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WATER SURFACE OVERGROWING OF THE TATRA'S LAKES

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Abstract

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Tatra's lakes are vulnerable ecosystems and an important element of the alpine landscape. Mainly some shallow lake basins succumb to intense detritus sedimentation, fine fractions of material from the catchment area or to the overgrowing of water level by vegetation. In this paper, changes and dynamics of the 12 Tatra's lake shorelines that were selected based on the detailed mapping of their extent are pointed out. Changes were assessed by accurate comparisons of historical and current orthophoto maps from the years 1949, 1955 and 2015 – and therefore, based on the oldest and the latest relevant materials. Due to the overgrowing of lakes caused by vegetation, their water surface decreased from -0.9% up to -47.9%, during the examined period. Losses were caused by the overgrowing of open water surface by the communities of sedges and peat bogs. The most significant dynamics of the shorelines during the last decades were reached by those lakes, into which fine sediments were simultaneously deposited by means of mountain water coarse. These sediments made the marginal parts of the lake basins shallower and accelerated rapid expansion of vegetation to the detriment of the open water surface. The overgrowing of shallow moraine lakes lying in the vegetation zone is a significant phenomenon of the High Tatras alpine landscape. It leads to their gradual extinction, turn into peat bogs and wet alpine meadows.

Key words: lakes, lake overgrowing, landscape changes, the High Tatra Mts.

Introduction

The glacial lakes of the High Tatra Mts. represent one of the most important and the most interesting natural elements of the alpine landscape. They are definitely complete and do not pose a natural threat to people today, as is the case in other alpine regions. They greatly increase the diversity of the alpine landscape and the whole landscape scenery as well.

According to Hreško et al. (2012), alpine lakes are vulnerable, integrated geomorphological-hydrological ecosystems. Their lake basins were finished, especially 27,000 to 19,000 years ago, during the climax of the last Ice Age peaked in the Tatra's. The last Würm glaciation lasted about 60,000 years and ended 10,000 to 8,500 years ago (Lukniš, 1973; Baumgart-Kotarba, Kotarba, 2001; Zasadni, Kłapyta, 2014; Engel et al., 2015). Most lakes were created in the last stages or immediately after the end of the Ice Age. According to Kłapyta et al.

(2015), deposition of sediments in lake basins of the Tatra's lakes began 9,000 to 8,000 years ago. Some shallow moraine lakes, after the appearance of their lake basins, were for certain time probably dry depressions. Their filling with water was only due to the onset of humid climate and consequent positive hydrological balance. It attests to the fact that there are no sediments older than those from the Holocene period in the shallow lakes.

The period after the final geomorphological completion of lake basins and the beginning of the sedimentation are considered as the beginning of the Holocene development of the Tatra's lakes and their basins. Since that time, exogenous geomorphological processes have begun. In many cases, it has strongly influenced the geomorphology of the lake basins and the shape of the shore lines. This development is caused mainly by the transport of sediments into lakes from the surrounding debris cones, rock gutters and walls. As a consequence, some lake basins become shallower by the gradual accumulation of the produced material, so that they gradually lose their open water and finally become extinct. The formation of lake sediments, according to Hreško et al. (2012), is a typical morphodynamic phenomenon of the alpine landscape in the High Tatra Mts. Debris flows and deposition of fine fractions in shallow parts of lake basins are the main causes of the creation of the sediments in lakes. Fine fractions are flooded out from adjacent debris cones, moraines and gutters, especially during their high water saturation due to extreme precipitation (Lukniš, 1973; Gregor, Pacl, 2005; Kapusta et al., 2010; Hreško et al., 2012; Długosz, Kapusta, 2015; Gallik, Bolešová, 2016). Intensive accumulation of weathered material is mainly due to the fact that the lake basins and their surroundings at highly rugged relief by elevation present a local erosive base for geomorphological processes. Debris flows and sediments that are washed out of debris cones and catchment loose movement energy, and deposit intensively as a result of a decrease in their positional energy. Especially in the shallower marginal parts of the lake basins, the sediments accumulate quickly to such extent that they gradually reach the water level and form a typical alluvial plains. These are characteristic geomorphological forms of the relief in the surroundings of many Tatra's lakes. Their extent might indicate the intensity of sedimentation processes. The abundant extension of these geomorphological forms on the bottom of the valleys indicates the distinctiveness of this phenomenon within the many lakes of the High Tatra Mts.

The exogenous geomorphological processes also include organogenic processes, which significantly represent the overgrowing of lakes by vegetation in the alpine region of the Tatra's. Based on the analyses of the peat sediment thickness (Dyakowska, 1932; Krippel, 1963; Obidowicz, 1996; Łajczak, 2014), it is evident that this process has long-term influence on the development of some lake basins in the alpine environment. From the view-point of the capturing the surface changes of glacial lakes caused by the growth of organic matter or by the overgrowing of open water by vegetation, attention has not been paid to this process. In the case of some lakes, the overgrowing of the lakes' marginal parts is a significant and typical phenomenon. According to our own measurements and field research, it is an exogenous geomorphological process, which — together with the draining of fine fractions and debris flows — causes the greatest changes and dynamics of the lake shorelines in the conditions of the High Tatra Mts. The shape of the shoreline and the rate of change over time can be an important indicator of the postglacial development of the Tatra's lakes.

