgrowth of vegetation – Smaller, shallower moraine-dammed tarns located in lower areas reduce their areas through gradual vegetation overgrowth in the peripheral parts of their lake basins. Subsequently, the area of the water surface decreases. This overgrowth is often associated with the deposition of fine-grained fractions when soil is carried out by water flow. This occurs in Veľké Biele pleso and Litworowy Staw Gąsienicowy. Sedge and peat moss communities also gradually spread into lake basins and decomposing vegetation remnants create the initial stages of alpine wetlands and peat bog development identified in the following tarns: Trojrohé pleso, Malé Čierne pleso, Wyżni and Niżni Toporowy Staw, Małe Morskie Oko, Nižné Furkotské pleso and Kobylie pleso.

5. Direct infilling by dry detritus – High altitude tarns are silted with debris flow and gravitational processes, which form debris cones under rock walls and gutters. The cryo-nival vegetation zone of the High Tatras has predominant rock massif frost-weathering. This provides the production of fragmented wastes, with gravitational descent and permanent deposition directly into lake basins. Direct silting is very slow compared to the above-mentioned mechanisms, so its occurrence is quite difficult to conclusively date within a few decades. Dlhé pleso and Modré pleso tarns are good examples of this type of lake dynamics.

6. Infilling by snow avalanches and transport on firn fields mainly occurs at higher altitudes with favourable microclimatic and topographical spring conditions when lake surfaces are covered with ice and snow. Snow accumulates in the immediate environs of a frozen tarn, and cone surfaces transform over time into hard firn. The process creates an ideal sliding surface for falling detritus to settle a few metres inside the lake shoreline. Surface melt enables gradual accumulation on the lake basin bed, forming debris islands or alluvial plains. This is seen in tarns Zmrzlé pleso, Zamrznuté pleso, Vyšné and Nižné Bielovodské Žabie pleso, Czarny Staw Polski and Kriváňske Zelené pleso.

7. Drying-up and aridity from negative water balance – This situation relates to the stability of moraine sediments and their ability to retain water in the lake basin. When cementing fractions from the bottom of moraines or moraine ramparts are washed out, tarns can dry-up due to negative water balance. This results in the arid lake basin or a seasonal tarn. Increasingly longer periods of low water levels have occurred recently, as experienced in Skalnaté pleso.

8. Cutting through moraine-dammed tarns – cutting and erosion rely on the kinetic energy of running water-courses. The channel becomes deeper in the morainic rampart, thus weakening the barrier effect and producing water loss and lower water level. Morraine material is gradually removed by water drainage, with consequent crevasse formation. Sudden drainage is classified as the 'moraine-dam-breaking' apparent in Zelené Kežmarské pleso and the dry lake basins in the Dolina Zeleného plesa and Christlová valleys. This rampart-breaking process can occur in mountains where deglaciation is induced by the GLOF effect, and this mechanism often has catastrophic consequences.

9. Infilling by sudden rockfall processes – Unstable valley rock walls were released after glacier extinction in the early Holocene phases. Lake basins, such as Popradské pleso, Ľadové pleso and Kolové pleso have lost their original volume and extent due to these dynamics.

All these infilling and overgrowth processes can combine in tarns with a disastrous cumulative effect within a single lake basin.

Changes in global lake water surfaces and shorelines are reliant on many factors. The most important factor is climatic change, altered with hydrological balance and occasionally through tectonic activity and inappropriate water resource management (Liu et al. 2009, Necsoiu et al. 2013, Song et al. 2014, Hwang et al. 2016, Taravat et al. 2016). Climate change causes both glacier melting and permafrost degradation, which results in the changes in the hydrological regime, and consequent lake expansion (Bolch et al. 2008, Bajracharya et al. 2009, Watanabe et al. 2009, Ives et al. 2010). There is also a loss of water resources and lake surface area (Yoshikawa and Hinzman, 2003, Necsoiu et al. 2013). However, a decrease in open-water surface and lake shrinkage is not primarily caused by the loss of water resources and lakes drying-up, these changes mainly result from the infilling of water reservoirs and lake basins with sediments from their catchment areas. This is also independent of climate change influences (Choiński and Ptak 2009, Kapusta et al. 2010, Hreško et al. 2012, Kubinský et al. 2015). In particular, smaller shallow lakes react much more sensitively to the change than large lakes because of their small water volume and these are therefore the best indicators of ongoing catchment changes (Adrian et al. 2009).