In this paper, surface changes and changes in the shorelines of 12 selected shallow moraine lakes of the Tatra's are assessed. Analysis of changes is based on the detailed comparison of the oldest aerial photos (1949, 1955) and the latest orthophoto maps (2015). Changes in the shoreline due to the overgrowing of their open water by vegetation for the last 60–65 years are depicted. These particular lakes have been chosen according to the apparent overgrowing of the water surface by vegetation. This choice represents Tatra's lakes where the biggest parts of the water surface have been overgrown.

Study area

The High Tatras are one of the smallest high mountains in the world with a typically developed alpine relief – with glacial valleys and peaks. It was formed by multiple actions of mountain glaciers during the Pleistocene. The mountains were glaciated at least three times, being the most glaciated mass of the entire Carpathians. The High Tatras lie in an area of only 341 km^2, at the borderline of Slovakia and Poland (more than three quarters of their area spread out in the Slovak part). The whole mountain range of the Carpathian Mountains reaches the highest elevation by the peak Gerlachovský štít (2,654.4 m a.s.l.), with another 24 peaks exceeding the 2,500 m a.s.l. The research area is part of the Tatra National Park.

Nowadays, there are about 150–230 lakes of various sizes and depths (depending on the size and periodicity criteria) in the High Tatras. Approximately half of them are periodic. In addition, there is a significant number of already extinct, fully overgrown lakes and peat bogs. Mostly, there are small lakes with a surface of less than 1 ha and depth up to 2 m (Gregor, Pacl, 2005). The biggest lakes are Morskie Oko and Wielki Staw Polski (both with a surface of more than 0.3 km^2), the deepest being Wielki Staw Polski with a depth of 79.3 m.

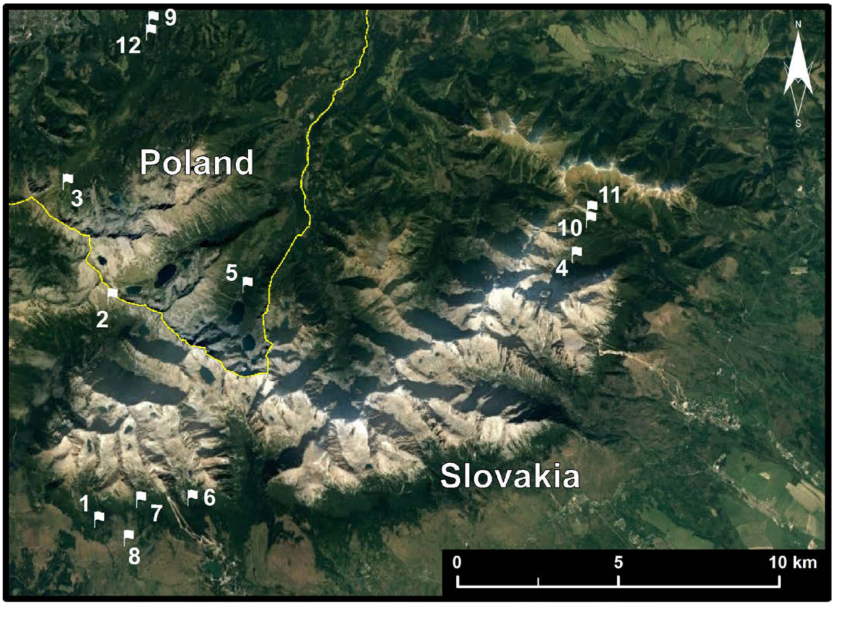

Fig. 1. The High Tatra Mountains – location of representative lakes: (1) Jamské pleso, (2) Kobylie pleso, (3) Litworowy Staw Gąsienicowy, (4) Malé Čierne pleso, (5) Małe Morskie Oko, (6) Mlynické pliesko, (7) Nižné Furkotské pleso, (8) Nižné Rakytovské pliesko, (9) Niżni Toporowy Staw, (10) Trojrohé pleso, (11) Veľké Biele pleso, (12) Wyżni Toporowy Staw.

The selected 12 lakes are located predominantly in the lower parts of different valleys, mostly in the forest zone or dwarf pine zone (Fig. 1). They lie at different elevations (from 1,089.0 to 1,734.3 m a.s.l.), as well as the northern and southern side of the mountain. All these lakes are relatively shallow (maximum depth ranges from 0.8 to 5.9 m). The average depth of the water in some lakes is only about 0.5 m. Selected lakes were created either as depression – melted hollows – by melting the dead ice floes buried under the detritus or by the rising of the water level behind waterproof moraine dams. The depth of water in some lakes of the interest ranges significantly during the year.

Material and methods

For each lake, the surface changes of the selected lake shorelines were identified based on a detailed comparison of the oldest historical aerial photo and the current orthophoto map. Historical aerial photos and current high-resolution orthophoto maps represent the ideal basis for the assessment of the landscape changes in the hardly accessible terrain in connection with the GIS tools. Such combination can be considered as a unique tool for mapping spatial changes in the glacial lake shorelines and assessing their dynamics over a longer time horizon. Today, remote sensing of the Earth (RSE) materials are the most accurate basis for detailed mapping and assessment of long-term changes of lake shorelines and alpine landscapes, generally. Twelve lakes, where changes in their shorelines are most clearly visible, were selected based on the preliminary analysis of the orthophoto maps of the entire High Tatra Mts. territory and on the terrain research.

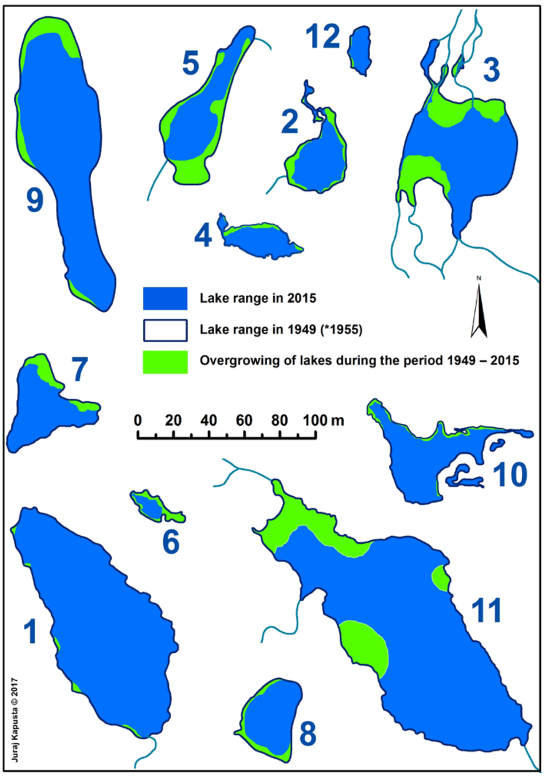

Fig. 2. Overgrowing of the Tatra´s lakes during the period 1949–2015.

For the identification of the current state, colour orthophoto maps from 2015 were used. They were created by Eurosense s.r.o. Bratislava and are of high resolution – up to 20 cm/pixel. Based on these orthophoto maps, current state of the lake shorelines of selected lakes were mapped in detail in the ArcView GIS — ArcMap 9.3 program. Digitisation was performed via the method of visual interpretation ('on screen') at a scale of 1:300 – 1:500. The punctuality of digitalization depends on the source's resolution, whereby the scale 1:500 provides precise results and for this type of the problem is above standard.

With the use of GIS tools, the oldest historical aerial photos were precisely matched with current orthophoto maps, based on a larger number of pass points. Based on this operation, historical photos were transformed into historical orthophoto maps, while positional distortion was minimised. In most of the lakes, the oldest material from which their historical range could be conquered, were aerial photographs from the year 1949. Boundaries of the historical shorelines on the Polish side were marked based on the aerial photos from 1955. These were panchromatic aerial photos scanned at a high resolution of 1,200 dpi and converted to digital format. Panchromatic aerial photos were provided by the Topographical Institute in Banská Bystrica.

The digitization of shorelines from historical orthophoto maps followed the rules of 'backdating' (Feranec et al., 2005). A current orthophoto map was always compared with a historical orthophoto map. Boundaries of the lake shorelines were based on the current orthophoto maps. Changes occurred only at the point of evident changes in their overlap with the historical orthophoto map. This method is useful particularly for identification of changes in landscape cover and structure (Boltižiar, 2007; Falťan, Bánovský, 2008; Solár, 2013; Solár, Janiga, 2013; Haladová, Petrovič, 2015; Kaczka et al., 2015; Kubinský et al., 2015), but it seems to be applicable for the assessment of geomorphological processes (Kapusta et al., 2010; Hreško et al., 2012; Długosz, Kapusta, 2015) and dynamics of lake shorelines (Kapusta, 2016). When digitizing the data in GIS (shorelines in this case), only a copy of the original layer, not the completely new layer is created. Then the original layer is modified so that the common boundaries of logically unchanged areas are left unchanged. Only boundaries of the shorelines are modified in places where there has been a definite change. The purpose of this method is to minimise the inaccuracies that result from the simple uncorrected overlapping of the digital map layers on each other.

Results

Based on the analysis of the oldest and the latest orthophoto maps of the selected Tatra's lakes in the years 1949, 1955 and 2015, changes of their shorelines mapped in detail are presented (Fig. 2). Determined dynamics of the shorelines is projected into surface losses calculated in the GIS environment. These surface losses represent losses of the open water level of individual lakes, due to the overgrowing of their water levels by vegetation. Some of the monitored lakes underwent significant changes in the above mentioned period (Figs 2, 3, 4, Table 1).

In the case of absolute changes, due to overgrowing, the losses of the open water level ranged from 15.4 m^2 (lake Wyżni Toporowy Staw) to 1,595.8 m^2 (lake Veľké Biele pleso – Fig. 5) during the monitored period. For some lakes, the ab-

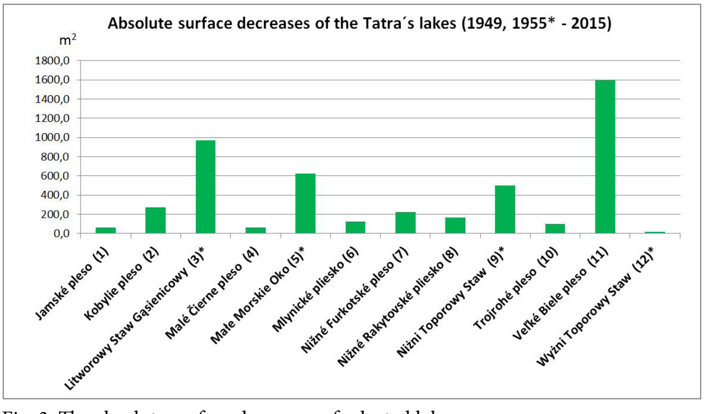

Fig. 3. The absolute surface decreases of selected lakes.