In particular, the redeposition of older sediments is essential for sedimentation in mountain lakes. This is directly influenced mainly by suitable geomorphological and topographic conditions (Rubensdotter and Rosqvist, 2009). From our analysis, we can confirm that all tarns where changes were identified showed a high predisposition to key geomorphological processes. Detritus inputs (grooves of debris flow and riverbeds flowing directly into the lake basins of tarns) and the vicinity of alluvial cones or alluvial plains had the greatest predisposition to tarns that were backfilled with sediments. In the case of the most overgrown tarns, the key predispositions were, in particular, the supply of fine sediments by streams and the presence of older organic material in the marginal parts of lake basins.

Area loss in the High Tatras tarns is not primarily caused due to climate change (e.g. due to a negative water balance), as has been demonstrated in other regions (e.g. Yoshikawa and Hinzman 2003, Adrian et al. 2009, Liu et al. 2009, Song et al. 2014). However, it turns out that climate change can have an indirect effect on the areal changes of the Tatry tarns and their extinction by affecting the size and intensity of geomorphological processes. Increased redeposition of older sediments from the slopes to the lake basins, and thus increased sedimentation in the tarns during some periods is obviously influenced by the increased intensity of extreme precipitation (Kapusta et al. 2010, Hreško et al. 2012, Gądek et al. 2016). Additions of organic material in lake basins and organogenically caused surface losses of tarns are in turn clearly influenced by the supply of fine sediments and increasing shallowness of the peripheral parts of lake basins but are probably also influenced by conducive temperature conditions for the growth of expanding vegetation (Kapusta et al. 2010).

Historical and current orthophotomaps are in most cases the most suitable materials for detailed monitoring of lake surface changes. High resolution and positional accuracy are their biggest advantages. However, their objective interpretation in heavily shaded locations or in the mapping of water areas in forest stands can be problematic. Misinterpretation can result in relatively high positional inaccuracies in mapping shorelines. Extreme fluctuations in water levels could also be a source of errors in the interpretation of surface changes. For this reason, it is imperative to sensitively compare the identified area changes with the existing bathymetric maps, equally to focus on a comprehensive and logical evaluation of the entire time series of historical orthophotomaps, or to regularly survey the terrain over a longer period of time.

Conclusion

Lake shrinkage is an important indicator of the postglacial development of lake basins in the High Tatras. This paper highlights the great benefits of using orthophotomaps and high-resolution historical aerial photos in the research of glacial lake and shoreline dynamics. It also presents the first known analysis and spatial identification of changes in the High Tatras glacial lake shorelines from the assessment of the oldest and the latest high-resolution orthophotomaps. Accurate retrospective analysis of these lakes from 1949 to 2018 captures significant glacial lakes changes driven by morphodynamic processes and infilling of the lake basins.

All available aerial photography materials of both Slovak and Polish Tatry areas were analysed. We established maximum losses of up to 32% of the original 1949 open-water surface area in ten representative shallow lakes during the study period. Detailed retrospective analysis of lake shorelines based on RES materials has enabled long-term monitoring of changes in lake basins and their interactions with morphodynamic processes. Future research will also place greater emphasis on the investigation of arid lake basin micro-catchments.

The research should continue with regular monitoring of changes at selected tarns, thus capturing further developments over time. In some cases, area changes also deduce significant volume changes of the tarns. Based on the identified area changes, it is then possible to focus on analysing the expected changes in volume. Further research should therefore be aimed at capturing volume changes over a period of time.

The combination of retrospective analysis and field surveys has proven to be the most suitable method of monitoring lake shoreline dynamics over time, and also the best way to determine area changes from ongoing morphodynamic processes. Our overall results and the current complex course of lake shorelines highlight that some High Tatras lakes are already in advanced stages of development. Significant loss of open-water surface over several decades was confirmed in selected lakes which have succumbed to sediment deposition and vegetation overgrowth. Although the long-term systematic infilling is confirmed by the development of typical alluvial plains, our research established no major change to the High Tatras lake shorelines over the past 65 years. Many lakes have successfully endured systematically reduced retention capacity due to sediment supply from their catchments. Further, current infilling is not reflected in surface changes because of the sufficient depth, volume, and size of these lake basins.