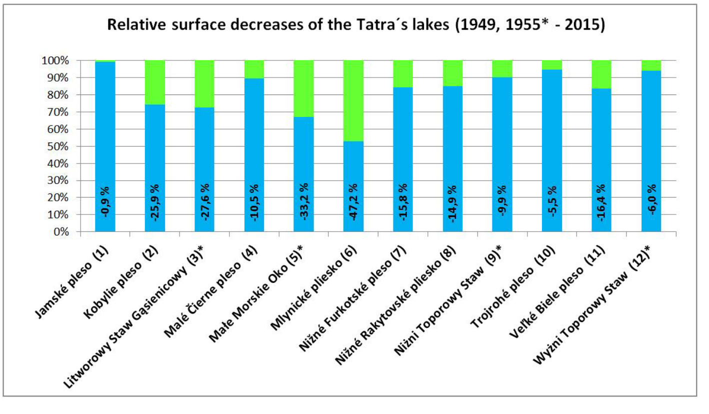

Fig. 4. The relative surface decreases of selected lakes.

T a b l e 1. Surface decreases of selected Tatra lakes.

The lake (Country)		Elevation (a.s.l.)	Max. depth (m)	Surface (m^2)			Absolute decrease of the surface (m^2) 1949, 1955*-2015	Relative decrease of the surface (%) 1949, 1955*-2015
				1949	1955*	2015		
1	Jamské pleso (SK)	1,447.5	4.3	6,383.7	-	6,323.9	59.8	-0.9
2	Kobylie pleso (SK)	1,734.3	1.0	1045.2	-	774.6	270.6	-25.9
3	Litworowy Staw Gąsienicowy (PL) *	1,618.0	1.1	-	3,517.1	2,546.5	970.6	-27.6
4	Malé Čierne pleso (SK)	1,565.9	2.0	608.3	-	544.4	63.9	-10.5
5	Małe Morskie Oko (PL) *	1,391.7	3.3	-	1,881.5	1,256.8	624.7	-33.2
6	Mlynické pliesko (SK)	1,552.0	-	262.9	-	138.8	124.1	-47.2
7	Nižné Furkotské pleso (SK)	1,626.0	1.2	1,406.4	-	1,184.3	222.1	-15.8
8	Nižné Rakytovské pliesko (SK)	1,307.0	2.1	1,136.0	-	966.2	169.8	-14.9
9	Niżni Toporowy Staw (PL) *	1,089.0	5.9	-	5,067.5	4,565.9	501.6	-9.9
10	Trojrohé pleso (SK)	1,610.8	1.4	1,811.5	-	1,711.4	100.0	-5.5
11	Veľké Biele pleso (SK)	1,615.4	0.8	9,726.8	-	8,131.0	1,595.8	-16.4
12	Wyżni Toporowy Staw (PL) *	1,120.0	1.1	-	256.7	241.3	15.4	-6.0
	Note: * - the oldest historical aerial images of the given lake.							

Fig. 5. The lake Veľké Biele pleso, view from the peak Jahňací štít – 2,229 m a.s.l. (Photo: J. Kapusta, 11.10.2014).

solute losses of the surface are inconsiderable (lake Wyżni Toporowy Staw – 15.4 m^2, lake Jamské pleso – 59.8 m^2, lake Malé Čierne pleso – 63.9 m^2, lake Trojrohé pleso – 100 m^2 (Fig. 6), lake Mlynické pliesko (Fig. 7) – 124.1 m^2). However, in the case of the last one, due to its small size, the above stated absolute loss represents up to 47.2%

of its loss compared to the year 2015 (Table 1). However, for some lakes, losses of the open water levels over the past 60 – 65 years, in consideration of the Tatra lake sizes, are significant (lake Veľké Biele pleso – 1595.8 m^2, lake Litworowy Staw Gąsienicowy – 970.6 m^2 (Fig. 8), lake Małe Morskie Oko – 624.7 m^2 (Fig. 9), lake Niżni Toporowy Staw – 501.6 m^2). In the case of relative changes, losses of the open water level ranged from -0.9% (lake Jamské pleso) up to -47.2% (lake Mlynické pliesko) compared to their original surfaces in 1949 and 1955 (Fig. 2, Table 1).

All surface losses of monitored lakes were caused by overgrowing of their open water level by vegetation. Based on a field survey, two dominant ways of overgrowing with different intensity can be distinguished within the selected set of lakes: peat bog communities (Fig. 6, Fig. 10) and sedge communities (Fig. 5, Fig. 8). While the decrease in surface extent of lakes due to the accumulation of organic material is relatively slow nowadays, the overgrowing of water levels by sedges is in the case of some lakes considerably fast.

Fig. 6. The lake Trojrohé pleso, view from the peak Jahňací štít – 2229 m a.s.l. (Photo: J. Kapusta, 11.10.2014).

Fig. 7. The lake Mlynické pliesko. (Photo: J. Kapusta, 04.08.2017).

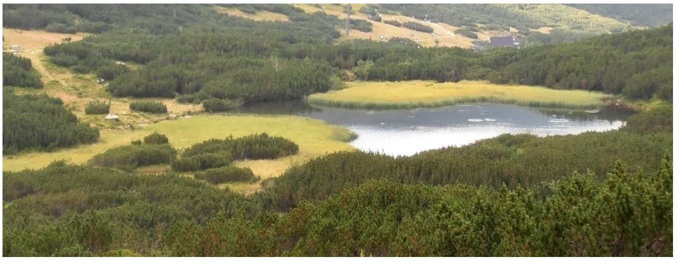

Fig. 8. The lake Litworowy Staw Gąsienicowy. (Photo: J. Kapusta, 06.08.2015).

Typical examples of decrease of open water level due to the accumulation of organic material are lakes Wyżni Toporowy Staw and Trojrohé pleso (Fig. 6). Both lakes are a part of typical Tatra's peat bogs. The extent of peat bogs is several times larger than the surfaces

Fig. 9. The lake Małe Morskie Oko. (Photo: J. Kapusta, 03.09.2016).

Fig. 10. The lake Malé Čierne pleso. (Photo: J. Kapusta, 03.08.2017).

of the current lake open water levels. In the monitored period, their absolute decrease of the open water levels was relatively small (Fig. 2, Table 1). In the case of the lake Trojrohé pleso, the extremely complicated shape of the shoreline evokes the rapid and intense overgrowing of water level. In the 65 years, approximately 100 m^2 of its water surface was overgrown, which represents a decrease of only -5.5% of its surface compared to the year 1949. Parallel with other lakes (Fig. 3, Table 1), it is a low surface decrease. However, part of this decrease was caused by the overgrowing of the northwest shallow lake bay by sedge communities. The maximum depth of the lake is 1.4 m, but the edges of its lake basin are probably still too deep to become more overgrown with sedges also in other parts.

However, overgrowing of the open water level of the lakes by sedge communities shows to be much faster and more dynamic. This type of overgrowing mainly affects shallow lake basins. Their marginal parts have a depth of only a few centimetres in some places, resp. several tens of centimetres. Aggressive vegetation is spreading extremely fast here at the expense of open water level. Typical examples of water level decrease due to overgrowing by sedges are the lake Veľké Biele pleso (Fig. 5) and the lake Litworowy Staw Gąsienicowy (Fig. 8). In the case of these lakes, significant changes of shorelines in a relatively short time are multiplied by the input of fine sediments from their catchments. The surface of the lake Veľké Biele pleso decreased between 1949 and 2015 by 1,595.8 m^2, which represents a decrease of the open water level by 16.4% compared to its surface in 1949 (Fig. 11). Similarly, the lake Litworowy Staw Gąsienicowy showed a very large surface decrease (-970.6 m^2) in the period 1955–2015. This surface area represents loss of the open water level by up to -27.6% compared to the year 1955 (Fig. 11).

Watercourses flow through the both of lakes. In particular, during extreme precipitation and high-water conditions, watercourses bring larger quantities of suspended loads and sand from the higher lying catchment areas. Sediments accumulate in the lake basins and gradually make the lake shallower. At the same time, in the marginal shallow parts of lakes, suitable substrate conditions are created for sedge root systems, which can then rapidly expand at the expense of open water. Their old dying parts, which accumulate under the water, also contribute to the expansion. This creates a layer of organic remains mixed with fine sediments and flooded sand. Both basins are very shallow, the average depth of the lake Veľké Biele pleso is only about 0.5 m. The combination of an acceptable substrate for the root systems of the sedges and of lake shallowness creates suitable conditions for the rapid overgrowing of the open water level of the lake.

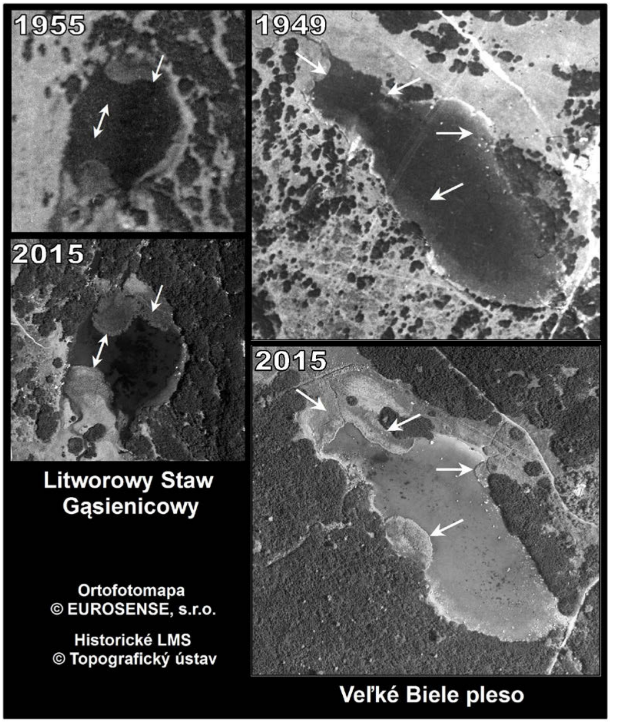

Fig. 11. Comparison of the oldest (1949, 1955) and the newest (2015) orthophoto maps - Litworowy Staw Gąsienicowy and Veľké Biele pleso. (Author: J. Kapusta, 2017).