The tarns in the High Tatras are very sensitive indicators of recent changes in their catchments. The changes in shorelines presented in this paper, and their causes, are intended to enhance understanding of the complex dynamics and intensity of processes near these lakes. Finally, the tarns in the High Tatras provide a perfect example of the development of glacial lakes after complete deglaciation of relief in high mountains which are still glaciated.

References

ADRIAN, R., O'REILLY, C.M., ZAGARESE, H., et al. 2009: Lakes as sentinels of climate change. *Limnology and Oceanography,* 54, 2283-2297. DOI: http://dx.doi:10.4319/lo.2009.54.6_part_2.2283.

AGETA, Y., IWATA, S., YABUKI, H., NAITO, N., SAKAI, A., NARAMA, CH. 2000: Expansion of glacier lakes in recent decades in the Bhutan Himalayas. In Nakawo, M., Raymond, C. F., Fountain, A. eds. *Debris-covered Glaciers, Proceedings of a Workshop*. Seattle (IAHS), 264, pp. 165-175.

BAJRACHARYA, B., SHRESTHA, A. B., RAJBHANDARI, L. 2007: Glacial Lake Outburst Floods in the Sagarmatha Region. *Mountain Research and Development*, 27(4), 336-344. DOI: http://dx.doi.org/10.1659/mrd.0783.

BAJRACHARYA, S.R., MOOL, P. 2009: Glaciers, glacial lakes and glacial lake outburst floods in the Mount Everest region, Nepal. *Annals of Glaciology*, 50, 81-86.

BAUMGART-KOTARBA, M., KOTARBA, A. 2001: Deglaciation in the Sucha Woda and Pańszczyca Valleys in the Polish High Tatras. *Studia Geomorphologica Carpatho-Balcanica*, 35, 7-38.

BOLCH, T., BUCHROITHNER, M.F., PETERS, J., BAESSLER, M., BAJRACHARYA, S. 2008: Identification of glacier motion and potentially dangerous glacial lakes in the Mt. Everest region/Nepal using spaceborne imagery. *Natural Hazards and Earth System Sciences,* 8, 1329-1340. DOI: www.nat-hazards-earth-syst-sci.net/8/1329/2008/.

BOLTIŽIAR, M. 2001. Evaluation of vulnerability of high-mountain landscape on example Velicka dolina valley in the Vysoke Tatry Mountains. *Ekológia (Bratislava)*, 20 (Supplement 4), 101-109 .

BOLTIŽIAR, M. 2007: *Štruktúra vysokohorskej krajiny Tatier.* Nitra (Ústav krajinnej ekológie SAV), 248 p.

BOLTIŽIAR, M., BISKUPIČ, M., BARKA, I. 2016. Spatial modelling of avalanches by application of gis on selected slopes of the Western Tatra Mts. And Belianske tatry Mts. Slovakia. *Geographia Polonica*, 89(1), 79-90.

BYERS, A.C., MCKINNEY, D.C., SOMOS-VALENZUELA, M., WATANABE, T., LAMSAL, D. 2013: Glacial lakes of the Hinku and Hongu valleys, Makalu Barun National Park and Buffer Zone, Nepal. *Natural Hazards*, 69(1), 115-139. DOI: http://dx.doi:10.1007/s11069-013-0689-8.

CLAGUE, J.J., EVANS, S.G. 2000: A review of catastrophic drainage of moraine-dammed lakes in British Columbia. *Quaternary Science Reviews*, 19, 1763-1783.

DELPARTE, D.M., BELT, M., NISHIOKA, C., TURNER, N., RICHARDSON, R.T., ERICKSEN, T. 2014: Monitoring Tropical Alpine Lake Levels in a Culturally Sensitive Environment Utilizing 3D Technological Approaches. *Arctic, Antarctic, and Alpine Research*, 46(4), 709-718. DOI: http://dx.doi.org/10.1657/1938-4246-46.4.709.

DŁUGOSZ, M., KAPUSTA, J. 2015: Debris Flows In Dąbrowska, K., Guzik, M., eds. *Atlas of the Tatra Mountains – Abiotic Nature, plate V.2.*. Zakopane (Wydawnictwo Tatrzańskiego Parku Narodowego).