The third highest decrease in open water level during the monitored period was recorded in the lake Małe Morskie Oko (624.7 m^2, -33.2%). It is also a flow-through lake. Although this lake reaches a relatively large maximum depth (3.3 m), it intensively overgrows along the edges (Fig. 9). In the case of other explored lakes, open water level decreased mostly by sedge communities as well as peat bogs.

The highest relative surface decrease was reached in the case of the lake Mlynické pliesko during the period of years 1949–2015; it was up to -47.2%. The area that was covered by vegetation is relatively small (124.1 m^2). However, this lake is generally of very small size, therefore, even the low absolute decrease of the surface was manifested by a high relative decrease. It is a periodic lake, relatively less known, and it is marked in more detailed maps only. From an ecological point of view, however, in case of such small dimensions, it is also the lake ecosystem.

The overgrowing of individual lakes has a different dynamic. While some of the representative lakes show a relatively negligible speed of the overgrowing, the dynamics and changes of other lake shorelines are literally extreme (Fig. 2, Fig. 11, Table 1). Moreover, the degree of the overgrowing also significantly affects the periodicity and the changing hydrological balance of the lake basins. The most significant changes show lakes that have their bottoms with distinct shallow areas, into which fine sediments are brought by the water stream and that are significantly overgrown with sedge communities (Litworowy Staw Gąsienicowy, Veľké Biele pleso). During the low water levels, sedges can expand rapidly; while during the high-water levels, occasionally, some overgrown areas are temporarily below the water surface. These lakes probably become overgrown much faster than those with typical overgrowing by peat bog communities (e.g.the lake Trojrohé pleso). In 1949, the lake Veľké Biele pleso had surface of open water level about 5.3 times larger than the lake Trojrohé pleso. However, the overgrown area between the years 1949–2015 at the lake Veľké Biele pleso is up to almost 16 times bigger than the overgrown area at the lake Trojrohé pleso (Table 1). It follows that the overgrowing intensity of the water level in the lake Veľké Biele pleso is thus more than 3 times higher than in the lake Trojrohé pleso.

The strong spatial dynamics of some lake shorelines suggests the intense interaction of mountain glacial lakes and organogenic deposition processes. Overgrowing of the open water levels of Tatra's lakes by vegetation leads to their gradual extinction and it is the result of this interaction. At the bottom of the valley, it is possible to identify a large number of already overgrown lakes or lakes filled with peat (e.g. the lake Slepé pleso near to the lake Štrbské pleso) on the basis of orthophoto map and field survey. These are the lake basins of the former lakes, which nowadays represent the final stage of organogenic processes – the full coverage of open water by vegetation. Nowadays, they are valuable biotopes in the form of peat bogs and alpine wetlands with rare plant species.

Discussion

The display of the negative changes of the Tatra's lakes' shorelines, based on the historical and current orthophoto maps, is still rare in scientific works published so far. It has been used in researches where it emerged secondary from a study of other landscape phenomena (Kapusta et al., 2010; Hreško et al., 2012; Długosz, Kapusta, 2015; Gallik, Bolešová, 2016; Kapusta, 2016).

Displayed dynamics of the shorelines (Fig. 2, Fig. 11) shows their real-time development as a result of the overgrowing of the open water levels with vegetation. Based on the presented changes, many alpine lakes are not stable and unchangeable, but they are an open and dynamic system. The most intense overgrowing by vegetation is associated with the deposition of fine-grained fractions and the accumulation of organic material in their shallow coastal parts. The biggest changes occurred in shallow moraine lakes, where the process of extinction is much more distinct than in deeper and in bigger lakes by volume.

According to Mason et al. (1994), lakes are a sensitive indicator of changing geomorphology in catchment areas and of the climate change. This fact is confirmed in particular by the analyses of lake sediments (Owens, Slaymaker, 1994; Kotarba, 1996; Šporka et al., 2002; Irmler et al., 2006; Rybníčková, Rybníček, 2005; Hamerlík, Bitušík, 2009; Mîndrescu et al., 2010; Hutchinson et al., 2016; Kłapyta et al., 2015), and also by the results of other studies (Kotarba, 2004; Kapusta et al., 2010; Hreško et al., 2012; Necsoiu et al., 2013; Kohler et al., 2014; Gądek et al., 2015; Kubinský et al., 2015; Gallik, Bolešová, 2016). In particular, smaller and shallower lakes react much more sensitively to changes than larger lakes because of their small volume of the water. They can thus be a strong indicator of the ongoing changes in their catchment areas (Mason et al., 1994; Gerten, Adrian, 2000; Adrian et al., 2009).

Glacial lakes in high mountains, where glaciers are currently melting as a cause of climatic change, react via significant surface expansion of water levels due to the positive hydrological balance (Ives et al., 2010; Strozzi et al., 2012; Emmer et al., 2015). According to Adrian et al. (2009), shallow lakes have a strong potential to become natural indicators of ongoing climate change. It seems that some shallow moraine Tatra's lakes respond to the ongoing changes by rapid overgrowing of the open water level and consequent surface decrease. In many cases, the spatial losses of Tatra's lakes, according to our own depth measures of the lake bottom, undoubtedly indicate a significant reduction in the retention capacity of the lake basins too.