DRUGA, M., FALŤAN, V., HERICHOVÁ, M. 2014. The purpose of historical land cover change mapping in the territory of Slovakia in the scale 1: 10 000 – case study of historical cadastral area of Batizovce. *Geographia Cassoviensis*, 9(1), 17-34.

EMMER, A., VILÍMEK, V. 2013: Lake and breach hazard assessment for moraine-dammed lakes: an example from the Cordillera Blanca (Peru). *Natural Hazards and Earth System Sciences*, 13, 1551-1565. DOI: http://dx.doi:10.5194/nhess-13-1551-2013.

EMMER, A., MERKL, S., MERGILI, M. 2015: Spatiotemporal patterns of high-mountain lakes and related hazards in western Austria. *Geomorphology,* 246, 602-616. DOI: http://dx.doi.org/10.1016/j.geomorph.2015.06.032.

EMMER, A. 2017: Geomorphologically effective floods from moraine-dammed lakes in the Cordillera Blanca, Peru. *Quaternary Science Review,* 177, 220-234.

ENGEL, Z., MENTLÍK, P., BRAUCHER, R., MINÁR, J., LÉANNI, L., TEAM, A. 2015: Geomorphological evidence and 10Be exposure ages for the Last Glacial Maximum and deglaciation of the Veľká and Malá Studená dolina valleys in the High Tatra Mountains, central Europe. *Quaternary Science Reviews*, 124, 106-123. DOI: http://dx.doi.org/10.1016/j.quascirev.2015.07.015.

FALŤAN, V., BÁNOVSKÝ, M. 2008: Changes in land cover in the area of Vyšné Hágy-Starý Smokovec, impacted by the wind calamity in November 2004 (Slovakia). *Moravian Geographical Reports*, 16, 16-26.
FALŤAN, V., BÁNOVSKÝ, M., BLAŽEK, M. 2011. Evaluation of land cover changes after extraordinary windstorm by using the land cover metrics: a case study on the High Tatras foothill. *Geografie*, 116(2), 156-171.
FERANEC, J., CEBECAUEROVÁ, M., CEBECAUER, Et.al. 1997: *Geographia Slovaca 13: Analýza zmien krajiny aplikáciou údajov diaľkového prieskumu Zeme*. Bratislava (Geografický ústav SAV), 64 p.
FERANEC, J., CEBECAUER, J., OŤAHEĽ, J. 2005: *Photo-to-photo interpretation manual*. Bratislava (Institute of Geography, Slovak Academy of Sciences, BIOPRESS), 104 p.
GĄDEK, B., GRABIEC, M., KĘDZIA, S., RĄCZKOWSKA, Z. 2016: Reflection of climate changes in the structure and morphodynamics of talus slopes (the Tatra Mountains, Poland). *Geomorphology*, 263, 39-49. DOI: http://dx.doi.org/10.1016/j.geomorph.2016.03.024.
GALLIK, J., BOLEŠOVÁ, L. 2016: sUAS and their application in observing geomorphological processes. *Solid Earth*, 7, 1033-1042. DOI: http://dx.doi:10.5194/se-7-1033-2016.
GIARDINO, C., OGGIONI, A., BRESCIANI, M., YAN, H. 2010: Remote Sensing of Suspended Particulate Matter in Himalayan Lakes. *Mountain Research and Development*, 30, 157-168. DOI: http://dx.doi.org/10.1659/MRD-JOURNAL-D-09-00042.1.
GÖTZ, J., KRISAI, R., SCHROTT, L. 2013: Sediment storage quantification and postglacial evolution of an inner-alpine sedimentary basin (Gradenmoos basin, Schober Mountains, National Park Hohe Tauern, Austria). In Bauch, K. ed. *Nationalpark Hohe Tauren – 5th Symposium Conference Volume for Research in Protected Areas*. Mittersill (Nationalpark Hohe Tauren), pp. 237-242. Retrieved from: https://www.zobodat.at/publikation_volumes.php?id=37550.
GREGOR, V. 2005: Morfologické zmeny tatranských plies zanášaním. *Geodetický a kartografický obzor*, 1, 9-14.
GREGOR, V., PACL, J. 2005: Hydrológia tatranských jazier. *Acta Hydrologica Slovaca*, 6, 161-187.
HINDERER, M. 2001: Late Quaternary denudation of the Alps, valley and lake fillings and modern river loads. *Geodinamica Acta*, 14(4), 231-263.
HREŠKO, J. 1994: The morphodynamic aspect of high mountain ecosystem research (Western Tatras – Jalovec valley). *Ekológia (Bratislava)*, 13, 309-322.
HREŠKO, J, BOLTIŽIAR, M. 2001: Influences of the morphodynamic processes on the landscape structure in the high mountains (Tatry Mts area). *Ekológia (Bratislava)*, 20 (Supplement 3), 141-148.
HREŠKO, J, BOLTIŽIAR, M, BUGÁR, G. 2003. Spatial structures of geomorphic processes in high-mountain landscape of the Belianske Tatry Mts. *Ekológia (Bratislava)*, 22 (Supp. 2), 341-348.
HREŠKO, J. BUGÁR, G., BOLTIŽIAR, M., KOHÚT, F. 2008: The dynamics of recent geomorphic processes in the Alpine zone of the Tatra Mountains. *Geographia Polonica*. 81(1), 53-65.
HREŠKO, J., KANÁSOVÁ, D., BUGÁR, G., PETROVIČ, F., MAČUTEK, J. 2012: Morphodynamic effect on lacustrine deposits in the High Tatra Mts. *Ekológia (Bratislava)*, 31, 390-404. DOI: http://dx.doi:10.4149/ekol_2012_03_390.
HWANG, C., CHENG, Y., HAN, J., KAO, R., HUANG, Ch., WEI, Sh., WANG, H. 2016: Multi-Decadal Monitoring of Lake Level Changes in the Qinghai-Tibet Plateau by the TOPEX/Poseidon-Family Altimeters: Climate Implication. *Remote Sensing*, 8, 446. DOI: http://dx.doi:10.3390/rs8060446.
CHOIŃSKI, A., PTAK, M. 2009: Lake Infill as the Main Factor Leading to Lake's Disappearance. *Polish Journal of Environmental Studies*, 18, 347-352.
IVES, J.D., SHRESTHA, R.B., MOOL, P.K. 2010: *Formation of Glacial Lakes in the Hindu Kush-Himalayas and GLOF Risk Assessment*. Kathmandu (ICIMOD), 66 p.
JANSKÝ, B., ŠOBR, M., ENGEL, Z. 2010: Outburst flood hazard: Case studies from the Tien-Shan Mountains, Kyrgyzstan. *Limnologica*, 40, 358-364. DOI: http://dx.doi:10.1016/j.limno.2009.11.013.
KACZKA, R., LEMPA, M., CZAJKA, B., JANECKA, K., RĄCZKOWSKA, Z., HREŠKO, J., BUGAR, G. 2015: The recent timberline changes in the Tatra Mountains: a case study of the Mengusovská valley (Slovakia) and the Rybi potok valley (Poland). *Geographia Polonica*, 88(2), 71-83. DOI: http://dx.doi.org/10.7163/GPol.0016.

KALVODA, J. 1974: *Geomorfologický vývoj hřebenové části Vysokých Tater*. Praha (Academia – Nakladatelství ČSAV), 65 p.

KAPUSTA, J., HREŠKO, J., PETROVIČ, F., TOMKO-KRÁLO, D., GALLIK, J. 2018: Water surface overgrowing of the Tatra lakes. *Ekológia (Bratislava)*, 36(1), 11-23. DOI: https://doi.org/10.2478/eko-2018-0002.

KAPUSTA, J., STANKOVIANSKY, M., BOLTIŽIAR, M. 2010: Changes in activity and geomorphic effectiveness of debris flows in the High Tatra Mts. within the last six decades (on the example of the Velická dolina and Dolina Zeleného plesa valleys). *Studia Geomorphologica Carpatho-Balcanica*, 44, pp. 5-34.

KÄÄB, A., HAEBERLI, W. 2011: Evolution of a high mountain thermokarst lake in the Swiss Alps. Arctic. *Antarctic and Alpine Research*, 33(4), 385-390.