Overgrowing of the shallow moraine lakes on the bottom of the valleys is one of the typical phenomena of the alpine landscape in the Tatras. Together with the accumulation of sediments from debris flows and fine fractions of material flooded from debris flow fans, it can be classified as an exogenous process that over the last decades affected the development of lakes and their shorelines to a high extent. Surrounding shallow moraine glacial lakes is a powerful indicator of the changes taking place in the Tatra's alpine landscape. The above stated glacial lakes are strong indicators of changes that occur in the high mountainous landscape of the High Tatra Mts.

Conclusion

The mapping of negative changes in the shorelines of Tatra's lakes, based on historical and current orthophoto maps, represents one of the ways to capture, analyse and quantitatively visualize their dynamics and development. Between 1949 and 2015, the number of significant decreases in the open water level of the moraine lakes was identified as a result of their overgrowing with sedge and peat bog communities. Lakes that succumbed to the accumulation of fine sediments from water streams during this period generally show much more intense extent of overgrowing than others. Systematic overgrowing of water levels of the shallow moraine lakes is one of the typical phenomena of the Tatra's alpine landscape. Since the beginning of the Holocene, many lakes, due to the action of these organogenic processes, have been changed to a typical alluvial plains, alpine wetlands and peat bogs. These are the final stages of the development of shallow moraine lakes located at the lower elevations in the vegetation zone. Accumulation of fine sediments and organogenic material in the lake basins of such lakes is undoubtedly reflected in a systematic reduction of their original volume. Overgrown lakes thus become the sensitive indicator of long-term changes taking place in the alpine landscape of the High Tatra Mts.

A following research would be focused on further systematic monitoring of the development of representative lake shorelines and their interactions with organogenic processes. The attention is currently focused on the identification of not only the original range of some of the existing basins of Tatra's lakes, but also extinct.

Historical and current orthophoto maps in combination with GIS tools and field research have a great potential for providing valuable information on changes of the alpine glacial lakes.

Confirmed dynamics of the lake shorelines presented in this paper can serve as a clear example of the future development of shallow lakes also in other high mountains of the temperate climatic zone.

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References

Adrian, R., O'Reilly, C.M., Zagarese, H., Baines, S.B., Hessen, D.O., Keller, W., Livingstone, D.M., Sommaruga, R., Straile, D., Van Donk, E., Weyhenmeyer, G.A. & Winder M. (2009). Lakes as sentinels of climate change. *Limnol. Oceanogr.*, 54(6), 2283–2297. DOI: 10.4319/lo.2009.54.6_part_2.2283.

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.

Boltižiar, M. (2007). *Štruktúra vysokohorskej krajiny Tatier*. Nitra: ÚKE SAV.

Dąbrowska, K. & Guzik M. (Eds.) (2015). *Atlas of the Tatra Mountains – Abiotic Nature*. Zakopane: Wydawnictwo Tatrzańskiego Parku Narodowego.

Długosz, M. & Kapusta J. (2015). Debris flows. (Plate V.2). In K. Dąbrowska & M. Guzik (Eds.), *Atlas of the Tatra Mountains – Abiotic Nature*. Zakopane: Wydawnictwo Tatrzańskiego Parku Narodowego.

Dyakowska, J. (1932). Analiza pyłkowa kilku torfowisk tatrzańskich. *Acta Botanica Polonica*, 9(3–4), 473–530.

Emmer, A., Merkl, S. & Mergili M. (2015). Spatiotemporal patterns of high-mountain lakes and related hazards in western Austria. *Geomorphology*, 246, 602–616. DOI: 10.1016/j.geomorph.2015.06.032.

Engel, Z., Mentlík, P., Braucher, R., Minár, J., Léanni, L. & Team A. (2015). Geomorphological evidence and ^{10}Be 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: 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.

Feranec, J., Cebecauer, J. & Oťaheľ J. (2005). *Photo-to-photo interpretation manual*. Bratislava: Institute of Geography, Slovak Academy of Sciences, BIOPRESS.

Gądek, B., Grabiec, M. & Kędzia S. (2015). Application of ground penetrating radar to identification of thickness and structure of sediments in postglacial lakes, illustrated with an example of the Mały Staw lake (the Karkonosze Mts.). *Studia Geomorphologica Carpatho-Balcanica*, 49, 5–13. DOI: 10.1515/sgcb-2015-0006.

Gallik, J. & Bolešová L. (2016). sUAS and their application in observing geomorphological processes. *Solid Earth*, 7, 1033–1042. DOI: 10.5194/se-7-1033-2016.

Gerten, D. & Adrian R. (2000). Climate-driven changes in spring plankton dynamics and the sensitivity of shallow polymictic lakes to the North Atlantic Oscillation. *Limnol. Oceanogr.*, 45, 1058–1066. DOI: 10.4319/lo.2000.45.5.1058.

Gregor, V. & Pacl J. (2005). Hydrológia tatranských jazier. *Acta Hydrologica Slovaca*, 6(1), 161–187.

Haladová, I. & Petrovič F. (2015). Classification of land use changes (model area: Nitra town). *Ekológia (Bratislava)*, 34(3), 249–259. DOI: 10.1515/eko-2015-0024.