KŁAPYTA, P., ZASADNI, J., POCIASK-KARTECZKA, J., GAJDA, A., FRANCZAK, P. 2016: Late Glacial and Holocene paleoenvironmental records in the Tatra Mountains, East-Central Europe, based on lake, peat bog and colluvial sedimentary data: A summary review. *Quaternary International*, 415, 126-144. DOI: https://doi.org/10.1016/j.quaint.2015.10.049

KLIMASZEWSKI, M. 1988: *Rzeźba Tatr Polskich.* Warszawa (Państwowe Wydawnictwo Naukove), 668 p.

KOMORI, J. 2008: Recent expansions of glacial lakes in the Bhutan Himalayas. *Quaternary International*, 184, 177-186.

KOTARBA, A. 2007: Geomorphic activity of debris flows in the Tatra Mts. and in other European mountains. *Geographia Polonica*, 80, 137-150.

KRÁLIKOVÁ, S., VOJTKO, R., SLIVA, Ľ., J. MINÁR, J., FÜGENSCHUH, B., KOVÁČ, M., HÓK, J. 2014: Cretaceous-Quaternary tectonic evolution of the Tatra Mts. (Western Carpathians): constraints from structural, sedimentary, geomorphological and fission track data. *Geologica Carpathica*, 65, 307-326.

KUBINSKÝ, D., WEIS, K., FUSKA, J., LEHOTSKÝ, M., PETROVIČ, F. 2015: Changes in retention characteristics of 9 historical artificial water reservoirs near Banská Štiavnica, Slovakia. *Open Geosciences*, pp. 1-8. DOI: http://doi.org/10.1515/geo-2015-0056.

LIU, J., WANG, S., YU, S., YANG, D., ZHANG, L. 2009: Climate warming and growth of high-elevation inland lakes on the Tibetan Plateau. *Global and Planetary Change*, 67, 209-217. DOI: http://dx.doi:10.1016/j.gloplacha.2009.03.010.

LUKNIŠ, M. 1973: *Reliéf vysokých Tatier a ich predpolia.* Bratislava (SAV), 175 p.

MAKOS, M. 2015: Deglaciation of the High Tatra Mountains. *Cuadernos de Investigación Geográfica*, 41, 317-335. DOI: http://dx.doi:10.18172/cig.2697.

NECSOIU, M., DINWIDDIE, C.L., WALTER, G.R., LARSEN, A., STOTHOFF, S.A. 2013: Multitemporal image analysis of historical aerial photographs and recent satellite imagery reveals evolution of water body surface area and polygonal terrain morphology in Kobuk Valley National Park, Alaska. *Environmental Research Letters*, 8,(2), 025007. DOI: http://dx.doi.org/10.1088/1748–9326/8/2/025007.

NECSOIU, M., MÎNDRESCU, M., ONACA, A., WIGGINTON, S. 2016a: Recent morphodynamics of alpine lakes in Southern Carpathian Mountains using high-resolution optical imagery. *Quaternary International*, 415, pp.164-174. DOI: https://doi.org/10.1016/j.quaint.2015.12.032.

NECSOIU, M., ONACA, A., WIGGINTON, S., URDEA, P. 2016b: Rock glacier dynamics in Southern Carpathian Mountains from high-resolution optical and multi-temporal SAR satellite imagery. *Remote Sensing of Environment*, 177, 21-36. DOI: http://dx.doi.org/10.1016/j.rse.2016.02.025.

NOVIKMEC, M., SVITOK, M., KOČICKÝ, D., ŠPORKA, F., BITUŠÍK, P. 2013: Surface Water Temperature and Ice Cover of Tatra Mountains Lakes Depend on Altitude, Topographic Shading, and Bathymetry. *Arctic, Antarctic, and Alpine Research*, 45, 77-87. DOI: http://dx.doi.org/10.1657/1938-4246-45.1.77.

ONACA, A., ARDELEAN, F., URDEA, P., MAGORI, B. 2016: Southern Carpathian rock glaciers: Inventory, distribution and environmental controlling factors. *Geomorphology*, 293, 391-404. DOI: http://dx.doi.org/10.1016/j.geomorph.2016.03.032.

OWENS, P., SLAYMAKER, O. 1994: Post-glacial temporal variability of sediment accumulation in a small alpine lake. *Variability in Stream Erosion and Sediment Transport, Proceedings of the Canberra Symposium*. Canberra (Int. Association of Hydrological Sciences), 224, 187-195.

PACL, J., GREGOR, V. 2010: Plesá. In Koutná, A., Chovancová, B. eds. *Tatry – príroda.* Praha (Nakladatelství Miloš Uhlíř – BASET), pp. 237-246.

PARYSKA-RADWAŃSKA, Z., PARYSKI, W.H. 2004: *Wielka Encyklopedia Tatrzańska*. Poronin (Wydawnictwo Górskie), 1555 p.

PETRAKOV, D., SHPUNTOVA, A., ALEINIKOV, et al. 2016a: Accelerated glacier shrinkage in the Ak-Shyirak massif, Inner Tien Shan, during 2003–2013. *Science of the Total Environment,* 562, 364-378. DOI: http://dx.doi.org/10.1016/j.scitotenv.2016.03.162.

POCIASK-KARTECZKA, J., GAJDA, A., FRANCZAK, P. 2014: Regional distribution and relevance in paleonvironmental studies of lakes in the Tatra Mts. (Western Carpathians). In Mindrescu, M., ed. *Late Pleistocene and Holocene Climate Variability in the Carpatho-Balcan Region.* Suceava (Stefan cel Mare University Press), 137-143.

RĄCZKOWSKA, Z. 2006: Recent geomorphic hazards in the Tatra Mountains. *Studia Geomorphologica Carpatho-Balcanica,* 40, 45-60.

REHMAN, A. 1892: Zanikłe jeziora Tatr i bifurkacja rzeki Młynicy. *Wszechświat*, 11, 67.

RYBNÍČKOVÁ, E., RYBNÍČEK, K. 2005: Pollen and macroscopic analyses of sediments from two lakes in the High Tatra mountains, Slovakia. *Vegetation History and Archaeobotany,* 15, 345-356. DOI: http://doi:10.1007/s00334-006-0050-1.

RUBENSDOTTER, L., ROSQVIST, G. 2009: Influence of geomorphological setting, fluvial-, glaciofluvial- and mass-movement processes on sedimentation in alpine lakes. *The Holocene,* 19(4), 665-678. DOI: https://doi.org/10.1177/0959683609104042.

QUINCEY, D.J., GLASSER, N.F. 2009: Morphological and ice-dynamical changes on Tasman Glacier, New Zealand, 1990-2007. *Global and Planetary Change*, 68, 185-197. DOI: https://doi.org/10.1016/j.gloplacha.2009.05.003.

QUINCEY, D.J., LUCAS, R.M., RICHARDSON, S.D., GLASSER, N.F., HAMBREY. M.J., REYNOLDS, J.M. 2005: Optical remote sensing techniques in high-mountain environments: application to glacial hazards. *Progress in Physical Geography,* 29, 475-505. DOI: https://doi.org/10.1191/0309133305pp456ra.

SCHAFFER, J. 1930: Die Formen der Seenbecken der Hohen Tatra. I. Teil. *Arbeiten des Geographischen Institutes des Deutschen Universität in Prag*, 8, 1-44.

SCHAUB, Y., HAEBERLI, W., HUGGEL, C., KÜNZLER, M., BRÜNDL, M. 2013: Landslides and New Lakes in Deglaciating Areas: A Risk Management Framework. *Landslide Science and Practice,* 7, 31-38. DOI: http://dx.doi:10.1007/978-3-642-31313-4_5.

SCHROTT, L., HAUFSCHMIDT, G., HANKAMMER, M., HOFFMAN, T., DIKAU, R. 2003: Spatial distribution of sediment storage types and quantification of valley fill deposits in an alpine basin, Reintal, Bavarian Alps, Germany. *Geomorphology,* 55, 45-63. DOI: http://dx.doi:10.1016/S0169-555X(03)00131-4.

SONG, C., HUANG, B., KE, L., RICHARDS, K.S. 2014: Remote sensing of alpine lake water environment changes on the Tibetan Plateau and surroundings: A review. *ISPRS Journal of Photogrammetry and Remote Sensing,* 92, 26-37. DOI: http://dx.doi.org/10.1016/j.rse.2013.03.013.