Hamerlík, L. & Bitušík P. (2009). The distribution of littoral chironomids along an altitudinal gradient in High Tatra Mountain lakes: Could they be used as indicators of climate change? *Ann. Limnol. – International Journal of Limnology*, 45, 145–156. DOI: 10.1051/limn/2009021.

Hreško, J., Kanásová, D., Bugár, G., Petrovič, F. & Mačutek J. (2012). Morphodynamic effect on lacustrine deposits in the High Tatra Mts. *Ekológia (Bratislava)*, 31(4), 390–404. DOI: 10.4149/ekol_2012_03_390.

Hutchinson, S.M., Akinyemi, F.O., Mîndrescu, M., Begy, R. & Feurdean A. (2016). Recent sediment accumulation rates in contrasting lakes in the Carpathians (Romania): impacts of shifts in socio-economic regime. *Regional Environmental Change*, 16(2), 501–513. DOI: 10.1007/S10113-015-0764-7.

Irmler, R., Daut, G. & Mäusbacher R. (2006). A debris flow calendar derived from sediments of lake Lago di Braies (N. Italy). *Geomorphology*, 77, 69–78. DOI: 10.1016/j.geomorph.2006.01.013.

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.

Kaczka, R., Lempa, M., Czajka, B., Janecka, K., Rączkowska, Z., Hreško, J. & Bugár 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: 10.7163/GPol.0016.

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, 5–34.

Kapusta, J. (2016). *Metodika rekonštrukcie brehovej čiary tatranských plies*. Rigorózna práca, UKF Nitra.

Kłapyta, P., Zasadni, J., Pociask-Karteczka, J., Gajda, A. & Franczak P. (2015). 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: 10.1016/j.quaint.2015.10.049.

Kohler, T., Wehrli, A. & Jurek M. (Eds.) (2014). *Mountains and climate change: A global concern. Sustainable Mountain Development Series*. Bern: Centre for Development and Environment (CDE), Swiss Agency for Development and Cooperation (SDC), Geographica Bernensia.

Kotarba, A. (1996). Osady jeziorne jako wskaźnik przemian środowiska naturalnego Tatr Wysokich. In A. Kotarba (Ed.), *Z badań fizycznogeograficznych w Tatrach, Dokumentacja Geograficzna*, 4 (pp. 33–47). Warszawa: IGiPZ PAN.

Kotarba, A. (2004). *Rola małej epoki lodowej w przekształcaniu śrdowiska Tatr*. Warszawa: IGiPZ PAN.

Krippel, E. (1963). Postglaciálny vývoj lesov Tatranského národného parku. *Biologické Práce*, 9(40), 5–44.

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*, 1, 1–8. DOI: 10.1515/geo-2015-0056.

Łajczak, A. (2014). Rola podłoża w rozwoju torfowisk w polskich Karpatach. *Studia Limnologica et Telmatologica*, 8(1), 19–36.

Lukniš, M. (1973). *Reliéf Vysokých Tatier a ich predpolia*. Bratislava: SAV.

Mason, I., Guzkowska, M., Rapley, C. & Street-Perrott F. (1994). The response of lake levels and areas to climatic change. *Clim. Change*, 27, 161–197. DOI: 10.1007/BF01093590.

Mîndrescu, M., Cristea, I. & Hutchinson S.M. (2010). Bathymetric and sedimentological changes of glacial Lake Ştiol, *Rodna Masiff. Carpathian Journal of Earth Environmental Sciences*, 5(1), 57–65.

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: 10.1088/1748–9326/8/2/025007.

Obidowicz, A. (1996). A Late glacial-Holocene history of the formation of vegetation belts in the Tatra Mts. *Acta Paleobot.*, 36(2), 159–206.

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, December 1994. *International Association of Hydrological Sciences*, 224, 187–195.

Rybníčková, E. & Rybníček K. (2005). Pollen and macroscopic analyses of sediments from two lakes in the High Tatra mountains, Slovakia. *Veg. Hist. Archaeobot.*, 15, 345–356. DOI: 10.1007/s00334-006-0050-1.

Solár, J. (2013). Effect of climate change on Mountain Pine distribution in Western Tatra Mountains. In B.R. Singh (Ed.), *Change - Realities, Impacts Over Ice Cap, Sea Level and Risks*, pp. 437–458. Rijeka: InTech. DOI: 10.5772/54724.

Solár, J. & Janiga M. (2013). Long-term changes in Dwarf Pine (Pinus mugo) cover in the High Tatra Mountains, Slovakia. *Mt. Res. Dev.*, 33(1), 51–62. DOI: 10.1659/MRD-JOURNAL-D-12-00079.1.

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: 10.5194/nhess-12-2487-2012.

Šporka, F., Štefková, E., Bitušík, P., Thompson, A.R., Agustí-Panareda, A., Appleby, P.G., Grytnes, J.A., Kamenik, C., Krno, I., Lami, A., Rose, N. & Shilland N.E. (2002). The paleolimnological analysis of sediments from High Mountain Lake Nižné Terianske pleso in the High Tatras (Slovakia). *J. Paleolimnol.*, 28, 95–109. DOI: 10.1023/A:1020376003123.

Zasadni, J. & Kłapyta P. (2014). The Tatra Mountains during the Last Glacial Maximum. *Journal of Maps*, 10(3), 440–456. DOI: 10.1080/17445647.2014.885854.