STROZZI, T., WIESMANN, A., KÄÄB, A., JOSHI, S., MOOL, P. 2012: Glacial lake mapping with very high resolution satellite SAR data. *Natural Hazards and Earth System Sciences,* 12, 2487-2498. DOI: http://dx.doi:10.5194/nhess-12-2487-2012.

SZAFŁARSKI, J. 1933: Jeziora dolin Kieżmarskiej o Staroleśnej. *Zbiorowe prace naukowe Koła geografów* U. J., I. B., 3-24.

ŠILHÁN, K., TICHAVSKÝ, R. 2016: Recent increase in debris flow activity in the Tatras Mountains: Results of a regional dendrogeomorphic reconstruction. *Catena*, 143, 221-231. DOI: http://dx.doi.org/10.1016/j.ca tena.2016.04.015.

TARAVAT, A., RAJAEI, M., EMADODIN, I., HASHEMINEJAD, H., MOUSAVIAN, R., BINIYAZ, E. 2016: Spaceborne Multisensory, Multitemporal Approach to MonitorWater Level and Storage Variations of Lakes. *Water,* 8, 478. DOI: http://dx.doi:10.3390/w8110478.

TOURIAN, M.J., ELMI, O., CHEN, Q., DEVARAJU, B., ROOHI, SH., SNEEUW, N.A 2015: Spaceborne multisensor approach to monitor the desiccation of Lake Urmia in Iran. *Remote Sensing of Environment,* 156, 349–360. DOI: http://dx.doi.org/10.1016/j.rse.2014.10.006.

YE, Q., ZHONG, Z., KANG, S., STEIN, A., WEI, Q., LIU, J. 2009: Monitoring Glacier and Supraglacier Lakes from Space in Mt. Qomolangma Region of the Himalayas on the Tibetan Plateau in China. *Journal of Mountain Science,* 6, 211-220. DOI: http://dx.doi.10.1007/s11629-009-1016-4.

YOSHIKAWA, K., HINZMAN, L.D. 2003: Shrinking thermokarst ponds and groundwater dynamics in discontinuous permafrost near Council, Alaska. *Permafrost Periglacial Processes*, 14, 151-160. DOI: http://dx.doi:10.1002/ppp.451.

WATANABE, T., LAMSAL, D., IVES, J.D. 2009: Evaluating the growth characteristics of a glacial lake and its degree of danger of outburst flooding: Imja Glacier, Khumbu Himal, Nepal. *Norwegian Journal of Geography*, 63, 255-267. DOI: http://dx.doi:10.1080/00291950903368367.

ZASADNI, J., KŁAPYTA, P. 2014: The Tatra Mountains during the Last Glacial Maximum. *Journal of Maps*, 10, 440-456. DOI: http://dx.doi.org/10.1080/17445647.2014.885854.

Acknowledgments

The authors thank Eurosense s.r.o. Bratislava, the Topographical Institute Banská Bystrica and the Centralny Ośrodek Dokumentacji Geodezyjnej i Kartograficznej institute for providing ortophoto maps and historical aerial photos. This study was supported by VEGA 1/0207/17 project: Development and changes in the Tatra mountainous landscape.

Authors´ affiliations

Juraj Kapusta
Department of Ecology and Environmental Sciences
Faculty of Natural Sciences, Constantine the Philosopher University in Nitra
Tr. A. Hlinku 1,
949 01 Nitra
Slovakia
juraj.kapusta@gmail.com

František Petrovič
Department of Ecology and Environmental Sciences
Faculty of Natural Sciences, Constantine the Philosopher University in Nitra
Tr. A. Hlinku 1,
949 01 Nitra
Slovakia
fpetrovic@ukf.sk (corespondent autor)

Juraj Hreško
Department of Ecology and Environmental Sciences
Faculty of Natural Sciences, Constantine the Philosopher University in Nitra
Tr. A. Hlinku 1,
949 01 Nitra
Slovakia
jhresko@ukf.sk

Zofia Rączkowska
Department of Geoenviromental Research
Institute of Geography and Spatial Organization, Polish Academy of Sciences
Świętego Jana 22,
31-018 Cracow
Poland
raczk@zg.pan.krakow.pl